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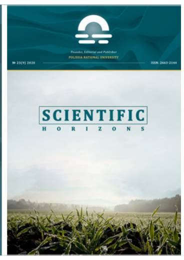

Patterns of ^{137}Cs accumulation in the fruiting bodies of mushrooms in moist relatively fertile forest sites of the Zhytomyr Polissia region

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Abstract. The aim of the study was to investigate the existing patterns of radioactive contamination in mushrooms growing under moist, relatively fertile forest site conditions. The investigation was carried out in Zhytomyr Polissia region within a widespread but poorly studied forest site type in terms of radioecology – moist relatively fertile forest site. The study elucidated the values of indicators characterising

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the intensity of ^{137}Cs accumulation in fresh and dry mushroom fruiting bodies, namely the ^{137}Cs concentration ratio and the aggregated transfer coefficient of ^{137}Cs. The high concentration ratios observed in dry samples connected with the substantial loss of moisture during drying. Significant interspecific differences in ^{137}Cs accumulation in mushroom fruiting bodies were identified, allowing the establish of a ranked series reflecting the intensity of radionuclide uptake by different species. Values of concentration ratio of radionuclide in fresh mushrooms varied from 0.01 ± 0.005 (*Lepista sordida*) to 7.4 ± 1.23 (*Paxillus involutus*). The excess of the maximum value of this index over the minimum reached 740 times. Values of concentration ratio of radionuclide in dry mushrooms varied from 0.15 ± 0.02 in *Hygrophorus eburneus* to 90.9 ± 16.54 in *Paxillus involutus*. In fresh fruiting bodies ranked series in descending order of concentration ratio can be build up: *Paxillus involutus* → *Imleria badia* → *Suillus luteus*, and in dry mushroom fruiting bodies – *Paxillus involutus* → *Suillus luteus* → *Imleria badia*. The results have practical significance for identifying forest areas which require radiological control of edible mushrooms during harvesting. The results can also be applied for organisation and implementation of radioecological monitoring programme in radioactively contaminated forest ecosystems

Keywords: type of forest site conditions; radionuclide; activity concentration; concentration ratio; aggregated transfer coefficient; drying coefficient

INTRODUCTION

High fungi (mushrooms) play an important role in the biogeochemical cycle of chemical elements in forest ecosystems, including radionuclides introduced as a result of anthropogenic nuclear accidents. This role – redistribution of radioactive elements within the soil and in the pathways and intensity of their transfer to various components of forest ecosystems. Moreover, the capacity of mushrooms to influence the radionuclide redistribution in forest ecosystems contributes to their accumulation within mushroom fruiting bodies. Since the fruiting bodies of many mushroom species are consumed by humans, this process can lead to the transfer of radionuclides into the human body.

Over time, the number of publications addressing radioactive contamination in edible mushrooms has not substantially increased. Most scientific works have focused on measuring radionuclides content in mushrooms during specific time periods, with results varying considerably among European countries. These differences are largely attributed to varying degrees of radioactive contamination across regions. For instance, German researchers investigated the ^{137}Cs content in two mushroom species – *Imleria badia* (Fr.) Vizzini and *Boletus edulis* Bull. – in the Bavarian Forest National Park, an area affected by fallout from the Chornobyl accident (Ernst *et al.*, 2022). Their results showed that the ^{137}Cs activity concentration in *Imleria badia* was significantly higher than in *Boletus edulis*. Based on these findings, the researchers recommended the consumption of *Boletus edulis* only, as approximately one-third of the tested *Imleria badia* samples exceeded the permissible levels of ^{137}Cs content. The elevated radionuclide levels in mushroom fruiting bodies were attributed to the high ^{137}Cs concentrations in soil layers rich in organic matter. Similar results have been observed when comparing the ^{137}Cs content in various species of *Tricholoma* spp. across different European countries between 1971-2016 (Falandysz *et al.*, 2022).

Similar results were obtained by J. Falandysz *et al.* (2019), who examined ^{137}Cs concentrations in fruiting bodies of *Cortinarius caperatus* (Pers.) Fr. across 22 locations in Northern Poland. Their findings also revealed high levels of radioactive contamination in mushroom fruiting bodies, leading the authors to recommend further studies on radioactive contamination of forest soils. A comparison of the radioactive contamination of *Boletus eduli* over time showed that contamination levels were lower during 1986-1994 than during 1995-2016. The researchers attributed this trend to the gradual downward migration of ^{137}Cs into deeper soil layers following their initial deposition. Similar conclusions were drawn by O. Ronda *et al.* (2022), who analysed seven wild mushroom species from different regions of the country – edible species (*Imleria badia*, *Cantharellus cibarius* Fr., *Xerocomus subtomentosus* (L.) Quél., and *Suillus luteus* (L.) Roussel) and inedible but animal-edible species (*Paxillus involutus* (Batsch) Fr., *Tylopilus felleus* (Bull.) P. Karst., and *Russula emetica* (Schaeff.) Pers.). Similar results have been obtained by I. Mirończuk-Chodakowska *et al.* (2025) and M. Gembal *et al.* (2026).

