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Modeling Radiocesium Contamination of Sunflower Products in the Zaporizhzhia Region

Anatolii Polevoy[1], Galyna Lyashenko[2], Olena Zhygailo[1*], Oksana Volvach[1], Taras Zhygailo[3], Iryna Popovych[1], Alla Tolmachova[1], Valeriya Kolosovska[1], Tetyana Kostyukevych[1], Olena Barsukova[1]

[1] Odesa State Environment University, 15 Lvivska Street, Odesa, 65016, Ukraine

[2] National Scientific Center "V.Ye. Tairov Institute of Viticulture and Winemaking", 27 the 40th anniversary of Victory Street, 65496, village Tairove, Odesa region, 65496, Ukraine

[3] State Enterprise "Experimental Farm "Andriivske" Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine", 58 Central Street, village Andriivka, Bilgorod-Dnistrovsky district, Odesa region, 67742, Ukraine

* Corresponding author's e-mail: elenajigaylo@gmail.com

ABSTRACT

The accident at the Chornobyl nuclear power plant was one of the most serious nuclear incidents in human history. A radioactive plume covered a whole strip of northeastern Europe. The consequences of this catastrophe are still being felt, both in Ukraine and around the world. The article is devoted to the assessment of the consequences of radiocesium contamination of agricultural lands and irrigated waters during a possible accident at the Zaporizhzhia NPP and the associated Cs^{137} contamination of sunflower products in the Zaporizhzhia region. The studies were carried out using a dynamic mathematical model for the formation of radionuclide activity in the "water-soil-plant-product" system, ECOSIS-87 (Ecoplant). The article presents the results of studies of possible contamination of the environment by radiocesium according the Chornobyl NPP-86 scenario and sunflower production by the method of mathematical dynamic modeling. The calculations were carried out on the basis of the results of an agrochemical and agroecological survey of the state of soils in Ukraine and the Dnipro cascade of reservoirs. If an explosion occurs at the Zaporizhzhia NPP, the power of which will be equal to the Chornobyl NPP, then 100,000 hectares of agricultural land in the region will be taken out of the agricultural production of the Zaporizhzhia region. On agricultural lands where soil contamination with radiocaesium will be more than 5 Ci/km^2, and the concentration in irrigated waters will reach 2 Bq/dm^3, sunflower, which was grown for seeds to produce oil will need to be replaced with an industrial crop, which will also lead to loss of seed yield sunflower. Crop losses will lead to a decrease in the volume of sunflower oil. It should also be taken into account that the purification of soil and water does not occur in one year. At least in 5 years the situation will begin to improve.

Keywords: modeling, scenario, nuclear accident, radiocesium, soils, water, sunflower.

INTRODUCTION

As global in its scope and consequences, the accident at the Chornobyl nuclear power plant in 1986 was a stern warning to mankind and showed the need for extremely responsible handling of any potentially hazardous technologies. The accident in one way or another affected millions of people living both in Ukraine and in other countries. Activities to minimize its effects contributed to the development of relevant scientific research. Domestic scientists and scientists from a number of countries have carried out scientific studies of the behavior of radionuclides in the environment and studied all the ways of their migration from sources to humans.

Much of the published data on the behavior and migration of radionuclides in soils comes from pilot plots where observations were made after initial deposition on the soil surface. For a number of radionuclides, including Sr^{90} and Cs^{137}, more detailed results of scientific observations and migration models are available. At present, data on radiocesium contamination of the soil surface in Europe after the Chornobyl accident have been published [Evangeliou et al., 2016, Begy et al., 2017].

The results of monitoring water bodies in the zone of influence of the Chornobyl accident reveal the dynamics of the formation of radioactive contamination of Sr^{90} and Cs^{137} in the Pripyat, the Dnipro and the Dnipro reservoirs [Voitsekhovych et al, 2016], make it possible to model the contamination of surface and ground waters with radionuclides in rivers and reservoirs, as after the accident at Chornobyl NPP, and after the accident at the Fukushima Daiichi nuclear power plant [Konoplev et al., 2021].

Absorption and distribution of radionuclides in plants are carried out in two ways - by leaves and roots. Adsorption of dissolved radionuclides by leaves occurs through the stomata or cuticle, and the longer the pollutants are on the leaf surface, the higher the probability of their absorption. Therefore, precipitation is an important factor. Two factors influence the process of uptake by roots - the soil and the plant. There are several approaches to the study of radionuclides uptake by roots from the soil solution. For radiostrontium and radiocesium an approach is practiced that based on the similarity of the ecological behavior of cesium and potassium, as well as strontium and calcium. The hypothesis is based on the fact that the mineral composition of a crop is fairly constant and the content of cesium and strontium in a crop can be derived from the corresponding ratios of the contents of cesium and potassium, as well as strontium and calcium. Using the experience of agriculture after the accident at the Chornobyl nuclear power plant, after the accident at the Fukushima Daiichi nuclear power plant, to reduce the transfer of radioactive cesium from soil to plants, the level of exchangeable potassium in the soil was increased. These methods have successfully reduced the radioactivity of agricultural products in the disaster area. [Shinano, 2020, Shinano et al., 2018].

