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ACCUMULATION OF CADMIUM IONS IN TABLE BEET (*BETA VULGARIS* L.) PLANTS AS AFFECTED BY THE USE OF FERTILIZERS AND AMELIORANTS

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Dydiv A., Kachmar N., Datsko T., Ivankiv M., Rosa R. Accumulation of cadmium ions in table beet (*Beta vulgaris* L.) plants as affected by the use of fertilizers and ameliorants

The article presents the findings of a study examining how different fertilization systems and calcium-based soil amendments affect the accumulation of cadmium (Cd^{2+}) ions in various parts of table beet plants (cv. Bordo Kharkivskyi). This was analyzed under simulated conditions of cadmium contamination in dark-gray podzolic soil in the Western Forest-Steppe of Ukraine. The research assessed the effects of organic, mineral, and organic-mineral fertilization systems, combined with liming, on cadmium mobility in the soil and its uptake by table beet plants. The study calculated the hazard coefficients for mobile Cd^{2+} forms in the soil, cadmium accumulation in plants, and the biological absorption coefficient.

Results indicated that increasing the levels of cadmium contamination in the soil - from 1 to 5 maximum permissible concentrations (MPC) - led to a rise in mobile Cd^{2+} forms across all treatments, resulting in greater accumulation of cadmium in table beet plants. Cadmium was found to accumulate most significantly in the underground parts (root tail) and least in the core of the root. Notably, the concentration of Cd^{2+} in the leaf blades was 3.5 to 4.1 times higher than in the root pulp.

The study also found that applying organic fertilizers (Biohumus) and mineral fertilizers (Nitroammophoska), along with soil liming (+ $CaCO_3$), reduced cadmium mobility in the soil and its accumulation in table beet plants. The lowest concentrations of mobile Cd^{2+} in the soil - and thus the least accumulation of the metal in the roots - were observed with the application of Biohumus at 4 t/ha combined with $CaCO_3$ at 5 t/ha (treatment 6) and $N_{34}P_{34}K_{34}$ combined with Biohumus at 2 t/ha and $CaCO_3$ at 5 t/ha (treatment 7). These results differed significantly from the control group ($p < 0.001$) and had hazard coefficients of 0.20 and 0.33, respectively.

A strong correlation ($r = 0.85$) was found between the concentration of mobile Cd^{2+} forms in the soil and their content in the table beet plants across all experimental treatments, with a coefficient of determination $R^2=0.73$. The findings of this research can be utilized to optimize agricultural practices in areas contaminated with heavy metals, thereby minimizing the risk of cadmium accumulation in table beet produce.

Keywords: cadmium ions, translocation, table beet, hazard coefficient, biological absorption coefficient, fertilizers, calcium-based ameliorants.

Дидів А., Качмар Н., Дацко Т., Іванків М., Роса Р. Нагромадження іонів кадмію рослинами буряка столового (*Beta vulgaris* L.) залежно від застосування добрив та меліорантів

У статті висвітлено результати досліджень щодо впливу різних систем удобрення та кальцієвих меліорантів на нагромадження іонів Cd^{2+} у різних органах рослин буряка столового сорту Бордо Харківський за змодельованих рівнів забруднення темно-сірого опідзоленого ґрунту кадмієм в умовах Західного Лісостепу України. Проаналізовано вплив органічної, мінеральної та органо-мінеральної систем удобрення у поєднанні з вапнуванням на рухомість кадмію у ґрунті та його транслокацію в рослини буряка столового. За результатами дослідження визначено коефіцієнт небезпеки рухомих форм Cd^{2+} у ґрунтовому середовищі, коефіцієнт небезпеки накопичення елемента в рослинах, а також коефіцієнт біологічного поглинання.

Встановлено, що із збільшенням рівнів змодельованого забруднення ґрунту кадмієм від 1 до 5 ГДК збільшувалась і концентрація рухомих форм Cd^{2+} у ґрунті у всіх варіантах, що позначилось на інтенсивнішому нагромадженню катіонів металу в рослинах буряка столового. З'ясовано, що найбільше кадмій акумулювався у підземній частині (хвостику коренеплоду), а найменше – у серцевині. У листковій пластині концентрація Cd^{2+} перевищувала вміст у м'якуші коренеплоду в 3,5–4,1 рази.

