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Ganna Grodzynska, Vitaliy Nebesnyi, Igor Teslenko

RADIOACTIVE CONTAMINATION OF WILD MUSHROOMS IN CHERNIHIV POLESIE

Ганна Гродзинська, Віталій Небесний, Ігор Тесленко

РАДІОАКТИВНЕ ЗАБРУДНЕННЯ ДИКОРОСЛИХ ГРИБІВ У ЧЕРНІГІВСЬКОМУ ПОЛІССІ

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ABSTRACT

Purpose. We continue our retrospective investigations of radioactive contamination of wild mushrooms from Ukrainian Polesie. The aim of the current study is an assessment of radioactive contamination of wild mushrooms from some locations of Chernihiv Polesie in 1991-2021.

Methodology. A study of radiocaesium activity in 66 wild mushroom species (edible, inedible, conditionally edible, poisonous) (from 2 to 25 fruitbodies per sample) and soils (0-5 cm of upper mineral layer, taken by the envelope method) from 14 locations of Chernihiv Polesie was carried out with γ-spectrometry (Ge-detector Canberra GLX 4019, USA). In some mushrooms, ^{90}Sr activity was determined radiochemically on the basis of ^{90}Y accumulation according to the standard method.

Scientific novelty. The results of γ-spectrometric studies of the activity of radiocaesium in 66 species of wild mushrooms from the localities of Chernihiv Polesie over a 30-year period are given, the coefficients reflecting the bioaccumulation activity of each species counted, the hyperaccumulator species of radiocaesium are determined, and the potential annual equivalent doses for adults are calculated under the conditions of consumption of some valuable culinary-medicinal mushrooms (*B. edulis, C. cibarius, I. badia*, *Suillus* spp, *T. equestre*).

Conclusions. Activity levels of ^{137}Cs in wild mushrooms of Chernihiv Polesie varied over the years 1991-2021 depending on the mushroom species, its ecological affiliation, radioecological situation at the sampling sites, showing a certain tendency to decrease over time. Hyper-accumulative properties in relation to ^{137}Cs are demonstrated by *Cortinarius, Sarcodon, Paralepista, Tricholoma, Lactarius, Suillus* spp. Widely distributed on the territory of Ukrainian Polesie – *I. badia*, *P. involutus* and *L. rufus*, remain representative bioindicators of radiocaesium contamination. A potential calculated annual effective doses due to the mushrooms consumption by adults, considering only the effect of the ^{137}Cs, reached a high values in *Suillus* spp., *T. equestre*, and *I. badia* – 0.041, 0.035 and 0.025 mSv, respectively, which indicates a relatively insignificant dose load when consuming mushrooms in these localities compared to other localities of Ukrainian Polesie that have higher levels of soil contamination with radionuclides. However, radiation monitoring can still be recommended during mushroom procurement and mass collections.

Key words: ^{137}Cs, ^{90}Sr, accumulation, mushrooms, bioindication

АНОТАЦІЯ

Мета роботи. Ми продовжуємо наші ретроспективні дослідження радіоактивного забруднення дикорослих грибів Українського Полісся. Метою даного дослідження є оцінка радіоактивного забруднення дикорослих грибів з деяких локалітетів Чернігівського Полісся впродовж 1991-2001 рр.

Методологія. Дослідження активності радіоцезію у плодових тілах дикорослих грибів (їстівних, неїстівних, умовно їстівних, отруйних)(2-25 плодових тіл у зразку) і ґрунтів з 14 локалітетів Чернігівського Полісся було проведено методом γ-спектрометрії (Ge-детектор Canberra GLX 4019, США). В деяких грибних зразках стандартним радіохімічним методом визначали активність ^{90}Sr.

Наукова новизна. Наведено результати γ-спектрометричних досліджень активності радіоцезію у 66 видах дикорослих грибів з локалітетів Чернігівського Полісся за 30 річний період, обраховані коефіцієнти, що відображають біоакумуляційну активність кожного виду, визначені види-гіперакумулятори радіоцезію, розраховані потенційні річні еквівалентні дози для дорослих за умов споживання деяких видів цінних їстівних та лікарських грибів (*B. edulis, C. cibarius, I. badia, Suillus* spp., *T. equestre*).

Висновки. Рівні активності ^{137}Cs у дикорослих грибах Чернігівського Полісся протягом 1991-2021 рр. відрізнялися в залежності від виду гриба, його екологічної належності, радіоекологічної ситуації в місцях збору, виявляючи певну тенденцію до зниження з часом. Гіперакумулятивні властивості щодо ^{137}Cs демонструють *Cortinarius, Sarcodon, Paralepista, Tricholoma, Lactarius, Suillus* spp. Репрезентативними біоіндикаторами забруднення радіоцезієм залишаються широко поширені на території Українського Полісся *I. badia, P. involutus* та *L. rufus*.

Найвищі потенційні річні ефективні дози від споживання грибів дорослими (враховуючи лише внесок ^{137}Cs) встановлені у *Suillus* spp., *T. equestre* та *I. badia* – 0,041, 0,035 та 0,025 мЗв відповідно, що свідчить про відносно незначне дозове навантаження при споживанні грибів у цих населених пунктах порівняно з іншими населеними пунктами Українського Полісся, які мають більш високий рівень забруднення ґрунтів радіонуклідами. Проте, у випадку заготівлі та масових зборів грибів рекомендовано радіаційний контроль.

Ключові слова: ^{137}Cs, ^{90}Sr, акумуляція, гриби, біоіндикація

Introduction

Deterioration of the quality of the environment as a result of numerous man-made impacts (radiation and toxic emissions, growth of industrial waste and transport load, war actions, disturbance of natural landscapes) requires constant monitoring. A wide range of biological objects is involved for biotesting and bioindication of the state of the environment, among which some species of mushrooms are recognized as accumulative indicators, in particular radionuclides and heavy metals (Haselwandter et al., 1988; Fraiture et al., 1990; Wasser, Grodzinskaya, 1993; Grodzinskaya et al., 1995, 2003; 2011; 2022; Wasser et al., 1995; Baeza, Guillen, 2007; Kalač, 2012; 2019; Falandysz, Borovička, 2013; Grodzynska, 2017; Ernst, 2022). The forests of Ukrainian Polesie suffered the most as a result of the Chornobyl disaster, which reduced their resource and economic value and led to the fact that for more than three decades they are a constant source of radiation danger for the population (Landin, 2013). It is known that wild berries and mushrooms pose a special danger in the formation of a dose of internal radiation under the conditions of their consumption. Despite the rather extensive published results on the radioactive contamination of mushrooms, this topic continues to be of interest after the Chornobyl and the Fukushima accidents, due to the high accumulative capacity of mushrooms, in connection with the estimation of the long-term consequences and the danger of mushroom consumption (Guillen & Baeza, 2014; Nakashima et al., 2015; Orita et al., 2018; Komatsu et al., 2019; Grodzinskaya et al., 2022; Saniewski et al., 2022; Gabriel et al., 2023).