Plants are primary derivatives and can accumulate radioactive material. Based on the data of long-term radioecological monitoring of Ukrainian lands contaminated as a result of the Chornobyl accident, the dynamics of Cs^{137} accumulation by plants in a wide range of environmental conditions was studied, and a kinetic model of Cs^{137} behavior in the "soil-plant" system was created [Prister et al, 2011]. The obtained results of radiocesium uptake by plants make it possible to assess the contamination of both the plants themselves and the soil [Noor et al., 2017, Panov et al., 2022].

At present, a large amount of experimental material has been collected on the accumulation of radioactive substances in agricultural products grown on soils contaminated with radionuclides. Relationships have been found between various characteristics of soil, irrigation water, and the activity of radionuclides in crop production. The experience gained by scientists around the world on the example of the Chornobyl nuclear power plant in 1986 was used by scientists during the accident at the Fukushima Daiichi nuclear power plant in 2011 and expanded by studies on the distribution of radionuclides in soils and plants [Oshita et al., 2011, Tanoi et al., 2011, Sasaki et al., 2013, Steinhauser et al., 2014]. On soils contaminated with radiocesium at the time of the accident more than 5000 Bq/kg, the content of radioactive cesium in soybean grain reached 400-500 Bq/kg [Hachinohe et al., 2013]. The parameters values of radionuclide transfer into the environment were obtained to assess the concentrations of their activity in agricultural crops with direct contamination. A comparative analysis of the obtained indicators after the accident at the nuclear power plant in Japan with the values of the accident at the Chornobyl nuclear power plant in Ukraine was carried out [Tagami et al., 2020, 2021].

For Ukraine this topic remains urgent. After the accident at the Chornobyl nuclear power plant, a significant part of the lands of Polissya was contaminated with radionuclides that were taken out of land use. Northern Polissya was and remains the most polluted territory. Some of the contaminated areas are under full-scale and limited economic activities. An analysis of the density of soil contamination with Cs^{137} isotopes in the northern part of the Zhytomyr region in the post-accident period shows that even 30 years after the tragedy significant areas of arable land under certain conditions remain potentially dangerous due to contaminated plant products. [Romanchuk et al., 2017]. Studies of the contamination of fiber flax grown on lands contaminated with radionuclides in this zone showed that at a contamination density of Cs^{137} of 20.5 Ci/km^2, its content in the chaff reached 1539 Bq/kg, and in seeds it was 510 Bq/kg [Kovalev et al., 2020]. The results of monitoring of radioactive contamination of agricultural crops under irrigation conditions in the steppe zone of Crimea indicate that at present the levels of radionuclide activity concentration in cultivated crops do not exceed the temporarily permissible level [Mirzoeva et al., 2022].

When studying the phytorehabilitation of soils contaminated with radionuclides it was found that sunflower most actively accumulates radiocesium in its biomass [Soudek et al., 2006].

In Ukraine sunflower is one of the most popular oilseeds. The high level of profitability and the demand for seeds led to a significant expansion of the acreage. The Zaporizhzhia region takes fourth place in the rank of regions in terms of sunflower sowing areas. Sunflower is the main oilseed crop of the country. In terms of economic value and importance, it is not inferior to such widespread crops as wheat, corn, soybeans. Compared to other oilseeds, sunflower yields the highest oil yield per unit area. Sunflower oil accounts for 98% of the total oil production in Ukraine. Ukraine occupies a leading position in the ranking of world producers and exporters of sunflower seeds. The share of the country in the production of oilseeds is 50%.

The purpose of the presented study is to assess the possible radiocesium contamination of sunflower products in the Zaporizhzhia region during a hypothetical accident at the Zaporizhzhia NPP.

MATERIALS AND METHODS

The studies of pollution of sunflower products were carried out using the dynamic mathematical model ECOSIS-87 (Ecoplant) [Polevoy, 1993]. The structure of the model is determined by biological ideas about the growth and development of cultivated plants; regularities in the formation of the climatic regime and soil-forming processes and their influence on the productivity and quality of the crop.

