Studii şi Cercetări Ştiinţifice
Chimie şi Inginerie Chimică, Biotehnologii, Industrie Alimentară
2019, **20** (4), pp. 541 – 550

Scientific Study & Research
Chemistry & Chemical Engineering, Biotechnology, Food Industry
ISSN 1582-540X

ORIGINAL RESEARCH PAPER

TRANSLOCATION OF LEAD, CADMIUM AND ZINC IN CORN PLANTS DEPENDING ON DEVELOPMENT PHASES

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Received: December, 07, 2018
Accepted: October, 28, 2019

Abstract: The problem of soil contamination with heavy metals over the past three decades is growing and is relevant not only in Ukraine, Europe, but throughout the world. The content of heavy metals in the soil increases and creates a risk to the environment and human health. To eliminate this problem, various technologies of soil recovery from ecotoxicants are used. In agricultural production, one way is to grow crops that are resistant to the adverse effects of heavy metals. This article presents the study results of heavy metals translocation in corn plants during the entire growing season. It was experimentally established that the most intensive accumulation occurred in the early period of growth and development of the culture and decreased until the maturation period. It is found that the corn grain of the hybrid Zdvizh MV in all variants corresponds to the standards of feed raw materials, and can be used for technical purposes.

Keywords: *corn plants, environmental pollution, heavy metals, physiological barriers, phytoremediation*

INTRODUCTION

Environmental Pollution by chemical substances is one of the weighty destructive factors of the biosphere components [1, 2]. Intensive agricultural and industrial use of natural resources has led to a significant change in the biogeochemical cycle of chemical elements, which conduct to change their directions and pace of migration, volumes of removal and accumulation. The exacerbation of the ecological situation in the industrial regions is caused by excessive stress on ecosystems, including soil cover, in turn, leads to the accumulation of high concentrations of toxic substances in the soil and pollution of cultivated products [3 – 9].
The heavy metal contamination of soil is one of the most pressing concerns in the debate about food safety in Europe and globally. It is of interest to study the effect of heavy metals on human health, as well as the mechanism of absorption, transformation and bioaccumulation of heavy metals by plants is relevant [10, 11].
One of the important aspects of conducting agricultural production on contaminated lands is the cultivation of crops resistant to the adverse effects of heavy metals, which is mainly due to their biological characteristics. The work of protective mechanisms of the root system and aerial vegetative organs helps to reduce the flow of excess ions into the organs storing of assimilated. The main load falls on the root system, which detains a significant part of the harmful elements. The distribution of toxic heavy metals in a corn plant has a distinct acropetal character: roots – stems – leaves – heads [4].
In terms of resistance to pollution, crops are divided into: the most stable – winter and spring cereals, sunflower; medium-hard – sugar beet, potatoes, carrots, tomatoes, peppers; weakly resistant – legumes, annual grasses, perennial legumes, parsley, lettuce [4, 12]. Excessive metal concentrations cause a decline in crop productivity and deterioration in the quality of the products. Several scientific studies were dealt with the negative effect of excessive metal concentrations on the development and productivity of plants [13 – 15].
The aim of the work was to establish the content of heavy metals in the roots and aerial organs of corn plants, depending on the background of contamination by the agroecotope with the pollutants in the phases of development.

RESEARCH METHODS

The studies were conducted in the small-scale experiment "Influence of zinc, lead, and cadmium on the productivity of agricultural crops, agrochemical and ecotoxicological characteristics of gray forest soils", which was founded in 1999 on the territory of Kyiv region (experimental farm “Chabany" of the National Scientific Center "Institute of Agriculture of the National Academy of Sciences”).
The experiment included four variants with artificially created ground backgrounds. A complex contamination of the upper layer (0-20 cm) of soil with zinc, lead, and cadmium was modeled: variant № 1 - the natural (local) background of heavy metals (control); variant № 2 - exceeding the natural metal background by 10 times; variant № 3 - exceeding the natural background by 100 times; variant № 4 - exceeding the natural background by 5 times. The area of the registration site was 4 m^2, the repetition - four times.