Materials and methods

Samples of whole fruitbodies of wild mushrooms and average soil samples (0-5 cm of upper mineral layer, taken by the envelope method) were collected in 14 locations of Chernihiv region of Ukraine. The sampling sites were approximately 25 × 25 m in size. Levels of soil contamination were determined both by the results of our field measurements and General dosimetry classification data (https://docs.google.com/presentation/d/15AxieLuqKiv5N5lAMrPfdetEUUfz8HUvF6wN1CryzvQ/htmlpresent?usp=gmail_thread) (Table 1).

Mushrooms (2 to 25 complete fruitbodies per species) were carefully cleaned from plant and soil debris, dried at 60°C, ground to a fine dispersion, dried again at 80°C during 24 hours, then placed in polyethylene bags with a zip lock. The same procedure was used for the soil samples. We used gamma-spectrometry (Ge-detector Canberra GLX 4019, USA) to determine radiocaesium activity in fruitbodies of 66 mushroom species (Table 2). The currently valid names of mushrooms including authors are listed according to *Index Fungorum* (www.indexfungorum.org), and edibility of the species is indicated according to *World of mushrooms of Ukraine* (http://gribi.net.ua).

Table 1

List of locations and levels of soil surface contamination with ^{137}Cs and ^{90}Sr in Chernihiv region of Ukraine

Location	The average levels of soil surface contamination, kBq/m^2 (recalculation for 2021)		Coordinates
	^{137}Cs	^{90}Sr	
Nizhyn district			
City of Bobrovytsia	5.0	1.7	50º45'18''N /31º25'49''E
Vil. Kobyzhcha	4.9	1.6	50º51'04''N /31º27'31''E
Snovs'k district			
Vil. Kuchynivka	2.4	1.6	51º42'01''N /31º53'51''E
Kozelets' district			
Vil. Evmynka	7.8	2.0	50º50'06''N /30º50'05''E
Settl. Desna	17	3.9	50º55'28''N /30º44'31''E
Vil. Karpylivka	14	3.9	51º00'53''N /30º45'30''E
Vil. Krehayiv	8.7	2.0	50º48'52''N /30º48'22''E
Vil. Loshakova Guta	17.0	8.8	51º02'23''N /30º39'12''E
Regional landscape park Mizhrichyns'kyi	12.0	2.1	51º10'21''N /30º47'26''E
Vil. Nadynivka	3.9	1.0	51º12'19''N/ 31º04'14''E
Vil. Pavlivka	2.0	0.9	51º28'39''N /31º12'17''E
Vil. Sokolivka	7.8	1.0	51º08'59''N /30º53'40''E
Vil. Syrai	6.8	1.0	50º49'11''N /31º02'09''E
Chernihiv district			
Vil. Smolyn	7.8	1.6	51º16'31''N /30º57'26''E

Table 2

List of studied species and their edibility

Species, authors*	Edibility**
1	2
Agaricus campestris L.	Edible
Amanita citrina Pers.	Poisonous
A. muscaria (L.) Lam.	Poisonous
A. panterina (DC.) Krombh.	Poisonous
A. rubescens Pers.	Edible
Ampulloclitocybe clavipes (Pers.) Redhead, Lutzoni, Moncalvo & Vilgalys	Edible
Armillaria mellea (Vahl) P. Kumm.	Edible
Boletus edulis Bull.	Edible
Cantharellus cibarius Fr.	Edible
Chlorophyllum rhacodes (Vittad.) Vellinga	Edible
Clitocybe nebularis (Batsch) P. Kumm.	Edible
Coltricia perennis (L.) Murrill	Inedible
Cortinarius caperatus (Pers.) Fr.	Edible
C. malicorius Fr.	Its edibility is not known
C. praestans (Cordier) Gillet	Edible
C. varius (Schaeff.) Fr.	Conditionally edible
C. semisanguineus (Fr.) Gillet	Poisonous
C. trivialis J.E. Lange	Inedible

Продовження табл. 2

1	2
C. decipiens (Pers.) Zawadzki	Inedible
Hortiboletus rubellus (Krombh.) Simonini, Vizzini & Gelardi	Edible
Hygrophoropsis aurantiaca (Wulfen) Maire	Inedible
Hypholoma capnoides (Fr.) P.Kumm.	Edible
H. fasciculare (Huds.) P. Kumm.	Poisonous
Fistulina hepatica (Schaeff.) With.	Edible
Fomitopsis betulina (Bull.) B.K. Cui, M.L. Han & Y.C. Dai	Inedible
Imleria badia (Fr.) Vizzini	Edible
Infundibulicybe gibba (Pers.) Harmaja	Edible
Lactarius helvus (Fr.) Fr.	Inedible
L. rufus (Scop.) Fr.	Conditionally edible
L. turpis (Weinm.) Fr.	Conditionally edible
Lactifluus volemus (Fr.)Kuntze	Conditionally edible
Leccinum aurantiacum (Bull.) Gray	Edible
L. scabrum (Bull.) Gray	Edible
Lycoperdon perlatum Pers.	Edible
Macrolepiota procera (Scop.) Singer	Edible
Marasmius oreades (Bolton) Fr.	Edible
Paralepista gilva (Pers.) Raithelh.	Poisonous
Paxillus involutus (Batsch) Fr.	Poisonous
Pseudoclitocybe cyathiformis (Bull.) Singer	Edible
Rhodocollybia butyraceae (Bull.) Lennox	Edible
R. maculata (Alb.&Schwein.) Singer	Inedible
Russula aeruginea Lindblad ex Fr.	Edible
R. amethystina Quél.	Edible
R. cyanoxantha (Schaeff.) Fr.	Edible
R. delica Fr.	Edible
R. emetica (Shaeff.) Pers.	Inedible
R. foetens Pers.	Conditionally edible
R. fragilis Fr.	Conditionally edible
R. ochroleuca Fr.	Edible
R. paludosa Britzelm.	Edible
R. roseipes Secr. ex Bres.	Edible
R. vesca Fr.	Edible
R. violeipes Quél.	Edible
R. xerampelina (Schaeff.) Fr.	Edible
Sarcodon imbricatus (L.) P. Karst.	Edible
Suillus bovinus (L.) Roussel	Edible
S. granulatus (L.) Roussel	Edible
S. luteus (L.) Roussel	Edible
Thelephora terrestris Ehrh. ex Fr.	Inedible
Tricholoma equestre (L.) P. Kumm	Edible
T. fulvum (DC.) Bigeard & H. Guill.	Edible
T. portentosum (Fr.) Quél.	Edible
T. saponaceum (Fr.) P.Kumm.	Inedible
Tricholomopsis rutilans (Schaeff.) Singer	Conditionally edible
Tylopilus felleus (Bull.) P.Karst.	Inedible
Xerocomellus chrysenteron (Bull.) Šutara	Edible

The measurement time of the sample ranged from 6 to 36 hours. The measurement error of ^{137}Cs was usually less than 10 %. In some mushroom samples, the activity of ^{90}Sr was determined with the radiochemical method on the basis of ^{90}Y accumulation according to the standard method. To assess the intensity of radionuclide accumulation by fruiting bodies, we calculated BAF – bioaccumulation factor (or coefficient of accumulation), which is equal to the ratio of the activity of the radionuclide in the mushroom fruitbody to its activity in the soil of the relevant habitat. For estimation of the potential risk to human health, the possible average dose of internal irradiation was calculated according to the formula:

$$H_{int} = c \times d_{int} \times e \times k,$$

where H_{int} – dose of internal irradiation; c – the specific activity of ^{137}Cs, Bq/kg of crude weight; d_{int} – coefficient to calculate the consumption of mushrooms by an adult (1.3×10^{-5} mSv/Bq for ^{137}Cs); e – estimated volume of annual consumption of mushrooms, kg (5 kg per person per year); k – the coefficient of culinary processing (0.5) (Grodzinskaya et al. 2022).