The model has a block structure (Fig. 1). The block of input information assumes the use of meteorological (average ten-day air temperature), agrometeorological (moisture reserves in

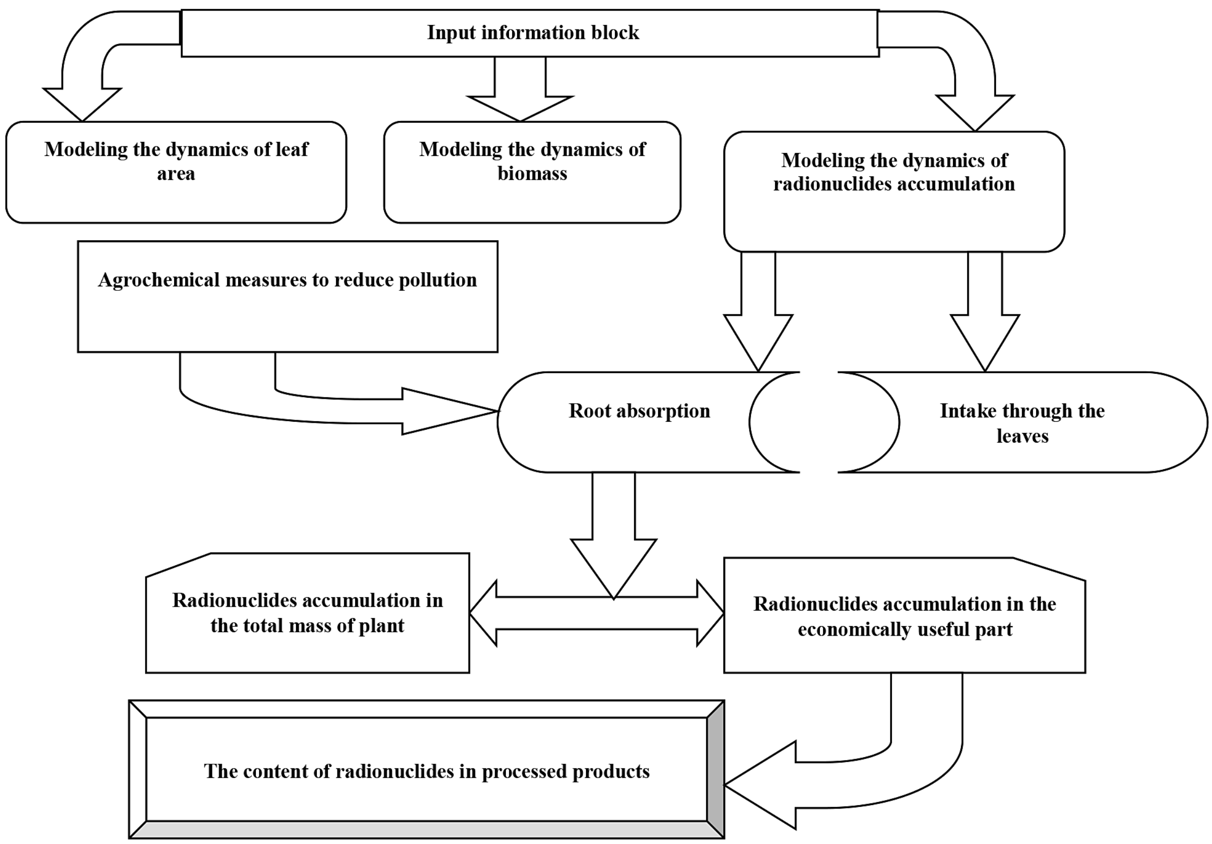

Figure 1. Block diagram of radionuclide activity formation model in the system "soil - irrigation water - plant - product"

the soil in the 0-20 cm layer, norm and time of vegetation irrigation) information, agrophysical characteristics (soil density) and agrochemical (humus and mobile potassium content in soil, soil solution pH) soil conditions, contamination of soil and irrigation water with radionuclides. The initial characteristics of the vegetation cover, the initial boundary conditions for solving the system of equations are set.

The leaf area and biomass dynamics as well as dynamics of accumulation of radionuclides both due to root absorption and due to the intake of radionuclides through the leaves are modeled. The processes of accumulation of radionuclides in the total mass of plants and in the economically useful part are modeled separately. The formation of radionuclide activity in the products of processing closes the chain of migration of radionuclides in the system "water - soil - plant - product". There is a block of agrochemical measures in the model for reducing radioactive contamination.

A mathematical description of the model of radioactive contamination of primary biological products under irrigation conditions is described in [Zhygailo, 2007]. The data of radioecological monitoring of soil pollution (Institute for Safety Problems of Nuclear Power Plants of the National Academy of Sciences of Ukraine) and surface waters (Ukrainian Hydrometeorological Institute of the State Emergency Service of Ukraine and the National Academy of Sciences of Ukraine) were used in the work.