Before laying experience it has been found that on the gray forest soils of the Chabany farm, the natural (local) background of the content of the acid-soluble fraction of the elements was: lead - 10 mg·kg^{-1}, zinc - 5 mg·kg^{-1}, cadmium - 0.2 mg·kg^{-1}. According to the gradation given in the “Method of continuous soil-agrochemical monitoring of agricultural lands in Ukraine” [16], this content of heavy metals corresponds to a low level of pollution with cadmium, a moderate level of lead contamination and noted the absence of zinc contamination.
During the 2012-2014, on the experimental sites, corn was grown for the grain of the hybrid Zdwizh in permanent seeding. The culture cultivation technology was common for the forest-steppe zone. The content of zinc, cadmium, and lead in vegetative and generative organs was determined by atomic absorption spectrophotometry after the destruction of organic matter by means of nitric acid and heat treatment according to GOST 30178-96 [17]. The determination of metal concentrations in samples was conducted using the method of atomic adsorption in the propane-air flame (atomic-adsorption spectrometer AAS-3, Carl Zeiss, Germany). The sources of radiation were hollow cathode lamps, working wavelengths - 228.8 nm for cadmium, 283.3 nm for lead and 213.9 nm for zinc. Statistical data processing was made using the StatSoft Statistica 7 software.

RESULTS AND DISCUSSION

The results of our investigations indicate that, due to the excess of background concentration of heavy metals in the soil the content of lead, cadmium and zinc is sharply increased in the roots and ground vegetative mass of corn plants.
In all variants, a decrease in the concentration of toxic elements during the phases of intensive growth was observed: 13 leaves, flowering, lactic and full ripeness of corn as compared to the beginning of vegetation, namely, 3-4 leaves. The obtained results are confirmed by the data of other researchers, where the intake of metals in plants occurred throughout the growing season, but intensive it was in the early period of development and decreased by the maturation period [18].
Scientists have proved that high concentrations of heavy metals show a toxic effect on plants by disturbing the patterns of intake and distribution of other chemical elements. Thus, an excessive amount of zinc reduces the intake of phosphorus in plants [19]. Cadmium in elevated concentrations reduces the availability of phosphorus, calcium, magnesium, iron, zinc, and in biochemical reactions replaces zinc, leads to disruption of photosynthetic activity, inhibition of plants before their death [20]. Lead limits the supply of phosphorus, calcium, iron, copper, zinc [21]. Our studies confirm this pattern, the largest number of metals, especially in cases with excess of natural background, accumulated roots, as a powerful barrier to toxic substances, much less - ground vegetative mass (Figure 1).

