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ACCUMULATION OF HEAVY METALS IN BIRD'S EGGS IN VARIOUS TRANSFORMED AREAS OF POLTAVA REGION (UKRAINE)

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Background. Most heavy metals (HMs) enter the bodies of birds through food chains. The increase in sources of contamination raises the concentrations of HMs in the soil, leading to their greater absorption into bird tissues and accumulation in eggs. The concentrations of HMs can vary significantly between the eggshell and the contents of eggs in different species.

Materials and Methods. The study focused on the eggs of four passerine bird species in 2024. The analysis of HM content (Cd, Co, Cr, Mn, Fe, Cu, Zn, Pb, Ni) in the eggs was conducted using the atomic absorption method in the Laboratory of Instrumental Soil Research Methods, Standardization, and Metrology at the National Scientific Center "O. N. Sokolovsky Institute of Soil Science and Agrochemistry".

Results. The levels of HMs detected in the eggs of house martin, great tit, blackbird, and song thrush from technogenic (Poltava Mining and Processing Plant (PMPP)) and natural (Regional Landscape Park "Nyzhniovorsklianskyi" (RLP) and Vakalivshchyna ravine complex (VAK)) areas indicate significant variability in their accumulation. Iron was the dominant element in all samples. In eggshells, iron ranged from 17.76±0.3 mg/kg (RLP) in the blackbird to 169.25±0.8 mg/kg (PMPP) in the song thrush. In egg contents, iron levels were consistently high across all samples, from 70.76±0.5 mg/kg (PMPP) in the great tit to 1107.8±2.51 mg/kg (RLP) in the house martin. Iron plays a crucial role in oxygen transport, storage, and utilization, which is essential for most enzymes and proteins during embryo development. Zinc levels were lower, ranging in eggshells from 1.55±0.26 mg/kg (RLP) in the blackbird to 27.58±0.89 mg/kg (RLP) in the song thrush. In egg contents, zinc levels showed less variation, from 9.19±0.2 mg/kg (PMPP) in the blackbird to 30.08±0.61 mg/kg (PMPP) in the great tit. Antioxidant properties of zinc strengthen the immune system and support metabolism. Manganese levels in eggshells ranged from 1.72±0.28 mg/kg (VAK) to 30.76±0.49 mg/kg (PMPP) in the great tit. In egg contents, manganese levels varied from 2.63±0.45 mg/kg (VAK) to 61.43±0.41 mg/kg (PMPP) in the great tit. Manganese compounds are less toxic than those of more common metals such as nickel and copper, but prolonged exposure may lead to reproductive dysfunction. A significant lead level (35.45±0.53 mg/kg) was detected in the egg contents of the blackbird (RLP), which could negatively affect embryo development. Such trace elements as chromium, copper, cadmium, cobalt, and nickel were detected in lower concentrations. The paper examines the influence of three factors on the content of heavy metals. Statistically significant interactions between the factors were identified, indicating the need for further research into the mechanisms of heavy metal accumulation and their environmental consequences.

Conclusion. The study confirmed that the level of heavy metals in bird eggs reflects the ecological state of the environment, allowing to assess the pollution of natural and man-made areas. Species and territorial features of the accumulation of Fe, Pb, Zn, Mn and other metals were identified suggesting the influence of the environment on their bioaccumulation. Three-factor analysis of variance showed that the main factors determining the concentrations of metals in eggs are environmental conditions and the habitat of birds. The results obtained emphasize the feasibility of using bird eggs as an effective tool for environmental monitoring.

Keywords: heavy metals, eggs, great tit, song thrush, common blackbird, house martin

INTRODUCTION

Environmental pollution with heavy metals (HM) represents a critical ecological issue of modern times, particularly in areas subjected to anthropogenic impacts (Mukhtar *et al*., 2020; Sarnowski & Kellam, 2023; Haas & Kočvara, 2023). HM accumulate in various ecosystem components, significantly affecting the health of both animals and humans (Dańczak *et al*., 1997).

In technogenic areas, such as industrial zones or regions with dense transportation infrastructure, the risk of toxic element accumulation in biota is notably high. Birds, as sensitive indicators of environmental conditions, play a vital role in monitoring pollution (Egwumah *et al*., 2017; Chaplygina *et al*., 2023). Due to diverse pathways of HM exposure – ranging from trophic transfer to contact with contaminated water bodies or atmospheric dust – birds serve as a reflective mirror of regional environmental health (Onyenweaku *et al*., 2018).

