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ORIGINAL ARTICLE

RADIOCAESIUM ACTIVITY IN POLISH *IMLERIA BADIA* MUSHROOMS: CONTAMINATION LEVELS AND TRENDS OVER THE LAST THREE DECADES

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ABSTRACT

Background. The Bay Bolete (*Imleria badia* Vizzini) is a prized edible wild mushroom. The fungus is unfortunately, also prone to mycelial uptake of anthropogenic radiocaesium ($^{134/137}$Cs) from contaminated substrates, which accumulates in the fruiting bodies.

Objective. To investigate, in light of historical atmospheric releases (including from Chernobyl) of radionuclides, the temporal and spatial distribution of radiocaesium and radiopotassium (^{40}K) activities in this species from eleven regions of Poland over the period 1995 to 2023. Literature data on this species over the same period were reviewed to supplement and support the findings.

Material and Methods. *Imleria badia* samples collected across eleven regions of Poland affected by radioactive fallout were determined for ^{137}Cs and ^{40}K activity by gamma spectrometry using a coaxial high purity germanium detector. The activity measurements were verified by using a reference solution of gamma emitting isotopes (BW/Z-62/27/07) for calibration.

Results. ^{137}Cs activity was detected in all but one sample with values ranging from < 6.4 to 11000 Bq·kg^{-1} dw. ^{134}Cs activity was not detected – in line with its shorter half-life. ^{40}K activity remained relatively stable despite the variable amounts of ^{137}Cs activity, confirming the validity of the measurements.

Conclusions. The high values of BCF calculated (up to 134) confirm the propensity of *I. badia* to accumulate harmful ^{137}Cs activity. In some cases, the measured activity was above the regulatory tolerance limits set for human dietary exposure. Although individual regional sampling sites varied in number, the mean data for the regions indicated that the North Eastern part of Poland was most affected by ^{137}Cs contamination. The temporal trend shows a decline in mean ^{137}Cs activity from 5617 Bq·kg^{-1} dw in the 1990s to 1095 Bq·kg^{-1} dw in 2020.

Keywords: *radiation exposure, Chernobyl accident, Bay Bolete, Xerocomus badius, ^{137}Cs and ^{134}Cs, edible wild mushrooms*

INTRODUCTION

The Bay Bolete, current Latin name *Imleria badia* (Fr.) Vizzini, is a relatively common and widespread edible fungus in temperate to colder latitudes, particularly in Europe and northeastern North America. When growing conditions are favorable the fruiting bodies (mushrooms) can be found in abundance in pine and spruce forests but also to a lesser extent, in mixed forests under chestnut, oak and beech. Culinarily, it is generally considered as a prized wild edible species. The genus *Imleria* was established by Alfredo Vizzini in 2014 as a renaming of *Boletus badius* or *Xerocomus badius* and consists of eight members of which the most known is *I. badia*. Other members include: *I. floridana* Farid, A.R. Franck & J. Bolin; *I. heteroderma* (J. Blum) T. Rödig; *I. obscurebrunnea* (Hongo) Xue T. Zhu & Zhu L. Yang; *I. pallida* (Frost) Farid, A.R. Franck & J. Bolin; *I. parva* Xue T. Zhu & Zhu L. Yang; *I. spadiceomaculans* (H. Engel & W. Härtl) C. Hahn, and *I. subalpina* Xue T. Zhu & Zhu L. Yang [1]. Earlier literature has used a number of other scientific titles and synonyms of *Imleria badia* including *Boletus badius* (Fr.) Fr., *Boletus castaneus* var. *badius* (Fr.) Fr., *Ixocomus badius* (Fr.) Quél., but it was most popularly referred to as *Xerocomus badius* (Fr.) E.-J. Gilbert.

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When included in the diet, wild mushrooms have been identified, for some time, as a major direct source of artificial radioactivity in humans [2, 3]. This includes *Imleria badia,* which has been identified since the late 1960s as one of a few species that can be characterized by a tendency to efficiently accumulate artificial caesium (in most cases, the ^{137}Cs) radioisotope deposited onto soil from the fallout of atmospheric nuclear weapons tests [4-6]. There is no information available in the literature on whether other members of the *Imleria* genus show a similar tendency.

Atmospheric nuclear weapons testing was recognized as a major threat to global human food supply in the mid-1950s. This realization was specifically driven by the accumulation of radioactive strontium (^{90}Strontium) and ^{137}Cs in environmental media followed by transfer into human and animal food webs. The Soviet-era Chernobyl (Czarnobyl, Chornobyl) nuclear power plant disaster on the 26th of April 1986 reinforced this realization with widespread public awareness in the period following the event [7-10]. The accident caused the largest known release of radionuclides to the environment, adversely affecting vast areas of the European continent. Much of the radionuclide contamination affected agricultural land and crops but forests were also impacted, including forest foods such as fruits, nuts, wild game and mushrooms. The awareness of the risk that radionuclide contamination poses to human health was recognized by regulatory authorities worldwide. In Europe, this acknowledgement took the form of regulation, specifying maximum permitted levels of radioactive contamination in food [11]. The regulation covers the most significant radionuclides and includes Strontium-90, Iodine-131, Plutonium-239, Americium-241 and the two most relevant radionuclides of Caesium, ^{137}Cs and ^{134}Cs (^{135}Cs is also produced in small amounts in reactors, it is mildly radioactive and is used diagnostically to fingerprint radiation sources, so is not included here) [11, 12]. The regulation covers a range of foods that can potentially be affected, including forest or wild mushrooms.

The range of wild mushrooms, whether edible, inedible or poisonous to humans, forms an important part of the diet of wild animals including game and can also be occasionally consumed by domestic ruminants. This constitutes an indirect source of dietary artificial radioactivity, largely from ^{137}Cs, which is considered as the major radioactive contaminant in the human food web [13-14].

The objective of this study was to evaluate the contamination from radiocaesium (nuclides ^{137}Cs and ^{134}Cs), of *I. badia* mushrooms obtained from locations in Poland during 1995 to 2023 and the potential human dietary exposure to consumers. In view of the Chernobyl incident, the temporal range of the collected samples also allows any trends in contamination to be investigated. Although *I. badia* has been investigated for the presence of ^{137}Cs and ^{134}Cs contamination since the Chernobyl accident, this is the first study on the species from Poland that encompasses such a representative period of time (approximately 30 years, with respect to the half-life of ^{137}Cs) and large parts of the country. As part of the evaluation, available literature data from Poland was also used, as well as some limited information on the contamination of local forest topsoils. Results on the intensity of natural ^{40}K radioactivity was examined in parallel to radiocaesium, not only for the additional information but also as a measure of the integrity of the radiocaesium data. Further, data for two composite samples of *I. badia* collected from two spatially diverse neighboring regions to the east of Poland, in Belarus were also included.