The so-called “ChNPP-86 scenario” (Chornobyl nuclear power plant) is used to assess the possible contamination of agricultural land and water bodies with radiocesium in the event of an accident at the Zaporizhzhia nuclear power plant (Energodar, Ukraine). The scenario takes into account that the total release of radioactive substances as a result of the accident will be about 14 EBq1 (as of April 26, 1986), including 0.085 EBq of Cs^{137}. Soil contamination with radiocesium in the 30 km zone will be more than 40 Ci/ km^2 (which is typical for the situation of soil contamination with radiocesium in 1986), within a radius of 30 km to 50 km, the density of soil contamination is more than 20 Ci/km^2, from 50 km to 100 km – within 15…2 Ci/km^2 (indications of soil pollution monitoring in 1986). Soils, the pollution of which is up to 1 Ci/km^2 are considered conditionally clean, they are located within a radius of more than 100 km. According to the ChNPP-86 scenario (indications of monitoring of radioactive contamination of surface waters immediately after the Chornobyl accident) in the Dnipro River basin radiocesium contamination reaches 2 Bq/l; in the Dnipro reservoirs are: in the Kyiv reservoir – 1700 Bq/m^3, in the Kaniv reservoir – 750 Bq/m^3, in the Kremenchuk reservoir – 180 Bq/m^3, in the Dnipro reservoir - 63 Bq/m^3 and the Kakhovka reservoir – 37 Bq/m^3.

Modeling radiocesium contamination of sunflower products (total biomass, seeds and oil) in 18 districts of the Zaporizhzhia region was performed and presented in the article.

RESULTS AND DISCUSSION

The soils of the Zaporizhzhia region are mainly represented by ordinary chernozems and southern chernozems, dark chestnut and chestnut soils (Table 1). They are characterized by medium and low humus content, neutral and close to neutral soil acidity, and a fairly high content of mobile forms of potassium. The density of contamination of agricultural land with radiocesium at present in all regions does not exceed 0.2 Ci/km^2. The content of Cs^{137} in irrigated water, which is supplied from the irrigation systems of the Kakhovka and the Dnipro reservoirs, is in the range of 0.068–0.11 Bq/dm^3.

The results of modeling radiocesium contamination of the total sunflower biomass in 2021 showed the least contamination in the areas of sunflower cultivation on rainfed crops (the Berdyansk and Pology subregions). The greatest pollution of sunflower biomass is in the areas of cultivation of crops on irrigated lands, moreover, by the waters of the Dnipro reservoir (the Novo-Mykolayivka and Orikhiv districts).

According to the ChNPP-86 scenario, within a radius of 30 km from the epicenter of the explosion, soil contamination with radiocesium of agricultural lands in the Kamyanka- Dniprovska district will exceed 40 Ci/ km^2, so agricultural activity here will be impossible (Table 1).

Within a radius of 30 km to 50 km soil contamination is expected to be more than 20 Ci/ km^2, and farmlands of the Vasylivka district will be in this zone. The concentration of radiocesium in the water irrigated from the Kakhovka reservoir will reach 2 Bq/dm^3. The results of modeling radiocesium contamination of the total biomass of irrigated sunflower showed that the concentration

Table 1. Radiocesium contamination of sunflower crops on agricultural lands of the Zaporizhzhia region

District	Soils	Cs^{137} soil contamination density, Ci/km^2		Cs^{137} concentration in total biomass, Bq/kg	
		2021	ChNPP-86 scenario	2021	ChNPP-86 scenario
Berdyansk subregion					
Berdyansk[1]	OMHCh	0.02	0.51	0.26	8.04
Prymorsk[1]	SLHCh	0.09	0.22	1.64	3.47
Chernigivka[1]	SChTO	0.04	0.44	0.63	9.94
Vasylivka subregion					
Vasylivka[2]	SChTO	0.05	21.36	21.67	740.17
K.-Dniprovska[2]	SLHCh	0.03	>40	22,33	is not allowed
Mykhailivka[2]	SChTO	0.06	5.61	21.83	491.85
Tokmak[2] (WP)	SChTO	0.12	5.12	22.77	484.12
Zaporizhzhia subregion					
Zaporizhzhia[2]	OLHCh	0.03	5.61	20.21	491.85
Vilnyansk[2]	OMHCh	0.03	2.11	20.21	436.66
N.-Mykolayivka[3]	OMHCh	0.05	2.30	52.89	455.42
Orikhiv[3]	OLHCh	0.04	7.02	55.74	514.08
Melitopol subregion					
Vesele[2]	SLHCh	0.04	5.61	22.52	491.85
Melitopol[2]	SLHCh	0.04	7.02	22.52	514.08
Yakymivka[2]	DChnWMS	0.05	3.28	21.67	455.11
Pryazovske[1]	ChnMSS	0.04	0.22	1.48	3.47
Pology subregion					
Pology[1]	OLHCh	0.14	0.44	2.96	9.94
Gulyaipole[1]	OLHCh	0.09	0.44	2.17	9.94
Bilmak[1]	OLHCh	0.16	0.93	3.27	14.66
Tokmak[1] (EP)	SChTO	0.12	5.12	2.64	80.73