There is a limited body of research investigating the accumulation of HM in various bird species across specific regions of Ukraine (Chaplygina & Yuzyk, 2016; Vakhutkevych, 2012; Vasylitseva & Paranyak, 2017; Kryshtal *et al*., 2021), despite regular environmental quality monitoring efforts (Yarys *et al*., 2021;). In contrast, the concentration of heavy metals in birds' bodies and feathers has been more extensively studied in various regions of Europe (Alleva *et al*., 2006; Zhang & Ma, 2011), Japan (Lee *et al*., 1987), India (Manjula *et al*., 2015), and the USA (Jimeneza *et al*., 2005; Celik *et al*., 2021; Kabeer *et al*., 2021).

Heavy metal presence has been examined in birds' feathers (Goede & DeBruin, 1986; Dauwea *et al*., 2003; Veerle *et al*., 2003; Grúz *et al*., 2018), organs and tissues (Norheim, 1987; Kim *et al*., 2009; Liu *et al*., 2015), and eggs (Abdulkhaliq *et al*., 2012; Chukwujindu *et al*., 2012; Sobhanardakani, 2017; Rokanuzzaman *et al*., 2022).

The aim of this study was to analyze the concentrations of heavy metals in the eggs of birds nesting in technogenic and natural areas. The results obtained will enhance understanding of the consequences of anthropogenic impact on natural ecosystems and serve as a basis for developing environmental measures to minimize pollution.

MATERIALS AND METHODS

Observations on nesting birds in Poltava Region, specifically in the Kremenchuk and Poltava districts were conducted from 2022 to 2024. The study sites included rock dumps, treatment facilities, bioengineering structures, the drainage channel of the Poltava Mining and Processing Plant, and areas within the "Nyzhniovorsklyanskyi" Regional Landscape Park.

In this research, we compared the concentrations of HMs in bird eggs collected from different areas: technogenic (rock dumps of the Poltava Mining and Processing Plant, hereafter PMPP) and natural (the "Nyzhniovorsklyanskyi" Regional Landscape Park, hereafter RLP), as well as with data from the literature. The study focused on the concentrations of trace elements (Zn, Cu, Fe, Mn, Ni, Pb, Cr, Co, Cb) in both the shells and contents of eggs of passerine birds: the great tit (*Parus major*), the song thrush (*Turdus philomelos*), the common blackbird (*T. merula*), and the western house martin (*Delichon urbicum*). For comparative purposes, we utilized previously collected data on HM accumulation in the great tit eggs from natural areas in the Vakalivshchyna ravine complex (hereafter VAK) (Chaplygina & Yuzyk, 2016).

The experiment adhered to bioethical standards. For analysis, we collected eggs left in nests after hatching or from abandoned clutches. In total, 43 eggs were collected, including 12 from great tits, 10 each from song thrushes and common blackbirds, and 11 from house martins:

Bird species	PMPP	RLP
Song thrush	5	5
Common blackbird	5	5
Great tit	12	-
House martin	-	11

Research Methodology. The egg contents and shells were weighed and dried in a drying oven for several days. The obtained samples were incinerated to ash, and the resulting dry matter was weighed. The ash was dissolved in concentrated HCl, with water added to a final volume of 50 mL. The results were expressed in mg/kg of dry mass (egg content and shell).

The analysis of HM concentrations in eggs was conducted using the atomic absorption method in the Laboratory of Instrumental Soil Research Methods, Standardization, and Metrology at the National Scientific Center "O. N. Sokolovsky Institute of Soil Science and Agrochemistry".

Data on the content of heavy metals were evaluated using a three-way ANOVA with a post-hoc analysis by the Tukey test. Factors in these analyzes were: factor 1: sample source for analysis (for two factor levels: shell and egg content); factor 2: sample collection area for analysis (for three factor levels: PMPP, RLP and VAK); factor 3: type of bird (for three factor levels: common blackbird, song thrush, great tit). To compare the content of individual heavy metals in the eggshell and egg contents, the Student's *t*-test for independent data was used. Data are presented as Mean ± Standard Deviation (M ± SD). The Statistica8 program was used for the analysis, and the Origin 2018 program was used to establish the influence of the interaction of factors.