MATERIALS AND METHODS

The Bay Bolete fruiting bodies that were used for the study included specimens collected from different regions of Poland that were identified as being affected, to various degrees, by fallout from the radioactive plume resulting from the collapse of the nuclear reactor at the Chernobyl Power Plant. These regions, numbered from 1 to 11 are indicated on the map in Figure 1 which shows the parts of Poland affected by the plume. Locations within these regions were sampled (n = 86) and the year of sample collection and quantity of mushrooms collected/analysed are given in Table 1. The principle adopted for each sampling area (forested sites were targeted in order to increase the likelihood of finding mushrooms) was that fruiting bodies were collected from 15 + 1 separate (more or less distant) spots. Practically, the number of fruiting bodies collected per site depended on the abundance at the time of collection. For the majority of sites, several (around 10 to 135) specimens were obtained. For a small handful (6) of the 86 samples, abundances were considerably lower resulting in the collection of two to six specimens. The fruiting bodies within each site were verified as *I. badia*, then combined to obtain a pool consisting of all individuals collected. This approach reduces the variability within sites that can arise from inhomogeneity of contaminant distribution, size of the fruiting body and stage of development. Typically, fruiting bodies were separated into caps and stems and then combined separately (knowledge of the biomass share may enable calculation of results for the entire fruiting body) or examined as a whole specimen (Table 1). Separating the fruiting body (or bodies) into caps and stems allows for additional quality control of the measurements (as does co-determination of

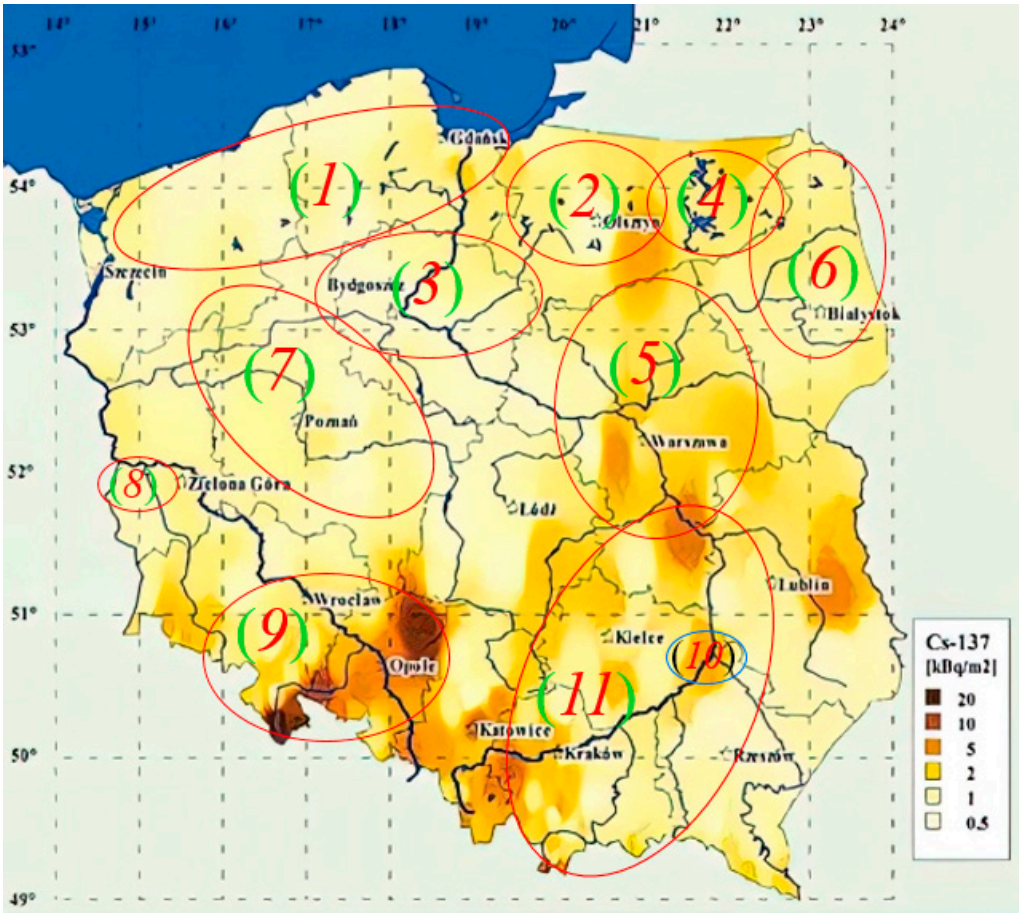

Figure 1. Map of Poland showing the distribution of ^{137}Cs background activity in soil (kBq·m^{-2}) as simulated for year 2011 (as described earlier [20]; adapted). The *Imleria badia* sampling regions are roughly indicated as follows: Pomerania (*1*), Warmia (*2*), Kuyavia (*3*), Masuria (*4*), Mazovia (*5*), Podlachia (*6*), Greater Poland (*7*), Terra Lubucensis (*8*), Lower Silesia (*9*), Terra Sandomiriensis (*10*) and Lesser Poland (*11*)

^{40}K activity). The *I. badia* samples from Belarus were collected in September, 2010 from the Chojniki site (n = 38) in the highly polluted Homel (Gomel) region, and from the outskirts of the Staroje Janycha site (n = 34) in Borysów district in the Minsk region.

The samples were sliced using a plastic or ceramic knife and initially dried for one to two days at room temperature, followed by drying for 24-48 hours in an electrically heated commercial vegetable dryer (model: MSG-01 dehydrator by MPM Product, Milanówek, Poland) at around 65°C. Dried samples were ground to a fine powder either using a porcelain mortar or a vibrating grinder with a zirconium bowl (LMK – W/S; Testchem, Poland). Ground samples were sealed in polyethylene bags. Individual bagged samples from a site were placed in larger plastic bags and stored separately, sealed under dry and clean conditions in a large plastic container until further analysis.

Apart from *I. badia* fruiting bodies, forest topsoil (0-10 cm layer) was also collected at a few locations (Parchowo – 2010, Lubichowo – 2008 and Włoszczowa – 2007) and measured for ^{137}Cs and ^{40}K. Air dried topsoil samples (free of stones, plant roots and branches) were ground using a porcelain mortar, graded to < 2 mm particle size through a plastic sieve and then stored in fresh polyethylene bags in tightly closed plastic containers. Before analysis, soil samples were additionally lyophilized for 48 h before measurement.

The methodology used to quantitatively determine nuclide activity in this study has been published in detail earlier [15-18]. In brief, a gamma spectrometer fitted with a coaxial high purity germanium (HPGe) detector with a relative efficiency of 40% and a resolution of 1.8 keV for a peak of 1332 keV of ^{60}Co, coupled to an 8192-channel computer analyzer, was used to measure the nuclide activity. The analyses of the radioactivity spectra, registered in 8000 channels, was carried out using Genie-2000 software. The instrument was calibrated with a multi-isotope standard using a fully validated method [18]. Measurements were carried out using sample aliquots of 10-20 g of dehydrated (ground) fungal material that were additionally lyophilized for 72 h before measurement. Measurement uncertainty is associated with each analytical result and includes

several components, including correction of sample geometry. The ^{137}Cs data (^{134}Cs was not detected) were decay corrected back to the time of mushrooms/soil collection. Measurements were validated using a standard solution of gamma emitting isotopes, 'code BW/Z-62/27/07' produced by IBJ-Świerk, Otwock, Poland. This standard was used to prepare reference samples for spectrometer calibration. The background activity (80000 s or 250000 s) determined before analysis, was subtracted (using the GENIE 2000 software) from the individual measurements of the samples. Potassium (total K) content can be calculated using the mean value of the activity concentration of ^{40}K in natural K which is in the range of 27.33 to 31.31 Bq·g^{-1} of K, as described earlier [19].