Results and discussion

Chernihiv Polesie is a low-lying, undulating plain. The general flatness of the territory is broken by the valleys of the Dnipro, Desna, and Snov rivers. The climate is moderately continental, with an average of 500-610 mm of precipitation per year. There are many lakes and marshes in the river valleys. The area of swamps is 4.5% of the territory of Chernihiv Polesie. Sod-podzolic, marshy, gray forest soils are common. Forest coverage of the territory is about 25%. The largest forest areas are kept on interfluves of the Dnieper and Desna, Snova and Desna. Pine and oak-pine forests predominate. In the landscape structure of Chernihiv Polesie, the main role is played by natural complexes of moraine-sand and sandy plains with turf podzolic soils and pine forests (Maslyak & Shishchenko, n.d.).

In the case of wild mushrooms in Ukrainian Polesie, we observe a danger preserved in time of mushrooms collected not only in the territories adjacent to the exclusion zone, but also in territories with a level of surface soil contamination of $^{137}Cs \geq 37$ kBq/m^2 (1 Ci/km^2) (Grodzinskaya et al., 2013; 2019; 2022, Grodzynska, 2017). In particular, in mushroom samples from the Drevlyanskyi Nature Reserve (Zhytomyr region), the highest levels of ^{137}Cs were observed in symbiotroph species – *I. badia* (≤ 2,680 kBq/kg dry mass), *T. equestre* (≤ 1,420 kBq/kg dm), *L. rufus* (≤ 602 kBq/kg dm), *S. imbricatus* (≤ 464 kBq/kg dm), *L. scabrum* (≤ 117 kBq/kg dm), *S. bovinus* (≤ 118 kBq/kg dm), and *B. edulis* (≤ 96 kBq/kg dm). Potential calculated annual effective doses due to mushroom consumption by adults, considering only the effect of ^{137}Cs, reached 0.311 and 8.71 mSv in *B. edulis* and *I. badia* (Grodzinskaya et al. 2022). At the same time, in the first post-Chornobyl period, 75-100% of mushrooms samples from the state enterprise Polissia forestry (Kyiv region) showed an exceedance of permissible radiocaesium content, then by 2018 this level decreased and amounted to 60.0 % for Zelenopolyansk and 37.84 % of Steshchynsk forestries. Despite the average levels of soil surface contamination with radiocaesium (1.1-2 Ci/km^2), declared at most Polissia forestry sites, it is impossible to recommended the picking and harvesting of mushrooms due to continued potential risk of acquiring significant internal radiation doses due the uncontrolled consumption of wild mushrooms, particularly in the case of *I. badia* and *Suillus* spp., in these cases the corresponding effective doses reached 0.130 and 0.239 mSv/y taking into account only a contribution of ^{137}Cs (Gabriel et al., 2023).

In previous years, some data on radioactive contamination of wild mushrooms in the Chernihiv region were published (Wasser, Grodzinskaya, 1993; Grodzinskaya et al., 2013). In 1991 the highest value of radiocaesium (^{134}Cs+^{137}Cs) was determined in symbiotroph *R. maculata*, the lowest – in humus saprotroph *A. campestris*, in which ^{134}Cs was not found, as in the soil sample from this location. In 1999, samples of symbiotroph *A. muscaria* (with BAF up to 174) still contained some amount of ^{134}Cs, while this radionuclide was not found in soil samples from three localities of Kozelets' district (Table 3).

In mushrooms and soils samples in 2001 ^{134}Cs was not detected. In the vicinity of the vil. Kuchynivka, symbiotrophs *P. involutus*, *C. cibarius*, and *S. luteus* were high contaminated with ^{137}Cs, and respectively their coefficients of bioaccumulation (BAFs) were – 5.15, 3.85, and 2.73 (Table 3). Given that the maximum permissible level (PL) for dry mushrooms in Ukraine is 2.5 kBq kg dry mass, it can be noted, that over 90 % of samples from this locality in 2001 exceeded this level (The Ministry of Health of Ukraine, 2006). In 2002, in the samples collected in the vicinity of the city of Bobrovytsya, the activity of radiocaesium was below the PL.

Table 3

^{134}Cs and ^{137}Cs-activity in mushrooms (kBq/kg dry mass) from Bobrovytsia (1991) and Kozelets' (1999) districts

Species, soil	^{134}Cs	^{137}Cs	BAF for ^{137}Cs
1991			
near vil. Kobyzhcha			
Agaricus campestris	-	7	0.1
Hypholoma capnoides	0.234	1.155	16.50
Rhodocollybia butyraceae	0.237	1.364	19.49
Rhodocollybia maculata	0.646	3.306	47.23
Tricholomopsis rutilans	0.226	1.154	16.49
Soil	BDL*	0.070	
1999			
near vil. Evmynka			
Amanita muscaria	0.100	1.740	174.0
Soil	BDL	0.010	
Near vil. Krehaiv			
Amanita muscaria	0.080	0.800	4.211
Soil	BDL	0.190	
Near vil. Desna			
Infundibulicybe gibba	BDL	0.150	0.225
Soil	BDL	0.667	

Note: *BDL – below detection limit

Table 4

^{137}Cs-activity in (kBq/kg d.m.) in mushrooms from Snovs'k and Nizhyn districts in 2001 and 2002

Species, soil	^{137}Cs	BAF
near vil. Kuchynivka		
Amanita muscaria	1.694	0.636
Amanita rubescens	3.703	1.390
Boletus edulis	3.162	1.187
Cantharellus cibarius	10.26	3.851
Imleria badia	6.413	2.407
Lactarius helvus	3.725	1.398
Paxillus involutus	13.71	5.146
Russula ochroleuca	4.959	1.861
Russula xerampelina	5.010	1.881
Suillus luteus	7.269	2.729
Tricholoma equestre	3.214	1.206
Soil	2.664	
near city of Bobrovytsya		
Amanita muscaria	0.071	0.670
Amanita pantherina	0.054	0.509
Suillus luteus	0.287	2.708
Soil	0.106	

In 2005, the highest ^{137}Cs-activity in mushroom samples from Kozelets district found in *S. luteus* – 12.29 (BAF – 42.84) from location near vil. Sokolivka, and in 2006 – in *B. edulis* (near vil. Nadynivka) – 11.25 kBq/kg dm (BAF-52.06) (Table 5). Since 2007, the collection of mushroom samples has been carried out in the localition on the border of the Kozelets' and Chernihiv districts, near the village of Smolyn, due to the sufficient occurrence of species. In 2007 from this location the highest ^{137}Cs-activities and BAFs detected in *L. rufus* – 125.0 kBq/kg d.m. (BAF – 33.48), *C. trivialis* – 61.49 (BAF – 304.4), *S. imbricatus* – 59.07 (77.32), and in 2008 – in *S. imbricatus* – 33.47 Bq/kg d.m. (BAF-157.9). In 2007 and 2008, in general, 75.61 % and 31.25 % of mushrooms samples from location near Smolyn, respectively, exceeded the PL.