Виявлено, що застосування органічних (Біогумус) і мінеральних (Нітроамофоска) добрив у поєднанні з вапнуванням ґрунту ($CaCO_3$) сприяло зменшенню рухомості кадмію у ґрунті та його акумуляції в рослинах буряка столового. Однак найнижчу концентрацію рухомих форм кадмію Cd^{2+} у ґрунті на фоні, а відповідно, й найменше нагромадження іонів металу в коренеплодах буряка столового спостерігали за внесення Біогумус 4 т/га + $CaCO_3$ 5 т/га (варіант 6) та $N_{34}P_{34}K_{34}$ + Біогумус 2 т/га + $CaCO_3$ 5 т/га (варіант 7) за вірогідної різниці до контролю $p < 0{,}001$, за коефіцієнтів небезпеки 0,20 та 0,33.

Встановлено тісний кореляційний зв'язок ($r = 0{,}85$) між концентрацією рухомих форм Cd^{2+} у ґрунті та його вмістом у рослинах буряка столового в усіх варіантах досліду за коефіцієнта детермінації $R^2 = 0{,}73$. Результати дослідження можуть бути використані для оптимізації агротехнологій в умовах забруднення агробіоценозів важкими металами з метою зменшення ризику нагромадження кадмію у продукції буряка столового.

Ключові слова: іони кадмію, транслокація, буряк столовий, коефіцієнт небезпеки, коефіцієнт біологічного поглинання, добрива, кальцієві меліоранти.

Problem statement. A pressing issue today is the increasing anthropogenic pressure on agrobiocenoses caused by the influx of various pollutants, particularly heavy metals. Among them, cadmium, lead, mercury, and arsenic belong to the first hazard class of chemical substances and are subject to continuous environmental monitoring and control [1].

As a result of russia's military aggression against Ukraine, the area of agricultural land contaminated with heavy metals has significantly increased in recent years [2]. The degree of soil contamination with heavy metals determines the level of environmental hazard for agricultural crops and, as a consequence, directly affects the safety of plant products and human health [3; 5].

Heavy metals in mobile forms are particularly hazardous in soil, as they are the most readily available for uptake by plant root systems and exert a direct phytotoxic effect. The phytotoxicity of heavy metals is manifested through the disruption of physiological, biochemical, and growth processes, as well as the deterioration of crop quality indicators, including a reduction in nutrient content and the accumulation of toxic compounds [4].

Analysis of recent research and publications. The accumulation of heavy metals in agricultural soils is one of the most pressing environmental threats today. Intensive anthropogenic activities, particularly the widespread use of mineral fertilizers and pesticides, as well as industrial emissions, result in the release of significant amounts of toxic substances into the environment [5]. An additional factor contributing to the deterioration of soil ecological status has been the military actions resulting from russia's aggression against Ukraine, which are accompanied by explosions of munitions and the release of harmful substances. All of this leads to the contamination of the topsoil, a decline in soil fertility, and the entry of toxicants into the food chain through plant-based products [2].

Among the root vegetable crops cultivated in Ukraine, table beet (*Beta vulgaris* L.) occupies a significant place. However, this crop is characterized by low biological resistance to the toxic effects of heavy metal ions, which is attributed to its genetic characteristics. In particular, an elevated content of mobile cadmium ions (Cd^{2+}) in the soil environment contributes to its excessive accumulation in plants, which adversely affects yield and the quality parameters of root crop production [4; 6; 11].

Plants are capable of restricting the uptake of excess ions into aboveground organs, particularly into the organs responsible for assimilate storage. The root serves as the primary organ and biological barrier in the pathway of heavy metal transport from the soil into the plant. A significant portion of the "primary transport" processes takes place in the root [3]. At higher levels of contamination, the inactivation of toxicants in the soil solution becomes incomplete, and the flux of heavy metal cations begins to affect the roots, into which they enter primarily through diffusion and passive transfer [7].