RESULTS

^{137}Cs and ^{40}K in *I. badia* mushrooms collected in Poland over time

^{137}Cs activity was detected in every pool of *I. badia* collected across Poland (Table 1), over the period from 1995 to 2022, except for a pool of three specimens sampled in the Kociewie region in 2023 which was below the detection limit of 6.4 Bq·kg^{-1} dry weight (dw). Overall, positive detections of ^{137}Cs were, as expected (Figure 1), highly variable between the regions of the country. Overall, ^{137}Cs concentrations in the studied mushrooms ranged from 87 ± 3 to 8800 ± 80 Bq·kg^{-1} dw for the whole fruiting bodies, from 290 ± 21 to 11000 ± 89 Bq·kg^{-1} dw for caps, and from 330 ± 8 to 7600 ± 130 Bq·kg^{-1} dw for stems (Table 1). Radioactivity from the shorter lived and less persistent nuclide, ^{134}Cs, was not detected (on the day of measurement) in any of the *I. badia* pools. It is known that *I. badia* is among several species of fungi that have a high potential for mycelial uptake and accumulation of radiocaesium in the fruiting body [4, 21-38]. Other fungal species with similarly high potential from genera such as *Amanita*, *Cortinarius*, *Lactarius*, *Paxillus*, *Sarcodon*, *Suillus*, *Tricholoma* or *Xerocomellus* are also native to the Northern Hemisphere [15, 19, 28, 29, 39-43]. The capabilities of tropical mushrooms for radiocaesium uptake are unknown.

Fungal fruiting bodies are rich in potassium, which is the major cation in cells, regulating osmosis and the cellular water balance at high levels (> 80%), and so this element undergoes strict regulation of uptake and retention by species [44]. Stijve [44] has reported on the species-specificity content of K in the fruiting bodies of various fungi. The occurrence of ^{40}K in studied *I. badia* was highly uniform (Table 1), and obtained values of BCF indirectly confirm this regulation of uptake [45]. The dose of radioactivity from natural ^{40}K isotope contained in the fruiting body is a part of background radiation received by all consumers of the mushrooms.

Table 1. Activity intensities of ^{137}Cs and ^{40}K (Bq·kg^{-1} dw; mean value ± measurement uncertainty) in cap, stem or a whole fruiting body of fungus *Imleria badia* collected occasionally in Poland in the period from 1995 to 2023 (all data rounded to show only two significant figures if different from zero)

Location, quantity of fruiting bodies in a composite sample and year of collection		^{137}Cs (Bq·kg^{-1} dw)	^{40}K (Bq·kg^{-1} dw)
		Cap // Stem	Cap // Stem
		(Whole fruiting body)	(Whole fruiting body)
Pomerania (1)[*]			
Kashubia, Kierzkowo [3][**]	2020	790 ± 15 // 380 ± 9	2500 ± 230 // 1700 ± 160
Gdańsk Coast, Sobieszewo Island [60]	2020	(720 ± 9)	(1000 ± 88)
Gdańsk Coast, Sobieszewo Island [15]	2011	930 ± 13 // 1200 ± 11	840 ± 31 // 930 ± 26
Kashubia, Parchowo [12]	2010	1400 ± 17 // 1200 ± 15	1300 ± 100 // 1200 ± 110
Kashubia, Coastal Landscape Park [32]	2007	1300 ± 17 // 1100 ± 15	1800 ± 120 // 1400 ± 110
Kashubia, Sierakowice/Mojusz [12]	2007	1900 ± 22 // 1700 ± 25	1500 ± 110 // 1000 ± 230
Kashubia, Lipusz [18]	2006	2300 ± 25 // 2000 ± 25	1400 ± 100 // 1400 ± 140
Szczecinek County [20]	2003	1300 ± 16 // 1000 ± 23	1700 ± 100 // 1700 ± 330
Szczecinek County [19]	2002	1700 ± 21 // 1200 ± 18	1300 ± 100 // 790 ± 140
Kashubia, Coastal Landscape Park, Ostrowo [15]	2002	2700 ± 21 // 1700 ± 16	1300 ± 33 // 1000 ± 31
Kashubia, Rzecznica [113]	2002	1700 ± 17 // 1400 ± 16	1500 ± 45 // 1100 ± 47
Gdańsk Coast, Moraine Hills, Polanki [135]	2002	1200 ± 15 // 960 ± 17	1600 ± 90 // 1700 ± 180
Gdańsk Coast, Moraine Hills, Niedźwiednik [3]	2002	1200 ± 15 // 850 ± 14	1700 ± 90 // 1600 ±130
Kashubia, Borowo [21]	2002	1100 ± 15 // 680 ± 16	1700 ± 230 // 1400 ± 120
Gdańsk Coast, Moraine Hills, Niedźwiednik [3]	2001	600 ± 49 // 610 ± 140	1200 ± 600 // WD