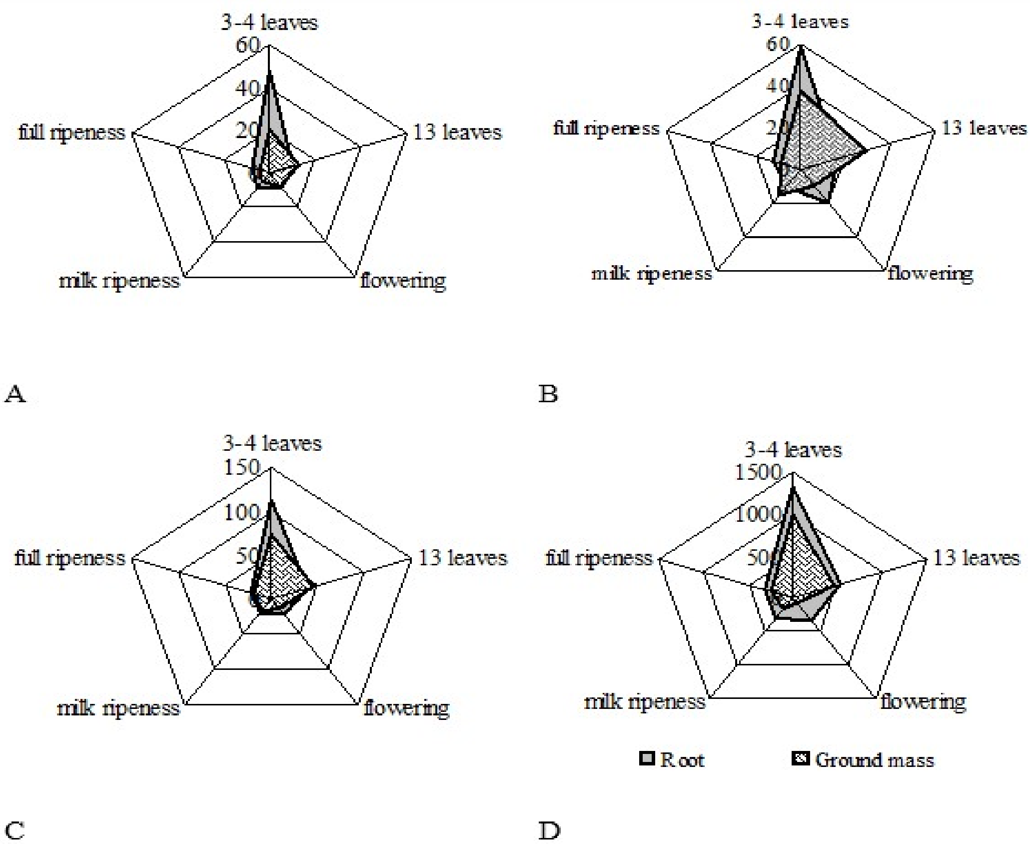

Figure 1. *The content of zinc in the roots and aerial organs of corn plants, depending on the background of contamination by the agroecotope by the pollutants according to the phases of development: A - is the natural background (control); B, C, D - the excess of the natural background of heavy metals, respectively, 5, 10, 100 times, average for 2012-2014, mg·kg^{-1} dry matter*

During the period of initial growth (phase 3-4 leaves) in the control variant, corn roots accumulated zinc 48.0 mg·kg^{-1} dry matter. With the increase in contamination by the agroecotope, the content of the element in the roots increased sharply, reaching 1316.9 mg·kg^{-1} per 100-fold contamination. After all, the bulk of the root mass at this stage of plant development was in the upper 20 cm layer of soil contaminated with heavy metals. At the end of the vegetation, when the root system developed deeper than 2 m, breaking the upper contaminated layer, the concentration of zinc in the roots decreased and amounted to 7.83 mg·kg^{-1} dry matter, and for excess of the natural background of heavy metals 100 times – 312.60 mg·kg^{-1} of dry matter.

The aerial vegetative mass was considerably inferior to the accumulation of zinc in comparison with the roots, indicating that the latter perform barrier functions. Only in the phase of 13 leaves, when the photosynthetic apparatus was actively developing and the demand for zinc as a trace element was high, the concentration of this metal in the dry matter of the ground organs was higher than in the root. This effect was observed only on the control, by 5 and 10-fold excess of the natural background. For a 100-fold increase in the concentration of zinc in the soil, the root barriers counteracted the transport of metal into the plant organism throughout the growing season.

Researchers note that lead enters the plant and is transported to the ground organs slower than other heavy metals [22]. V.B. Ilyin established that this element, coming from the soil, contaminates more roots, less leaves, and very little grain [23]. The results of our studies confirmed this pattern (Figure 2).