A small portion of metal ions is rendered inactive by plants even before entering the roots, where a certain amount is retained (chelated by root exudates and adsorbed onto the external root surface) [9]. A general pattern in plants is the distribution of heavy metals in such a way that the highest amounts are retained in the root system tissues, while the smallest amounts reach the generative organs [8]. Although plant root systems generally contain higher concentrations of heavy metals than their aboveground organs, there are exceptions in which more mobile forms of heavy metals, such as Cd^{2+}, Hg^{2+}, and Cu^{2+}, accumulate in the aerial parts of plants, particularly in seeds and leaves [4; 7; 10].

The study of distribution patterns of heavy metals in different organs of table beet plants remains a relevant area of research. Particular focus is made on the assessment of the environmental safety of table beet produce in relation to the toxic effects of heavy metal ions, through the determination of the hazard coefficient and the biological absorption coefficient. The obtained results can be used to improve agrotechnologies under conditions of heavy metal-contaminated agricultural fields in order to reduce the risk of cadmium accumulation in table beet produce [10; 11].

Thus, under current conditions of heavy metal contamination in agrobiocenoses, an urgent issue is to study and apply an effective and safe fertilization system adapted to specific soil and climatic conditions, in combination with calcium soil amendments. This approach enables rapid detoxification of contaminated soil, reduces the mobility of heavy metals, and limits their translocation into table beet plants, ultimately contributing to improved soil fertility and the production of environmentally safe vegetable products [6; 12; 16].

Setting objectives. To achieve this goal, the study investigated the effect of simulated levels of soil contamination with cadmium on the translocation of Cd^{2+} ions into various organs of *Beta vulgaris* L. plants under the application of organic and mineral fertilizers, as well as calcium ameliorants. The analysis made it possible to determine the hazard coefficient of mobile Cd^{2+} forms in the soil, the hazard coefficient in plants, and the biological accumulation coefficient of cadmium in *Beta vulgaris* L. plants. A correlation was established between the concentration of mobile cadmium forms in the soil and the concentration of cadmium ions in table beet plants.

Presenting main material. In the conditions of the Western Forest-Steppe of Ukraine, on dark- gray podzolic soils, the influence of fertilizers and ameliorants on the behavior of heavy metals in the "soil–plant" system was investigated. In particular, the study focused on the patterns of cadmium accumulation in table beet (*Beta vulgaris* L.) plants depending on the application rates and ratios of organic and mineral fertilizers, applied in combination with soil liming using calcium-based ameliorants.

Sowing of table beet (cv. Bordo Kharkivskyi) was carried out in the second ten-day period of May in soil pre-contaminated with heavy metals. Cadmium chloride ($CdCl_2$) was used as the contaminant and applied as an aqueous solution at simulated contamination levels of 1, 3, and 5 maximum permissible concentrations (MPC) of total forms. The contaminant was applied separately in the autumn, and two weeks later, limestone flour ($CaCO_3$) was applied as a soil amendment at a rate of 5 t/ha, based on the soil's hydrolytic acidity, in accordance with the experimental design [13]. This was based on data [12; 15], indicating that the maximum permissible concentration (MPC) of total cadmium forms is 3 mg/kg of soil. In the control treatment, cadmium salts were not applied. In the spring, during pre-sowing cultivation, the mineral fertilizer Nitroammophoska (grade 16:16:16) and the organic fertilizer Biohumus (a vermiculture product) were applied according to the experimental design.

The scheme of the micro-plot two-factor experiment on table beet cultivation included the following treatments: 1) Control (no fertilizers); 2) $N_{68}P_{68}K_{68}$; 3) Biohumus 4 t/ha; 4) $N_{68}P_{68}K_{68}$ + Biohumus 2 t/ha; 5) $N_{68}P_{68}K_{68}$ + $CaCO_3$ 5 t/ha; 6) Biohumus 4 t/ha + $CaCO_3$ 5 t/ha; 7) $N_{68}P_{68}K_{68}$ + Biohumus 4 t/ha + $CaCO_3$ 5 t/ha.

The accounting area of each micro-plot was 2 m². The experiment was conducted with five replications, and the treatments were arranged systematically [16]. The cultivation technology for table beet followed standard practices accepted for the conditions of the Western Forest-Steppe of Ukraine.

