Chemické Listy
Original and Methodical Papers
www.chemicke-listy.cz

MIGRATION OF MICRO-, MACROELEMENTS AND HEAVY METALS IN THE TROPHIC CHAIN OF BEES

NICOLAE G. EREMIA[a], OLGA COŞELEVA[a], VITALII JEREGHI[a], NATALIA SUCMAN[b], TATIANA MARDARI[a], IVAN CATARAGA[a], and FLIUR Z. MACAEV[b]

[a]Department of the Animal Resources and Food Safety, Technical University of Moldova, Chisinau, Moldova; [b]Laboratory of Organic Synthesis, Institute of Chemistry, Moldova State University, Academiei str., 3, MD-2028 Chișinău, Moldova
fliur.macaev@sti.usm.md

This study investigates the migration of microelements (iron, zinc, copper, manganese), macroelements (calcium, potassium, magnesium, sodium, phosphates) and heavy metals (cadmium, lead, nickel, chromium) through the trophic chain from soil to honey plants, bees, and their products (honey, propolis) across various soil-climatic zones of the Republic of Moldova over 2020–2023, employing standardized analytical methods. The findings highlight selective migration and bioaccumulation patterns, which are crucial for understanding element distribution in ecosystems.

Keywords: micro-, macro-elements, heavy metals, soil, honey plant flowers, honey, pollen, propolis, bees

Introduction

The effects of human activities, such as agriculture, urbanization, industrialization, transport, and climate change on plant life, are becoming increasingly apparent. Pollution arises when heavy metals are present in soil, water resources, and air in concentrations exceeding established standards[1]. Honey produced by bees can be a valuable source of essential microelements for human health. However, if the levels of these elements exceed safe limits, honey can become toxic[2]. The main pollutants that negatively impact the environment include heavy metals (Pb, Cd, Hg, Co, Cr, Cu, Ni, and Zn), which are released into the atmosphere as dust and smoke gases from fuel combustion and various high-temperature industrial processes[3].

Currently, significant attention is being paid to studying the properties of heavy metals, their migration into the environment, and their presence in various food products, including beekeeping products[4–6]. Sources of pollution include water, air, and soil, all of which are directly and indirectly impacted, resulting in negative environmental effects[7].

Pollution of the surrounding atmosphere by harmful emissions from industrial enterprises and road transport has a direct impact on bees and their metabolic products. Pollutants are carried into the bee nest along with nectar, honeydew, pollen, and water, contaminating honey, propolis, wax, and bee bread[8]. Bees, collecting nectar and pollen within a radius of 3–5 km from the apiary, also transport substances that pollute the environment. Consumption of contaminated nectar and pollen introduces pollutants into the bodies of bees, reducing their lifespan and sometimes causing death. Knowledge about the cumulative properties of honey plants and the presence of pollutants is essential when determining the location of an apiary[9].

Heavy metals found in the environment can be deposited on honeybees' hairy bodies, flowers, grasses, and water[10]. High accumulation of heavy metals in plants is dangerous to the food chain and can harm human and animal health. According to literature, the presence of lead, cadmium, and chromium in bee honey indicates micro-pollution of metals in the environment[11]. Trace amounts of metals such as Zn, Cu, and Mn are common in honey and are not harmful to health. However, toxic metals like Cd, Cr, and Pb can harm people's health[12]. Certain mineral elements, including toxic ones, are distributed and accumulated in beekeeping products along the trophic chain of bees. Bee colonies can serve as indicators of the level of pollution[13–15]. Heavy metals with high toxicity accumulate in soil and plants, spread along trophic chains, and pose a significant threat to both humans and honeybees[16].

The accumulation of heavy metals, including lead, in honey plants, beekeeping products, and the bodies of bees due to technogenic environmental pollution remains a current problem[17,18]. Therefore, the purpose of this research is to study the diversity and migration of micro-, macroelements, and heavy metals in the trophic chain (soil >> honey plant flowers >> honey >> pollen >> propolis >> bees) under the environmental conditions of the Republic of Moldova.

Methods and materials

To study the diversity and migration of micro-, macroelements, and heavy metals in the trophic chain, samples from various sources collected between 2020 and 2023 were analyzed. The study included 6 soil samples, 14 flower samples, and 20 honey samples from honey plants (acacia, linden, sunflower) across different soil-climatic zones (Southern, Central, and Northern) of the Republic of Moldova. Additionally, it was analyzed 6 pollen samples, 4 propolis samples, and 4 bee samples, totaling 54 samples. The results were presented as arithmetic averages for all years of observation across all zones.

For soil analysis, samples were taken using a drill at depths of up to 30 cm in areas where sunflowers grew and at depths of 60 cm in forest zones where acacia and linden grew. The soil samples were mixed, air-dried, and crushed using a laboratory mill (ML-3) to achieve a uniform mass for analysis.

