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Assessment of Phytoremediation of ^{137}Cs Contaminated Soils During the Cultivation of Nectar-Pollinating Plants

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ABSTRACT

The man-made activity of mankind has led to the emergence of many global problems and caused the deterioration of the quality of the natural environment (air, water, soil). Of particular concern is the contamination of agricultural land with toxicants, in particular, radionuclides, which, entering the soil – plant – human body food chain, can reach toxic levels. Therefore, an important task is the removal of hazardous substances from the soil. Phytoremediation can be one of the effective methods for reducing its pollution. The article examines the effectiveness of phytoremediation of soils contaminated as a result of the accident at the Chernobyl nuclear power plant in certain territories of Polissia of Ukraine (Korosten district of Zhytomyr region). Nectar-pollinating plants were selected for the research, which was carried out for two years: great globe-thistle (*Echinops sphaerocephalus*), milk thistle *(Silybum marianum)*, and white melilot *(Melilotus albus)*. The results of the research showed that in the dry vegetative mass of milk thistle, great globe-thistle, and white melilot, the specific activity of ^{137}Cs over the two years of research was in the range from 30.8 Bq/kg to 238.5 Bq/kg, the accumulation coefficient – from 0.135 to 0.985, and the hazard coefficient – from 0.055 to 0.395. The highest indicators of specific activity and accumulation coefficient of ^{137}Cs were observed in the vegetative mass of the white melilot, which amounted to 238.5 Bq/kg and 0.96, respectively, comparatively lower values – 2.3 times and 2.3 times were found in the vegetative mass of milk thistle, 2.8 times and 7.1 times – in the vegetative mass of the great globe-thistle. At this level of accumulation of ^{137}Cs in the vegetative mass of nectarine plants from the soil, on average, over two years of research, 1130550 Bq of this radionuclide was removed from the soil per hectare of agricultural land with milk thistle, 621250 Bq with great globe-thistle, and 2851650 Bq with white melilot. The removal of ^{137}Cs with the vegetative mass of nectarine plants reduced the content of this radionuclide in the soil per 1 kg – from 3.4% to 8% on average over two years of research.

Keywords: soil, milk thistle, white melilot, plants, phytoremediation, ^{137}Cs, accumulation coefficient, danger coefficient.

INTRODUCTION

The rehabilitation of soils contaminated with various toxicants is becoming more and more urgent, especially in conditions of man-made environmental stress, in particular, as a result of accidents at nuclear power plants, which presents the scientific community and the industrial sphere with the task of eliminating their negative consequences [Yamashita et al., 2014]. Thus, in 1986, Ukraine came under heavy contamination of certain territories with radionuclides due to the accident that occurred at the Chernobyl nuclear power plant. All components of the environment, in particular, air, soil, water bodies and others, were affected by radioactive pollution in some territories [Steinhauser et al., 2014; Cannon and Kiang, 2022].

A special danger after the accident at the Chernobyl NPP is caused by the contamination of agricultural soils, as well as the fact that a large area of agricultural land was removed from use in agricultural production.

Among all the radioisotopes that got into the soil of agricultural land as a result of the accident at the Chernobyl NPP, ^{137}Cs represents a high danger due to its active inclusion in the circulation system along the trophic chain (soil – plant products) and the food chain (food – human body) [Gupta et al., 2017; Burger and Lichtscheidl, 2018; Razanov et al., 2022]. This radionuclide has a decay period of 60 years and is actively accumulated by calliphilous plants.

Despite the fact that currently ^{137}Cs has passed the half-life period, there is still a certain danger of obtaining high-quality plant raw materials, which makes it impossible to return contaminated soils of agricultural lands to production [Shin and Adams, 2017; Kaste et al., 2021]. It is possible to speed up the possibility of returning these lands to agricultural use by cleaning them from this toxicant [Kato et al., 2014; Herlina et al., 2020].

It is known that one of the effective measures for soil purification from toxicants is phytoremediation (removal of pollutants with plant biomass, for example, with vegetative mass, seeds) [Ashraf et al., 2019; Dursun et al., 2020]. However, due to the extraction of radionuclide-contaminated soils from agricultural production, the removal of radioisotopes from them with vegetation by means of phytoremediation practically does not occur. Under such conditions, radioisotopes that accumulate in uncultivated vegetation after the end of vegetation fall back into the soil, which only leads to the movement of these toxicants into a certain layer of the soil [Sharma et al., 2015].