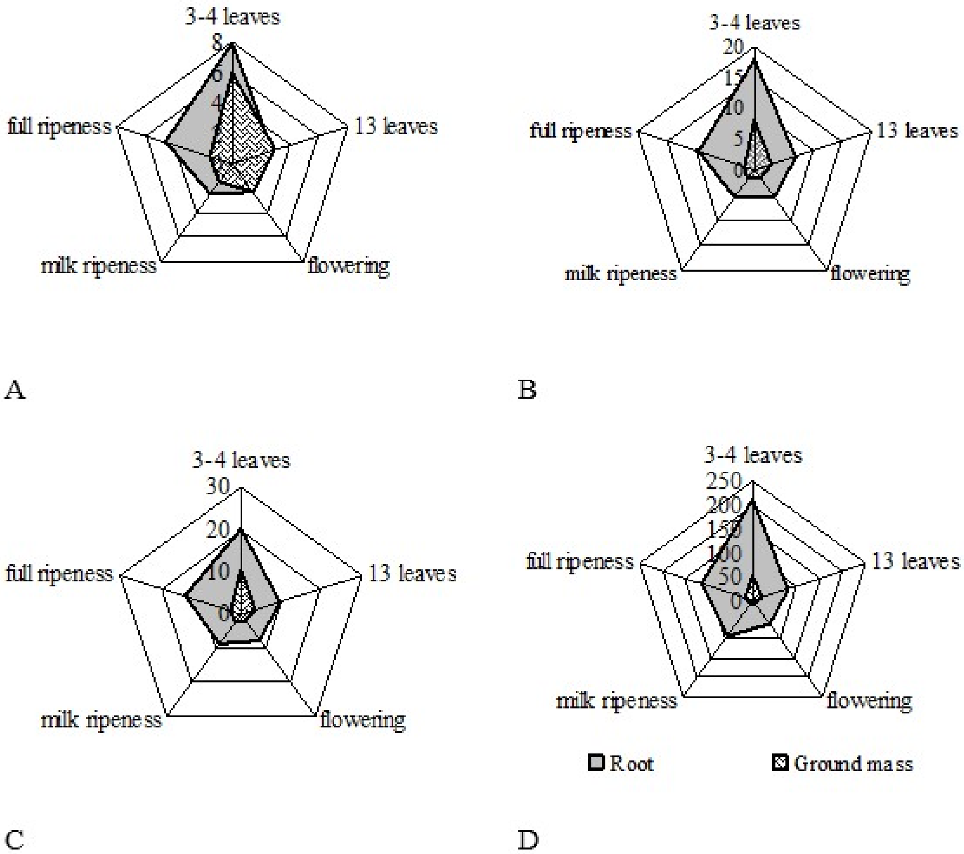

Figure 2. *The content of lead in the roots and ground organs of corn plants, depending on the background of contamination by the agroecotope by the pollutants according to the phases of development: A - is the natural background (control); B, C, D - the excess of the natural background of heavy metals, respectively, 5, 10, 100 times, average for 2012-2014, mg·kg^{-1} dry matter*

However, the content of lead in the organs of corn plants varied depending on the phase of development. Thus, the greatest accumulation of lead, both by roots and ground mass, was noted during the formation of 3-4 leaves. Depending on the variant of the experiment, its content varied within 7.94-210.57 mg·kg^{-1} and 5.97-52.75 mg·kg^{-1} of dry matter. It is important to note that only in control during the period of intensive growth of the vegetative mass (13 leaves) and flowering, the concentration of lead in the leaves and stem was higher than in the roots. In our opinion, this is explained by the very low availability of zinc in the output soil, and in the conditions of a deficiency of this microelement, the root barriers weakly delay the transport of lead and cadmium to other organs of the plant [24]. In the phase of complete ripeness, depending on the background of contamination, the root mass of the plants contained lead 4.63-112.10 mg·kg^{-1}, and the aerial vegetative mass 1.57-15.13 mg·kg^{-1} dry matter. In general, in ecotopes polluted with lead (variants 2, 3, 4), the content of this metal in the roots of plants is 1.9-8.22 times higher than the concentration in stems and leaves, which indicates a high intensity of counteraction of root barriers of toxicant transport in aerial organs corn in the period of growth and development of plants.

In the scientific literature there are indications of a certain increase in the yield of agricultural crops with small doses of cadmium. Scientists have experimentally proved the increase in the yield of beets and carrots at the admission of cadmium in a dose of 0.5 mg·kg^{-1} [25]. The authors attribute this fact to the stimulation by the metal of biosynthetic processes.

On average, over the years of research, it has been established that the largest amount of total cadmium in the plant had roots (Figure 3).