Honey samples (acacia, linden, and sunflower) were collected after being pumped in various zones. The honey was stored in laboratory conditions, sealed in glass jars at a temperature of 21 ± 2 °C. All physicochemical methods followed the harmonized methods of the International Honey Commission.

Flower samples from honey plants (acacia, linden, and sunflower) were collected during their flowering periods, dried to an air-dry state in the laboratory, crushed using a laboratory mill, and then analyzed.

Pollen samples were obtained using pollen traps during the flowering of honey plants. The pollen was dried to an air-dry state, crushed with a laboratory mill, and then analyzed.

Bee samples were taken from the same apiaries where honey was collected. Adult bees were selected from the outermost combs of the nests, frozen for a day, and then had their honey crops and intestines removed. The bees were dried in an oven at 65 °C, crushed using a laboratory mill, and then analyzed.

All assays were performed in triplicate, and data were expressed as mean ± standard deviation (SD). Data were processed using variation statistics methods and Microsoft Excel.

The content of micro- and macroelements, as well as heavy metals in the samples, was determined by atomic absorption spectrometry after dry ashing according to SM SR EN 14082:2006. The AAS-1N atomic absorption spectrophotometer was used to monitor absorption spectra in the wavelength range of 190-360 nm, with a single exposure time of 5 ms and sputtering pulses of 1–2 seconds for determining K, Na, Ca, Mg, Fe, Mn, Cu, and Zn. Cr, Ni, Cd, and Pb were determined using a Shimadzu A-7000 atomic absorption spectrophotometer with a GFA-7000A electrothermal atomizer.

The accumulative or migration coefficient (C) is calculated as the ratio of the element concentration in the subsequent trophic level to its concentration in the previous level[19].

Results and discussions

This study highlights the significant variations in microelement and macroelement content across different components of the trophic chain, emphasizing the complex interactions and dependencies within ecosystems.

Furthermore, it is important to note that the greatest variability in the data belongs to the iron concentrations in propolis, which deviate by almost 50% from the mean value over four years across different regions and honey types. Based on these data, it can be concluded that iron concentration in propolis is not a relatively constant value but rather depends on various factors.

Considering that copper and zinc compounds are often used in agriculture as fungicides and foliar feeds, determining the concentrations of these metals in the studied objects and their sequential migration is of particular interest (naturally, acacia and linden are not treated by fungicides and fertilizers). It was shown that zinc exhibits minimal presence in soil but dramatically increases in concentration through the trophic chain, particularly in the bee body (63.6 ± 6.0 mg kg^{-1}) and propolis (114.6 ± 16.6 mg kg^{-1}) (Table I, Entry 2). Notably, the concentration of zinc in flowers (20.8 ± 9.6 mg kg^{-1}) was much lower than the lethal concentration of zinc in nutrient solutions (LC_{50} = 66 mg/L)[23]. However, the substantial accumulation in propolis suggests zinc's strong migration potential and significant role in bee health[24–26].

It was found that copper, though in smaller quantities compared to zinc, also shows notable accumulation in the bee body (11.4 ± 3.4 mg kg^{-1}) compared to its initial content in the soil (1.0 ± 0.2 mg kg^{-1}). This trend indicates the bioavailability and mobility of copper within the ecosystem, albeit to a lesser extent than zinc. The lesser accumulation of copper might be explained by studies where authors conducted 2-choice 24-hour feeding experiments to determine feeding preference or avoidance for Cu, demonstrating a tendency for honey bees to be deterred by high concentrations of Cu in forage[23].

Manganese shows a relatively low concentration in soil but demonstrates considerable accumulation, especially in bee bodies (28.0 ± 7.7 mg kg^{-1}) and pollen grains (23.2 ± 9.1 mg kg^{-1}), indicating significant uptake from honey plant flowers (21.8 ± 5.7 mg kg^{-1}). The transfer from flowers to pollen and then to bee bodies highlights the movement of manganese through the food chain. This can be explained by the fact, that manganese is necessary for honey bees at different periods of ontogenesis[27].

For a better understanding of the migration processes the relationships for chemical elements accumulation in recipient and donor in the trophic chain were evaluated, also, by using the accumulation or migration coefficient (C), which was calculated and results were summarised in Fig. 1.