Following the Chornobyl accident, Ukrainian researchers periodically investigated the content of ^{137}Cs in the fruiting bodies of *Suillus luteus* both within the Chornobyl Exclusion Zone and in adjacent areas of the Kyiv region (Zarubina *et al.*, 2021). It was found that during the first 10-12 years after the radionuclides entered forest ecosystems, the activity concentration of ^{137}Cs in mushrooms increased, followed by a gradual decline that continues to the present day. Although the study included data from six research sites with different observation periods, the overall temporal trends in ^{137}Cs activity concentration in the fruiting bodies of *Suillus luteus* were consistent across all sites.

An analysis of the available literature allows several generalisations to be made. After the Chornobyl accident, systematic monitoring of radioactive contamination in mushrooms was not maintained in Ukraine or in other countries affected by radioactive fallout. This lack of consistency is largely due to the challenges of conducting long-term studies on permanent sample plots, since mushroom fruiting bodies do not appear regularly in the same locations. Furthermore, most previous investigations were limited to pure pine stands growing on poor or relatively poor soils (infertile and relatively infertile pine site types). Thus, the present study aimed to examine the current patterns of radioactive contamination of mushrooms under moist relatively fertile forest site conditions.

MATERIALS AND METHODS

The study was conducted on temporary sample plots located in the forests of the State Specialized Forest Enterprise "Forests of Ukraine", Branch "Stolychnyi Forest Office", Korostenske Forestry Management Unit, Luhynske Forestry, during August-September 2022-2023 (Fig. 1). The research was carried out in accordance with the general principles of sustainable forest management and biodiversity conservation as outlined in the Convention on Biological Diversity (1992). The preliminary selection of sampling sites was carried out in the office based on an analysis of forest management documentation. For field research, typical for the region forest stands in moist relatively fertile forest site conditions were selected. The selected stands had the following characteristics: Compartment 79, subcompartment 4, stand composition: alder (*Alnus glutinosa* (L.) Gaertn.) 50%, birch (*Betula pendula* Roth.) 20%, aspen (*Populus tremula* L.) 10%, pine (*Pinus sylvestris* L.) 10%, oak (*Quercus robur* L.) 10% + elm (*Ulmus glabra* Huds.), age – 49 years, stand quality class – II, forest type – moist relatively fertile hornbeam-oak-pine forest, relative density of stocking – 0.60, stock – 130 $m^3 \cdot ha^{-1}$; Compartment 79, subcompartment 6, stand composition: oak 90%, pine 10%, age – 130 years, stand quality class – II, forest type – moist relatively fertile hornbeam-oak-pine forest, relative density of stocking – 0.50, stock – 260 $m^3 \cdot ha^{-1}$; Compartment 79, subcompartment 8, stand composition: oak 70%, birch 20%, pine 10%, age – 65 years, stand quality class – II, forest type – moist relatively fertile hornbeam-oak-pine forest, relative density of stocking – 0.70, stock – 230 $m^3 \cdot ha^{-1}$; Compartment 85, subcompartment 34, stand composition: – oak 80%, pine 20% + aspen, age – 140 years, stand quality class – III, forest type – moist relatively fertile hornbeam-oak-pine forest, relative density of stocking – 0.40, stock – 200 $m^3 \cdot ha^{-1}$; Compartment 86, subcompartment 3, stand composition: – oak 50%, birch 30%, pine 20%, age – 64 years, stand quality class – II, forest type – moist relatively fertile hornbeam-oak-pine forest, relative density of stocking – 0.60, stock – 190 $m^3 \cdot ha^{-1}$; Compartment 86, subcompartment 14, stand composition: aspen 50%, oak 20%, birch 20%, pine 10%, age – 74 years, stand quality class – 2, forest type – moist relatively fertile hornbeam-oak-pine forest, relative density of stocking – 0.60, stock – 300 $m^3 \cdot ha^{-1}$.

Figure 1. *Map of mushroom fruiting body collection sites in moist relatively fertile forest (marked with white lines)*
Source: *created by the authors*

Samples of mushroom fruiting bodies were collected from each sample plot, with a minimum of three and a maximum of six samples per plot, depending on fruiting intensity. The fruiting bodies were cleaned of soil and placed in pre-labelled plastic bags. At each collection site, composite soil samples were taken using a cylindrical drill with a diameter of 5 cm to a depth of 20 cm. Each composite sample consisted of five subsamples collected around the fruiting bodies (SOU 74.14-37-425:2006, 2006). Fungal species were identified and verified according to the accepted nomenclature (Index Fungorum, 2025).