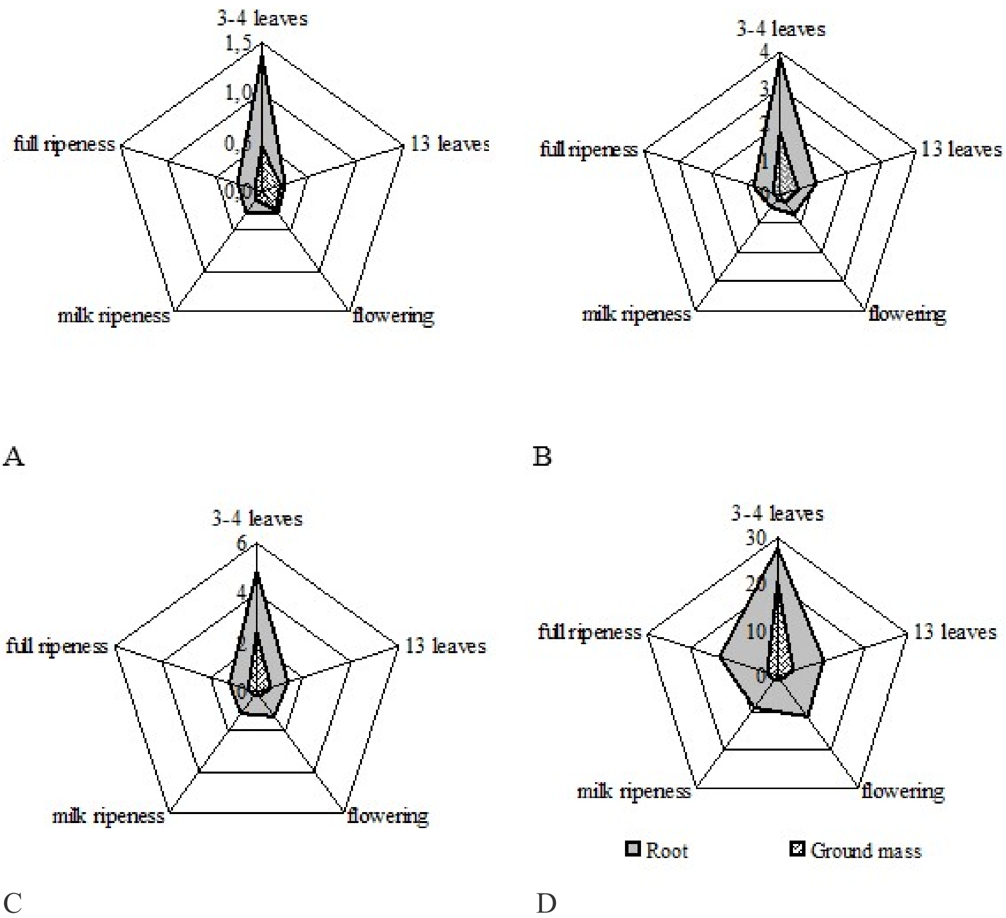

Figure 3. *The content of cadmium in the roots and ground organs of corn plants, depending on the background of contamination by the agroecotope by the pollutants according to the phases of development: A - is the natural background (control); B, C, D - the excess of the natural background of heavy metals, respectively, 5, 10, 100 times, average for 2012-2014, mg·kg^{-1} dry matter*

The aerial vegetative mass was significantly inferior to the content of this pollutants compared with the roots in all phases of development. Thus, the highest content of cadmium in the roots was in the 3-4-leaves phase: on the natural background of heavy metals it was 1.37 mg·kg^{-1} of dry matter, and for 5-100 times the natural background of heavy metals in agroecotopes, the concentration reached 3.83-27.8 mg·kg^{-1} of dry matter. Whereas, for growing plants on contaminated backgrounds, the aerial vegetative mass contained cadmium 1.77-20.5 mg·kg^{-1} dry matter and 0.47 mg·kg^{-1} dry matter on the control. Concentration in leaves and stem was 1.35-2.17 times lower than in the root mass. However, as in the analysis of the accumulation of lead by the plants (see Figure 2) in areas with natural heavy metal content, weakened the activity of root barriers with respect to cadmium in the period of 13 leaves and flowering, which is associated with the high demand of plants in zinc.

The obtained results by us on the character of the translocation of heavy metals in the soil-plant system are confirmed by data published in scientific sources. The receipt of heavy metals to the plant organism is not stochastic, but is regulated by physiological barriers of a biochemical nature. The absorption of heavy metals slows down under the influence of the mechanisms of the barrier function of the root, such as the reactive centers of the apoplast of the root, cell wall, compartmentalization in the vacuoles of the cell, stops the acropetal displacement of the elements. Investigators in this field have identified the important role of metalloproteins in providing the barrier function of vegetative organs of plants [26].