The concentration of cadmium in table beet plant tissues and soil samples was determined using atomic absorption spectrophotometry according to certified and standardized methods in accordance with DSTU 4770.3:2007 [17].

To assess the degree of cadmium hazard, the *hazard coefficient (H_c)* was used. It represents the ratio between the element concentration in the plant and its maximum permissible concentration, calculated according to formula (1). Under normal conditions, the hazard coefficient should be less than or equal to 1:

$$H_c = \frac{C_i}{MPC_i} \geq 1, \quad (1)$$

where: *Ci* – actual concentration of the contaminant in the plant, mg/kg; *MPCi* – maximum permissible concentration of the contaminant in the plant, mg/kg.

For the quantitative assessment of the uptake (translocation) of mobile Cd^{2+} forms from the soil into table beet plants, the *biological accumulation coefficient* (*BAc*) was used, calculated according to formula (2):

$$BA_c = \frac{C_p}{C_s}, \qquad (2)$$

where: C_p – concentration of the contaminant in the plant, mg/kg; C_s – concentration of the contaminant in the soil, mg/kg.

The statistical processing of the research results was presented as arithmetic means. To indicate statistical significance in the tables, the following symbols were used: * – $p < 0.05$, ** – $p < 0.01$, *** – $p < 0.001$.

The research program aimed to study the patterns of accumulation and redistribution of Cd^{2+} ions in different organs of *Beta vulgaris* L. under various levels of simulated soil contamination with cadmium, taking into account the application of fertilizers and calcium-based soil amendments.

According to the results of a three-year study, it was found that under the background (control) conditions, the highest cadmium accumulation occurred in the underground part of the root crop (the tail) – 0.324 mg/kg of fresh weight. In the peel of the root crop, the cadmium concentration was 0.058 mg/kg; in the pulp – 0.027 mg/kg; whereas in the core, it decreased to 0.012 mg/kg of fresh weight. However, in the petioles of the leaves, the cadmium concentration increased again to 0.043 mg/kg, while in the leaf blades it rose even further to 0.096 mg/kg of fresh weight. Thus, the Cd^{2+} concentration in the leaf blade was 3.5 times higher than in the pulp of the table beet root (Fig. 1).

The obtained research results confirm a certain regularity, namely: with the increase in the level of simulated soil contamination with cadmium up to 5 MAC, the concentration of mobile Cd^{2+} forms in the soil increased in all treatments, which led to a more intensive accumulation of these ions in various parts of the table beet plants. It was established that at this level of simulated contamination, the highest cadmium accumulation occurred in the underground part of the root crop – 1.185 mg/kg of fresh weight. In the peel of the root crop, the cadmium concentration was 0.209 mg/kg; in the pulp – 0.098 mg/kg; whereas in the core – it reached 0.043 mg/kg of fresh weight. As for the aboveground part of the plants, the cadmium concentration in the leaf petioles increased to 0.165 mg/kg, while in the leaf blades it amounted to 0.405 mg/kg of fresh weight. Thus, at the simulated soil contamination level of 5 MAC, the concentration of cadmium ions in the leaf blade increased by 4.13 times compared to the pulp of the table beet root, while in the core it was 9.42 times higher (Fig. 1).

However, the application of fertilizers and calcium-based ameliorants significantly influenced the mobility of Cd^{2+} in the soil, thereby affecting its accumulation in *Beta vulgaris* L. plants (Table 1).

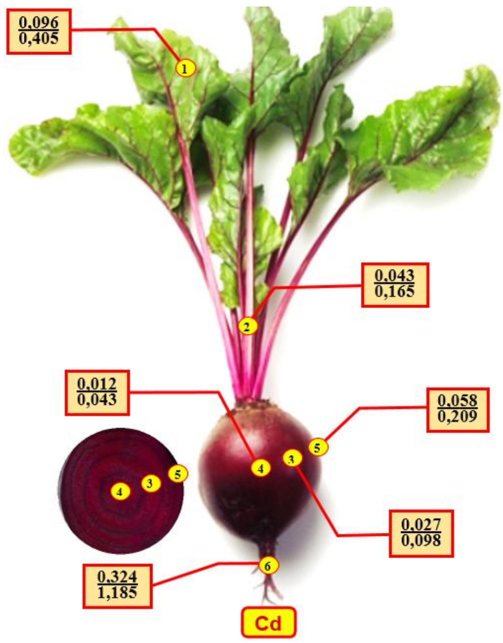

Fig. 1. Cadmium concentration in different organs of table beet plant,mg/kg of fresh weight