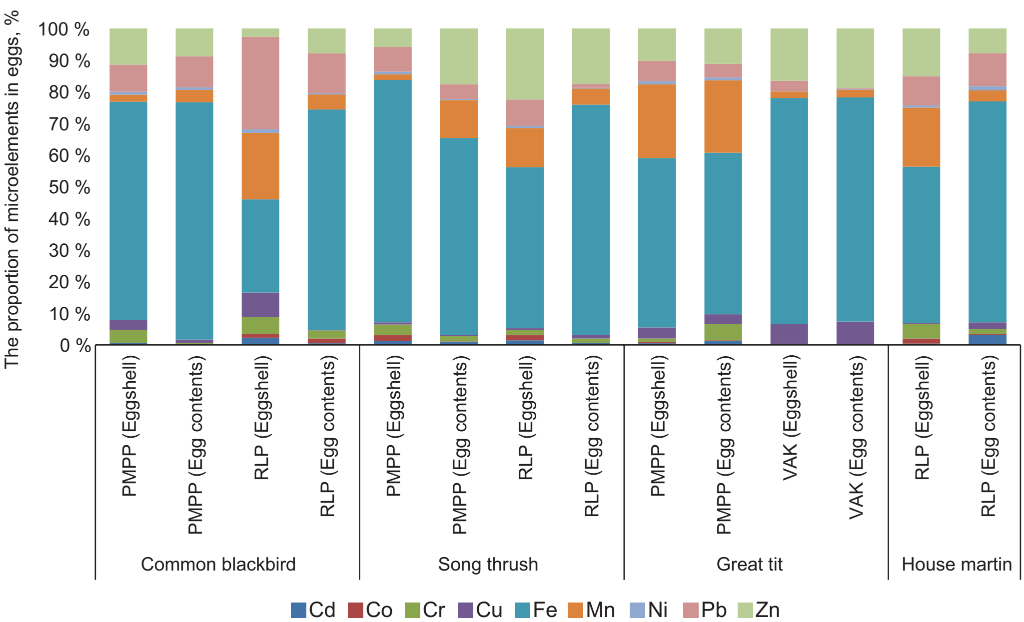
RESULTS AND DISCUSSION

The use of eggs as biological indicators to assess and monitor spatial and temporal trends in environmental pollution began to gain significant scientific interest several decades ago (Dauwea *et al*., 2003; Kim *et al*., 2009). Eggs reflect local pollution levels, demonstrating the absorption of contaminants by females feeding near anthropogenic areas prior to egg-laying. Most birds consume fruits of trees and shrubs.

Soil in different locations varies in its capacity to accumulate HMs, which are then transfered to plants, small invertebrates, and higher organisms. The greater the number of metal pollution sources, the higher the concentration in the soil (Liang *et al*., 2016). Consequently, more metals enter bird tissues and accumulate in their eggs, which accurately reflect the state of the local environment (Orłowski *et al*., 2015).

Some bird species, particularly thrushes, tend to forage in the understory and on the ground (Chaplygina *et al*., 2016; Chaplygina & Pakhomov, 2020).

The detected HMs in the samples, along with the proportional distribution of each element in the egg contents and shells of the studied bird species across all locations, are presented in **Figure**.



Concentrations of the accumulated HMs in the studied species across the examined territories

In all samples, iron predominated in the eggshell, ranging from 29.5 % (RLP) in the blackbird to 76.6 % (PMPP) in the song thrush. In the egg contents, a high proportion of iron was detected in all samples, from 51.1 % (PMPP) in the great tit to 75.0 % (PMPP) in the blackbird. The proportion of zinc in the eggshell was relatively high, varying from 2.6 % (RLP) in the blackbird to 22.5 % (RLP) in the song thrush. Zinc proportions in the egg contents showed less variation, ranging from 8.8 % (PMPP) in the blackbird to 18.8 % (VAK) in the great tit. Manganese proportions in the eggshell ranged from 1.8 % (PMPP) in the song thrush to 23.3 % (PMPP) in the great tit, while in the egg contents, manganese ranged from 2.4 % (VAK) to 22.9 % (PMPP) in the great tit. In the RLP area, a high percentage of lead was found in the eggshell of the blackbird (29.3 %) and in the egg contents of the song thrush (12.5 %).

In Spain, studies near a coal-fired power plant and in an uncontaminated area nearby examined metal accumulation in organs and tissues of passerine birds, including the great tit and the common blackbird. Analysis of blackbirds showed no significant differences in HM content between the two sites. However, in great tits from the coal power plant area, significantly higher levels of Cr were found in feathers compared to the uncontaminated area. Interspecies comparison revealed that blackbirds accumulated the highest levels of Cd and Cu in the liver and Cr, Pb, and Zn in bones (Llacuna *et al*., 1995).