Table I
The average concentration of the microelements in samples (mg kg^{-1})

Element	Soil	Honey plants flowers	Pollen grains	Bee body	Propolis	Honey
Mn	<0.7	21.8 ± 5.6	23.1 ± 9.1	28.0 ± 7.7	17.4 ± 5.6	1.5 ± 1.0
Zn	<0.75	20.8 ± 9.6	37.2 ± 1.6	63.6 ± 6.0	114.6 ± 16.6	1.2 ± 0.3
Cu	1.0 ± 0.2	7.1 ± 0.5	7.5 ± 2.8	11.4 ± 3.4	3.7 ± 0.4	1.3 ± 0.0
Fe	2.2 ± 0.7	74.3 ± 14.8	46.4 ± 7.8	126.2 ± 24.1	975.1 ± 491.9	3.7 ± 0.9

It is logical that in all cases, the migration of microelements, particularly the discussed metals, from the bee body to honey either does not occur or occurs at very low concentrations.

Overall, the cumulative coefficients indicate the efficiency of microelement migration and bioaccumulation in bees and their related products, with iron showing the highest levels of accumulation, followed by zinc, manganese and copper.

The migration process of macroelements (Ca, Mg, Na, K, P) from the soil through honey plants to bees and their products (honey, pollen grains, propolis, bee body) can be described based on the data presented in Table II.

The data on calcium, magnesium, potassium, and phosphate concentrations across various components of the trophic chain reveal a significant migration of these essential macroelements. So, the baseline concentration of calcium in the soil is recorded at 160.6 ± 24.6 mg kg^{-1}. The relatively low concentration in the soil compared to subsequent trophic levels indicates that calcium is efficiently absorbed by plants. Honey plant flowers show a dramatic increase in calcium concentration, reaching 6604.1 ± 1608.8 mg kg^{-1}. This substantial rise confirms that honey plants have a high affinity for calcium, which is vital for various physiological processes. Calcium plays a crucial role in cell wall stability, signal transduction, and enzyme activation in plants[20], which drives its accumulation in such high quantities.

The wide range in calcium concentration values can be explained by the fact that we analyzed not only the flowers of various honey plants, such as sunflower, acacia, and linden, which naturally have significantly different chemical compositions but also samples from different regions. The southern areas represent steppe zones with a fairly dry climate, the northern areas are forested, and the central zone is suburban. From the flowers, calcium migrates into pollen grains, where the concentration drops to 1459.7 ± 164.5 mg kg^{-1}. The concentration in bee

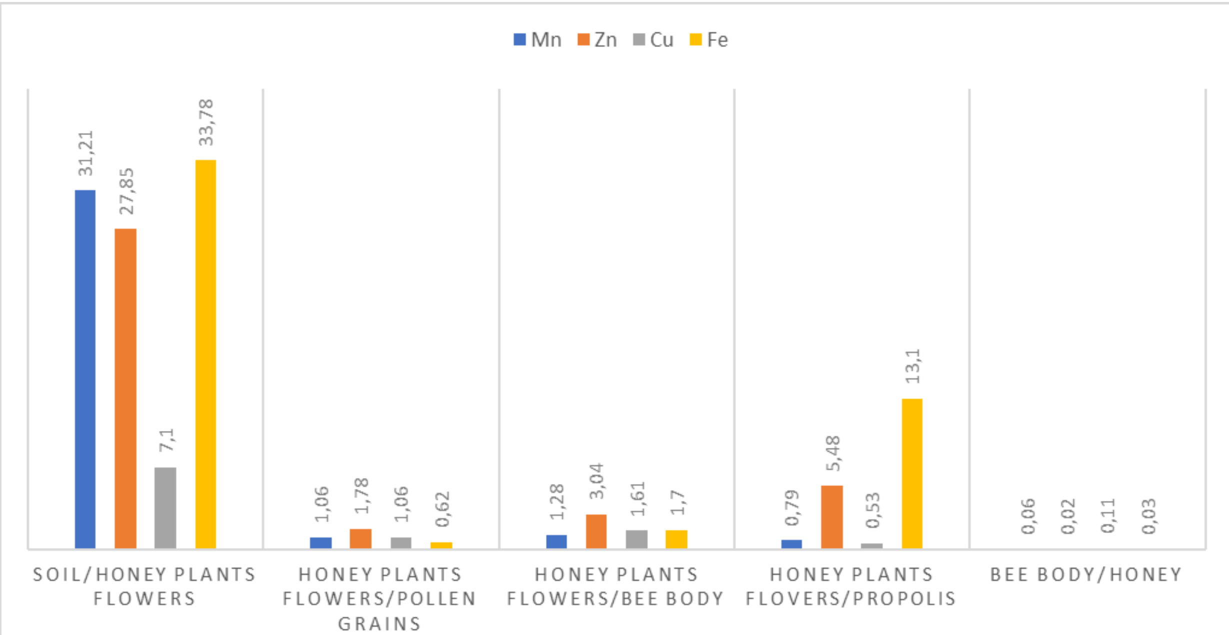

Fig. 1. **Diagram with migration coefficients of microelements in trophic chain**

Table II
The average concentration of the macroelements in samples (mg kg^{-1})