Considering the low level of accumulation of radionuclides in the nectar and pollen of plants, which is food for honey bees and raw material for the production of beekeeping products, it is promising to use phytoremediation of contaminated soils by growing nectar-pollen-bearing crops on them with the removal of their vegetative mass and subsequent utilization [Wieczorek et al., 2020; Singh et al., 2022].

Taking into account the fastidiousness of nectar-pollinating plants to the natural and climatic conditions of the research region, the most promising crops turned out to be: great globe-thistle, milk thistle, white melilot.

In particular, great globe-thistle is a fairly resistant plant in terms of adverse conditions, it belongs to drought-resistant plants, it actively secretes nectar even at a low level of moisture supply. This culture is characterized by high nectar productivity – up to 500 kg of honey can be obtained from 1 hectare of continuous area. Great globe-thistle is a perennial crop that blooms in July and August [Kutsenko, 2014; Shevchenko and Hlushchenko, 2018].

Milk milk thistle is also a drought-resistant plant, its nectar productivity is on average 100 kg of honey from 1 ha, the flowering period is from July to September. Nectar and pollen are secreted throughout the day [Razanov et al., 2021; Zakhariya et al., 2022].

White melilot is a drought-resistant plant and is a good honey bearer. So, from 1 hectare of its continuous sowing, you can collect up to 300 kg of honey, it has a long flowering period that lasts for two months [Lavrinenko et al., 2019].

The specified plants are characterized by a low need for moisture, which is a favorable indicator in the conditions of the Polissia of Ukraine, as well as high nectar productivity, which represents a certain interest in beekeeping [Tkachuk and Tsygansky, 2019].

Reducing the content of various toxicants in the soil is an important task today, especially in the conditions of technogenic stress on the environment. One of the methods of soil purification from radionuclides is phytoremediation, in particular, by growing nectar-pollinating plants.

It is known that nectar-pollinating plants in polluted areas are characterized by a certain accumulation of ^{137}Cs in the vegetative mass. In particular, active accumulation of ^{137}Cs by wild nectar-pollinating plants: heather, thyme, bombweed, etc. was found [Aleksenitser et al., 1996, Pourimani et al., 2016].

Along with this, the effectiveness of phytoremediation of ^{137}Cs-contaminated soils by nectar-pollinating plants (milk thistle, white melilot, great globe-thistle) is not sufficiently covered in scientific and practical publications.

The purpose of the research is to study the effectiveness of phytoremediation of ^{137}Cs-contaminated soils for the cultivation of nectar-pollinating plants.

MATERIALS AND METHODS

The research was conducted in the conditions of the territories affected by the accident at the Chornobyl NPP (Korosten district of Zhytomyr region). Contaminated areas are located in the central and northeastern parts of the district. This region is characterized by a low and very low content of nitrogen and phosphorus in the soil. The close location of crystalline rocks to the earth's surface promotes waterlogging, which slows down the process of soil formation and increases the formation of peat-swamp soils. The climate is moderately continental. Average monthly temperatures during the summer exceed +18 °C, the amount of precipitation during the summer period is 250 mm, which is 40% below the norm.

Soil sampling for radiological research was carried out by the envelope method at five points of the field, taking into account the distance of the protective (100 m) zone. Soil sampling was carried out at the depth of soil plowing (22–24 cm). The soil (0.5 kg) cleaned from the remains of vegetative mass was packed in a bag, numbered, and then delivered to the radiological laboratory as a representative sample. Vegetative mass of plants (milk thistle, great globe-thistle, white melilot) was selected by the method of point samples. From each batch of vegetative mass of nectarine plants, after threshing the seeds, 3–4 kg were taken for radiological analysis. The specific activity of ^{137}Cs in the soil and vegetative mass was determined by the gamma spectrometric method. The scheme of research is presented in Table 1.

The accumulation coefficient (C_{acc}) was determined by the formula:

$$C_{acc} = \frac{\text{Specific activity of 137Cs in the vegetative mass of nectar} - \text{-pollinating plants}}{\text{Specific activity of 137Cs in soil}} \quad (1)$$

The hazard ratio (R_{haz}) was determined by the formula:

$$R_{haz} = \frac{\text{Specific activity of 137Cs in the vegetative mass of nectar} - \text{-pollinating plants}}{\text{PL} - 2006} \quad (2)$$

where: PL – permissible levels;
C_{acc} – toxicant accumulation coefficient;
R_{haz} – the hazard ratio of toxicants.

RESULTS AND DISCUSSION

The analysis of research results (Fig. 1) shows certain differences between the intensity of ^{137}Cs accumulation in the vegetative mass of nectarine plants at the same level of soil contamination with this radionuclide.