Location, quantity of fruiting bodies in a composite sample and year of collection		^{137}Cs (Bq·kg^{-1} dw)	^{40}K (Bq·kg^{-1} dw)
		Cap // Stem	Cap // Stem
		(Whole fruiting body)	(Whole fruiting body)
Gdańsk Coast, Moraine Hills, Osowa [2]	2001	1300 ± 22 // 930 ± 45	1800 ± 220 // 950 ± 89
Gdańsk Coast, Sobieszewo Island [8]	2000	2200 ± 25 // 1800 ± 24	1200 ± 100 // 1300 ± 140
Kashubia, Wdzydze Landscape Park [16]	1998	1100 ± 17 // 790 ± 14	1500 ± 120 // 1300 ± 140
Kashubia, Wdzydze Landscape Park [10]	1998	9600 ± 100 // 5500 ± 59	1900 ± 180 // 940 ± 100
Kashubia, Wdzydze Landscape Park [6]	1998	7200 ± 77 // 6300 ± 71	1300 ± 150 // 1300 ± 190
Kashubia, Wdzydze Landscape Park [15]	1997	5600 ± 63 // 3400 ± 50	1300 ± 180 // 950 ± 330
Kociewie, Pomlewo outskrits [3]	2023	(< 6.4)	(1600 ± 310)
Kociewie, Pomlewo outskirts [21]	2022	(1100 ± 13)	(1700 ± 320)
Kociewie, Pomlewo outskirts [12]	2021	(87 ± 3)	(1000 ± 88)
Kociewie, Pomlewo outskirts [3]	2020	(250 ± 8)	(1300 ± 220)
Kociewie, Tuchola Pinewoods, Tleń [19]	2020	1400 ± 17 // WD	2000 ± 380 // WD
Kociewie, Tuchola Pinewoods, Śliwice [16]	2010	2500 ± 28 // WD	1300 ± 130 // WD
Kociewie, Tuchola Pinewoods, Śliwice [10]	2010	2100 ± 24 // 1400 ± 31	1500 ± 130 // 1500 ± 120
Kociewie, Tuchola Pinewoods, Lubichowo [23]	2008	3700 ± 37 // 2700 ± 30	1100 ± 120 // 1100 ± 120
Kociewie, Tuchola Pinewoods, Kasparus [15]	2000	5100 ± 45 // 4600 ± 48	1300 ± 52 // 1100 ± 43
Kociewie, Tuchola Pinewoods, Śliwice [20]	2000	4300 ± 46 // WD	1500 ± 110 // WD
Kociewie, Tuchola Pinewoods, Osiek [19]	2001	4500 ± 48 // 4300 ± 53	1800 ± 150 // 1600 ± 260
Kociewie, Tuchola Pinewoods, Osiek [19]	2000	4000 ± 44 // 3800 ± 41	1500 ± 110 // 1200 ± 110
Kociewie, Tuchola Pinewoods, Łuby [16]	1999	2600 ± 31 // 1800 ± 32	1600 ± 110 // 1100 ± 100
Kociewie, Zaborski Landscape Park [10]	1998	4400 ± 51 // 3300 ± 47	1600 ± 160 // 930 ± 300
Warmia (2)			
Commune Olsztynek, Orzechowo [30]	2007	4700 ± 48 // 4700 ± 47	1300 ± 100 // 990 ± 100
Kaszuny outskrits [10]	2003	5100 ± 47 // 2840 ± 26	1600 ± 49 // 1200 ± 40
Napiwodzko-Ramucka Forest [13]	2002	(7300 ± 73)	(1400 ± 100)
Olsztynek outskirts [16]	2002	2400 ± 20 // 1400 ± 12	1300 ± 35 // 920 ± 31
Puchałowo [16]	2001	3200 ± 33 // 5500 ± 53	1500 ± 59 // 1400 ± 65
Morąg outskirts [15]	2002	1600 ± 20 // 850 ± 14	1700 ± 110 // 1900 ± 140
Pasym outskirts [15]	1999	(8800 ± 80)	(1300 ± 55)
Morąg outskirts [16]	1998	(5200 ± 52)	(1300 ± 40)
Olsztyn outskirts [12]	1998	5800 ± 62 // 4900 ± 62	1100 ± 100 // ±1100 ± 80
Kuyavia (3)			
Toruń forests [15]	2006	760 ± 11 // 640 ± 13	1300 ± 52 // 1200 ± 68
Bukowiec [15]	2006	1500 ± 15 // 730 ±15	1300 ± 40 // 970 ± 63
Chełmno outskirts [10]	2002	1600 ± 14 // 730 ± 11	1700 ± 40 // 1400 ± 50
Gostynińsko-Włocławskie forests, Goreń [70]	2001	3900 ± 35 // 3200 ± 27	1300 ± 51 // 1100 ± 36
Chełmno outskirts [15]	2001	1500 ± 19 // 1800 ± 24	1500 ± 100 // 1300 ± 150
Kobylarnia near Bydgoszcz [60]	2000	(2200 ± 28)	(1200 ± 46)
Kobylarnia near Bydgoszcz [60]	2000	2600 ± 29 // 2000 ± 32	1100 ± 85 // 1100 ± 80
Masuria (4)			
Piska Forest [23]	2003	5600 ± 57 // 3900 ± 41	1400 ± 100 // 980 ± 100
Piska Forest [15]	2002	7300 ± 73 // 3000 ± 51	1300 ± 110 // 920 ± 94
Szczytno outskirts [16]	2002	9100 ± 90 // WD	1600 ± 99 // WD
Giżycko region, Pieczarki [34]	2000	(2700 ± 28)	(1000 ± 50)
Giżycko outskirts [15]	2000	11000 ± 89 // 7600 ± 130	880 ± 45 // 620 ± 40
Kętrzyn, Commune Pożarki [43] juvenile specimens	2000	8100 ± 81 // 2300 ± 25	1400 ± 92 // 1100 ± 69
Commune Mrągowo, Cierzpięta [22] mature – large	1999	1200 ± 16 // 3700 ± 42	1200 ± 86 // 680 ± 120

Location, quantity of fruiting bodies in a composite sample and year of collection		^{137}Cs (Bq·kg^{-1} dw)	^{40}K (Bq·kg^{-1} dw)
		Cap // Stem	Cap // Stem
		(Whole fruiting body)	(Whole fruiting body)
Mazovia (5)			
Commune Olszewo-Borki [15]	2007	5700 ± 57 // 4100 ± 44	1400 ± 120 // 1500 ± 170
Commune Lutocin, Chrapoń [15]	2000	3100 ± 55 // 3100 ± 49	1600 ± 120 // 2600 ± 41
Commune Lutocin, Chrapoń [26]	1999	6400 ± 67 // 5600 ± 64	1400 ± 120 // 1100 ± 210
Podlachia (6)			
Wasilków village outskirts [6]	2013	1100 ± 22 // WD	1300 ± 350 // WD
Augustów Primeval Forest [15]	2007	4600 ± 46 // 3000 ± 30	1200 ± 97 // 1300 ± 120
Augustów Primeval Forest [15]	2000	3400 ± 31 // 2200 ± 23	1300 ± 43 // 920 ± 46
Augustów Primeval Forest [15]	1998	6600 ± 73 // 5800 ± 64	1200 ± 180 // 1100 ± 160
Greater Poland (7)			
Terra Siradiae, Uniejów [21]	2022	(910 ± 11)	(1400 ± 270)
Terra Siradiae, Dłutów [22]	2022	400 ± 6 // WD	1400 ± 270 // WD
Terra Siradiae, Uniejów [21]	2021	780 ± 10 // WD	1600 ± 300 // WD
Terra Siradiae, Dłutów [19]	2021	860 ± 10 // WD	(700 ± 330 // WD
Notecka Wilderness, Jesionna [15]	2008	970 ± 8 // 690 ± 19	1100 ± 28 // 710 ± 52
Notecka Wilderness [15]	2008	1300 ± 16 // 850 ± 8	1300 ± 100 // 830 ± 75
Rogalin outskirts [14]	2008	710 ± 10 // 520 ± 8	950 ± 81 // 870 ± 79
Porażyn outskirts [29]	2008	430 ± 8 // 330 ± 8	1100 ± 94 // 840 ± 130
Terra Siradiae, Turek [11]	2003	1700 ± 22 // 1400 ± 27	1200 ± 120 // 1300 ± 320
Terra Lubucensis (8)			
Gubin outskirts [13]	1995	(1700 ± 22)	(1500 ± 97)
Lower Silesia (9)			
Lower Silesia Forests [11]	2008	(1900 ± 53)	(930 ± 60)
Złotoryja [9]	2008	(460 ± 11)	(1000 ± 55)
Złotoryja [9]	2008	700 ± 11 //WD	1300 ± 120 // WD
Sudety Mts., Karpacz [31]	2008	1700 ± 13 // 890 ± 12	940 ± 28 // 770 ± 27
Sudety Mts., Kłodzka Dale [5]	2001	290 ± 21 // WD	2000 ± 500 // WD
Terra Sandomiriensis (10)			
Starachowice forests, Lipie [15]	2008	1100 ± 9 // 1200 ± 13	1100 ± 27 // 1400 ± 32
Włoszczowa [15]	2007	1500 ± 21 // 920 ± 14	1600 ± 180 // 890 ± 130
Lesser Poland (11)			
Tatra Mts., Chochołowska Valley [9]	2000	WD // 1400 ± 25	WD // 860 ± 240
Lubelska Upland, Poniatowa [15]	2000	1300 ± 18 // 820 ± 27	1900 ± 140 // 2000 ± 200
Tatra Mts., Chochołowska Valley [10]	1999	2100 ± 28 // 1100 ± 110	1400 ± 150 // 1700 ± 210