In Beijing, concentrations of 11 HMs were analyzed in tissues of 10 body parts of the great tit to assess accumulation levels, distribution across body parts, and variations related to species and sex. The great tit demonstrated the highest levels of Hg, Cr, Ni, and Mn in body tissues (Deng *et al*., 2007).

A comparison of our data with studies by other researchers revealed certain differences. For example, according to our results, the house martin in the RLP area exhibited high HM concentrations in egg contents, including Fe (1107.8±2.51 mg/kg), Pb (165.0±2.01 mg/kg), and Zn (123.1±1.27 mg/kg) (**Table 1**, **2**, **3**). In the eggshell, the lowest levels were observed for Cd (0.60±0.25 mg/kg) and Cu (0.36±0.16 mg/kg) (**Table 2**, **5**). In contrast, G. Orłowski *et al*. (2015) reported the lowest levels of Cd and Pb and the highest levels of As in the feces of birds, specifically house martins, from agricultural areas in the temperate zone of Europe (Poland).

In Hungary, concentrations of various HMs, including As, Cd, Cr, Cu, Hg, Pb, Zn, were studied in contour feathers of barn swallows (*Hirundo rustica*), revealing the highest concentrations of Cd (0.13±0.06 mg/kg), Cr (1.69±0.44 mg/kg), and Pb (5.36±1.46 mg/kg) (Grúz *et al*., 2018). Research in the wetland area in New Jersey, where tree swallows (*Tachycineta bicolor*) nest, showed higher Pb levels in blood, relatively high Cr levels in eggs and blood compared to feathers, and low Cd levels across all tissues. Additionally, Fe levels in tree swallow body tissues in this study were significantly lower than those of all other metals (Tsipoura *et al*., 2008).

Iron (Fe) is an essential element for many enzymes and proteins, such as hemoglobin and myoglobin, which are involved in oxygen transport, storage, and utilization. Since iron is crucial for the process of hematopoiesis, high levels of this metal are normally found in the liver and kidneys, which play a role in blood filtration – a finding supported by scientific research. Elevated levels in the kidneys may be due to the limited number of samples. Iron homeostasis is also important for the efficient functioning of skeletal muscles (Orłowski *et al*., 2015).

The analysis of iron (Fe) concentrations across all studied species showed the highest levels in egg contents and lower levels in the eggshells. Concentration levels ranged from the lowest in the common blackbird's eggshell – 17.76±0.3 mg/kg (RLP), to the highest in the song thrush's eggshells – 169.25±0.8 mg/kg (PMPP). Surprisingly, Fe concentrations in the egg contents of the song thrush and blackbird were notably lower on the technogenic territory (PMPP) compared to the natural area (RLP). However, this pattern was not observed in the great tit where Fe levels in eggs on the territory of PMPP were 137.38±0.7 mg/kg, compared to 78.71±0.68 mg/kg in VAK (**Table 1**).

Overall, the iron content in eggs of all studied species showed levels 6–10 times higher than normal. Thrushes, as migratory species, may accumulate iron during migration, while the great tit is more closely tied to its nesting territory. However, determining the exact cause of this phenomenon requires further research.

Table 1. **Iron concentrations (Fe) (mg/kg, dry weight) in egg contents and eggshells (M±SD)**

Bird species	Area	Eggshell	Egg contents
Song thrush	PMPP	169.25±0.8	103.95±0.2****
	RLP	52.00±0.2	114.61±0.8****
Common blackbird	PMPP	88.35±0.5	78.48±0.9****
	RLP	17.76±0.3	197.00±0.6****
Great tit	PMPP	70.76±0.5	137.38±0.7****
	VAK	55.74±0.77	78.71±0.68****
House martin	RLP	76.90±1.32	1107.8±2.51

Marked: **** – $p < 0.0001$ – the difference is reliable as compared to the eggshell

Zinc, which is acquired through food and respiration, is an essential trace element in birds' bodies. Zinc primarily accumulates in calcified tissues, such as bones and eggshells, rather than in soft tissues (Sorensen, 1991; Mukhtar *et al.*, 2020). According to our data, the highest levels of zinc were found in egg contents across all study areas. Interspecies comparison of zinc levels revealed the highest values of this element on the technogenic territory in egg contents of the great tit (30.08±0.61 mg/kg) and the song thrush (29.44±0.33 mg/kg), while the lowest level was recorded in the blackbird (9.19±0.2 mg/kg) (**Table 2**).