Table 5

^{137}Cs-activity (kBq/kg d.m.) in mushrooms from Kozelets' and Chernihiv districts in 2005-2008

Species, soil	^{137}Cs	BAF
1	2	3
2005		
near vil. Sokolivka		
Amanita muscaria	1.125	3.920
Leccinum aurantiacum	0.544	1.895
Russula xerampelina	0.115	0.401
Suillus luteus	12.29	42.82
Soil	0.287	
2006		
near vil. Nadynivka		
Boletus edulis	11.25	52.06
Soil	0.216	
Boletus edulis	8.818	54.10
Soil	0.163	
2007		
near v. Syrai		
Clitocybe nebularis	0.101	1.507
Lycoperdon perlatum	0.231	3.448
Soil	0.067	
near vil. Smolyn		
Amanita citrina	2.225	0.596
Hygrophoropsis aurantiaca	5.248	1.405
Imleria badia	25.49	6.826
Lactarius rufus	125.0	33.48
Macrolepiota procera	0.116	0.031
Paxillus involutus	38.45	10.30
Pseudoclitocybe cyathiformis	6.493	1.739
Russula emetica	11.67	3.125
Russula fragilis	3.802	1.018
Russula xerampelina	6.656	1.783
Russula xerampelina	9.970	2.670
Soil	3.734	
Amanita citrina	3.779	4.895
Amanita muscaria	1.046	1.355
Boletus edulis	4.038	5.231
Hypholoma fasculare	1.817	2.354
Cantharellus cibarius	2.364	3.062
Cortinarius trivialis	34.38	44.53
Cortinarius varius	28.91	37.45

Продовження табл. 5

1	2	3
Imleria badia	20.09	26.02
Soil	0.772	
Lactarius rufus	37.58	49.19
Paxillus involutus	38.29	50.12
Sarcodon imbricatus	59.07	77.32
Suillus bovinus	11.08	14.50
Suillus luteus	3.622	4.741
Tricholoma equestre	3.710	4.856
Tricholoma portentosum	9.102	11.91
Tylopillus felleus	16.48	21.57
Soil	0.764	
Amanita muscaria	1.221	6.045
Amanita rubescens	7.492	37.09
Amanita rubescens	2.089	10.34
Cortinarius semisanguineus	23.27	115.2
Cortinarius trivialis	61.49	304.4
Hygrophoropsis aurantiaca	4.208	20.83
Hypholoma fasciculare	3.971	19.66
Imleria badia	15.94	78.91
Lactarius rufus	3.512	17.39
Paxillus involutus	29.12	144.2
Russula xerampelina	0.844	4.178
Russula xerampelina	9.970	49.36
Soil	0.202	
2008		
near vil. Smolyn		
Amanita muscaria	5.140	24.25
Boletus edulis	0.500	2.358
Hygrophoropsis aurantiaca	0.746	3.519
Hypholoma fasciculare	0.272	1.283
Imleria badia	3.054	14.41
Lactarius rufus	1.800	8.491
Lactarius turpis	1.023	4.825
Macrolepiota procera	0.707	3.335
Paxillus involutus	7.423	35.01
Russula aeruginea	0.142	0.670
Russula delica	1.437	6.778
Russula amethystina	0.137	0.646
Sarcodon imbricatus	33.47	157.9
Suillus luteus	6.533	30.82
Tricholoma portentosum	0.927	4.373
Tricholomopsis rutilans	0.893	4.212
Soil	0.212	
Regional landscape park «Mizhrichynskyi»		
Amanita muscaria	0.257	0.704
Amanita pantherina	0.576	1.578
Amanita rubescens	0.772	2.115
Ampulloclitocybe clavipes	0.218	0.597
Cortinarius malicorus	30.33	83.10
Hypholoma fasciculare	5.670	15.53
Imleria badia	8.238	22.57
Imleria badia	6.390	17.51
Lactarius helvus	49.03	134.3
Marasmius oreades	1.952	5.348
Suillus luteus	1.398	3.830
Tricholoma portenosum	8.207	22.48
Tricholoma saponaceum	1.500	4.110

Продовження табл. 5

1	2	3
Soil	0.365	
near vil. Loshakova Guta		
Cortinarius trivialis	25.22	91.05
Leccinum scabrum	6.523	23.55
Soil	0.277	
Imleria badia	9.973	74.98
Marasmius oreades	2.883	21.68
Russula vesca	3.347	25.17
Russula violeipes	1.257	9.451
Tricholomopsis rutilans	0.276	2.075
Soil	0.133	

In 2010, the highest level of contamination with radiocesium was also found in the symbiotrophs *C. praestans* – up to 246.0 kBq/kg dm (BAF – up to 708.0) (near the village of Karpylivka), *Paralepista gilva* – 68.0 (BAF – 283.3), *A. rubescens* – up to 50.0 (BAF up to 173.0), in *L. helvus* up to 48.0 (BAF-141.6). It should be noted a high level of radiocesium activity variability in the same species from the same location – for example, the level in *I. badia* differed by 2.56 times, *A. rubescens* differed by 9.63, and *M. procera* to 27.14 times.

Table 6

^{137}Cs-activity in (kBq/kg d.m.) in mushrooms from Kozelets' and Chernihiv districts in 2010

Species, soil	^{137}Cs	BAF
1	2	3
2010		
near vil. Karpylivka		
Amanita citrina	0.562	2.342
Amanita pantherina	0.069	0.288
Amanita rubescens	5.192	21.63
Armillariella mellea	0.524	2.183
Boletus edulis	0.208	0.867
Infundibulicybe gibba	0.138	0.575
Fomitopsis betulina	0.040	0.167
Imleria badia	6.012	25.05
Lactarius turpis	3.213	13.39
Lactifluus volemus	10.45	43.54
Macrolepiota procera	0.073	0.304
Paralepista gilva	68.00	283.3
Paxillus involutus	20.03	83.46
Russula cyanoxantha	2.554	10.64
Russula vesca	1.925	8.020
Russula xerampelina	3.040	12.67
Suillus granulatus	1.108	4.617
Suillus luteus	10.65	44.38
Tricholoma fulvum	2.708	11.28
Tricholomopsis rutilans	0.906	3.775
Soil	0.240	
Chlorophyllum rhacodes	0.324	0.956
Cortinarius praestans	240.0	708.0
Hypholoma fasciculare	0.059	0.174
Lactarius helvus	48.00	141.6
Macrolepiota procera	1.981	5.844
Russula aeruginea	0.901	2.658
Tricholoma equestre	3.428	10.11
Tricholoma fulvum	2.621	7.732