In particular, it was found that the specific activity of ^{137}Cs in the vegetative mass of nectarine

Table 1. Scheme of research

Researched material	Intensity of ^{137}Cs accumulation in vegetative mass, Bq/kg			
Vegetative mass of nectar-pollinating plants (great globe-thistle, milk thistle, white melilot)	Specific activity	Accumulation coefficient	Hazard coefficient	Intensity of removal with vegetative mass of ^{137}Cs from the soil

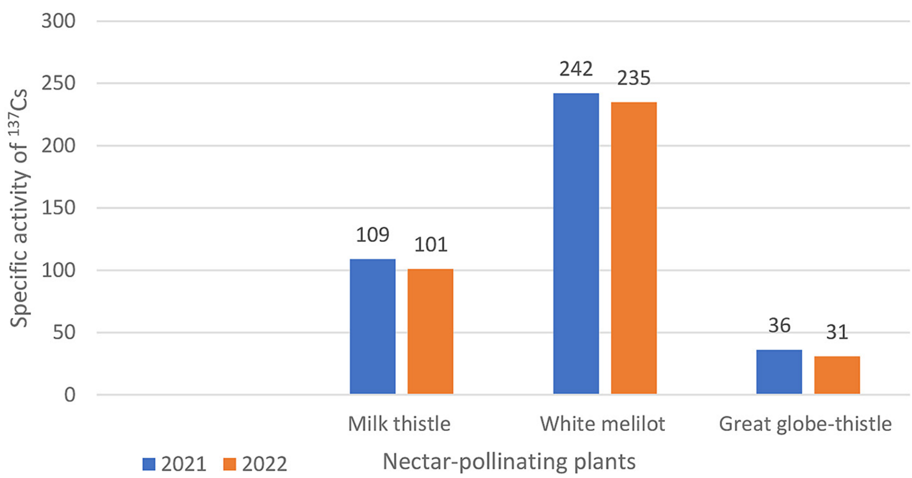

Figure 1. Specific activity of ^{137}Cs in the vegetative mass of nectar-pollinating plants, Bq/kg

plants in 2021 ranged from 36 Bq/kg to 242 Bq/kg. The highest specific activity of ^{137}Cs was characterized by the vegetative mass of the white gorse, which amounted to 242 Bq/kg. Compared with the similar raw materials of nectarine pollen grains of great globe-thistle and milk thistle, the specific activity of ^{137}Cs in the white melilot was 2.2 times and 6.7 times higher, respectively.

The specific activity of ^{137}Cs in the vegetative mass of nectarine plants in 2022 ranged from 30.8 Bq/kg to 235 Bq/kg. Among the studied plants, the highest specific activity of ^{137}Cs was also found in the white melilot, which amounted to 235 Bq/kg, comparatively lower – by 7.6 times and 2.3 times, respectively, in great globe-thistle and milk thistle.

The results of research on the intensity of accumulation of ^{137}Cs in the vegetative mass of nectarine pollen and their compliance with the maximum permissible levels (MPL) are presented in Table 2. These research results show that the specific activity of ^{137}Cs in the vegetative mass of milk thistle, great globe-thistle and white melilot was lower than the MPC in 2021 5.2 times, 16.6 times and 2.5 times, and in 2022 – 5.5 times, 19.5 and 2.5 times, respectively.

The coefficient of accumulation of ^{137}Cs in the vegetative mass of nectarine plants (Table 3) for 2021 ranged from 0.14 to 0.93. The coefficient of accumulation of ^{137}Cs in the vegetative mass of the white melilot was 2.5 times higher compared to the milk thistle and 6.6 times higher.

The coefficient of accumulation of ^{137}Cs in the vegetative mass of nectarine in 2022 was in the range from 0.13 to 1.0. At the same time, it should be noted that the coefficient of accumulation of ^{137}Cs in the vegetative mass of the white melilot was 2.5 times higher compared to the milk thistle, and 7.6 times higher in great globe-thistle.

The hazard ratio of ^{137}Cs in the vegetative mass of nectarine plants in 2021 (Table 4) was in the range from 0.06 to 0.40. The highest risk factor of ^{137}Cs was characterized by the white grunt. In particular, the hazard ratio of ^{137}Cs in the vegetative mass of white melilot in 2021 was 2.2 times higher compared to the milk thistle and 6.6 times higher in great globe-thistle. The hazard ratio of ^{137}Cs in white melilot grown in 2022 was 2.3 times higher than that of milk thistle and 7.8 times higher than great globe-thistle.