Element	Soil	Honey plants flowers	Pollen grains	Bee body	Propolis	Honey
Ca^{2+}	160.6 ± 24.6	6604.1 ± 1608.8	1459.7 ± 164.5	875.2 ± 453.1	2528.4 ± 1122.8	64.0 ± 16.2
Mg^{2+}	14.8 ± 1.5	2084.8 ± 830.4	626.0 ± 103.5	705.4 ± 73.6	300.6 ± 59.8	24.3 ± 8.4
K^{+}	37.9 ± 8.4	17475.7 ± 3437.8	4343.7 ± 814.2	8736.7 ± 1428.3	1252.4 ± 172.8	662.7 ± 266.3
Na^{+}	10.4 ± 6.1	38.1 ± 7.6	26.8 ± 2.2	461.1 ± 147.1	90.2 ± 5.1	22.6 ± 2.7
$(P_2O_5)^{3-}$	4.7 ± 2.0	10615.0 ± 689.6	10929.7 ± 2737.3	24250.9 ± 3883.2	1775.1 ± 192.2	175.9 ± 26.3

bodies is measured at 875.2 ± 453.1 mg kg^{-1}. This value reflects the dietary intake of calcium through pollen and nectar and its essential role in bee physiology. Calcium is critical for muscle function, neural transmission, and exoskeleton formation in bees[28]. It was revealed that its concentration is higher in propolis (2528.4 ± 1122.8 mg kg^{-1}) compared to bee bodies. Finally, honey exhibits the lowest concentration of calcium among the samples, with 64.0 ± 16.2 mg kg^{-1}. This low concentration suggests that the migration of calcium from bee bodies and pollen to honey is minimal.

Nevertheless, in the soil, magnesium concentration also is relatively low (14.8 ± 1.5 mg kg^{-1}), similar to calcium. It increases significantly in honey plants flowers (2084.8 ± 830.4 mg kg^{-1}). This substantial increase suggests that magnesium is readily taken up by plants from the soil. Magnesium is one of the most abundant cations in living cells[29], and a key element in the photosynthetic process. The concentration decreases in the bee body (705.4 ± 73.6 mg kg^{-1}) and in propolis (300 ± 60 mg kg^{-1}). This indicates that magnesium is efficiently transferred from the soil to the bees and propolis, but honey shows a much lower concentration (24.3 ± 8.4 mg kg^{-1}), indicating minimal transfer of magnesium from the bees into the honey.

Potassium is an essential macronutrient for both plants and animals, playing a crucial role in various physiological processes. The concentration of potassium in soil is 37.9 ± 8.4 mg kg^{-1}. This relatively low concentration undergoes a dramatic increase in honey plants flowers, reaching 17475.7 ± 3437.8 mg kg^{-1}. This significant uptake highlights the essential role of potassium in plant physiology, where it is critical for processes such as osmoregulation, enzyme activation, and photosynthesis[20]. In the bee body, potassium concentration increases to 8736.7 ± 1428.3 mg kg^{-1}. This significant accumulation underscores the important role of potassium in bee physiology, including muscle function, nerve signal transmission, and overall cellular metabolism[30,31]. The concentration of potassium in propolis drops to 1252.4 ± 172.8 mg kg^{-1}. Propolis is a complex mixture of plant resins and beeswax, and the lower potassium concentration compared to the bee body suggests selective incorporation or differential usage of potassium in propolis. Potassium may not be as critical in the composition of propolis, which serves primarily as a structural and protective material in the hive. Unlike the previously discussed macro and microelements, the potassium concentration in honey is content is quite high 662.7 ± 266.3 mg kg^{-1}. So, the major mineral content contribution is from potassium, which is confirmed by other studies[32].

The migration of phosphates through the trophic chain from soil to various bee-related samples demonstrates significant accumulation, with notable variations at each stage. The data which indicates the average concentrations of phosphates in different samples are presented in Table 2. Phosphate levels rise drastically from soil to honey plant flowers, showing an increase from 4.7 mg kg^{-1} in soil to 10615.0 mg kg^{-1} in honey plants flowers. This significant increase underscores the high uptake of phosphates by honey plants, similar to the substantial increase observed for potassium, which rose from 37.9 mg kg^{-1} in soil to 17475.7 mg kg^{-1} in honey plants flowers. From honey plants flowers to pollen grains, phosphate concentrations show a modest increase to 10929.74 mg kg^{-1}. This suggests that pollen grains serve as a concentrated reservoir for phosphates.

The most substantial increase in phosphate concentration occurs when moving from pollen grains to the bee body, reaching 24250.93 mg kg^{-1}. This highlights the bee's ability to accumulate and utilize phosphates intensively. So, phosphates exhibit a distinct pattern of accumulation, particularly peaking in the bee body, similar to other macroelements like potassium and magnesium. However, the relative retention in the bee body and minimal transfer to honey highlights the unique migration characteristics of these macroelements in the trophic chain, emphasizing their critical role in bee physiology and the selective regulation by bees to maintain optimal concentrations in their products as honey is the source of energy and not a construction material.