Продовження табл. 6

1	2	3
Soil	0.339	
Amanita muscaria	0.161	0.557
Amanita rubescens	50.00	173.0
Cantharellus cibarius	8.800	30.45
Cortinarius praestans	146.0	505.2
Imleria badia	15.40	53.29
Lactarius turpis	15.80	54.67
Russula cyanoxantha	45.00	155.7
Russula vesca	31.00	107.3
Russula xerampelina	5.400	18.69
Suillus luteus	12.90	44.64
Soil	0.289	
near vil. Pavlivka		
Hortiboletus rubellus	0.052	–
Imleria badia	0.104	–
Xerocomellus chrysenteron	0.396	–
Soil	BDL*	
near vil. Smolyn		
Cantharellus cibarius	1.709	4.644
Lycoperdon perlatum	0.501	1.361
Macrolepiota procera	0.089	0.242
Suillus luteus	5.738	15.59
Soil	0.368	
Amanita muscaria	0.092	0.979
Macrolepiota procera	0.040	0.426
Suillus luteus	0.215	2.287
Soil	0.094	

Note: *BDL – below detection limit; – - no data available

Due to the very high variability in the levels of radiocaesium contamination of mushrooms, observed even in the samples of one species from the same location, we calculated the geometric mean value. For all mushroom samples collected in 2005-2010, the geometric mean of ^{137}Cs activity amounted to 2.766 kBq/kg dm. The geometric means of ^{137}Cs activity differed significantly in some group of species – in *Amanita* spp. it was 1.180 kBq/kg dm (from 0.199 in *A. pantherina* to 5.004 kBq/kg dm in *A. rubescens*); in *Russula* spp. – 2.306 kBq/kg dm (from 0.137 in *R. amethystina* to 11.67 in *R. emetica*); in *Tricholomataceae* – 2.994 (from 0.496 in *T. rutilans* to 68.00 in *P. gilva*). In *Boletales* species, this value was 3.359 kBq/kg dm (from 0.052 in *H. rubellus* to 16.48 kBq/kg dm in *T. felleus*); in *Lactarius* spp. – 9.741 (from 3.731 in *L. turpis* to 49.03 in *L. helvus*); in *Cortinarius* spp. the geometrical mean was the highest – 49.85 kBq/kg dm (of 23.27 in *C. semisanguineus* to 187.2 in *C. praestans*).

D. Holiaka et al. (2020) confirmed significantly higher ^{90}Sr mobility in elements of forest ecosystems than ^{137}Cs. They noted a gradual further increase in the share of these radionuclides in the aboveground biomass components (up to 0.9 %·year^{-1} from the total activity in forest ecosystems) owing to the increase of organic matter stocks. On the one hand, this indicates the continuing danger of an additional source of contamination for mushrooms, on the other hand, the need for long-term radiation monitoring of all components of the biota.

Determination of ^{90}Sr activity in some samples of mushrooms from a location near the village of Karpylivka showed a significant level of contamination – of 0.099 for *A. muscaria* to 7.900 kBq/dm for *A. rubescens*. Considering that the maximum permissible level for dry mushrooms of this radionuclide, adopted in Ukraine, is 0.250 kBq/kg, in this case we are talking about quite serious contamination with radiostrontium (Table 7). The ^{137}Cs/^{90}Sr ratio in the studied samples ranged from 1.626 (*A. muscaria*) to 63.48 (*C. praestans*). For most mushroom species from the Zelenopolyansk forestry, this ratio was at the level of 10-10^{2} (Gabriel et al., 2023).

Table 7

^{90}Sr-activity (kBq/kg dm) and ratio ^{137}Cs/^{90}Sr in mushroom samples from location near vil. Karpylivka in 2010

Species	^{90}Sr	BAF	^{137}Cs/^{90}Sr
Amanita muscaria	0.099	0.031	1.626
Amanita rubescens	7.900	2.469	6.329
Cantharellus cibarius	0.400	0.125	22.00
Cortinarius praestans	2.300	0.719	63.48
Imleria badia	2.800	0.875	5.500
Lactarius turpis	1.200	0.375	13.17
Russula cyanoxantha	3.400	1.063	13.24
Russula vesca	4.000	1.250	7.750
Russula xerampelina	1.200	0.375	4.500
Suillus luteus	3.000	0.938	4.300
Soil	3.200		1.438

Table 8

^{137}Cs-activity in (kBq/kg d.m.) in mushrooms from Kozelets' and Chernihiv districts in 2018, 2020 and 2021

Species, soil	^{137}Cs	BAF
1	**2**	**3**
2018		
near vil. Smolyn		
Canthartellus cibarius	0.677	2.943
Coltricia perennis	0.303	1.317
Hypholoma fasciculare	0.589	2.561
Imleria badia	3.761	16.35
Tylopilus felleus	1.996	8.678
Soil	0.230	
Amanita panterina	0.143	0.917
Amanita rubescens	0.829	5.314
Fistulina hepatica	0.460	2.949
Hypholoma fasciculare	0.269	1.724
Imleria badia	3.363	21.56
Leccinum scabrum	0.931	5.968
Russula foetens	0.843	5.404
Russula vesca	0.146	0.936
Telephora terrestris	0.280	1.795
Tylopilus felleus	0.791	5.071
Soil	0.156	
Imleria badia	0.135	4.500
Russula vesca	0.041	1.367
Suillus granulatus	0.179	5.967
Soil	0.030	
2020		
Amanita citrina	0.999	1.986
Amanita muscaria	0.474	0.942
Amanita pantherina	0.310	0.616
Cortinarius caperatus	1.546	3.073
Cortinarius malicorus	13.66	27.16
Cortinarius trivialis	2.687	5.345
Hypholoma fasciculare	0.779	1.549
Hygrophoropsis aurantiaca	0.719	1.429
Hygrophoropsis aurantiaca	2.050	4.076
Lactarius rufus	2.030	4.036

Продовження табл. 8

1	2	3
Paxillus involutus	2.325	4.622
Russula amethystina	0.991	1.970
Russula xerampelina	0.381	0.757
Suillus bovinus	1.873	3.724
Soil	0.503	
Amanita muscaria	0.682	3.187
Cantharellus cibarius	2.254	10.53
Chlorophyllum rhacodes	0.113	0.528
Cortinarius malicorus	10.84	50.65
Cortinarius praestans	11.45	53.50
Imleria badia	7.682	35.90
Lactarius rufus	5.080	23.74
Russula cyanoxantha	2.974	13.90
Russula paludosa	0.578	2.701
Russula xerampelina	0.116	0.542
Soil	0.214	
Amanita muscaria	0.553	3.435
Cantharellus cibarius	1.885	11.71
Cortinarius caperatus	4.742	29.45
Cortinarius decipiens	11.42	70.93
Cortinarius malicorus	24.96	155.0
Hygrophoropsis aurantiaca	1.497	9.298
Imleria badia	2.259	14.03
Lactarius rufus	2.708	16.82
Lycoperdon perlatum	0.133	0.826
Paxillus involutus	2.540	15.78
Russula amethystina	1.562	9.702
Russula roseipes	0.413	2.565
Russula paludosa	1.906	11.84
Sarcodon imbricatus	10.84	67.33
Suillus bovinus	1.957	12.16
Suillus granulatus	12.73	79.07
Tricholoma equestre	10.85	67.39
Tricholoma fulvum	3.259	20.24
Soil	0.161	
2021		
near vil. Smolyn		
Amanita citrina	1.028	5.439
Amanita muscaria	0.416	2.201
Cantharellus cibarius	0.587	3.106
Fistulina hepatica	0.151	0.799
Hygrophoropsis aurantiaca	1.354	7.164
Hypholoma fasciculare	1.760	9.312
Imleria badia	3.869	20.47
Lactarius rufus	2.210	11.69
Lactarius turpis	0.863	4.566
Macrolepiota procera	0.032	0.169
Russula aeruginea	0.618	3.270
Russula xerampelina	0.265	1.402
Sarcodon imbricatus	16.49	87.25
Suillus bovinus	2.019	10.68
Suillus granulatus	3.890	20.58
Soil	0.189	
Amanita pantherina	0.682	2.890
Amanita rubescens	1.903	8.064
Cantharellus cibarius	0.426	1.805
Coltricia perennis	0.216	0.915
Cortinarius caperatus	6.140	26.02
Cortinarius malicorus	12.46	52.80