Note: 1. Numerator – background (control), denominator – simulated soil contamination with cadmium at the level of 5 MPC. 2. (1) leaf blade, (2) petiole, (3) root pulp, (4) root core, (5) root peel, (6) root tip (tail)

The study revealed that under the simulated soil contamination level of 3 MAC with cadmium, the highest concentration of Cd^{2+} in table beet root crops was recorded in the control variant (without fertilizer application), with a hazard coefficient of 2.07 and a biological absorption coefficient of 0.076. At this level of simulated contamination, the lowest concentrations of Cd^{2+} ions in table beet plants (0.018 and 0.021 mg/kg of fresh weight) were observed with the application of fertilizers and ameliorants at the rates of 4 t/ha of Biohumus + 5 t/ha of $CaCO_3$, and $N_{34}P_{34}K_{34}$ + 2 t/ha of Biohumus + 5 t/ha of $CaCO_3$, respectively. These results were statistically significant compared to the control ($p < 0.001$), with hazard coefficients of 0.60 and 0.70.

With the application of mineral and organic fertilizers at the rates of $N_{68}P_{68}K_{68}$ (treatment 2) and 4 t/ha of Biohumus (treatment 3) under the simulated soil contamination level of 5 MAC with cadmium, the concentration of Cd^{2+} ions in the root crops was 0.061

Table

Cadmium concentration in table beet plants depending on the levels of simulated soil contamination with this element under the application of fertilizers and ameliorants, mg/kg of fresh weight

Treatment	Natural background (control)			Levels of simulated soil contamination with cadmium (Cd^{2+})								
				1 MAC			3 MAC			5 MAC		
	Cd conc. in the plant, mg/kg	*Hc*	*BAc*	Cd conc. in the plant, mg/kg	*Hc*	*BAc*	Cd conc. in the plant, mg/kg	*Hc*	*BAc*	Cd conc. in the plant, mg/kg	*Hc*	*BAc*
1) Control (no fertilizers)	0.096 / 0.027	3.20 / 0.90	0.568 / 0.160	0.108 / 0.038	3.60 / 1.27	0.282 / 0.099	0.189 / 0.062	6.30 / 2.07	0.232 / 0.076	0.405 / 0.098	13.50 / 3.25	0.311 / 0.075
	0.169#			0,383			0.814			1.302		
2) $N_{68}P_{68}K_{68}$	0.071** / 0.019*	2.37 / 0.63	0.544 / 0.145	0.086* / 0.023**	2,87 / 0.77	0.282 / 0.075	0.145** / 0.033**	4.83 / 1.10	0.219 / 0.050	0.197** / 0.061**	6.57 / 2.03	0.180 / 0.056
	0.131			0.305			0.663			1.095		
3) Biohumus 4 t/ha	0.045** / 0.014**	1.50 / 0.47	0.375 / 0.117	0.075** / 0.019**	2.50 / 0.63	0.270 / 0.068	0.103** / 0.027**	3.43 / 0.90	0.171 / 0.045	0.155** / 0.046**	5.17 / 1.50	0.154 / 0.045
	0.120			0.278			0.602			1.003		
4) $N_{34}P_{34}K_{34}$ + Biohumus 2 t/ha	0.054** / 0.016**	1.80 / 0.53	0.439 / 0.130	0.081* / 0.022**	2.70 / 0.71	0.277 / 0.072	0.114** / 0.029**	3.80 / 0.97	0.176 / 0.045	0.182** / 0.056**	6.07 / 1.88	0.170 / 0.052
	0.123			0.293			0.649			1.070		
5) $N_{68}P_{68}K_{68}$ + $CaCO_3$ 5 t/ha	0.041** / 0.012**	1.37 / 0.40	0.371 / 0.109	0.064** / 0.017**	2.13 / 0.57	0.248 / 0.066	0.097** / 0.025***	3.23 / 0.83	0.170 / 0.044	0.119*** / 0.033***	3.97 / 1.10	0.125 / 0.035
	0.111			0.259			0.571			0.952		
6) Biohumus 4 t/ha + $CaCO_3$ 5 t/ha	0.029** / 0.006***	0.97 / 0.20	0.332 / 0.069	0.043*** / 0.010***	1.43 / 0.33	0.210 / 0.049	0.076*** / 0.018***	2.53 / 0.60	0.169 / 0.040	0.093*** / 0.026***	3.10 / 0.87	0.125 / 0.035
	0.087			0.204			0.449			0.743		
7) $N_{34}P_{34}K_{34}$ + Biohumus 2 t/ha + $CaCO_3$ 5 t/ha	0.034** / 0.010***	1.13 / 0.33	0.327 / 0.096	0.059** / 0.014***	1.97 / 0.47	0.261 / 0.062	0.083*** / 0.021***	2.77 / 0.70	0.167 / 0.042	0.106*** / 0.029***	3.53 / 0.97	0.130 / 0.036
	0.104			0.226			0.496			0.812		