The migration of sodium through the trophic chain, starting from the soil and progressing through honey plants, pollen grains, bee bodies, honey, and finally propolis (that is carried into the hive and does not come through the bee organism), provides essential insights into its transfer and utilization within the ecosystem. So the baseline concentration of sodium in the soil is recorded at 10.4 ± 6.1 mg kg^{-1} (Table II). This relatively low concentration suggests that sodium is present in minimal amounts in the soil, which is due to the specific mineral composition of the soil of Moldavian chernozem in the studied regions. Sodium, although not a major nutrient like potassium or calcium, still plays a crucial role in the physiology of plants and animals. It is involved in maintaining osmotic balance and proper cell function[33]. In honey plant flowers, sodium concentration increases to 38.1±7.6 mg kg^{-1}. This rise in sodium levels indicates that plants absorb sodium from the soil, albeit less efficiently compared to other macroelements like calcium or potassium. Sodium is important for certain plant species, particularly those that grow in saline environments, where it can substitute for potassium in some physiological processes. However, in most honey plants, sodium uptake is likely regulated to avoid toxicity and maintain cellular homeostasis[34]. Although the sodium concentration in pollen grains decreases a little bit to 26.8 ± 2.2 mg kg^{-1}, a significant increase in sodium concentration is observed in bee bodies, reaching 461.1 ± 147.1 mg kg^{-1}. This marked rise highlights the importance of sodium in bee physiology, where it is crucial for nerve signal transmission, muscle contraction, and overall cellular homeostasis. Bees, like other animals, require a stable internal environment, and sodium plays a vital role in maintaining this balance. The substantial accumulation in bees suggests that they may actively uptake sodium from their diet (pollen and nectar) to fulfill their physiological needs[35].

Considering the modest sodium levels in plants, it appears that sodium is primarily concentrated in the bee's body and only minimally transferred to propolis and honey. This hypothesis is further supported by the low sodium concentrations found in honey (22.6 ± 2.7 mg kg^{-1}). Minimal migration of sodium from bee bodies into honey in investigated samples aligns with the general observation that honey primarily serves as an energy source rather than a significant carrier of mineral elements. The limited sodium content in honey is consistent with other studies that have identified low mineral concentrations in honey, reflecting its composition and the selective retention of certain elements by bees[32].

Discussing the migration of macroelements along the trophic chain from the perspective of Migration Factors, the following conclusions can be drawn. Phosphates and potassium dominate the migration process, showing strong accumulation at every stage of the trophic chain, from soil to honey, with migration coefficients in the range of 0.007–2122 and 0.07–437 respectively.

Magnesium and calcium are more prominent at earlier trophic levels, with migration coefficients of 208 and 41.2 from soil to honey plant flowers, but their significance decreases as they move through the chain, especially in honey production, where their coefficients drop to 0.06 and 0.02, respectively. Sodium exhibits a unique pattern: its low initial uptake by plants, with a migration coefficient of 4 from soil to honey plant flowers, contrasts with its selective and substantial accumulation in bees, where the coefficient rises to 11.5, though it is not heavily transferred to final bee products like honey, with a coefficient of 0.04. This comparison highlights the tailored migration and utilization of macroelements based on their physiological roles, with phosphates and potassium being universally important, while sodium, calcium, and magnesium serve more specialized functions within the trophic chain.

The migration data of heavy metals through the trophic chain, from soil to various bee-related products are presented in Table III.

Lead, a highly toxic metal, is known for its ability to cause neurological damage, especially in children, and has been linked to cognitive impairments and cardiovascular issues in adults[36,37]. In the samples studied, lead concentration in the soil was relatively low at 0.43 mg kg^{-1}, and interestingly, it was not detected in honey plant flowers (<0.5 mg kg^{-1}). This suggests that plants in this region, due to selective absorption mechanisms (carbonate soil), prevent the accumulation of lead, which is a positive finding considering the toxic nature of this metal. However, lead is found in both pollen grains and bee bodies at a concentration of 0.39 mg kg^{-1}, indicating some level of bioaccumulation as it moves from plants to bees. Despite this, the concentration of lead in honey remains low at 0.41 mg kg^{-1}, which is comparable to the soil levels. The most significant accumulation of lead is observed in propolis, where the concentration reaches

Table III
The average concentration of heavy metals in samples (mg kg^{-1})