Продовження табл. 8

1	2	3
Cortinarius praestans	2.062	8.742
Cortinarius trivialis	10.39	44.03
Hygrophoropsis aurantiaca	0.914	3.873
Imleria badia	3.049	12.92
Lactarius rufus	3.211	13.61
Leccinum scabrum	0.842	3.568
Paxillus involutus	2.715	11.50
Pseudoclitocybe cyathiformis	0.248	1.051
Russula cyanoxantha	2.467	10.45
Russula emetica	0.851	3.606
Russula foetens	0.695	2.945
Russula xerampelina	0.180	0.763
Suillus bovinus	1.164	4.932
Tricholoma fulvum	9.452	40.05
Tylopilus felleus	0.813	3.445
Soil	0.236	
Amanita muscaria	1.249	6.123
Cortinarius decipiens	15.51	76.03
Cortinarius malicorus	28.97	142.0
Cortinarius praestans	8.613	42.22
Hygrophoropsis.aurantiaca	1.693	8.299
Imleria badia	2.916	14.29
Lactarius rufus	3.590	17.60
Lycoperdon perlatum	0.075	0.368
Paxillus involutus	6.521	31.97
Russula xerampelina	1.430	7.010
Sarcodon imbricatus	9.942	48.74
Suillus bovinus	1.634	8.010
Suillus granulatus	11.48	56.27
Tricholoma equestre	9.636	47.24
Tricholoma fulvum	3.007	14.74
Soil	0.204	
near v. Karpylivka		
Amanita citrina	0.976	14.35
Amanita rubescens	1.124	16.53
Armillaria mellea	BDL*	
Boletus edulis	0.189	2.779
Cantharellus cibarius	0.296	4.353
Cortinarius praestans	8.046	118.3
Fomitopsis betulina	0.083	1.221
Lycoperdon perlatum	BDL	
Macrolepiota procera	0.140	2.056
Paralepista gilva	11.81	173.7
Russula cyanoxantha	1.038	15.26
Russula vesca	1.687	24.81
Russula xerampelina	0.654	9.618
Suillus luteus	12.49	183.7
Tricholoma fulvum	16.52	242.9
Tricholomopsis rutilans	0.542	7.971
Soil	0.068	
Amanita muscaria	2.043	0.706
Russula vesca	14.11	4.879
Tricholoma fulvum	28.40	9.820
Xerocomellus chrysenteron	3.016	1.043
Soil	2.892	

Note: *BDL – below detection limit

The geometric mean of radiocaesium activity in the studied mushrooms for the period 2018-2021 amounted to 1.434 kBq/kg dm (from the minimum value – BDL in *A. mellea* to the maximum – 16.79 kBq/kg dm in *C. malicorus*). At the same time, the geometric mean values in groups of species differed significantly: in *Russula* spp. – 0.635 kBq/kg dm (from 0.345 in *R. vesca* to 1.967 in *R. cyanoxantha*); in *Amanita* spp. – 0.737 (from 0.312 in *A. pantherina* up to 1.210 in *A. rubescens*); in *Boletales* spp. – 1.905 Bq/kg dm (from 0.189 in *B. edulis* up to 12.490 in *S. luteus*); in *Lactarius* spp. – 2.502 kBq/kg dm (of 0.863 in *L. turpis* to 2.987 in *L. rufus*); *Tricholomataceae* spp. – 4.910 (from 0.542 in *T. rutilans* to 11.81 in *P. gilva*); in *Cortinarius* spp. –8.278 Bq/kg dm (from 4.437 in *C. caperatus* to 16.79 in *C. malicorus*). Previously, increased levels of radiocaesium were also determined in *Cortinariaceae* spp. (Haselwandter et al., 1988; Yoshida, Muramatsu, 1994; Grodzinskaya et al., 2003, 2011; Zalewska et al., 2016; Falandysz et al., 2019; Gabriel et al., 2023).

Significant differences in the levels of contamination of the same species are noted not only at different locations but also within the same sampling site, which is obviously associated with the extremely heterogenous nature of contamination, the depth of mycelium in the soil, and microclimatic conditions. Considering the variability in the levels of accumulation of radiocaesium by different species in different habitats, the BAF value is important for the assessment of the total accumulative ability of mushroom species (Table 9).

Table 9

Geometrical mean values of BAFs of wild mushroom species for 1991-2021

Species*	BAFs
A. campestris, H. rubellus, A. mellea, I. gibba, L. perlatum, F. betulina, A. clavipes, M. procera, Ch. rhacodes, A. pantherina	0.1 – 1.0
C. perennis, R. fragilis, P. cyathiformis, C. nebularis, F. hepatica, T. terrestris, R. aeruginea, R. ochroleuca, L. aurantiacum, R. violeipes, R. amethystina, R. roseipes, A. muscaria, R. paludosa, H. fasciculare, R. xerampelina	1.1 – 3.0
R. emetica, A. citrina,R. foetens,T. saponaceum, H. aurantiaca, B. edulis, C. cibarius, M. oreades, T. rutilans, R. delica, T. felleus, L. scabrum, S. bovinus, R. vesca	3.1 – 9.0
T. portentosum, L. turpis, A. rubescens, T. equestre, C. caperatus, S. luteus, L. rufus, H. capnoides, S. granulatus, I. badia, R. butyracea	9.1 – 20.0
R. cyanoxantha, T. fulvum, P. involutus, L. helvus, C. varius, L. volemus, R. maculata, C. trivialis	20.1 – 50.0
C. malicorus, C. decipiens, S. imbricatum, C. praestans	50.1 – 100.0
C. semisanguineus, P. gilva	> 100

Note: * The species in the first column are arranged in order of increasing BAFs

Summarizing data on the intensity of radiocaesium accumulation during the research period (1991-2021) showed that among the species with an average and high level of accumulation are only mycorrhizal species. Hyper-accumulative properties in relation to radiocaesium are demonstrated by *Cortinarius, Sarcodon, Paralepista, Tricholoma, Lactarius, Suillus* spp. Recommended by us earlier (Grodzinskaya et al., 2003, 2011, 2013), common on the territory of Ukrainian Polesie – *I. badia* (= *B. badius*), *P. involutus* and *L. rufus*, stably throughout the entire post-Chonobyl period serve as representative bioindicators of radiocaesium contamination.