Notes: 1. Numerator – Cd concentration in the tops (leaf blades); denominator – Cd concentration in the root crop (pulp); 2. # – concentration of mobile Cd^{2+} forms in the soil, mg/kg; 3. * – $p < 0.05$; ** – $p < 0.01$; *** – $p < 0.001$, the difference is statistically significant compared to the control (without fertilizers); 4. *Hc* – hazard coefficient, *BAc* – biological absorption coefficient, Maximum permissible concentration (MPC) of Cd in vegetables – 0.03 mg/kg of fresh weight.

and 0.046 mg/kg of fresh weight, respectively. The hazard coefficients (H_c) in these treatments were 2.03 and 1.50, with statistically significant differences compared to the control ($p < 0.01$). However, in treatment 6, where fertilizers and ameliorants were applied at the rate of $N_{34}P_{34}K_{34}$ + 2 t/ha of Biohumus + 5 t/ha of $CaCO_3$, the Cd^{2+} concentration in root crops decreased to 0.026 mg/kg ($p < 0.01$), with a hazard coefficient of 0.87.

It was found that in all treatments, the highest cadmium accumulation in *Beta vulgaris* L. plants occurred in the underground part of the root crop, particularly in the tapering end. The concentration of Cd^{2+} in the core of the root crop was the lowest. However, in the aboveground part, including the leaf petioles and leaf blades, the concentration of cadmium ions increased again.

It was established that the use of organic (treatment 6) and organic-mineral (treatment 7) fertilization systems in combination with soil liming resulted in the lowest concentrations of Cd^{2+} ions in table beet plants across all levels of simulated soil contamination with this element. Other treatments were less effective in reducing the mobility of cadmium ions in the soil. This led to more intensive accumulation of Cd^{2+} ions in table beet plants at all levels of simulated contamination.

According to the results of the correlation analysis, a strong positive relationship was established between the content of mobile Cd^{2+} forms in the soil and its accumulation in table beet root crops ($r = 0.85$). The coefficient of determination was $R^2 = 0.73$, indicating that 73 % of the variation in cadmium concentration in the plants is explained by its content in the soil solution (Fig. 2).

This suggests that table beet is a non-barrier-type plant with regard to Cd^{2+} ion accumulation. The plant does not effectively restrict the uptake and translocation of cadmium ions from the soil, allowing their movement into various organs, including edible parts. This characteristic increases the risk of cadmium entering the food chain through table beet consumption.