Element	Soil	Honey plants flowers	Pollen grains	Bee body	Propolis	Honey
Pb	0.4 ± 0.4	<0.5 ± 0.0	0.3 ± 0.1	0.3 ± 0.1	5.1 ± 2.3	0.4 ± 0.03
Cd	0.05 ± 0.01	<0.06 ± 0.0	0.1 ± 0.08	0.07 ± 0.01	0.06 ± 0.001	0.0 ± 0.03
Cr	<1.5	1.4 ± 0.08	<1.5	<1.5	2.5 ± 0.5	<1.5
Ni	2.0 ± 0.4	3.9 ± 1.7	<2.5	<2.1 ± 0.3	2.4 ± 0.0	<2.5

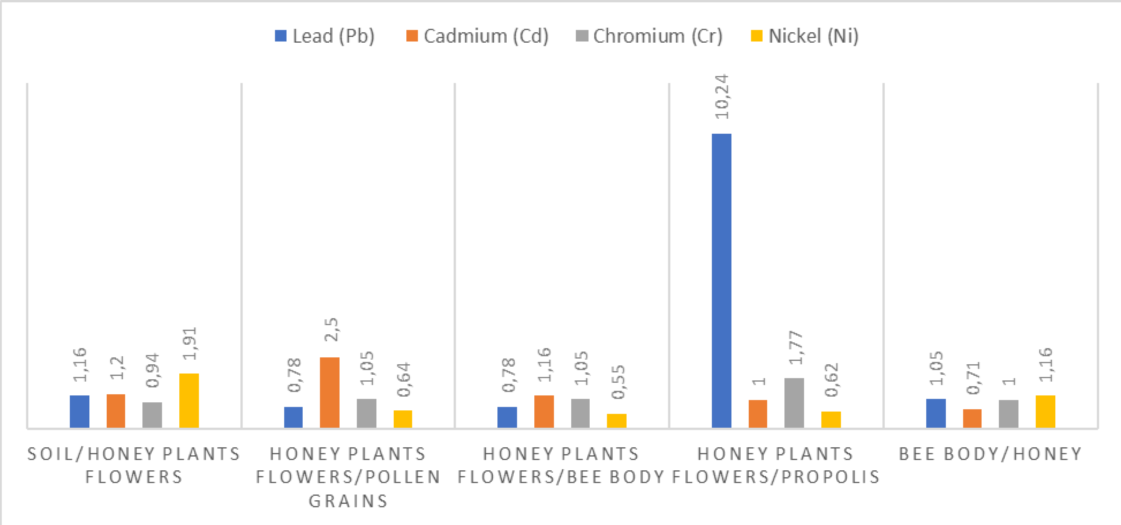

Fig. 2. **Diagram of heavy metal migration coefficients in the trophic chain**

5.12 mg kg^{-1}. The origin of the lead could be the dust, as the rest after the usage of leaded gas.

Cadmium, another toxic heavy metal, is notorious for its carcinogenic properties and its ability to cause kidney damage and bone demineralization over long-term exposure[37,38]. In the studied samples, cadmium concentration in soil is very low at 0.05 mg kg^{-1}. Its presence in honey plant flowers is barely detectable (<0.06 mg kg^{-1}), suggesting limited uptake by plants. However, in pollen grains, cadmium concentration increases to 0.15 mg kg^{-1}, indicating some bioaccumulation as it moves from soil to pollen. Interestingly, this concentration decreases slightly in the bee body to 0.07 mg kg^{-1}, which could imply that bees have mechanisms to regulate or excrete cadmium to avoid toxicity. Propolis contains cadmium at a concentration of 0.06 mg kg^{-1}, reflecting its level in honey plant flowers, while in honey, cadmium remains at the initial soil level of 0.05 mg/kg, indicating that the migration of cadmium through the trophic chain is minimal, which is beneficial for the safety of honey as a consumable product.

Chromium, while essential in trace amounts, becomes toxic at higher concentrations. In this study, chromium levels in the soil were below the detection limit (<1.5 mg kg^{-1}), which suggests a low baseline presence in the environment. Despite this, chromium is detected in honey plant flowers at a concentration of 1.42 mg kg^{-1}, indicating some uptake from the soil. However, it is not detected in pollen grains, bee bodies, or honey (<1.5 mg kg^{-1}), suggesting minimal transfer beyond the initial plant stage. Interestingly, the highest chromium concentration is found in propolis at 2.52 mg kg^{-1}, reinforcing the idea that propolis acts as a sink for potentially harmful metals, preventing their migration into honey.