It is known that at high concentrations of heavy metals in the soil, these elements can accumulate not only in vegetative organs, but also in generative ones, causing a deterioration in the quality of grain for use for both food and seed purposes. According to the research of a number of scientists, in the presence of elevated concentrations of lead, cadmium and zinc in the soil, cereals and legumes reduce the yield of seeds [27]. However, V.B. Ilyin (1975) notes that seeds contain the lowest concentration of toxicants in comparison with other plant organs, since the elemental chemical composition of generative organs is under strong genetic control [28]. That is, the seeds can contain such a concentration of chemical elements, including heavy metals, which meets the needs of sprout-heterotrophs and does not harm its development and growth. However, this concentration may exceed the sanitary and hygienic standards for the content of elements and substances found for food or forage grains.

Studies on the accumulation of heavy metals in grain were carried out in phases of milk and full ripeness (Table 1). It is established that, irrespective of the background of contamination, there is, at the time of maturation of the grains, the concentration of metals has decreased. It is likely that in the last stages of maturation of generative organs the amount of heavy metals in the grain was unchanged, but the accumulation of a genetically determined amount of organic and mineral compounds continued - the total mass of dry substances was increased, and therefore the effect of reducing the content of heavy metals in a mature crop was obtained.

It is important to note that none of the agroecotopes created in the experiment resulted in grain contamination with zinc and cadmium. The excess of Maximum permissible concentration in food grains for lead occurred for 10 and 100-fold excess of the background of heavy metals in the soil and amounted to 0.7 and 0.9 mg·kg^{-1}.

Table 1. *The content of heavy metals and trace elements in the grain of corn plants, depending on the background of contamination by the agroecotope pollutants in the phase of dairy and full ripeness, average for 2012–2014, mg·kg^{-1}*

Option	Content in grain, mg·kg^{-1}					
	Cd		**Pb**		**Zn**	
	Milk ripeness	Full ripeness	Milk ripeness	Full ripeness	Milk ripeness	Full ripeness
1 - natural background of heavy metals (control)	0.07	0	0.9	0.4	11.3	10.5
4 – fivefold excess of the natural background of heavy metals	0.10	0	1.03	0.5	12.0	10.8
2 – a tenfold excess of the natural background of heavy metals	0.15	0,05	1.2	0.7	14.3	12.6
3 – hundredfold excess of the natural background of heavy metals	0.35	0.05	1.73	0.9	27.3	22.8
$\overline{X} \pm S\overline{x}$	0.17±0.06	0.03±0.01	1.21±0.19	0.66±0.10	16.2±3.75	14.2±2.92
V, %	76.2	116	31.1	30.4	31.1	41.3
Maximum allowable concentration [29]*:* • grain for food • grain forage	–	0.10 0.30	–	0.50 5.00	–	50.0 50.0

This indicates a limited possibility of using corn grain for food purposes, obtained on the background of gray forest soil with a lead content of 100-1000 mg·kg^{-1}. In spite of this, corn grain in all variants corresponds to the norms of fodder raw materials, and can also be used for technical purposes (for example, production of bioethanol, starch).

CONCLUSIONS

So, on excess of background concentrations of heavy metals in the soil, the level of lead content increased in the roots and ground vegetative mass of corn plants, respectively, in 1.43-36.45 and 0.74-8.84 times, cadmium - 1.52-43.47 and 1.07-43.93, and zinc - 1.22-54.23 and 1.22-49.38 times compared with uncontaminated areas. Intensive intake of lead, cadmium and zinc in plants was in the 3-4-leaf phase and decreased in the following phases of development.

It has been confirmed that the translocation of heavy metals in the soil-plant system is not stochastic, but is regulated by physiological barriers of a biochemical nature. Due to the high intensity of counteraction of root barriers, corn plants grown in conditions of 5, 10, 100-fold soil contamination with lead, cadmium, zinc concentrated heavy metals in the roots, preventing their entry into the aerial vegetative mass and generative organs. During the period of growth of the development of the accumulation of these metals in the roots of corn plants, respectively: zinc at 1.90-8.22, lead - 1.35-8.77, cadmium - 0.55-3.91 times, exceeded their content in stems and leaves.

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