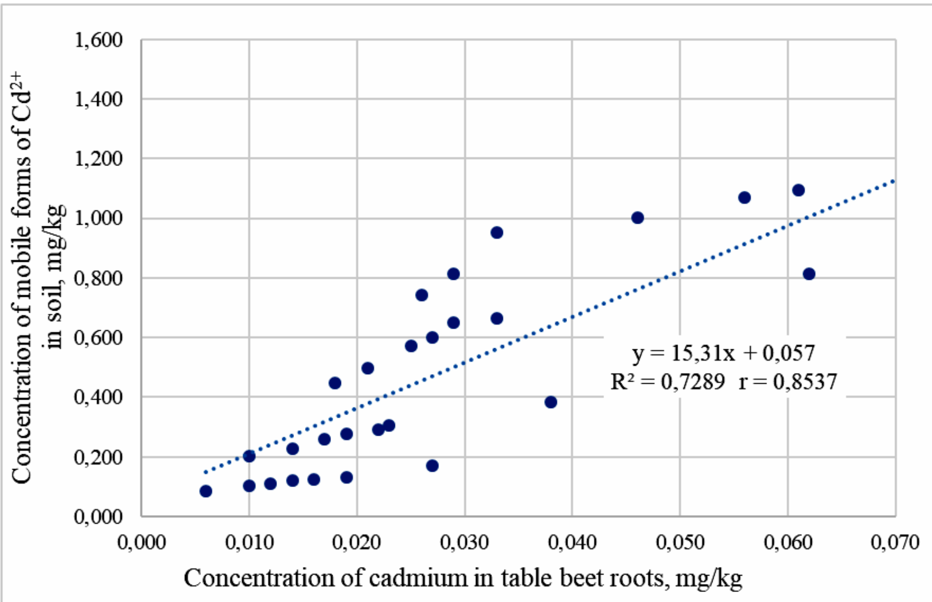

Fig. 2. Correlation graph showing the relationship between the concentration of mobile Cd^{2+} forms in the soil and the accumulation of the element in table beet root crops, depending on the simulated levels of cadmium contamination in the soil under the application of fertilizers and calcium-based ameliorants

Conclusions. It was established that the intensity of accumulation and redistribution of Cd^{2+} ions in different organs of *Beta vulgaris* L. plants depended on the levels of simulated soil contamination with cadmium, as well as on the application of different fertilization systems and liming.

It was determined that under natural background conditions (control), cadmium in *Beta vulgaris* L. plants accumulated most intensively in the underground part of the root crop (tapering end), reaching 0.324 mg/kg. In the root pulp, the Cd^{2+} concentration was 0.027 mg/kg, while in the root core it decreased to 0.012 mg/kg of fresh weight. In the aboveground part, the cadmium concentration in the petioles increased to 0.043 mg/kg. In the leaf blade, the Cd concentration was 3.5 times higher than in the root pulp and amounted to 0.096 mg/kg of fresh weight. It is worth noting that a similar pattern of cadmium accumulation and redistribution among different organs of table beet was also observed under the soil contamination level of 5 MAC.

The obtained results indicate that as the levels of simulated soil contamination with cadmium increased from 1 to 5 MAC, the concentration of mobile forms of heavy metals in the soil also increased, which correspondingly led to higher concentrations of Cd^{2+} ions in table beet plants across all treatments. However, the accumulation and redistribution of Cd^{2+} in different organs of *Beta vulgaris* L. were significantly influenced by the application of organic and mineral fertilizers, as well as calcium-based ameliorants.

It was established that the lowest accumulation of Cd^{2+} ions in table beet plants across all levels of simulated soil contamination occurred with the application of fertilizers and ameliorants at the rates of 4 t/ha of Biohumus + 5 t/ha of $CaCO_3$ and $N_{34}P_{34}K_{34}$ + 4 t/ha of Biohumus + 5 t/ha of $CaCO_3$. Under the organic fertilization system combined with soil liming (treatment 6), the cadmium concentration in the root crops decreased by 4.5 times, or by 77.7 %, compared to the control, with a statistically significant difference ($p < 0.001$). The highest cadmium accumulation in table beet plants was observed in the control treatment (without fertilizers).

Based on the conducted correlation analysis, a strong positive relationship ($r = 0.85$) was also established between the concentration of mobile Cd^{2+} forms in the soil and the accumulation of this element in table beet plants across all experimental treatments.

By selecting appropriate fertilization systems in combination with soil liming under specific soil and climatic conditions, it is possible to significantly reduce the mobility of heavy metals in the soil and, consequently, substantially decrease the accumulation of Cd^{2+} ions in *Beta vulgaris* L. plants, thereby ensuring the production of environmentally safe vegetable crops.

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