Note: *Sampling site id number; **Quantity of fruiting bodies in a composite sample; WD – without data

As part of the study, two sets of *I. badia* mushrooms were also collected from Belarus in 2010 and analysed along with the Polish samples. These sets from Chojniki and Staroje Janycha (Staroje Jančyna) differed substantially in the levels of ^{137}Cs contamination from the samples from Poland. Mushroom activity levels (caps // stems) were 21000 ± 200 // 15000 ± 120 Bq·kg^{-1} dw and 1400 ± 18 // 1400 ± 9 Bq·kg^{-1} dw, respectively for Chojniki and Staroje Janycha.

In this study ^{137}Cs and ^{40}K were determined in forest topsoils (0-10 cm layer) collected from the Parchowo (2010), Lubichowo (2008) and Włoszczowa (2007) locations, from beneath or from points adjacent to the sampled fruiting bodies. ^{137}C activity concentrations in these topsoils were 21 ± 1, 28 ± 1 and 69 ± 2 Bq·kg^{-1} dw, respectively.

Spatial distribution of activity

The variable distribution of the samples collected over the eleven sampling regions (Figure 1) makes spatial analysis difficult. This was not only due to the different numbers of samples for each site but also due to the differences in the years of sampling. The latter difficulty is mitigated to some extent as

the great majority of samples were collected from 1998 to 2007. Thus, any spatial analysis of the ^{137}Cs activity in *I. badia* from this data is at best, indicative. Despite these limitations, it was evident from the average ^{137}Cs activity for each of the eleven sampling regions that the highest mean activities were seen for the North East regions of Poland – Masuria, Mazovia, Warmia, Podlachia (regions 2, 5, 4 and 6 respectively, in Figure 1) with ^{137}Cs activities ranging from 3925 ± 2300 Bq·kg^{-1} dw (Podlachia – region 6) to 6429 ± 3500 Bq·kg^{-1} dw (Masuria – region 4; as derived from data in Table 1). In contrast, the lowest values of ^{137}Cs activities were recorded for locations in the Western part of Poland – Greater Poland (region 7) and Lower Silesia (region 9) with mean values of 896 ± 407 and 1012 ± 737 Bq·kg^{-1} dw, respectively. Unfortunately, there was only a single sample for the Western-most location (Terra Lubucensis – region 8), also with a relatively low value of 1700 Bq·kg^{-1} dw. The *I. badia* mushrooms from regions such as Kashubia, Kociewie, Warmia, Masuria, Mazovia and Podlachia originated from sites that were substantially contaminated with radiocaesium until around 2007 (Tables 1 and 2), which at least in part, does not correlate to the simulated pattern of soil background activity distribution that was shown in Figure 1.

DISCUSSION

^{137}Cs and ^{40}K in *I. badia* mushrooms collected in Poland over time

The ^{137}Cs and ^{40}K activities given in Table 1 represent data for the largest number of *I. badia* fungi samples collected in Poland over a period of 30 years. This information is supplemented with data on radiocaesium (^{137}Cs and ^{134}Cs) and ^{40}K activity in *I. badia* on a country-wide scale, which were collated from available literature (Table 2). The data reaches back to 1985, i.e. shortly before the Chernobyl incident, when the source of radiocaesium was atmospheric nuclear weapons testing. The ^{134}Cs isotope has a much shorter physical persistence (half-life of 2.06 years) than ^{137}Cs (half-life of 30.07 years) and post-sampling data on ^{134}Cs are relatively scarce. The ^{134}Cs is not produced in the nuclear bomb explosions. Directly after the Chernobyl disaster ^{134}Cs could be detected in domestic *I. badia* in 1988 with a contribution of up to about 20% of the total $^{134/137}$Cs, which gradually declined to about 5% in 1994 [29], after which it was either not detected or close to detection limits (Figure 2 and Table 2).

The most contaminated *I. badia* samples were reported, as described earlier [26-28], for the heavily affected region of Homel which in 2010, showed levels of ^{137}Cs activity that was roughly comparable to levels observed twenty years earlier in specimens collected in the regions of Podlachia, Masuria and especially, the Opole region (where anomalously high levels were experienced following deposition of radionuclides released from the Chernobyl fallout during a spell of rainy weather) in Lower Silesia in Poland (Table 2). However, these activity levels for the two sites in Belarus are consistent with their geographical locations relative to Chernobyl. The sample from Staroje Janycha which showed the lower of the two ^{137}Cs activity levels was from the North-East of Minsk and much further away from Chojniki in Homel which is less than 100 km north of Chernobyl. In Poland, higher ^{137}Cs activity levels than these were reported [29] for specimens collected 20 years earlier from the Szczytno region in Masuria and the Augustowska Primeval Forest in Podlachia (Table 2). The report however, lacks more detailed information related to sample size (here assumed as one specimen) and analytical details [29].

Bioconcentration potential of ^{137}Cs in fruiting bodies of studied *I. badia*

Imleria badia is an ectomycorrhizal species with its mycelium hidden in the soil, in symbiosis with forest trees [1]. The life activities of the *I. badia* mycelium, like that of other ectomycorrhizal fungi, are determined by the seasons – growth and mutualistic relationships with the host plant (e.g., supplying the plant with phosphorus and receiving sugars in return, water management) and reproduction – the cyclic emergence of above-ground fruiting bodies (mushrooms) with spores at the end of the growing season. Once mature, the fungus releases these spores into the environment (e.g., the atmosphere) for the expansion and survival of the species. The mycelium absorbs minerals throughout the growing season and may also share some of these nutrients or compounds in general with the plant(s) with which it lives in symbiosis. The ability of a species to absorb minerals from the environment and accumulate them in the body is usually assessed on the basis of the bioconcentration factor (BCF), calculated as the quotient of the dry weight content of a specific component (or its specific chemical form) in the fruiting body, to the content in the substrate (e.g. a layer of soil of a specific thickness; bulk layer 0-10 cm, 0-15 cm or other) [43, 46]. Practically, the soil layer is collected from several points beneath the fruiting body or in its vicinity, and averaged [43].