In the laboratory, mushroom fruiting bodies were placed in Marinelli beakers with a volume of 1.000 cm^3, or in other calibrated containers, depending on the sample volume (135 or 500 cm^3). After measuring the activity concentration of ^{137}Cs in fresh mushroom samples, they were dried in a drying chamber for 72 hours, and measurements of radioactive contamination were repeated for the dried sampls. Soil samples were also dried in a drying chamber and homogenised before analysis. The activity concentration of ^{137}Cs in all samples was determined using a SEG-001 AKP-S-150 gamma spectrometer (Ukraine) equipped with a BDEG20-R1 scintillation detector (Ukraine). The measurement error of ^{137}Cs did not exceed 15%.

To evaluate the intensity of radionuclide uptake by mushroom fruiting bodies, the following parameters were calculated: the concentration ratio (CR) – defined as the ratio of the ^{137}Cs activity concentration in the fruiting bodies of a given mushroom species (Bq·kg^{-1}) to the ^{137}Cs activity concentration in the soil (Bq·kg^{-1}); and the aggregated transfer coefficients (*Tag*) – defined as the ratio of the ^{137}Cs activity concentration in the fruiting bodies of a given mushroom species (Bq·kg^{-1}) to soil radioactive contamination density of ^{137}Cs (kBq·m^{-2}). The latter parameter is expressed in the generally accepted units of m^2·kg^{-1}·10^{-3} (Belli *et al.*, 1999; IAEA, 2009). The shrinkage coefficient of mushroom fruiting bodies was determined as the ratio of the fresh weight to the dry weight of the samples. Statistical analyses were performed using standard methods (Tsarenko *et al.*, 2000) with the MS Excel and Statistica 10 software packages.

RESULTS

The study area encompasses a wide variety of forest site conditions that differ in both soil fertility and moisture regime – ranging from nutrient-poor pine forests to rich oak forests, and from very dry habitats like sand dune tops to wet, swampy areas. In terms of soil fertility, the most widespread habitats in the Zhytomyr Polissia region are relatively infertile pine forest sites, occupying 329,779.2 ha (49.86%), and relatively fertile hardwood forest sites, covering 218,858.5 ha (33.09%) (Table 1). The moist relatively infertile pine forest is the dominant type of forest site conditions in the study region, accounting for 152,517.3 ha (23.06%) of the forested area. Other common site types include fresh relatively infertile pine forests (126,683.0 ha; 19.15%), moist relatively fertile forests (116,019.6 ha; 17.54%), and fresh relatively fertile forests (70,337.9 ha; 10.64%). The remaining forest site types each occupy less than 10% of the total forested area. These data indicate that moist relatively fertile forest sites are well represented within the study region and provide favourable conditions for the growth and diversity of edible mushrooms, making them an important focus for radioecological research.

***Table 1**. Distribution of forest areas of the State Specialised Forest Enterprise*

Forest site type	**Area**	
	ha	%
Dry infertile pine forest	8,457.9	1.28
Fresh infertile pine forest	48,168.1	7.29
Moist infertile pine forest	10,013.5	1.51
Damp infertile pine forest	5,461.8	0.83
Wet infertile pine forest	5,706.2	0.86
Infertile pine forests in total	**77,807.5**	**11.77**
Fresh relatively infertile pine forest	126,683.0	19.15
Moist relatively infertile pine forest	152,517.3	23.06
Damp relatively infertile pine forest	40,202.7	6.08
Wet relatively infertile pine forest	10,376.2	1.57
Relatively infertile pine forests in total	**329,779.2**	**49.86**
Fresh relatively fertile hardwood forest	70,337.9	10.64
Moist relatively fertile hardwood forest	116,019.6	17.54
Damp relatively fertile hardwood forest	29,855.7	4.51
Wet relatively fertile hardwood forest	2,645.3	0.40
Relatively fertile hardwood forests in total	**218,858.5**	**33.09**
Fresh fertile hardwood forest	17,874.6	2.70
Moist fertile hardwood forest	15,408.2	2.33
Damp fertile hardwood forest	1,615.9	0.24
Wet fertile hardwood forest	60.6	0.01
Fertile hardwood forests in total	**34,959.3**	**5.28**
Total	**661,404.5**	**100**

Source: *created by the authors*

Values of ^{137}Cs concentration ratio in fresh mushroom fruiting bodies varied substantially among the studied species – from 7.4 ± 1.23 in *Paxillus involutus* to 0.01 ± 0.005 in *Lepista sordida* (Schumach.) Singer (Table 2). The highest value thus exceeded the lowest by a factor of approximately 740. A similarly wide range of this coefficient for ^{137}Cs in mushrooms has been reported in other forest site types (Krasnov *et al.*, 2006; Gabriel *et al.*, 2023). The maximum ^{137}Cs concentration ratios were recorded for *Paxillus involutus* (7.4 ± 1.23), *Imleria badia* (5.4 ± 0.62) and *Suillus luteus* (4.7 ± 0.02). Other species, including *Russula albonigra* (Krombh.) Fr., *R. delica* Fr., *Lactarius rufus*, and *Boletus edulis*, also exhibited elevated CR values, ranging from 1.4 ± 0.38 to 4.7 ± 0.02, and can therefore be classified as effective accumulators of ^{137}Cs. The markedly lower concentration ratios observed in other species may be attributed to differences in the depth of mycelium location and the ecological and biological characteristics of the fungi, particularly their affiliation with specific ecological and trophic groups (Krasnov *et al.*, 2006).