Note: [1] – farmland without irrigation; [2] – irrigation from the Kakhovka reservoir; [3] – irrigation from the Dnipro reservoir; WP – western part; EP – eastern part.
Radiocesium concentration in irrigated water: 0.068–0.11 Bq/dm^3 (2021); 2.0 Bq/dm^3 (ChNPP-86 scenario).
Soils: OMHCh – ordinary medium-humus chernozem; SLHCh – southern low-humus chernozem; SchTO – southern chernozem turning into ordinary; OLHCh – ordinary low-humus chernozem; DChnWMS – dark chestnut, weakly and medium solonetzic; ChnMSS – chestnut medium and strongly solonetzic.

of Cs^{137} would reach 740 Bq/kg, with a temporary allowable level of 600 Bq/kg. The situation will be catastrophic in all areas where sunflower is grown on irrigation. In these areas, the content of radiocesium according to the scenario will be ten times higher than its content in crops in 2021. So, for example, in the Zaporizhzhia region, the concentration of radiocesium in crops will increase from 20 Bq/kg to 490 Bq/kg, in the Melitopol region – from 23 Bq/kg to 514 Bq/kg.

Only in areas located within a radius of more than 100 km (the Pology and Berdyansk subregions), where the density of agricultural land contamination with radiocesium will be less than 1 Ci/ km^2 and without irrigation the concentration of Cs^{137} in the total biomass will not exceed 15 Bq/kg.

Using the model, calculations of the radiocesium specific activity dynamics were made during the growing season for all districts of the region. There is a general trend in the radiocesium specific activity dynamics during the vegetative period. The modeling results for the Berdyansk and Vasylivka districts are presented in Figure 2.

On the rainfed lands of the Berdyansk district in 2021, during the germination period, the specific activity of radiocesium in the vegetative organs was 0.001 Bq/kg (Fig. 2a), on irrigated plots in the Vasylivka district it reached 0.59 Bq/kg (Fig. 2b). In the period from seedlings to the formation of inflorescences, the specific activity of radiocesium in the vegetative organs increased and at the time of the formation of the inflorescence-busket was 0.022 Bq/kg and 3.29 Bq/kg,

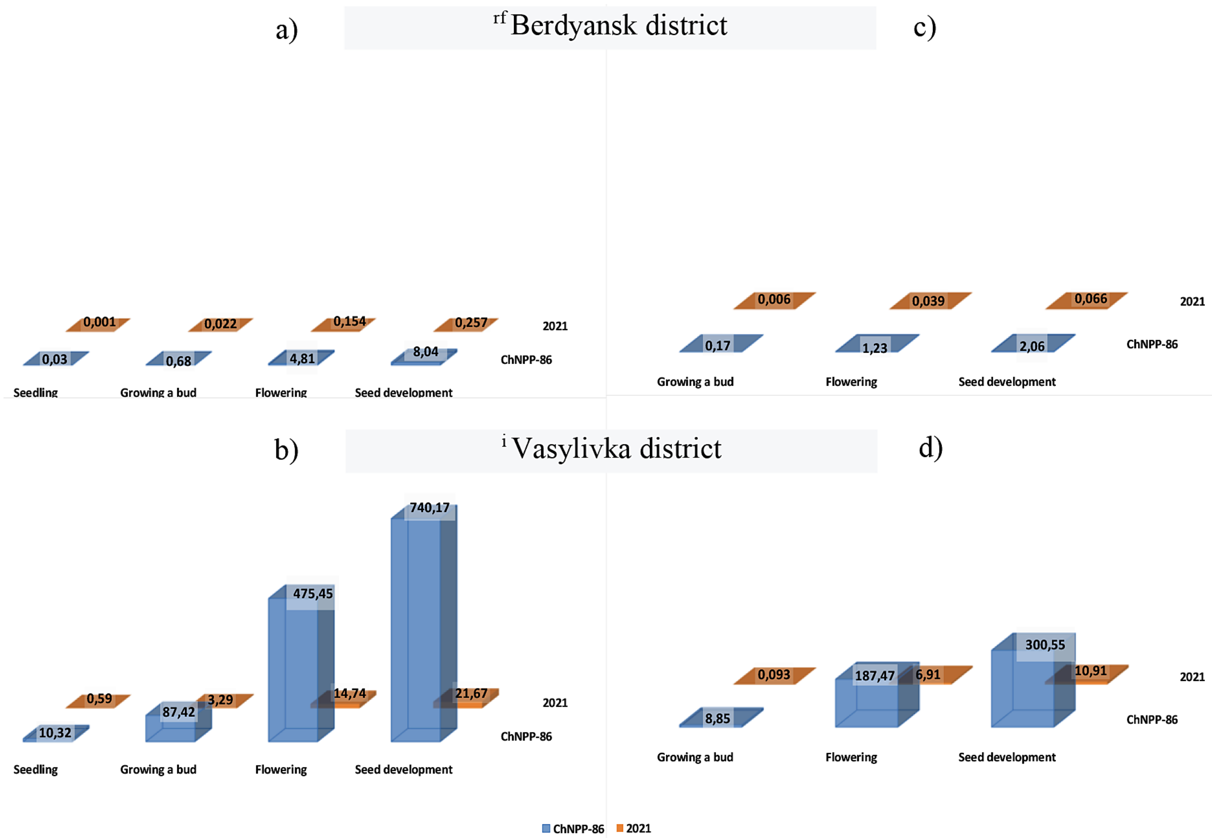

Figure 2. Cs^{137} specific activity dynamics (Bq/kg) in sunflower (Heliantus annus) according development phases: (a) and (b) – in vegetative organs; (c) and (d) – in the generative organs