Copper (Cu) is a vital component of redox enzyme system and plays a key role in iron metabolism. It is also involved in the formation of bone and connective tissues. Significant Cu accumulation has been reported in the heart, liver, and kidneys (Mukhtar *et al.*, 2020). Our results and data obtained from the VAK area show the highest copper concentrations in the egg content of the great tit: 8.02±0.21 mg/kg (PMPP) and 8.02±0.54 mg/kg (VAK). In the blackbird's eggshells, Cu levels were similar across both research sites, PMPP – 4.12±0.39 mg/kg, and RLP – 4.61±0.31 mg/kg (**Table 2**).

Manganese (Mn) is an essential element for all living organisms that plays a key role in the functioning of most proteins and enzymes. Manganese compounds are less toxic compared to the compounds of such common metals as nickel and copper. However, prolonged exposure to this element can lead to reproductive dysfunction. In higher vertebrates, excess manganese predominantly accumulates in bone tissue, while its smaller amounts are deposited in soft tissues, such as the liver and kidneys (Sarnowski & Kellam, 2023).

Table 2. **Concentrations of zinc (Zn) and copper (Cu) (mg/kg, dry weight) in egg contents and eggshells (M±SD)**

Bird species	Area	Zn		Cu	
		Eggshell	Egg contents	Eggshell	Egg contents
Song thrush	PMPP	12.88±0.12	29.44±0.33****	1.51±0.29	0.49±0.26***
	RLP	22.96±0.23	27.58±0.89****	0.60±0.22	1.78±0.20****
Common blackbird	PMPP	14.63±0.8	9.19±0.2****	4.12±0.39	1.06±0.31****
	RLP	1.55±0.26	22.35±0.41****	4.61±0.31	0.36±0.20****
Great tit	PMPP	13.58±0.30	30.08±0.61****	4.64±0.50	8.02±0.21****
	VAK	55.74±0.63	2.63±0.36****	2.58±0.38	0.38 ± 0.32****
House martin	RLP	23.45±0.16	123.1±1.27	0.36±0.16	32.50±0.94

Marked: *** – p <0.001; **** – p <0.0001 – the difference is reliable as compared to the eggshell

Our results show that manganese predominantly accumulates in the egg contents of all studied species, both in the technogenic area (PMPP) and the natural area (RLP). Interspecies comparison showed that the great tit exhibited considerably higher manganese levels in egg contents in PMPP (61.43±0.41 mg/kg) than in VAK (2.63±0.22 mg/kg) (Chaplygina & Yuzyk, 2016) (**Table 3**).

Lead (Pb) accumulates in small amounts in bones, while the remainder is excreted from the body through urine and feces within a few weeks after exposure. The highest concentrations of lead are typically observed in the blood immediately after absorption, followed by accumulation in the liver and kidneys over several days or months. However, in bones, lead can remain for many years (Fisher *et al.*, 2006).

Despite a significant reduction in atmospheric lead (Pb) concentrations in urban areas of most industrialized countries, researchers in eastern France suggested that blackbirds (*Turdus merula*) inhabiting urban areas, whose blood as well as washed and unwashed feathers of the tail and breast were examined, may still be exposed to increased concentrations of Pb. This fact raises concerns due to the potential entry of this trace element into the food chain from soil. Blackbirds from urban areas were found to have significantly higher lead concentrations in their tail and breast feathers, and blood compared to rural individuals. High levels of external contamination in urban birds' tail feathers were likely caused by dust deposition, while the high lead content in blood may be associated with the food chain involving urban soils (Scheifler *et al.*, 2006).

Our results indicate that Pb may still pose an ecological issue for blackbirds due to the persistence of Pb in soil and its transfer through the food chain. Its highest levels were observed in egg contents in PMPP – 10.25±0.62 mg/kg, and in RLP – 35.45±0.53 mg/kg. Other studied species also demonstrated high lead levels, particularly in the eggshells of the song thrush and in the egg contents of the great tit (**Table 3**).