According to Table 3, the highest ^{137}Cs concentration ratio in dry mushroom fruiting bodies was observed in *Paxillus involutus* – 90.9 ± 16.54. Lower values were recorded for *Suillus luteus* (64.2 ± 3.78, representing 70.6% of the *P. involutus* value) and *Imleria badia* (63.7 ± 18.32, or 70.1%, respectively). The next two species showed considerably lower CR values: *Russula albonigra* – 36.6 ± 3.15 (40.3% of the *P. involutus* value) and *Lactarius rufus* – 32.1 ± 3.23 (35.3%, respectively).

Table 2. *Average values of ^{137}Cs concentration ratios in fresh fruiting bodies of mushrooms in moist relatively fertile forest sites in 2022-2023*

Mushroom species	Statistics of the distribution series				
	M	± m	± σ	V, %	P, %
Paxillus involutus	7.4	1.23	2.13	28.6	16.5
Imleria badia	5.4	0.62	1.38	25.7	11.5
Suillus luteus	4.7	0.02	0.03	0.6	0.3
Russula albonigra	2.5	0.40	0.80	31.6	15.8
Russula delica	2.2	0.14	0.25	11.4	6.6
Lactarius rufus	1.9	0.21	0.37	20.0	11.6
Boletus edulis	1.4	0.38	0.92	65.4	26.7
Armillaria mellea	0.5	0.01	0.01	2.6	1.5
Cantharellus cibarius	0.4	0.03	0.06	16.3	8.2
Amanita rubescens	0.2	0.03	0.05	23.4	13.5
Russula aeruginea	0.1	0.01	0.02	15.8	9.1
Hygrophorus eburneus	0.1	0.01	0.01	25.2	14.6
Chlorophyllum rhacodes	0.04	0.010	0.02	46.9	27.1
Paralepista flaccida	0.02	0.004	0.01	33.9	19.6
Lepista sordida	0.01	0.005	0.01	74.3	42.9

Source: *created by the authors*

Table 3. *Average values of ^{137}Cs concentration ratio in dry fruiting bodies of mushrooms in moist relatively fertile forest sites in 2022-2023*

Mushroom species	Statistics of the distribution series				
	M	± m	± σ	V, %	P, %
Paxillus involutus	90.9	16.54	28.6	31.5	18.2
Suillus luteus	64.2	3.78	6.6	10.2	5.9
Imleria badia	63.7	18.32	41.0	64.4	28.8
Russula albonigra	36.6	3.15	6.3	17.2	8.6
Lactarius rufus	32.1	3.23	5.6	17.4	10.1
Boletus edulis	15.0	4.66	11.4	76.3	31.2
Russula delica	10.7	0.92	1.6	14.9	8.6
Armillaria mellea	4.4	0.11	0.18	4.2	2.4
Cantharellus cibarius	2.3	0.25	0.51	21.7	10.9
Amanita rubescens	1.5	0.24	0.41	27.2	15.7
Russula aeruginea	1.2	0.13	0.23	19.3	11.2
Paralepista flaccida	0.94	0.112	0.19	20.7	12.0
Lepista sordida	0.26	0.049	0.08	32.8	19.0
Chlorophyllum rhacodes	0.18	0.053	0.09	50.2	29.0
Hygrophorus eburneus	0.15	0.020	0.04	23.8	13.8

Source: *created by the authors*

A comparison of the ranked series of species based on average CR values in fresh and dry mushroom fruiting bodies (Tables 2 and 3) reveals certain differences. In fresh mushrooms, the descending order of CR values was *Paxillus involutus* → *Imleria badia* → *Suillus luteus*, whereas in dry mushrooms the sequence changed to *Paxillus involutus* → *Suillus luteus* → *Imleria badia*. These discrepancies likely reflect differences in the moisture content of fruiting bodies among macromycete species, as supported by the pronounced variation in their drying coefficients (Table 4). The highest drying coefficient was recorded for *Paralepista flaccida* – 24.5 ± 1.39, while the lowest was observed for *Chlorophyllum rhacodes* (Vittad.) Vellinga, – 4.5 ± 0.08. It is also noteworthy that the coefficients of variation of this parameter were relatively high in many species, highlighting the importance of increasing the sample number in radioecological studies of mushroom contamination to ensure the reliability and representativeness of the results.