The results of studies on the effectiveness of phytoremediation of radioactively contaminated soils (Table 5) showed that with the vegetative mass of nectarine plants, from each hectare of arable land is carried from 551320 Bq to 3000800 Bq of ^{137}Cs.

Table 2. Specific activity of ^{137}Cs in the vegetative mass of nectar-pollinating plants, Bq/kg

Nectar-pollinating plants	2021	2022	MPL
Milk thistle	109 ± 1.7	101 ± 1.5	600
Great globe-thistle	36 ± 0.4	31 ± 0.8	600
White melilot	242 ± 2.1	235 ± 1.8	600

Table 3. The coefficient of accumulation of ^{137}Cs in the vegetative mass of nectar-pollinating plants

Nectar-pollinating plants	2021			2022		
	Specific activity of ^{137}Cs in soil, Bq/kg	Specific activity of ^{137}Cs in plants, Bq/kg	$C_{acc.}$	Specific activity of ^{137}Cs in soil, Bq/kg	Specific activity of ^{137}Cs in plants, Bq/kg	$C_{acc^*.}$
Milk thistle	258	109	0.42	251	101	0.40
Great globe-thistle	258	36	0.14	255	31	0.13
White melilot	258	242	0.93	234	235	1.0

Table 4. The hazard ratio of ^{137}Cs in the vegetative mass of nectar-pollinating plants

Nectar-pollinating plants	2021			2022		
	Specific activity of ^{137}Cs in plants	MPL	$R_{haz.}$	Specific activity of ^{137}Cs in plants	MPL	R_{haz}
Milk thistle	109	600	0.18	101	600	0.17
Great globe-thistle	36	600	0.6	31	600	0.05
White melilot	242	600	0.40	235	600	0.39

Table 5. Removal of ^{137}Cs from the soil with the vegetative mass of nectar-pollinating plants

Vegetative mass of nectar-pollinating plants	Specific activity of ^{137}Cs in soil, Bq/kg				Outcome of vegetative mass, t/ha		Removed with a vegetative mass of ^{137}Cs, Bq/ha	
	Soil		Vegetative mass					
	Vegetation start	Vegetation termination						
	2021	2022	2021	2022	2021	2022	2021	2022
Milk thistle	258	243	109	101	11.2	10.3	1220800	1040300
Great globe-thistle	258	249	36	31	19.1	17.9	687600	554900
White melilot	258	206	242	235	12.4	11.5	3000800	2702500

The highest intensity of removal of ^{137}Cs from the soil was observed during the cultivation of white burkun on average over two years of research – 2851650 Bq from one hectare of arable land. With the vegetative mass of the white melilot, 2.5 times more ^{137}Cs was removed from the soil per one hectare of arable land compared to the milk thistle and 4.6 times compared to great globe-thistle.

During the two years of cultivation of milk thistle, great globe-thistle, and white melilot, the specific activity of ^{137}Cs in the soil decreased by 5.8%; 3.4% and 8.0%, respectively.

CONCLUSIONS

Based on the results of the research, it was established that for the content of ^{137}Cs in sod-podzolic sandy soils from 240 Bq/kg to 258 Bq/kg, excesses of PL-2006 of this nuclide were not observed in the vegetative dry mass of such plants as: milk thistle, great globe-thistle, and white gorse.

The specific activity of ^{137}Cs in the dried vegetative mass of plants (milk thistle great globe-thistle, and white melilot) averaged over two years of research in the range from 33.5 Bq/kg to 238.5 Bq/kg. The highest indicators of specific activity and accumulation coefficient of ^{137}Cs were observed in the vegetative mass of the white melilot, which amounted to 238.5 Bq/kg and 0.96, respectively, comparatively lower values – 2.3 times and 2.3 times were found in the vegetative mass of milk thistle, 2.8 times and 7.1 times – in the vegetative mass of great globe-thistle.

At this level of accumulation of ^{137}Cs in the vegetative mass of nectarine plants from the soil, on average, over two years of research, 1130550 Bq of this radionuclide was removed from the soil per hectare of agricultural land with milk thistle, 621250 Bq with great globe-thistle, and 2851650 Bq with white melilot. The removal of ^{137}Cs with the vegetative mass of nectarine plants reduced the content of this radionuclide in the soil per 1 kg – from 3.4% to 8% on average over two years of research.

The prospect of further research is to study the intensity of ^{137}Cs accumulation in the seeds of milk thistle, white melilot, great globe-thistle, as well as in the nectar, pollen of these plants, in the products of their processing by bees – honey, bee bread.

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