The BCF (organism *versus* an abiotic part of the environment such as soil, sediment, soil solution, pore water) is analogous to the bioaccumulation factor, BAF (organism *versus* a biotic part of the environment such as food or feed in food webs). For nuclides such as radiocaesium, the fungal potential for uptake and accumulation in fruiting bodies may also be expressed (approximated) as a transfer factor (TF)

or aggregated transfer factor, which takes into account a simulated rate of aerial deposition of a nuclide from fallout (Bq per square meter) for a given area of land (usually large) when it occurred (and if necessary, correct for the rate of physical decay). Temporally, the fallout event is followed by radioactive decay of the radionuclide and its depletion in the soil (substrate) as a result of environmental factors (e.g. surface runoff, washing into the soil profile, accumulation by plants, inadvertent consumption by animals (with their food), release into the atmosphere in spores ejected by fungi). This requires the "fallout status" to be updated, typically based on the radioactive half-life of the nuclide, e.g., as seen for the simulated spatial distribution of the background deposition density of ^{137}Cs in Ukraine on May 10, 1986 and May 10, 2008, as described earlier [46].

Thus, calculated BCF values of ^{137}Cs for the specimens at these locations and time of sampling were 67, 130 and 22 (caps) and 57, 96 and 13 (stems), respectively. Taking into account the consensus on the high predilection of the species to accumulate radiocaesium from fallout, these values suggest a site-specific dependency of the BCF. Using (probably) the largest data set so far on ^{137}Cs in *I. badia* and underlying soil substrata, recently [46], provided BCF values were in the range from 296 (from ^{137}Cs in the whole fruiting bodies from the Chernobyl exclusion zone with activity at 5530000 Bq·kg^{-1} dw) down to 0.56 (^{137}Cs in the whole fruiting bodies from the Steshchynske forest, quarter 39, in the district of Vyshhorod at 1162 Bq·kg^{-1} dw).

Activity concentration of ^{40}K in forest topsoils collected from the Parchowo (2010), Lubichowo (2008) and Włoszczowa (2007) locations were at levels of 330 ± 40, 220 ± 33 and 250 ± 38 Bq·kg^{-1} dw, respectively. Thus, the calculated values of BCF for *I. badia* specimens at these sites were 3.9, 5.0 and 6.4 (caps), and 3.6, 5.0 and 3.6 (stems), respectively. In Poland, the natural occurrence of potassium in topsoils (characterised as ^{40}K) exhibits some spatial diversity, i.e., between 250 and 1000 Bq·kg^{-1} dw, as described earlier [20]. Thus, the occurrence levels of ^{40}K in forest topsoils in the present study could be towards the lower end of the values reported for all of Poland [20].

^{137}Cs statutory limits and *I. badia*

The activity of ^{137}Cs makes it highly toxic to humans and animals. Following internal exposure, it concentrates in soft tissue. This build-up coupled with emissions of high-energy gamma rays and beta (ß$^-$) particles results in elevated long-term carcinogenic risk due to the resulting severe cellular damage and bone marrow degradation. Dietary exposure to ^{137}Cs is therefore a topic of great interest among mushroomers. Since the Chernobyl incident, affected proximate countries like Poland have disseminated information locally on contamination in various wild fungi and initiated research activities and monitoring programs aimed at understanding the environmental fate of radiocaesium. These included studies on the susceptibility of various fungal species to accumulate radionuclides, regulatory activities aimed at minimizing exposure and assessing the safety of various edible species for human consumers. These studies and wider research confirm that prior to and particularly after, the Chernobyl incident in April 1986, the consumption of wild fungi had become the main source of artificial radioactivity (from radiocaesium) in humans [2, 3, 47, 48].

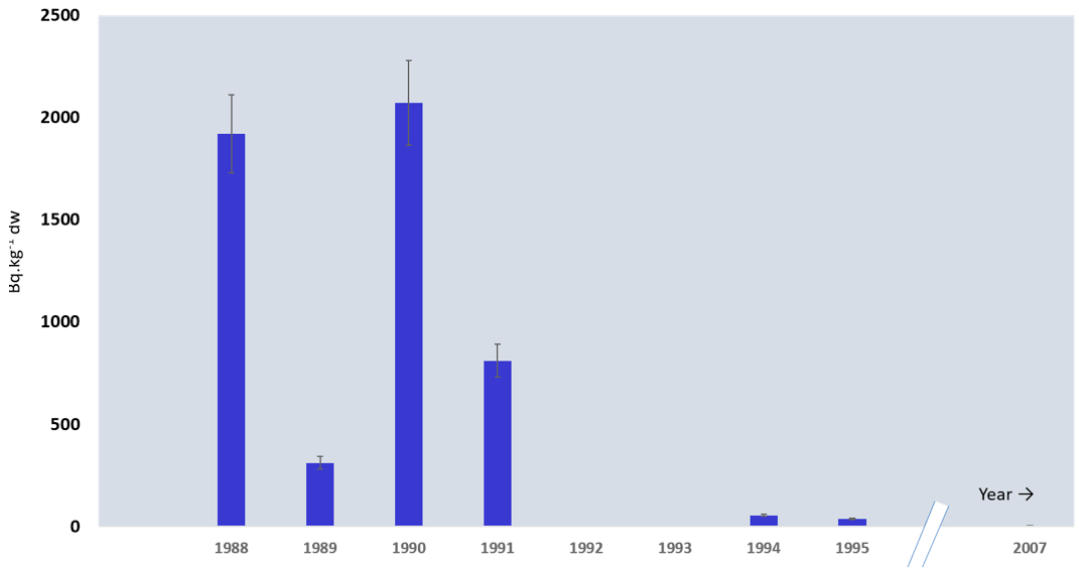

Figure 2. ^{134}Cs activity in *I. badia* from Poland reported in the literature (data for 1990 and 1994 are averaged values)

Table 2. Summary of literature data on chronology of ^{137}Cs, ^{134}Cs and ^{40}K activity intensities in Bq·kg^{-1} dw in the cap, stem or whole fruit body of *Imleria badia* for regions of Poland. Mean, median (M), range (total or per sample set) and uncertainty (± SD)