***Table 4**. Coefficients of drying of fungal fruiting bodies (times) in moist relatively fertile forest sites in 2022-2023*

Mushroom species	Statistics of the distribution series				
	M	± m	± σ	V, %	P, %
Paralepista flaccida	24.5	1.39	2.41	9.9	5.7
Russula aeruginea	24.2	0.46	0.80	3.3	1.9
Amanita rubescens	17.3	0.57	0.99	5.7	3.3
Armillaria mellea	14.4	1.45	2.50	17.4	10.0
Lepista sordida	13.8	1.26	2.18	15.8	9.1
Suillus luteus	11.6	0.67	1.16	10.0	5.8
Paxillus involutus	9.8	0.39	0.67	6.9	4.0
Imleria badia	9.3	0.95	2.13	22.8	10.2
Boletus edulis	8.9	0.47	1.16	13.1	5.3
Lactarius rufus	8.5	0.59	1.02	12.0	7.0
Russula albonigra	8.4	0.53	1.07	12.7	6.4
Cantharellus cibarius	7.5	0.11	0.22	3.1	1.5
Hygrophorus eburneus	4.9	0.19	0.32	6.5	3.8
Russula delica	4.8	0.10	0.17	3.6	2.1
Chlorophyllum rhacodes	4.5	0.08	0.14	3.1	1.8

***Source:** created by the authors*

For practical applications, particularly in identifying forest areas suitable for mushroom harvesting under conditions of radioactive contamination, the aggregated transfer coefficient (*Tag*) is used (Fig. 2).

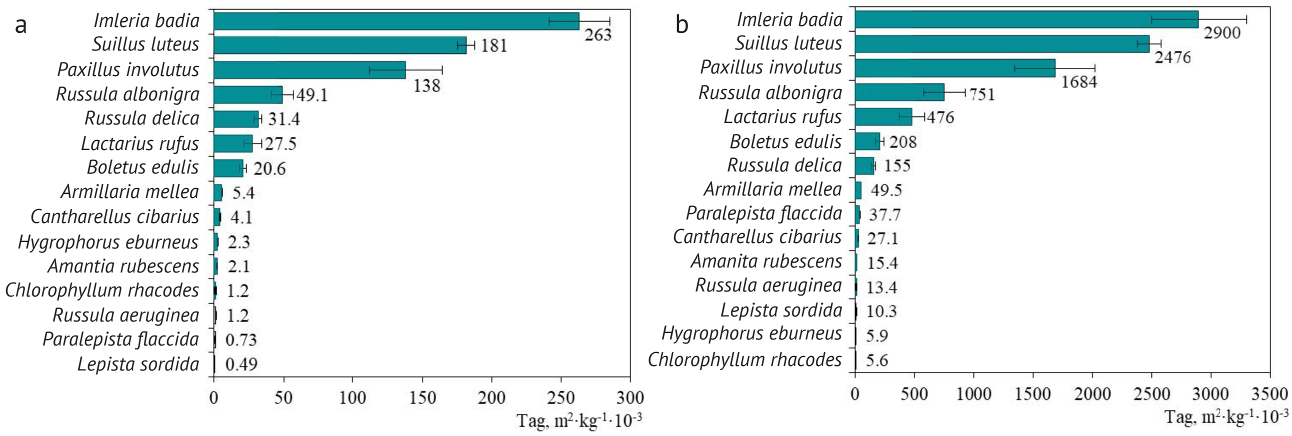

***Figure 2**. ^{137}Cs aggregated transfer coefficients from soil to dry (A) and fresh (B) mushrooms in moist relatively fertile forest sites in 2022-2023*

***Source:** created by the authors*

This indicator became widely applied following the Chornobyl accident and serves as a valuable tool for predicting radionuclide concentrations in mushrooms based on existing maps of forest radioactive contamination. The maximum ^{137}Cs aggregated transfer coefficient was recorded for *Imleria badia* – 263.3 ± 21.5 m^2·kg^{-1}·10^{-3}, while the minimum value was observed for *Lepista sordida* – 0.5 ± 0.20 $m^2 \cdot kg^{-1} \cdot 10^{-3}$. Thus, the maximum value exceeded the minimum by a factor of 526.6. The species exhibiting the highest transfer coefficients were *Imleria badia* (263.3 ± 21.5 $m^2 \cdot kg^{-1} \cdot 10^{-3}$), *Suillus luteus* (181.2 ± 6.2 $m^2 \cdot kg^{-1} \cdot 10^{-3}$), and *Paxillus involutus* (49.1 ± 7.9 $m^2 \cdot kg^{-1} \cdot 10^{-3}$).

To further elucidate interspecific differences, a cluster analysis was conducted incorporating the concentration ratios (CR), aggregated transfer coefficients (*Tag*) for both fresh and dry mushroom fruiting bodies, and the drying coefficient (Fig. 3). The cluster analysis revealed that the studied mushroom species can be grouped into four distinct clusters based on the above parameters. The first cluster comprises fungi with the smallest Euclidean distances, indicating the highest degree of similarity. This group includes *Paralepista flaccida*, *Lepista sordida*, *Russula aeruginea* Lindblad ex Fr., *Chlorophyllum rhacodes*, *Amanita rubescens*, *Hygrophorus eburneus* (Bull.) Fr., *Armillaria mellea*, and *Cantharellus cibarius*. This cluster contains the largest number of macromycete species. The second and third clusters each include two species: *Boletus edulis* and *Russula delica* in the second, and *Russula albonigra* and *Lactarius rufus* in the third. Minor differences in ^{137}Cs accumulation were observed between these two groups and the first cluster. The fourth cluster consists of *Suillus luteus*, *Paxillus involutus*, and *Imleria badia* – species identified as the most efficient accumulators of ^{137}Cs.