The potential risk of radioactivity to human health is expressed as the equivalent dose in mSv per year. Based on the obtained data, we calculated the potential average dose of internal irradiation considering only the part connected with ^{137}Cs by consumption of some popular culinary-medicinal species in 2020-2021, taking the average annual consumption of an adult inhabitat of Chernihiv Polesie (5 kg of fresh mushrooms) and a culinary processing coefficient of 0.5 (Table 10).

Table 10

Potential annual doses of internal radiation (mSv/y) due to consumption of *Boletus edulis, Imleria badia, C.cibarius, Suillus* spp, *T.equestre* by adults from monitoring localities (near the villages of Smolyn and Karpylivka)

Species	Min ^{137}Cs activity (kBq/kg dry mass)	Min Dose (mSv/y)	Max ^{137}Cs activity (kBq/kg dry mass)	Max Dose (mSv/y)
Boletus edulis	189	0.0006	-	-
Imleria badia	2259	0.0073	7682	0.0250
Cantharellus cibarius	296	0.0010	2254	0.0073
Suillus spp.	1164	0.0038	12730	0.0414
Tricholoma equestre	9636	0.0313	10850	0.0353

In 2020-2021, the potential annual equivalent dose reached maximum values in *Suillus* spp., *Tricholoma equestre* and *I. badia*, in which it reached, respectively, 4.1, 3.5 and 2.5 % of the annual dose (1 mSv).

Conclusions

Activity levels of ^{137}Cs in wild mushrooms of Chernihiv Polesie varied over the years 1991-2021 depending on the mushroom species, its ecological affiliation, radioecological situation at the sampling sites, showing a certain tendency to decrease over time.

Hyper-accumulative properties in relation to ^{137}Cs are demonstrated by *Cortinarius, Sarcodon, Paralepista, Tricholoma, Lactarius, Suillus* spp. Widely distributed on the territory of Ukrainian Polesie – *I. badia*, *P. involutus* and *L. rufus*, remain representative bioindicators of radiocaesium contamination.

A potential calculated annual effective doses due to the mushrooms consumption by adults, considering only the effect of the ^{137}Cs, reached a high values in *Suillus* spp., *T. equestre*, and *I. badia* – 0.041, 0.035 and 0.025 mSv, respectively, which indicates a relatively insignificant dose load when consuming mushrooms in these localities compared to other localities of Ukrainian Polesie that have higher levels of soil contamination with radionuclides.

However, radiation control can still be recommended during mushroom procurement and mass collections because of the persistent spotty and uneven nature of contamination of the territory of Chernihiv Polesie.

References

Baeza, A., & Guillén, J. (2007). Role of fungi in the determination of the radiological status of terrestrial ecosystems. *Bioremed Biodiver Bioavail.*, 1, 78–87.

Ernst, A.-L., Reiter, G., Piepenbring, M., & Bässler, C. (2022). Spatial risk assessment of radiocesium contamination of edible mushrooms – Lessons from a highly frequented recreational area. *Sci. Total Environ., 807*(2), 150861. https://doi.org/10.1016/j.scitotenv.2021.150861

Falandysz, J., & Borovička, J. (2013). Macro and trace mineral constituents and radionuclides in mushrooms: Health benefits and risks. *Appl. Microbiol. Biotechnol.*, 97, 477–501. https://doi.org/10.1007/s00253-012-4552-8

Falandysz, J., Zalewska, T., & Fernandes, A.R. (2019). ^{137}Cs and ^{40}K in *Cortinarius caperatus* mushrooms (1996-2016) in Poland – Bioconcentration and estimated intake: ^{137}Cs in *Cortinarius* spp. from the Northern Hemisphere from 1974 to 2016. *Environ. Pollut., 255*(1), 113208. https://doi.org/10.1016/j.envpol.2019.113208

Fraiture, A., Guillite, O., & Lambinon, G. (1990). Interest of fungi as bioindicators of the contamination in forest ecosystems. In Desmet G., Nassimbeni P., Belli M. (eds.), *Transfer of radionuclides in natural and semi-natural environments* (pp. 477–484). Elsevier Applied Science.

Gabriel, J., Grodzynska, G.A., Nebesnyi, V.B., & Landin, V.P. (2023): Radioactive contamination of mushrooms from Polis'ke Forestry (Kyiv Region, Ukraine) long after the Chornobyl accident. *Czech Mycol.*, *75*(2), 117–137. https://doi.org/10.33585/cmy.75202

Grodzinskaya, A.A., Nebesnyi, V.B., Landin, V.P., & Gabriel, J. (2022). Radioactive contamination of wild mushrooms from Ukraine under conditions of contrasting radiation loads: 36 years after Chernobyl NPP catastrophe. *International Journal of Medicinal Mushrooms*, *24*(9), 25–40. https://doi.org/10.1615/IntJMedMushrooms.2022044725

Grodzinskaya, A.A., Berreck, M., Wasser, S.P., & Haselwandter, K. (1995). Radiocesium in fungi: Accumulation pattern in the Kiev district of Ukraine including the Chernobyl zone. *Sydowia,* 10, 88–96.

Grodzinskaya, A.A., Berreck, M., Haselwandter, K., & Wasser, S.P. (2003). Radiocesium contamination of wild-growing medicinal mushrooms in Ukraine. *International Journal of Medicinal Mushrooms, 5*(1), 61–86. https://doi.org/10.1615/IntJMedMushr.v5.i1.90

Grodzinskaya, A.A., Samchuk, A.I., Nebesnyi, V.B., Honchar, H.Yu. (2019). Radiocesium (^{137}Cs) and mineral elements in culinary-medicinal mushrooms from the southern outskirts of Kyiv (Ukraine). *International Journal of Medicinal Mushrooms, 21*(1), 71–77. https://doi.org/10.1615/IntJMedMushr.2018029583

Grodzinskaya, A.A., Syrchin, S.A., Kuchma, N.D., & Bilay, V.T. (2011, October 4–7). *Radioactive contamination of Ukrainian wild-growing mushrooms.* [Conference presentation]. Mushroom Biology and Mushroom Products, Arcachon, INRA. Paris, France.

Grodzynska, G.A. (2017). Radionuclide contamination of macromycetes. *Visn. Reports of the National Academy of Sciences of Ukraine,* 6, 61–76. (in Ukrainian). https://doi.org/10.15407/visn2017.06.061
Гродзинська Г. А. Радіонуклідне забруднення макроміцетів. *Вісник НАН України*. 2017. № 6. С. 61–76.

Guillén, J., & Baeza, A. (2014). Radioactivity in mushrooms: A health hazard? *Food Chem.*, 154, 14–25. https://doi.org/10.1016/j.foodchem.2013.12.083

Haselwandter, K., Berreck, M., & Brunner, P. (1988). Fungi as bioindicators of radiocesium contamination: Pre- and post-Chernobyl activities. *Trans. Brit. Mycol. Soc.*, 90, 171–4. https://doi.org/10.1016/S0007-1536(88)80085-8

Holiaka, D.M., Levchuk, S.E., Yoschenko, V.I., Kashparov, V.A., Yoschenko, L.V., Holiaka, M.A., Pavliuchenko, V.V., Diachuk, P.P., Zadorozhniuk, R.M., & Morozova, V.S. (2020). ^{90}Sr and ^{137}Cs inventories in the depots and biogenic fluxes of the typical forest stands in the Chernobyl exclusion zone. *Nucl. Phys. At. Energy, Section: Radiobiology and Radioecology*, *21*(3), 256-264. https://doi.org/10.15407/jnpae2020.03.256

Kalač, P. (2012). Radioactivity of European wild growing edible mushrooms: In Andres, S., & Baumann, N. (ed.) *Mushroom types, properties and nutrition* (pp. 215–230). Nova Science Publishers.