Nickel like chromium, is essential in small amounts but can be toxic when accumulated in the body, potentially causing allergic reactions, lung fibrosis, and increased cancer risks with prolonged exposure[39]. In the samples studied, the nickel concentration in soil is 2.04 mg kg^{-1}. Nickel shows a notable increase in honey plant flowers, reaching 3.90 mg kg^{-1}, reflecting a higher uptake by plants compared to other heavy metals. However, it is not detected in pollen grains or bee bodies (<2.5 mg kg^{-1} and <2.15 mg kg^{-1}, respectively), indicating limited bioaccumulation in these stages. In propolis, the concentration of nickel is 2.42 mg kg^{-1}, suggesting some retention, though not significantly higher than in soil. In honey, nickel is below detection limits (<2.5 mg kg^{-1}).

The migration process of lead through the trophic chain from soil to honey plant flowers shows migration coefficients of 1.16, with the highest coefficient observed in propolis at 10.24 (Fig. 2).

Cadmium accumulates up to pollen grains, with a migration coefficient of 2.5. However, as it progresses along the chain, this decreases, reaching 0.71 in honey. Chromium and nickel exhibit lower initial absorption by plants, with migration coefficients from soil to honey plant flowers of 0.94 and 1.91, respectively. In bee bodies, these values are 1.05 and 0.55, in propolis – 1.77 and 0.62, and in honey – 1 and 1.16.

These findings emphasize the importance of understanding the selective migration and retention of heavy metals within the trophic chain. The low concentrations of these metals in honey indicate effective barriers against their transfer, which is crucial for maintaining the safety of honey as a consumable product. The study was conducted in an ecologically favorable region of Moldova, which likely contributes to the low baseline concentrations of heavy metals in the environment. However, even in such regions, it is essential to monitor the migration of these metals, as they pose significant health risks if accumulated in higher concentrations.

Conclusions

In this study results on the migration of microelements, macroelements, and heavy metals through the trophic chain from soil to bee products across various climatic zones of the Republic of Moldova over four years are presented. Manganese and copper exhibited moderate migration through the trophic chain, with manganese concentrations increasing from <0.7 mg kg^{-1} in the soil to 28.0 mg kg^{-1} in bees and 17.4 mg kg^{-1} in propolis, while copper showed lower accumulation, rising from 1.0 mg kg^{-1} in the soil to 11.4 mg kg^{-1} in bees and 3.7 mg kg^{-1} in propolis. Zinc and iron showed strong bioaccumulation throughout the trophic chain. Zinc concentrations increased from <0.75 mg kg^{-1} in soil to 63.6 mg kg^{-1} in bees and 114.6 mg kg^{-1} in propolis, with minimal presence in honey (1.2 mg kg^{-1}). Iron exhibited even higher migration, rising from 2.2 mg kg^{-1} in soil to 126.2 mg kg^{-1} in bees and reaching 975.1 mg kg^{-1} in propolis, while its transfer to honey remained low (3.7 mg kg^{-1}). The migration of macroelements through the trophic chain showed significant variation. Calcium exhibited efficient uptake from soil (160.6 mg kg^{-1}) to honey plant flowers (6604.1 mg kg^{-1}), but its concentration decreased substantially in pollen (1459.7 mg kg^{-1}) and bee bodies (875.2 mg kg^{-1}), with minimal transfer to honey (64.0 mg kg^{-1}). Potassium demonstrated the highest accumulation in bees, increasing from 37.9 mg kg^{-1} in the soil to 8736.7 mg kg^{-1} in bee bodies, with moderate migration into honey (662.7 mg kg^{-1}). Magnesium followed a similar pattern, while sodium, despite its low concentration in soil (10.4 mg kg^{-1}), peaked at 461.1 mg kg^{-1} in bee bodies, but remained low in honey (22.6 mg kg^{-1}). Phosphates showed strong migration through the chain, with the highest accumulation in bee bodies (24250.9 mg kg^{-1}), yet limited transfer to honey (175.9 mg kg^{-1}). Heavy metals showed minimal migration through the trophic chain, with the highest lead and chromium concentrations observed in propolis (5.1 mg kg^{-1} and 2.5 mg kg^{-1}, respectively), with cadmium peaking in pollen grains (0.15 mg kg^{-1} and) and nickel showing moderate uptake in honey plant flowers (3.9 mg kg^{-1}).

This study revealed significant variations in the migration patterns of microelements, macroelements, and heavy metals through the trophic chain, with notable accumulation in bee bodies and propolis, while their transfer to honey remained limited.