respectively. In generative organs, the concentration of Cs137 was 0.006 Bq/kg (Fig. 2c) and 0.093 Bq/kg (Fig. 2d), respectively. At the flowering phase the specific activity of radiocesium continues to increase, reaching 0.154 Bq/kg and 14.74 Bq/kg in the vegetative biomass, and 0.039 Bq/kg and 6.91 Bq/kg in the generative biomass, respectively. Compared to the period of seedlings - formation of inflorescences in the period of flowering - maturation, the activity of accumulation of radiocesium decreases, but continues to accumulate. At the time of maturation, the concentration of radiocesium in the vegetative mass is 0.257 Bq/kg and 21.67 Bq/kg, in the generative mass it is 0.067 Bq/kg and 10.91 Bq/kg, respectively.

According to the ChNPP-86 scenario, in the rain-fed areas of the Berdyansk region, the concentration of radiocesium in the vegetative and generative organs of sunflower will be 28–31 times higher than the concentration of radiocesium in the crops in 2021. On irrigated farmland in the Vasylivka district, at the time of sunflower seedlings, the concentration of radiocesium in the vegetative organs will be 10.32 Bq/kg (Fig. 2b), which is 18 times higher than in 2021, and the level of contamination in the period of inflorescence formation will be 26 times higher. During the flowering and maturation phases, the concentration of Cs^{137} will increase by more than 30 times. During the period of the beginning of the formation of generative organs in plants (the formation of inflorescences), the specific activity of radiocesium in them will be 95 times higher compared to the indicators for 2021 (Fig. 2d). Such a high concentration of Cs^{137} during this period is associated with vegetation irrigation with radioactive water, the concentration of radiocesium in which, according to the scenario, is 2 Bq/dm^3.

Modeling of radiocesium contamination of sunflower products is presented in Table 2. It was established that the concentration of radiocesium in sunflower seeds grown on rainfed land in the Berdyansk and Pology subregions in 2021 was within 0.07...0.65 Bq/kg. In the Vasylivka, Zaporizhzhia and Melitopol subregions, where sunflower was grown under irrigation, the concentration of radiocesium in seeds was 10.90–29.08 Bq/kg. In both cases, the concentration of radiocesium in the seeds is much less than the temporary permissible level. In sunflower oil obtained from

Table 2. Radiocesium contamination of sunflower products. The Zaporizhzhia region

Subregion	District	Cs^{137} concentration, Bq/kg in:			
		seeds		oil	
		2021	ChNPP-86 scenario	2021	ChNPP-86 scenario
Berdyansk	Berdyansk [1]	0.07	2.06	0.013	0.411
	Prymorsk [1]	0.42	0.89	0.084	0.177
	Chernigivka [1]	0.16	0.78	0.032	0.354
Vasylivka	Vasylivka [2]	10.9	300.55	2.173	59.845
	K.-Dniprovska [2]	11.08	–	2.207	–
	Mykhailivka [2]	10.95	236.87	2.181	47.166
	Tokmak [2] (WP)	11.19	234.89	2.229	46.772
Zaporizhzhia	Zaporizhzhia [2]	10.54	236.87	2.098	47.106
	Vilnyansk [2]	10.54	222.72	2.098	44.348
	N.-Mykolayivka [3]	28.35	227.53	5.645	45.310
	Orikhiv [3]	29.08	242.57	5.790	48.301
Melitopol	Vesele [2]	11.13	236.87	2.216	47.106
	Melitopol [2]	11.13	242.57	2.216	48.301
	Yakymivka [2]	10.91	227.45	2.173	45.290
	Pryazovske [1]	0.19	0.89	0.037	0.177
Pology	Pology [1]	0.57	1.78	0,113	0.354
	Gulyaipole [1]	0.36	1.78	0.072	0.354
	Bilmak [1]	0.65	3.76	0.129	0.748
	Tokmak[1] (EP)	0.49	20.7	0.097	4.122

Note: [1] – rainfed farmland; [2]- irrigation from the Kakhovka reservoir; [3]- irrigation from the Dnipro reservoir; WP - western part; EP - eastern part.

the seeds of the 2021 crop, the concentration of Cs^{137} was 5 times lower than in the seeds. Thus, both seeds and oil in 2021 could be used in the human diet without restrictions.