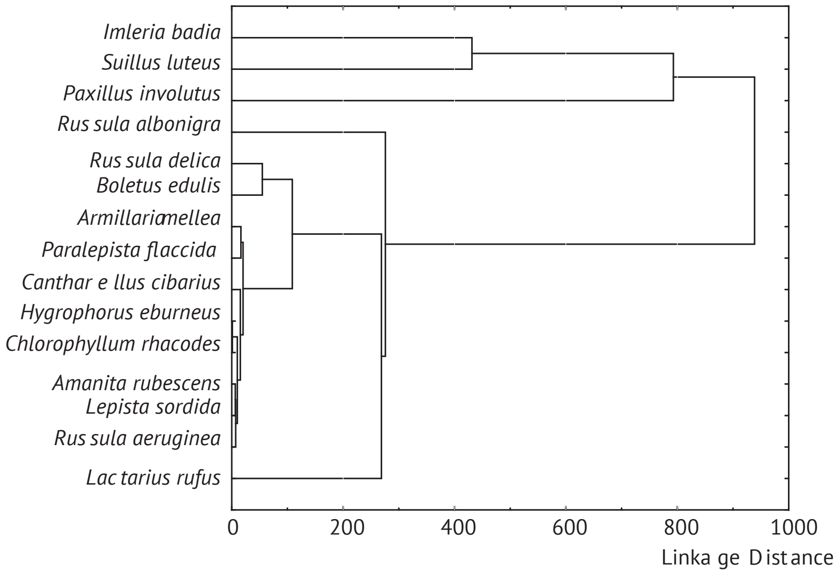

***Figure 3**. Dendrogram of similarity of mushroom species in moist relatively fertile forest sites based on radioecological characteristics*
Source: *created by the authors*

The analysis revealed distinct species-specific patterns of ^{137}Cs accumulation in the fruiting bodies of mushrooms in moist relatively fertile forest sites. The study also confirmed the inherent challenges of monitoring radioactive contamination of macromycete fruiting bodies, which stem from both the irregular formation of mushrooms and the pronounced spatial heterogeneity of ^{137}Cs contamination of the area. The scientific novelty of this research lies in establishing a foundation for development of models describing radionuclide migration in forest ecosystems and for predicting the levels of radioactive contamination in edible mushrooms. From a practical standpoint, the results can be applied to improve the management and regulation of wild mushroom harvesting by integrating them with existing forest radioactive contamination maps, thereby supporting radiological safety and sustainable resource use.

DISCUSSION

Over 20 years after the Chornobyl accident in 1986, an international research team summarised the findings of studies on radionuclide migration in forest ecosystems and their accumulation in edible mushrooms (IAEA, 2009). The researchers concluded that radionuclide migration in forest ecosystems differs significantly from other environments, that the uptake of ^{137}Cs by mushrooms is generally high, and that the forest-derived food products – particularly mushrooms – represent an important source of internal radiation exposure for the population. It had been estimated that mushrooms may account for up to 56% of the daily intake of ^{137}Cs by humans, based on studies P. Strand *et al.* (1996).

Czech researchers O. Harkut *et al.* (2021) measured ^{137}Cs activity concentrations in three of the most common mushroom species – *Imleria badia*, *Russula ochroleuca* Fr., and *Armillaria mellea* (Vahl) P. Kumm. – in the

Opava region (Silesia) and the Beskids Mountains. The highest radionuclide concentrations were detected in the pilei of *Imleria badia* and *Russula ochroleuca* in the Opava region, reaching 11.8 and 8.77 $kBq \cdot kg^{-1}$, respectively. However, calculations of the effective gamma radiation dose indicated that these levels do not pose a significant risk to public health, given the relatively low consumption of mushrooms by the local population. Similarly, low levels of radioactive contamination were reported by Slovak researchers P. Dvořák *et al.* (2020) in nine mushroom species collected from forests near Dolní Rožinka (Bohemian-Moravian Highlands), by Bulgarian scientists M. Lacheva *et al.* (2020), studying ^{137}Cs content in *Craterellus cornucopioides* (L.) Pers. in forests on Mount Batak and in various regions of the country by R. Lazarova & M. Hristozova (2025), and by Turkish researchers A. Pekşen *et al.* (2021) and A. Akkaya & S. Aktas (2025) investigating mushrooms from various regions of Turkey.