Table 3. **Concentrations of manganese (Mn) and lead (Pb) (mg/kg, dry weight) in egg contents and eggshells (M±SD)**

Bird species	Area	Mn		Pb	
		Eggshell	Egg contents	Eggshell	Egg contents
Song thrush	PMPP	3.97±0.19	19.94±0.57****	17.26±0.28	7.78±0.23****
	RLP	12.69±0.39	7.97±0.48****	8.46±0.61	1.89±0.37****
Common blackbird	PMPP	2.74±0.30	4.10±0.72**	11.14±0.76	10.25±0.62
	RLP	12.67±0.37	13.20±0.26*	17.64±0.35	35.45±0.53****
Great tit	PMPP	30.76±0.49	61.43±0.41****	8.34±0.40	11.67±0.59****
	VAK	1.72±0.28	2.63±0.45****	2.58±0.51	0.38 ± 0.24****
House martin	RLP	28.93±0.26	54.38±0.35	14.35±0.45	165.0 ± 2.01

Marked: * – p <0.05; ** – p <0.01; **** – p <0.0001 – the difference is reliable as compared to the eggshell

Chromium (Cr) influences carbohydrate and lipid metabolism, reduces stress responses, and stimulates the immune system in birds. It can also enhance productivity and decrease fat levels (Stępniowska *et al*., 2020). Chromium accumulation is primarily observed in the liver, kidneys, and spleen, with smaller amounts in the heart, muscles, bones, and brain. Bones are one of the tissues capable of storing Cr for extended periods, in contrast to the heart, pancreas, and brain, where Cr accumulation is short-term (Haas & Kočvara, 2023).

The highest chromium accumulation in the technogenic territory of PMPP was observed in the egg content of the great tit (14.13±0.24 mg/kg), as well as in the eggshells of the song thrush (7.40±0.50 mg/kg), while the common blackbird had lower levels of Cr (5.07±0.35 mg/kg). On the territory of RLP, a high Cr content was found in the egg content of the common blackbird (7.35±0.60 mg/kg) (**Table 4**).

In Portugal, metal concentrations (As, Cd, Cu, Hg, Ni, Pb, Se, and Zn) were measured in the feathers and feces of nestlings and adult females of great tits (*Parus major*) near a paper mill and in a pine forest. The study showed similar patterns of metal accumulation in these areas, with nickel showing significantly higher levels in the proximity of the paper mill (Costa *et al*., 2013). According to our results, nickel levels were low overall. The highest levels were found in the eggshells of the song thrush (2.19±0.37 mg/kg) and in the egg content of the great tit (2.14±0.26 mg/kg) on the territory of PMPP, while these levels were considerably lower in RLP and VAK (**Table 4**).

Other metals, such as cadmium (Cd) and cobalt (Co), were found in small quantities in both eggshells and egg content across all bird species analyzed. However, Cd was detected in higher concentrations in the eggshells of the song thrush (2.53±0.53 mg/kg) and in the egg content of the great tit (3.49±0.32 mg/kg) in the technogenic area of PMPP. Significant Co levels were observed only in the eggshells of the song thrush (3.90±0.55 mg/kg) in the area of PMPP. In general, relatively small concentrations of Co and Cd, compared to other HMs, may suggest accumulation of these trace metals during migration (**Table 5**).

Table 4. **Concentrations of chromium (Cr) and nickel (Ni) (mg/kg, dry weight) in egg contents and eggshells (M±SD)**

Bird species	Area	Cr		Ni	
		Eggshell	Egg contents	Eggshell	Egg contents
Song thrush	PMPP	7.40±0.50	2.93±0.32****	2.19±0.37	0.59±0.25****
	RLP	1.63±0.17	2.17±0.28**	0.72±0.24	0.50±0.25
Common blackbird	PMPP	5.07±0.35	0.38±0.11****	1.18±0.27	0.84±0.11*
	RLP	3.24±0.28	7.35±0.60****	0.67±0.13	1.25±0.14***
Great tit	PMPP	1.29±0.54	14.13±0.24****	1.42±0.22	2.14±0.26****
	VAK	0.25±0.24	0.19±0.08	0.10±0.10	0.31±0.20**
House martin	RLP	7.32±0.13	26.88±0.56	1.13±0.05	21.25±0.67

Marked: * – p<0.05; ** – p<0.01; *** – p<0.001; **** – p<0.0001 – the difference is reliable as compared to the eggshell

Table 5. **Concentrations of cadmium (Cd) and cobalt (Co) (mg/kg, dry weight) in egg contents and eggshells (M±SD)**

Bird species	Area	Cd		Co	
		Eggshell	Egg contents	Eggshell	Egg contents
Song thrush	PMPP	2.53± 0.53	1.64±0.23**	3.90±0.55	0.12±0.11****
	RLP	1.44± 0.32	1.00±0.11*	1.68±0.28	0.07±0.05****
Common blackbird	PMPP	0.66± 0.34	0.25±0.16*	0.11±0.13	0.03±0.02
	RLP	1.36± 0.34	1.30±0.13	0.72±0.29	4.30±0.42****
Great tit	PMPP	0.66± 0.26	3.49±0.32****	0.70±0.25	0.32 ± 0.24**
	VAK	-	-	-	-
House martin	RLP	0.60± 0.25	51.25±0.58	2.56±0.07	1.88±0.08

Marked: * – p<0.05; ** – p<0.01; **** – p<0.0001 – the difference is reliable as compared to the eggshell

As a result of the conducted three-factor dispersion analysis, a statistically significant influence of the three investigated factors on the content of heavy metals was established (**Table 6**). In general, factors 2 and 3 have the greatest influence on the metals content, while factor 1 affects only certain elements (cadmium, manganese, iron).