In the case of the implementation of the ChNPP-86 scenario on irrigated plots in the Vasylivka district, the concentration of radiocesium in the seeds will be ten times higher than the contamination in 2021 (300.55 Bq/kg against 10.9 Bq/kg). Sunflower oil obtained from seeds will contain 60 Bq/kg of radiocaesium, which corresponds to the temporary allowable concentration. However, given that vegetable oil is present in the diet of Europeans every day, and radiocesium has the ability to accumulate in the body, it will be impossible to use such a product without restrictions.

The level of Cs^{137} contamination of seeds will also be catastrophically high in other districts of the region (within a radius of up to 100 km^2), where sunflower will be grown under irrigation. The modeling results showed that the concentration of radiocesium in sunflower seeds which will be grown on irrigated plots in the Zaporizhzhia and Melitopol subregions will be 227–242 Bq/kg, with a temporary allowable level of 70 Bq/kg. When processing seeds for oil, the concentration of radiocesium will be five times less, but such a product cannot be called environmentally friendly.

CONCLUSIONS

Modeling of radiocesium contamination of sunflower products in the event of an accident at the Zaporizhzhia NPP shows that 100,000 hectares of agricultural land in the region will be withdrawn from agricultural production. Approximately 70% of them are arable land, a fifth (and in some farms a fourth) of which is allocated for sunflower. Consequently, sunflower crop losses in total, taking into account irrigated and rainfed lands, will amount to approximately 30.9 thousand tons per year. A critical type of ecological situation will develop in most of the territory, 1,143,000 hectares of agricultural land will be contaminated with radiocesium from 5 to 20 Ci/km^2. On agricultural lands, where soil contamination with radiocaesium will be more than 5 Ci/km^2, and the concentration in irrigated waters will reach 2 Bq/dm^3, sunflower which was grown for seeds to produce oil will need to be replaced with an industrial crop, which will also lead to crop losses. According to preliminary estimates, crop losses will amount to 347.5 thousand tons per year. Crop losses will lead to a decrease in the volume of sunflower oil. Losses will amount to 166.5 thousand tons per year. It should also be taken into account that the purification of soil and water does not occur in one year. At least in 5 years the situation will begin to improve. Pay attention that our estimates are based on the fact that the explosion at the Chornobyl nuclear power plant was only at the fourth power unit, so the true contamination of the soil and vegetation cover in the Zaporizhzhia region during the accident at the ZNPP can be tens or even hundreds of times more powerful, therefore, the consequences of soil and water pollution will lead to even higher levels of radiocesium contamination of sunflower products. We hope that this study will contribute to the understanding of the food problem in the event of targeted terrorist actions against the Zaporizhzhia nuclear power plant.