Kalač, P. (2019). *Mineral composition and radioactivity of edible mushrooms*. Academic Press.

Komatsu, M., Nishina, K., & Hashimoto S. (2019). Extensive analysis of radiocesium concentrations in wild mushrooms in eastern Japan affected by the Fukushima nuclear accident: Use of open accessible monitoring data. *Environ. Pollut., 255*(2), 113236. https://doi.org/10.1016/j.envpol.2019.113236

Landin, VP. (2013). *Methodology for rehabilitation and sustainable use of forest ecosystems contaminated with radioactive substances* [Thesis for doctoral degree in Agricultural Sciences, National Academy of Agrarian Sciences of Ukraine, Institute of Agroecology and Nature Management] (in Ukrainian). Abstract database «Ukrainica Scientific». http://irbis-nbuv.gov.ua/publ/REF-0000488787

Ландін В.П. Методологія реабілітації та збалансованого використання радіоактивно забруднених лісових екосистем: автореф. дис. … д-ра с.-г. наук: 03.00.16 / Нац. акад. аграр. наук України, Ін-т агроекології та природокористування. Київ, 2013. 41 с.

Maslyak, P.O., & Shishchenko, P.G. (n.d.). Zone of mixed coniferous-deciduous forests**.** Kyiv Polesie. Chernihiv Polesie. Novhorod-Siverskyi Polesie. In *Online library of educational and scientific literature EduKnigi.com*. (in Ukrainian). https://eduknigi.com/geo_view.php?id=42

Масляк П. О., Шищенко П. Г. Зона мішаних хвойно-широколистих лісів. Київське Полісся. Чернігівське Полісся. Новгород-Сіверське Полісся. *Онлайн бібліотека освітньої та наукової літератури EduKnigi.com*. URL: https://eduknigi.com/geo_view.php?id=42 (дата звернення: 05.10.2023).

Nakashima, K., Orita, M., Fukuda, N., Taira, Ya., Hayashida, N., Matsuda, N., & Takamura, N. (2015). Radiocesium concentrations in wild mushrooms collected in Kawauchi Village after the accident at the Fukushima Daiichi Nuclear Power Plant. *PeerJ 3:e1427.* https://doi.org/10.7717/peerj.1427

Orita, M., Kimura, Y., Taira, Y., Fukuda, T., Takahashi, J., Gutevych, O., Chornyi, S., Kudo, T., Yamashita, S., & Takamura, N. (2018). Activities concentration of radiocesium in wild mushroom collected in Ukraine 30 years after the Chernobyl power plant accident. *PeerJ 6:e4222*. https://doi.org/10.7717/peerj.4222

The Ministry of Health of Ukraine. (2006). *Permissible levels of the ^{137}Cs and ^{90}Sr radionuclides in food and drinking water* (State Hygiene Standard DR-97: 2006). (in Ukrainian). https://zakon.rada.gov.ua/rada/show/v0255282-97

ДР-97. Допустимі рівні вмісту радіонуклідів ^{137}Cs and ^{90}Sr у продуктах харчування та питній воді. Державні гігієнічні стандарти. [Чинний від 2006-05-03]. Вид. офіц. Київ : МОЗ України, 2006. URL: http://https://zakon.rada.gov.ua/rada/show/v0255282-97 (дата звернення: 15.09.2023).

Saniewski, M., Falandysz, J., & Zalewska, T. (2022). 137Cs and 40K activity concentrations in edible wild mushrooms from China regions during the 2014–2016 period. *Foods and Raw Materials, 10*(1), 86–96. https://doi.org/10.21603/2308-4057-2022-1-86-96

Wasser, S.P., Bolukh, V.O., Brun', G.O., Virchenko, V.M., Grodzynska, G.A., Kondratyuk, S.Ya., Navrotska, I.L., Stupina, V.V., & Tsarenko, P.M. (Eds. Wasser S.P.). (1995). *Uptake of radionuclides by cryptogame plants and higher fungi of Ukraine.* Kyiv. 131 p. (in Ukrainian)

Вассер, С.П., Болюх, В.О., Брунь, Г.О., Вірченко, В.М., Гродзинська, Г.А., Кондратюк, С.Я., Навроцька, І.Л., Ступіна В.В., Царенко П.М. Накопичення радіонуклідів споровими рослинами і вищими грибами України /Під заг. ред. С.П. Вассера. Київ, 1995, 131 с.

Wasser, S.P., & Grodzinskaya A.A. (1993). Content of radionuclides in macromycetes of the Ukraine in 1990–1991. In *Fungi of Europe: Investigation, recording and conservation* (pp. 189–210). Royal Botanic Gardens, Kew.

Макромицеты: лекарственные свойства и биологические особенности / Под ред. проф. С.П. Вассера. Киев: Наш формат, 2012. 285 с.

Yoshida, S., & Muramatsu, Y. (1994). Concentrations of radiocesium and potassium in Japanese mushrooms. *Environ. Sci., 7*(1), 63-70.

Zalewska, T., Cocchi, L., & Falandysz J. (2016). Radiocaesium in *Cortinarius* spp. Mushrooms in the regions of the Reggio Emilia in Italy and Pomerania in Poland. *Environ. Sci. Pollut. Res.*, 23, 23169–23174. https://link.springer.com/article/10.1007/s11356-016-7541-0

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Information about the authors:

Grodzynska G. [*in Ukrainian*: Гродзинська Г.] [1], Senior Researcher, PhD in Biol. Sc., email: a.grodzinskaya@gmail.com
ORCID – 0000-0002-5128-8695 *Researcher ID* – AAF-3287-2020 *Scopus-Author ID* – 6506163276
Department of Phytoecology, Institute for Evolutionary Ecology, National Academy of Sciences of Ukraine
Acad. Lebedeva St.37, Kyiv, 03143, Ukraine

Nebesnyi V. [*in Ukrainian*: Небесний В.] [2], Researcher, email: nebvit@gmail.com
ORCID – 0000-0003-2455-1715 *Researcher ID* – AAF-9171-2019 *Scopus-Author ID* – 6505658753
Department of Phytoecology, Institute for Evolutionary Ecology, National Academy of Sciences of Ukraine
Acad. Lebedeva St.37, Kyiv, 03143, Ukraine

Teslenko I. [*in Ukrainian*: Тесленко І.] [3], Lead Engineer, email: igor3654@ukr.net
ORCID – 0000-0002-4184-4774
Department of Phytoecology, Institute for Evolutionary Ecology, National Academy of Sciences of Ukraine
Acad. Lebedeva St.37, Kyiv, 03143, Ukraine

[1] Study design, data collection, statistical analysis, manuscript preparation.
[2] Data collection, statistical analysis, manuscript preparation.
[3] Data collection, statistical analysis, manuscript preparation.