Table 6. **Results of three-factor analysis of variance ANOVA**

Metals	Factor 1	Factor 2	Factor 3
Cd	**p = 0.0018**	p = 0.98	**p = 0.0017**
Ni	p = 0.422	**p = 0.0000**	**p = 0.000202**
Pb	p = 0.734	**p = 0.00001**	**p = 0.000109**
Zn	p = 0.082	**p = 0.0401**	**p = 0.0428**
Mn	**p = 0.000115**	**p = 0.00000**	**p =0.00000**
Fe	**p = 0.000115**	**p = 0.00000**	**p = 0.033**
Cu	p = 0.118940	**p = 0.00000**	**p = 0.00000**
Co	p = 0.202910	**p = 0.012575**	p = 0.412977
Cr	**p = 0.000183**	**p = 0.00000**	p = 0.9333

Note: Significant effects are indicated in bold

CONCLUSIONS

Based on the conducted study, it was established that bird eggs serve as reliable bioindicators of heavy metal (HM) contamination in the environment, as their composition reflects pollution levels in the studied areas. Significant differences in HM concentrations were observed between natural (RLP, VAK) and technogenic (PMPP) zones, confirming the impact of anthropogenic factors on the spread of toxic elements. Different bird species exhibit specific patterns of metal accumulation, likely due to their ecological niches and feeding habits.

The highest iron (Fe) concentrations in egg contents were recorded in the house martin (1107.8±2.51 mg/kg, RLP), song thrush (103.95±0.2 mg/kg, PMPP), and common blackbird (197.00±0.6 mg/kg, RLP). Lead (Pb) also accumulated in significant amounts, particularly in the eggs of the common blackbird (35.45±0.53 mg/kg, RLP) and house martin (165.0±2.01 mg/kg, RLP). Zinc (Zn) levels were the highest in the egg contents of the great tit (30.08±0.61 mg/kg, PMPP). Manganese (Mn) showed the greatest accumulation in the egg contents of the great tit (61.43±0.41 mg/kg, PMPP) and house martin (54.38±0.35 mg/kg, RLP).

The distribution of metals between eggshells and egg contents revealed that Fe, Zn, and Mn predominantly accumulate in the eggshell, whereas Pb, Cr, and Ni are mainly found in the egg contents.

The three-factor variance analysis (ANOVA) showed a statistically significant effect of the investigated factors on the accumulation of heavy metals in bird eggs. Among the three studied factors, factors 2 and 3 had the most substantial influence on metal concentrations, while factor 1 affected only specific elements such as Cd, Mn, and Fe. This suggests that environmental conditions, such as habitat type and pollution sources, play a greater role in metal accumulation than species-specific traits. The observed patterns indicate that birds living in more polluted areas, particularly in technogenic zones, tend to accumulate higher levels of metals.

Overall, the results emphasize the importance of using bird eggs as bioindicators for monitoring environmental pollution. They also underline the need for further research to determine the long-term effects of heavy metal contamination on avian populations and ecosystems, particularly in areas exposed to anthropogenic pollution.

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest: the authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as apotential conflict of interest.

Animal studies: the experiment was conducted in compliance with bioethics, in accordance with the provisions of the Convention on the Protection of Vertebrate Animals Used for Experimental and Other European Scientific Purposes (Strasbourg, 1986), and does not violate the conventions on wildlife protection in Europe (Berne Convention), the Law of Ukraine "On Fauna" (March 3, 1993), the Law of Ukraine "On Environmental Protection" (June 26, 1991).

AUTHOR CONTRIBUTIONS

Conceptualization, [L.L; A.Ch.] methodology, [L.L; A.Ch.]; validation, [L.L.; A.Ch.]; formal analysis [L.L.; A.Ch.]; investigation, [L.L; A.Ch.] resources, [L.L.; A.Ch.]; data curation, [L.L.; A.Ch.]; writing – original draft preparation, [L.L.]; writing – review and editing, [L.L.; A.Ch.]; visualization, [L.L.]; supervision, [L.L.; A.Ch.]; project administration, [L.L.; A.Ch.]; funding acquisition, [L.L.; A.Ch.].