REFERENCES

1. Begy RC, Simon H, Vasilache D, Kelemen S, Cosma C. 2017. ^{137}Cs contamination over Transylvania region (Romania) after Chernobyl Nuclear Power Plant Accident. Sci Total Environ, 599-600, 627-636. https://doi: 10.1016/j.scitotenv.2017.05.019.
2. Evangeliou N, Hamburger T, Talerko N, Zibtsev S, Bondar Y, Stohl A, Balkanski Y, Mousseau TA, Møller AP. 2016. Reconstructing the Chernobyl Nuclear Power Plant (CNPP) accident 30 years after. A unique database of air concentration and deposition measurements over Europe. Environ Pollut. Sep, 216, 408-418. https://doi: 10.1016/j.envpol.2016.05.030.
3. Hachinohe M., Kimura K., Kubo Y., Tanji K., Hamamatsu S., Hagiwara S., Nei D., Kameya H., Nakagawa R., Matsukura U., Todoriki S., Kawamoto S. 2013. Distribution of Radioactive Cesium (^{134}Cs Plus ^{137}Cs) in a Contaminated Japanese Soybean Cultivar during the Preparation of Tofu, Natto, and Nimame (Boiled Soybean). J Food Prot, 76(6), 1021–1026. https://doi.org/10.4315/0362-028X.JFP-12-441.
4. Konoplev A., Kanivets V., Zhukova O., Germenchuk M., Derkach H. 2021. Mid- to long radiocesium wash-off from contaminated catchments at Chernobyl and Fukushima. Water Research, 188. https://doi.org/10.1016/j.watres.2020.116514
5. Kovalev V., Derebon I., Klymenko T., Fedorchuk S., Trembitska O., Lisovyy M. 2020. Production of textile crops in conditions of radioactive contamination. Agroecological journal, 3, 73-79. https://doi.org/10.33730/2077-4893.3.2020.211529
6. Mirzoeva N., Tereshchenko N., Korotkov A. 2022. Artificial Radionuclides in the System: Water, Irrigated Soils, and Agricultural Plants of the Crimea Region. Land, 11(9), 1539. https:// doi.org/10.3390/land11091539.
7. Noor M.J., Ashraf M.A. 2017. Accumulation and Tolerance of Radiocesium in Plants and its Impact on the Environment. Environment & Ecosystem science, 1(1), 13-16. http://dx.doi.org/10.26480/ees.01.2017.13.17 .
8. Oshita S, Kawagoe Y, Yasunaga E, Takata D, Nakanishi TM, Tanoi K, Makino Y, Sasaki H. 2011. Radioactivity measurement of soil and vegetables contaminated from low level radioactive fall out arised from Fukushima Daiichi Nuclear accident: A study on Institute for Sustainable Agro-Ecosystem Services, Graduate School of Agricultural and Life Sciences, The University of Tokyo. Radioisotopes, 60, 329–333.
9. Panov A.V, Isamov N.N., Tsygvintsev P.N., Geshel I.V., E.V. 2022. Comprehensive radioecological monitoring of terrestrial ecosystems in the vicinity of the Rooppur nuclear power plant (People's Republic of Bangladesh). Environmental Nanotechnology, Monitoring & Management, 17. https://doi.org/10.1016/j.enmm.2021.100623.
10. Polevoy A.N. 1993. Modeling the process of formation of the productivity of grain crops under conditions of radioactive contamination of agroecosystems. Meteorology and hydrology, 3, 97-105.
11. Prister B. S., Vinogradskaya V. D. 2011. Kinetic model of ^{137}Cs behavior in the "soil-plant" system, taking into account the agrochemical properties of the soil. Safety problems of nuclear power plants and Chornobyl, 16, 151-161.
12. Romanchuk, L. D., Fedonuk, T. P., & Khant, G. O. 2017. Radiomonitoring of plant products and soils of Polissia during the long-term period after the disaster at the Chornobyl Nuclear Power Plant. Regulatory Mechanisms in Biosystems, 8(3), 444-454. https://doi.org/10.15421/021769
13. Sasaki H, Shirato S, Tahara T, Sato K, Takenaka H. 2013. Accumulation of radioactive cesium released from Fukushima Daiichi Nuclear Power Plant in terrestrial cyanobacteria Nostoc commune. Microbes Environ, 28(4), 466-469. https://doi: 10.1264/jsme2.me13035
14. Shinano T. 2020. Mitigation of radioactive caesium transfer from soil to plant. In Strategies and Practices in the Remediation of Radioactive Contamination in Agriculture. In book: Strategies and Practices in the Remediation of Radioactive Contamination

in Agriculture, Proceeding Series of IAEA, 67-70.

15. Shinano T., Matsunami H., Kubo K. 2018. Decontamination of agricultural fields and mitigation of radioactive cesium uptake after nuclear contamination by TEPCO's FDNPP accident - situation after 7 years. Global symposium on soil pollution. FAO HQ. |Rome, Italy, 958-963.
16. Soudek P, Valenová Š, Vavříková Z, Vaněk T. 2006. ^{137}Cs and ^{90}Sr uptake by sunflower cultivated under hydroponic conditions. J Environ Radioact, 88, 236-250.
17. Steinhauser G, Brandl A, Johnson TE. 2014. Comparison of the Chernobyl and Fukushima nuclear accidents: a review of the environmental impacts. Science of The Total Environment, 470-471, 800-817. https://doi.org/10.1016/j.scitotenv.2013.10.029
18. Tagami K., Uchida S. 2020. Major factors affecting weathering half-lives of iodine-131 and radiocaesium in leafy vegetables directly contaminated by Fukushima Daiichi Nuclear Power Plant accident fallout (2) Comparison of the weathering half-lives observed for herbaceous plants after the Chernobyl and the Fukushima nuclear accidents. Radioisotopes, 69, 353-364. https:/doi: 10.3769/radioisotopes.69.353.
19. Tagami K., Shigeo Uchida S. 2021. Mass Interception Fractions and Weathering Half-lives of Iodine-131 and Radiocesium in Leafy Vegetables Observed after the Fukushima Daiichi Nuclear Power Plant Accident. Journal of Radiation Protection and Research, 46(4), 178–183. https://doi.org/10.14407/jrpr.2021.00164.
20. Tanoi K, Hashimoto K, Sakurai K, Nihei N, Ono Y, Nakanishi TM. 2011. An Imaging of radioactivity and determination of Cs-134 and Cs-137 in wheat tissue grown in Fukushima. Radioisotopes, 60, 317-322.
21. Voitsekhovych O.V., Kanivets V.V. Kireev S.I., Laptev G.V., Obrizan S.M. 2016. State of radioactive contamination of surface waters. 30 Years of the Chornobyl disaster (reviews). A collection of informational and analytical reports. Kyiv: KIM, 129-139.
22. Zhygailo O.L. 2007. Method for agroecological assessment of radioactive contamination of primary biological products. Ukrainian Hydrometeorological Journal, 2, 16-23.