Region and place, year of collection and total number [*n* in bracket] of fruiting bodies in a pool	^{137}Cs	^{134}Cs	^{40}K	Ref.
	Whole fruiting body or cap // stem			
Terra Lublinensis, Rogóźno, 1985 [*n* = 1]	470	–	1300	[21]
Site unreported, 1985 [*n* = 1]	1700#	–	WD	[22]
Terra Lublinensis, Rogóźno, 1986 [*n* = 1]	3600	–	670	[21]
Whole country, 1986 [*n* = 42]	3800 (600 – 15000)#	–	WD	[22]
Terra Lublinensis, Rogóźno, 1987 [*n* = 1]	1500	–	1000	[21]
Whole country, 1987 [*n* = 30]	3800 (870 – 23000)#	–	WD	[22]
Terra Lublinensis, Rogóźno, 1988 [*n* = 1]	8900	–	920	[21]
Whole country, 1988 [*n* = 26]	6300 (570 – 17000)#	–	WD	[22]
Lesser Poland, Świetokrzyskie region, Krzyż, 1988 [*n* = 1; ~50 g dw]	8700 ± 490)	1920 ± 145	WD	[23]
Lesser Poland, Świetokrzyskie region, Niebo, 1989 [*n* = 1; ~50 g dw]	2030 ± 115	310 ± 20	WD	[23]
Whole country, 1989 [*n* = 22]	6700 (890 – 24300)#	–	WD	[22]
Kashubia, Kościerzyna forests, 1989 [*n* = 8]	13000	–	WD	[24]
Kociewie, Graniczna Wieś, 1989 [*n* = 15]	18000	–	WD	[24]
Whole country, 1990 [*n* = 46]	5500 (360 – 19000)#	–	WD	[22]
Podlachia, Augustowska Primeval Forest, 1990 [*n* = 4]	18550M (18000 ± 1000 – 20000 ± 2000)	2320M (2100 ± 560 – 2400 ± 400)	WD	[25]
Podlachia, Augustowska Primeval Forest, 1990 [*n* = 1; 39.26 g dw]	18200 ± 1600	1800 ± 400	WD	[26]
Silesia, 1990 [*n* = 10]	23000M (13600 ± 400 – 156700 ± 6300)	2160M (1130 ± 190 – 16260 ± 200)	WD	[27]
Masuria, 1990 [*n* = 10]	20600M (3800 ± 800 – 27000 ± 500)	2000M (250 ± 20 – 2500 ± 100)	WD	[27]
Warmia, Olsztyn, 1990 [*n* = 2]	5620#	WD	WD	[28]
Masuria, Szczytno, 1990 [*n* = 1]	73120#	WD	WD	[29]
Podlachia, Augustowska Primeval Forest, 1990 [*n* = 1]	62340#	WD	WD	[29]
Whole country, 1991 [*n* = 278; each 50-100 g dw]	8100 (120 ± 10 – 157000 ± 6000) 5310M	WD (ca 10% of ^{137}Cs intensity)	1300M	[26]
Whole country, 1991 [*n* = 31]	5200 (1300 – 13000)#	–	WD	[22]
Mazovia, Kampinos National Park, Truskaw, 1994 [*n* = 10]	2588 ± 1636	58 ± 28	37 ± 11 (K; g·kg^{-1})	[30]
Mazovia, Kampinos National Park, Palmiry, 1994 [*n* = 26]	2434 ± 1081	49 ± 28	39 ± 8 (K; g·kg^{-1})	[30]
Warmia, Olsztyn, 1995 [*n* = 2]	3900#	–	WD	[28]
Warmia, Olsztyn, 1995 [*n* = 2]	3000#	–	WD	[28]
Warmia, Miodówko near Olsztyn, 1995 [*n* = 2]	1200#	–	WD	[28]

Region and place, year of collection and total number [*n* in bracket] of fruiting bodies in a pool	^{137}Cs	^{134}Cs	^{40}K	Ref.
	Whole fruiting body or cap // stem			
Warmia, Zgniłocha near Olsztyn, 1995 [*n* = 2]	2700[#]	–	WD	[28]
Warmia, Zgniłocha near Olsztyn, 1995 [*n* = 2]	2500[#]	–	WD	[28]
Warmia, Uniszewo near Olsztyn, 1995 [*n* = 2]	1870[#]	–	WD	[28]
Warmia, Łańsk near Olsztyn, 1995 [*n* = 2]	956[#]	–	WD	[28]
Warmia, Butryny near Olsztyn, 1995 [*n* = 2]	1420[#]	–	WD	[28]
Warmia, Mojdy near Olsztyn, 1995 [*n* = 2]	864[#]	–	WD	[28]
Warmia, Dadaj lake site, 1995 [*n* = 2]	320[#]	–	WD	[28]
Warmia, Pluski, 1995 [*n* = 2]	3220[#]	–	WD	[28]
Warmia, Pasłęk, 1995 [*n* = 2]	420[#]	–	WD	[28]
Warmia, Kalwia near Pasym, 1995 [*n* = 2]	4090[#]	–	WD	[28]
Warmia, Barczewo, 1995 [*n* = 2]	3460[#]	–	WD	[28]
Warmia, Tylkowo, 1995 [*n* = 2]	1120[#]	–	WD	[28]
Kuyavia, Golub-Dobrzyń, 1995 [*n* = 2]	524[#]	–	WD	[28]
Mazovia, Rozogi near Myszyniec, 1995 [*n* = 2]	1930[#]	–	WD	[28]
Podlachia, Białystok, 1995 [*n* = 2]	540[#]	–	WD	[28]
Podlachia, north-eastern region, 1995 [*n* = 19]	1950 ± 12500 (321 – 4090)[#]	–	WD	[28]
Place of collection unknown, 1995 [*n* = 1; kg fresh weight]	2600 ± 200	36 ± 2	1570 ± 90	[31]
Pomerania, Wdzydze Landscape Park, 1996 [*n* = 15]	4600 ± 61 (4260 – 5400) // 2180 ± 190 (1390 – 3620)	–	1000 ± 170 // 1260 ± 660	[32]
Pomerania, Kołobrzeg outskrits, 1997 [*n* = 7]	2300 ± 83 (1430 – 3110) // 2040 ± 72 (1590 – 2500)	–	700 ± 320 // 1200 ± 380	[32]
Podlachia, Augustowska Primeval Forest, 1998 [*n* = 16]	3960 ± 106 (3270 – 4440) // 3500 ± 87 (1690 – 4270)	–	1120 ± 420 // 910 ± 390	[32]
Podlachia, Białowieża Forest, 1998 [*n* = 16]	2740 ± 110 (1990 – 3510) // 1860 ± 82 (1240 – 2770)	–	950 ± 590 // 730 ± 410	[32]
Warmia, Borecka Forest, 1998 [*n* = 15]	3160 ± 68 (330 – 6670) // 2620 ± 86 (580 – 4360)	–	1100 ± 260 // 890 ± 390	[32]
Warmia, Morag, 1998 [*n* = 16]	2470 ± 58 (470 – 5080) // 1750 ± 110 (190 – 3400)	–	1070 ± 270 // 470 ± 220	[32]
Lower Silesia, Opole region, 1998 [*n* = 29]	25227 ± 965 (2600 – 64825) 21457[M]	WD	WD	[33]
Kociewie, Tuchola Pinewoods, 2000 [*n* = 19]	5100 ± 45 // 4600 ± 48	–	1300 ± 52 // 1100 ± 43	[34]
Kuyavia, Aleksandrów Kujawski, 2004 [*n* = 1]	2700 ± 140 // 2500 ± 140	–	1120 ± 9 // 930 ± 80	[35]
Kuyavia, Aleksandrów Kujawski, 2004 [*n* = 1]	813 ± 47 // 768 ± 44	–	1586 ± 301 // 1761 ± 340	[35]
Commercial specimens, ~ 2004 [*n* = 42 // 30]	1470 ± 117 – 4290 ± 344 // 1070 ± 220 – 1520 ± 249	–	840 ± 83 – 1240 ± 87 // 460 ± 75 – 1130 ± 145	[32]
Lower Silesia, Łambinowice forest, 2006 [*n* = 1]	8900 ± 110	–	1457 ± 89	[36]