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АКУМУЛЯЦІЯ ВАЖКИХ МЕТАЛІВ У ЯЙЦЯХ ПТАХІВ НА РІЗНИХ ТРАНСФОРМОВАНИХ ТЕРИТОРІЯХ ПОЛТАВСЬКОЇ ОБЛАСТІ (УКРАЇНА)

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Обґрунтування. Більшість важких металів (ВМ) потрапляють до організму птахів по ланцюгах живлення. Збільшення джерел забруднення полютантами підвищує концентрацію їх у ґрунті, а також більше ВМ потрапляє у тканини птахів і накопичується в яйцях. Накопичення ВМ може значно варіювати у шкаралупі та у вмісті яєць різних видів птахів.

Матеріали та методи. Об’єктами досліджень були яйця 4 видів горобцеподібних птахів у 2024 р. Аналіз вмісту ВМ (Cd, Co, Cr, Mn, Fe, Cu, Zn, Pb, Ni) у яйцях проводили атомно-абсорбційним методом у лабораторії інструментальних методів досліджень ґрунтів, стандартизації та метрології ННЦ “Інститут ґрунтознавства та агрохімії імені О. Н. Соколовського”.

Результати. Виявлені ВМ у ластівки міської, синиці великої, дроздів чорного та співочого на техногенній (Полтавський гірничо-збагачувальний комбінат (ПГЗК)) та природній (Регіональний ландшафтний парк “Нижньоворсклянський” (РЛП) і урочище Вакалівщина (ВАК)) територіях свідчать про значну варіабельність у їхньому накопиченні. За складом у всіх зразках домінувало залізо. У шкаралупі від 17,76±0,3 мг/кг (РЛП) у дрозда чорного до 169,25±0,8 мг/кг (ПГЗК) у дрозда співочого. У вмісті яєць виявлено високу частку заліза в усіх зразках: від 70,76±0,5 мг/кг (ПГЗК) у синиці великої до 1107,8±2,51мг/кг (РЛП) у ластівки міської. Залізо бере участь у транспортуванні, зберіганні та використанні кисню, що є важливим для більшості ферментів і білків під час розвитку ембріона. Менше виявлено цинку: у шкаралупі від 1,55±0,26 мг/кг (РЛП) у дрозда чорного до 27,58±0,89 мг/кг (РЛП) у дрозда співочого. У вмісті яєць частка Zn варіювала менше: від 9,19±0,2 мг/кг (ПГЗК) у дрозда чорного до 30,08±0,61 мг/кг (ПГЗК) у синиці великої. Антиоксидантні властивості Zn підвищують імунну систему та беруть участь у метаболізмі. Марганець у шкаралупі від 1,72±0,28 мг/кг (ВАК) до 30,76±0,49 мг/кг (ПГЗК) у синиці великої. У вмісті яєць: від 2,63±0,45 мг/кг (ВАК) до 61,43±0,41 мг/кг (ПГЗК) у синиці великої. Сполуки Mn є менш токсичними, порівняно зі сполуками таких поширених металів як Ni і Cu, проте тривалий вплив може призводити до порушень репродуктивної функції. У вмісті яєць дрозда чорного (РЛП) виявлено значний показник свинцю (35,45±0,53 мг/кг), який може негативно впливати на розвиток зародка. Концентрацію Cr, Cu, Cd, Co, Ni виявлено меншу. У роботі досліджено вплив трьох

факторів на вміст важких металів. Виявлено статистично значущі взаємодії між факторами, що вказує на необхідність подальших досліджень механізмів накопичення важких металів та їхніх екологічних наслідків.

Висновки. Дослідження підтвердило, що рівень важких металів у яйцях птахів відображає екологічний стан середовища, даючи змогу оцінювати забруднення природних і техногенних територій. Виявлено видові й територіальні особливості накопичення Fe, Pb, Zn, Mn та інших металів, що свідчить про вплив середовища на їхню біоакумуляцію. Трьохфакторний дисперсійний аналіз показав, що головними чинниками, які визначають концентрації металів у яйцях, є екологічні умови та місце проживання птахів. Отримані результати підкреслюють доцільність використання яєць птахів як ефективного інструменту екологічного моніторингу.

Ключові слова: важкі метали, яйця, синиця велика, дрізд співочий, дрізд чорний, ластівка міська

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