REFERENCES

1. Tunca R. I., Ozgul O., Yabanli M., Sener I.: Fresenius Environ. Bull. *27*, 9812 (2018).
2. Das S., Sultana K. W., Ndhlala A. R., Mondal M., Chandra I.: Environ. Health Insights *2023*, 17.
3. Ashraf M. W., Akram S.: Fresenius Environ. Bull. *17*, 877 (2008).
4. Ligor M., Kowalkowski T., Buszewski B.: Molecules *27*, 5474 (2022).
5. EMEP/CCC-Report 4/2013. Heavy metals and POP measurements, 2011. Norwegian Institute for Air Research PO Box 100, NO-2027, Kjeller, Norway, 2013.
6. Кодесь Л. Г., Бычкова Н. В.: Пчеловодство *2010*, 53.
7. Tejada-Purizaca T. R., a 10 co-authors: Foods *13*, 762 (2024).
8. Eremia N.: Apicultura, Ediţia a II. Tipografia „Print-Caro", Chişinău 2020.
9. Lee J. G., Hwang J. Y., Lee H. E., Kim T. H., Choi J. D., Gang G. J.: Appl. Biol. Chem. *62*, 64 (2019).
10. Красочко П., Еремия Н.: *Технология продуктов пчеловодства и их применение. Учебник для вузов (Technology of beekeeping products and their application. Textbook for Universities)*. Лань, St. Petersburg 2022.
11. Eremia N., Coşeleva O., Sucman N., Balan G., Lupaşcu L., Mardari T., Modvala S., Macaev F.: Sylwan *63*, 207 (2023).
12. Пичушкин И. С., Мордвинова Е. И.: Пчеловодство *2005*, 16.
13. Angon P. B., Islam M. S., Kc S., Das A., Anjum N., Poudel A., Suchi S. A.: Heliyon *26*, e28357 (2024).
14. Русакова Т. М., Репникова Л. В., Мартынова В. М.: Пчеловодство *2001*, 52.
15. Пашаян С. А.: Пчеловодство *2005*, 10.
16. Ibrahim M., Vildana A., Stela J., Emdzad G., Dilajla J., Damirseulja M.: Pol. J. Environ. Stud. *2011*, 719.
17. Tesfaye B., Begna D., Eshetu M.: Int. J. Agric. Sci. Food Technol. *2*, 021 (2016).
18. Sharma P. 9 co-authors: PLoS One *7*, e47877 (2012).
19. Chaplygin V. and 10 co-authors: Eurasian J. Soil Sci. *9*, 165 (2020).
20. Houmani H., Corpas F. J.: Plant Physiol. Biochem. *206*, 108313 (2024).
21. Riaz N., Guerinot M. L.: J. Exp. Bot. *72*, 2045 (2021).
22. Zhang X., Zhang D., Sun W., Wang T.: Int. J. Mol. Sci. *20*, 2424 (2019).
23. Glavan G., Benko G., Božič J.: J. Econ. Entomol. *117*, 1485 (2024).
24. Navarro J. A., Schneuwly S.: Front. Genet. *8*, 223 (2017).
25. Cardoso-Jaime V., Broderick N. A., Maya-Maldonado K.: Curr. Opin. Insect Sci. *52*, 100924 (2022).

26. Camilli M. P., Kadri S. M., Alvarez M. V. N., Ribolla P. E. M., Orsi R. O.: BMC Genomics *23*, 282 (2022).
27. Kovalskyi Y., Kovalska L., Golovach P., Fedak V., Druzhbiak A.: Sci. Messenger LNU Vet. Med. Biotechnol., Ser. Agric. Sci. *22*, 74 (2020).
28. Collet C., Charreton M., Szabo L., Takacs M., Csernoch L., Szentesi P.: Sci. Rep. *11*, 16731 (2021).
29. Kobayashi N. I., Tanoi K.: Int. J. Mol. Sci. *16*, 23076 (2015).
30. Fellows C. J., Simone-Finstrom M., Anderson T. D., Swale D. R.: Virol. J. *20*, 134 (2023).
31. Dow J. A. T.: Curr. Opin. Insect Sci. *23*, 43 (2017).
32. Da Silva P. M., Gauche C., Gonzaga L. V., Costa A. C. O., Fett R.: Food Chem. *196*, 309 (2016).
33. Flowers T. J., Colmer T. D.: Ann. Bot. (Oxford, U. K.) *115*, 327 (2015).
34. Shabala S.: Ann. Bot. (Oxford, U. K.) *112*, 1209 (2013).
35. Aronstein K. A., Murray K. D.: J. Invertebr. Pathol., *103*, S20 (2010).
36. Focus E., Rwiza M. J., Mohammed N. K., Banzi F. P.: J. Environ. Public Health. *2021*, 9976048.
37. Bora J., Kumari M., Panda I., Gupta S., Priya S., Mondal S., Malik S., Lata S.: in: *Nanotechnology Applications and Innovations for Improved Soil Health* (V. Rajput Ed.) pp. 254-275, IGI Global, Hershey 2024.
38. Godt J., Scheidig F., Grosse-Siestrup C., Esche V., Brandenburg P., Reich A., Groneberg D. A.: J. Occup. Med. Toxicol. *1*, 22 (2006).
39. Sunderman F. W.: Ann. Clin. Lab. Sci. *31*, 3 (2001).