Studies conducted by L. Cui *et al.* (2020) and T. Matsuura (2021) in the 30 km exclusion zone of the Fukushima Daiichi Nuclear Power Plant, near the village of Kawauchi, revealed that ^{137}Cs activity concentrations in mushrooms exceeded Japan's permissible limit of 100 $Bq \cdot kg^{-1}$. The differences varied by year: 75% of permissible limit in 2016, 48% in 2017, 84% in 2018, 79% in 2019. Based on these findings, the researchers recommended continuing radioecological monitoring of radionuclide content in mushrooms. Japanese researchers Y. Sasaki *et al.* (2025) have also studied the accumulation of ^{137}Cs in certain mushroom species grown at specially prepared sites under natural conditions. They confirmed significant levels of radioactive contamination in fungal fruiting bodies and emphasised the crucial role of moisture and organic matter in the uptake of radioactive isotopes from the soil.

The majority of publications concerning the radioactive contamination of mushrooms have originated from Ukraine, particularly during the first 15-20 years following the Chornobyl accident. In previous years, researchers V.P. Krasnov *et al.* (2006) summarised long-term investigations on this topic conducted in the Zhytomyr Polissia. Their studies examined, the intensity of radioactive contamination among mushrooms belonging to different ecological groups, the patterns of ^{137}Cs accumulation in the fruiting bodies of edible species across various forest site conditions, interspecies differences in radionuclide uptake, and the relationship between ^{137}Cs content in mushrooms and soil contamination density.

The results of a study of several mushroom species by O. Hromyk *et al.* (2024) – *Cantharellus cibarius*, *Boletus edulis*, and *Leccinum scabrum* (Bull.) Gray – conducted in the Kamin-Kashyrsky district of the Volyn region were published. The researchers compared the measured ^{137}Cs concentrations in mushrooms with the permissible levels of radioactive contamination and found exceedances in 6.8% of the samples. Despite the relatively low soil contamination levels in the forests of this district, the authors emphasised the need for continued radioecological monitoring of edible mushrooms. In the Zhytomyr region, O. Orlov *et al.* (2023) investigated ^{137}Cs accumulation in 18 mushroom species across different forest site conditions – namely fresh infertile pine sites and fresh and moist relatively infertile pine sites – at varying soil contamination densities (109 ± 13 to 410 ± 30 $kBq \cdot m^{-2}$). The study revealed the highest ^{137}Cs aggregated transfer coefficients (*Tag*) in the fruiting bodies of symbiotrophic species such as *Cortinarius mucosus* (Bull.) J. Kickx f., *C. caperatus*, *Sarcodon imbricatus* (L.) P. Karst., *Imleria badia*, *Tricholoma equestre*, *Paxillus involutus*, *Hygrophorus hypothejus*, while the lowest values were observed in xylotrophic saprotrophs – *Armillaria mellea* and *Tapinella atrotomentosa*. In fresh infertile pine sites, increased ^{137}Cs accumulation was recorded in the following order: *Cortinarius mucosus* → *Hygrophorus hypothejus* → *Tricholoma equestre* (L.) P. Kumm. → *Sarcodon imbricatus*, with average *Tag* values ranging from 434.5 ± 23.25 to 205.4 ± 25 50 $m^2 \cdot kg^{-1} \cdot 10^{-3}$. The maximum value was observed for *Sarcodon imbricatus* (161.48 ± 10.415 $m^2 \cdot kg^{-1} \cdot 10^{-3}$) and the minimum for *Armillaria mellea* (2.26 ± 0.472 $m^2 \cdot kg^{-1} \cdot 10^{-3}$). Based on the intensity of ^{137}Cs accumulation in fruiting bodies, the top five species in this type of forest site conditions were ranked as follows: *Sarcodon imbricatus* → *Cortinarius caperatus* → *Paxillus involutus* → *Russula vinosa* Lindblad → *Lactarius rufus* (Scop.) Fr. In moist relatively infertile pine sites, the highest aggregated transfer coefficient was recorded for *Imleria badia* (110.8 ± 18.21 $m^2 \cdot kg^{-1} \cdot 10^{-3}$), while the lowest was found in *Leccinum scabrum* (9.2 ± 2.58 $m^2 \cdot kg^{-1} \cdot 10^{-3}$). The order of ^{137}Cs accumulation intensity (*Tag*) in the four most active species under these site conditions was as follows: *Imleria badia* → *Lactarius rufus* → *Cortinarius caperatus* → *Paxillus involutus* (Orlov *et al.*, 2023).

The accumulation of ^{137}Cs by various fungal species (54 species in total) has been investigated by J. Gabriel *et al.* (2023) in the forests managed by the Ivankivske Forest Management Unit of the State Specialised Forest Enterprise "Forests of Ukraine" (formerly the State Enterprise "Polissia Forest Economy"), located in the northern part of the Kyiv region, outside the 30 km exclusion zone of the Chornobyl Nuclear Power Plant. The study confirmed that mushrooms remain an important source of radionuclide intake into the human body (Grodzynska *et al.*, 2025). The highest radionuclide concentration ratios were recorded for *Suillus granulatus* (L.) Roussel (392.6), *Imleria badia* (164.3), and *Suillus luteus* (120.8). Similar research conducted in the Chernihiv region identified somewhat different species that actively accumulate ^{137}Cs. The concentration ratios for *Cortinarius semisanguineus* (Fr.) Gillet and *Paralepista gilva* (Pers.) Raithelh. exceeded 100, while those for *Cortinarius malicorus* Fr., *Cortinarius decipiens* (Pers.)

Zawadzki, *Sarcodon imbricatus*, and *Cortinarius praestans* (Cordier) Gillet ranged between 50 and 100. Overall, mushrooms demonstrate a high capacity to accumulate ^{137}Cs, with significant differences observed between species and environmental conditions. Despite generally low health risks in some regions, they remain an important source of internal radiation exposure, highlighting the need for continued monitoring.

CONCLUSIONS

The research data obtained over the 37 years since radionuclides entered forest ecosystems allow for several important scientific and practical conclusions. First, the intensity of ^{137}Cs accumulation in the fruiting bodies of wild mushrooms remains consistently high. The maximum concentration ratio of this radionuclide reached 7.4 ± 1.23 in *Paxillus involutus* for fresh mushrooms and 90.9 ± 16.54 for dry mushrooms in moist relatively fertile forest sites. Secondly, there are significant interspecific differences in the intensity of ^{137}Cs accumulation among mushroom species. Based on the concentration ratios for dry mushrooms, the species can be ranked in descending order as follows: *Paxillus involutus* → *Suillus luteus* → *Imleria badia* → *Russula albonigra* → *Lactarius rufus* →*Boletus edulis* → *Russula delica* → *Armillaria mellea* → *Cantharellus cibarius* → *Amanita rubescens* → *Russula aeruginea* → *Paralepista flaccida* → *Lepista sordida* → *Chlorophyllum rhacodes* → *Hygrophorus eburneus*. Thirdly, significant interspecies differences were also established in the drying coefficients of mushroom fruiting bodies. This indicator can serve as a useful predictor of potential radioactive contamination levels in mushrooms. Finally, the issue of radioactive contamination of mushrooms in the forests of Zhytomyr Polissia remains relevant and pressing, even decades after the Chornobyl Nuclear Power Plant accident. As prospects for further research, continued attention should be given to the long-term dynamics of radioactive contamination in forest ecosystems, particularly in relation to wild mushrooms. Future studies should focus on refining forest typology-based monitoring approaches to better predict the accumulation of radionuclides in different ecological conditions. The development of improved radioecological control strategies for the harvesting and consumption of edible mushrooms by local populations remains an important direction for ensuring environmental and public health safety.

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Особливості накопичення ^{137}Cs у плодових тілах грибів у вологих сугрудах лісів Житомирського Полісся

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Анотація. Метою дослідження було вивчення існуючих закономірностей радіоактивного забруднення грибів, що ростуть у вологих, відносно родючих лісових умовах. Дослідження були проведені у Житомирському Поліссі у поширеному, але мало вивченому у радіоекологічному відношенні типі лісорослинних умов – вологому сугруді. Було проведено порівняння показників, які характеризують інтенсивність накопичення ^{137}Cs у свіжих і сухих плодових тілах грибів – коефіцієнту накопичення та коефіцієнту переходу. Встановлено, що значні коефіцієнти накопичення ^{137}Cs у сухих грибах пояснюються значною усушкою плодових тіл. Виявлено значні міжвидові відмінності у накопиченні ^{137}Cs у плодових тілах грибів, на основі чого побудований рангований ряд видів, який демонструє інтенсивність накопичення радіонукліду. Величини коефіцієнтів накопичення ^{137}Cs у свіжих грибах коливаються у межах $0{,}01 \pm 0{,}005$ (*Lepista sordida*) – $7{,}4 \pm 1{,}23$ (*Paxillus involutus*). Перевищення максимального значення над мінімальним сягає 740 разів. Величини коефіцієнтів накопичення ^{137}Cs у сухих грибах коливаються від $0{,}15 \pm 0{,}02$ у *Hygrophorus eburneus* до $90{,}9 \pm 16{,}54$ у *Paxillus involutus*. У свіжих плодових тілах грибів ряд у порядку зменшення коефіцієнтів накопичення радіонукліду є наступним: *Paxillus involutus* → *Imleria badia* → *Suillus luteus*, а у сухих плодових тілах – *Paxillus involutus* → *Suillus luteus* → *Imleria badia*. Результати мають практичне значення для визначення лісових масивів, які потребують радіологічного контролю їстівних грибів при заготівлі. Матеріали досліджень можуть бути використані в практиці організації та втілення програми радіоекологічного моніторингу радіоактивно забруднених лісових екосистем

Ключові слова: тип лісорослинних умов; радіонуклід; питома активність; коефіцієнт накопичення; коефіцієнт переходу; коефіцієнт всихання