Region and place, year of collection and total number [*n* in bracket] of fruiting bodies in a pool	^{137}Cs	^{134}Cs	^{40}K	Ref.
	Whole fruiting body or cap // stem			
Lower Silesia, Łambinowice forest, 2007 [*n* = 2]	6100 ± 86	4.3 ± 1.1	1690 ± 64	[36]
Greater Poland, Puszcza Notecka, Jesionna, 2008 [*n* = 32]	970 ± 8 // 690 ± 19	–	1060 ± 28 // 710 ± 52	[34]
Greater Poland, Porażyn, 2008 [*n* = 29]	45 ± 2 // WD	–	1240 ± 55 // WD	[34]
Pomerania, Jarosławiec, 2019 [*n* = 6]	368 ± 12	–	1398 ± 176	[37]
Pomerania, Przechlewo, 2019 [*n* = 5]	1085 ± 40	–	1026 ± 152	[37]
Warmia, Gady, 2019 [*n* = 4]	959 ± 34	–	903 ± 137	[37]
Masuria, Ełk, 2019 [*n* = 3]	368 ± 14	–	1204 ± 169	[37]
Lower Silesia, Szumirad, 2019 [*n* = 7]	17143 ± 614	–	Not found	[37]
Lower Silesia, Sowin/Łambinowice, 2019 [*n* = 5]	3878 ± 140	–	Not found	[37]
North-Eastern Poland, 2017-2021 [*n* = 31]	696^{M} (394 – 855)	–	1110 (938 – 1140)	[38]

$^{\#}$Adapted, assuming moisture content at 90%; WD – without data; ^{M}median; – not measured or not reported; Not found – undetected.

The mineral or metalloid content (in this case, radiocaesium) of a food may increase or decrease during the process of cooking. The final cooked product (here, a mushroom dish) will however, reflect the potential dose of radiocaesium present in the raw mushrooms [28, 49-53]. The particular edible species used in the dish, amount consumed and the resulting radiocaesium exposure thus becomes a primary food safety issue. In addition to being an edible species, *I. badia* is also prized for its taste and so, is eagerly foraged. It is also suitable for being preserved, processed and transported [54]. Thus, its propensity to readily accumulate radiocaesium is of particular concern.

There are various statutory limits for radiocaesium contents in foods depending on the type, the regulatory body and the country. European regulatory bodies limit forest edibles at 600 Bq·kg^{-1} wet (fresh) weight (ww) [11] which is equivalent to 6000 Bq·kg^{-1} dw for wild mushrooms (assuming moisture at 90%). The tolerance limit in foodstuffs recommended by the International Atomic Energy Agency (IAEA) is 1000 Bq·kg^{-1} ww (equivalent to 10000 Bq·kg^{-1} dw in forest mushrooms). The tolerance limit for mushrooms in Ukraine (from 2006) is 2500 Bq·kg^{-1} dw (~250 Bq·kg^{-1} ww), while in Japan, the limit for foods including wild mushrooms, is 100 Bq·kg^{-1} ww (~1000 Bq·kg^{-1} dw), as described earlier [46]. The collated data presented in Tables 1 and 2 leaves no doubt as to the scale of radiocaesium contamination in *I. badia* samples collected over the years in various regions of the country, and in some cases on the exceedance of the above-mentioned tolerance limits.

Time trend of ^{137}Cs depletion in *I. badia*

Radiocaesium occurs to a high degree of variability in soils [55] globally and can range over orders of magnitude (e.g., 0.075–55 Bq·kg^{-1} dw [56]). In addition to variable fallout rates, the distribution in soils is also governed by factors such as the mineralogy, soil chemistry, climate, and topography. Some soil minerals such as illite are highly selective at binding ^{137}Cs, effectively immobilizing it [56]. Although the Chernobyl incident had a strong influence on soil contents, particularly of proximate countries, the depositions complemented earlier ^{137}Cs levels originating from past atmospheric nuclear weapons testing. This soil variability also affects the levels in fungal fruiting bodies (including *I. badia*) as seen in Tables 1 and 2.

When considered collectively, the reported ^{137}Cs activity levels seen in *I. badia* appear to occur at variable levels depending on the sampling location and period (Tables 1 and 2). However, if sufficient volume of data is available for a particular region over a sustained period, then some indications of the occurrence trend may be observed. Among the ^{137}Cs activity levels presented in Table 1, there were 43 samples of *I. badia* caps located in Northern Poland (mostly for the regions, or *voivodeships* of Pomerania, Masuria and Warmia). ^{137}Cs activities for this data set plotted over the period from 1997 to 2020, show a declining trend in *I. badia* concentrations (Figure 3). This trend is consistent with the expected decline resulting partly from the half-life of ^{137}Cs and also from the absence of any new inputs. The most recent globally known release of radioactivity from the Fukushima-Daichi plant in 2011 was not considered

to have any effect on the occurrence of radiocaesium in wild mushrooms in continental Asia or Europe [34].

In addition to radioactive decay rates and tolerance limits, another practical element of food safety for wild mushroom consumers is the real (effective) removal rate (over time) or the "ecological half-life" of ^{137}Cs [57, 58]. Based on physical ^{137}Cs decay which is considered as persistent (T ½ 30.7 y), activity in *I. badia* sampled from defined sites in this study, i.e. the Sobieszewo Island, over 20 years (2000-2020) and from the Tuchola Pinewoods over 22 years (1998-2020), is projected to be 1000 Bq·kg^{-1} dw at Sobieszewo Island area in 2030 and up to 2200 Bq·kg^{-1} dw at the Tuchola Pinewoods in 2028. In practice, the effective decline of ^{137}Cs in *I. badia* both at the Sobieszewo and Tuchola Pinewoods areas as predicted based on time-trend data appears to be substantially faster (Figure 4).

CONCLUSIONS

In line with the tendency of *I. badia* to accumulate radioactivity, ^{137}Cs was detected in all samples collected across Poland except for one site. Values ranged from < 6.4 to 11000 Bq·kg^{-1} dw and varied across regions, showing both the temporal and spatial effects of the radioactive fallout from the Chernobyl accident. The low end of the range represents the most recent sample taken in 2023, while the highest value of 11000 Bq·kg^{-1} dw was found in a sample from one of the most impacted areas of Poland, Masuria, 20 years earlier, in 2000. In some cases, the measured activity in this prized edible mushroom was above the regulatory tolerance limits set for human dietary exposure. Spatially, the highest mean activities were indicated in samples from the North East regions of the country – Masuria, Mazovia, Warmia and Podlachia, with mean activities ranging from 3925 Bq·kg^{-1} dw to 6429 Bq·kg^{-1} dw. Contrastingly, *I. badia* from locations in Western regions – Greater Poland and Lower Silesia were considerably less contaminated with mean values of 896 and 1010 Bq·kg^{-1} dw. ^{134}Cs activity was not detected which is consistent with its shorter half-life and also with the earliest samples (1997) collected in this study, relative to the Chernobyl accident. ^{40}K activity remained relatively stable during the period of the study despite the variable amounts of ^{137}Cs activity, confirming the validity of the measurements.

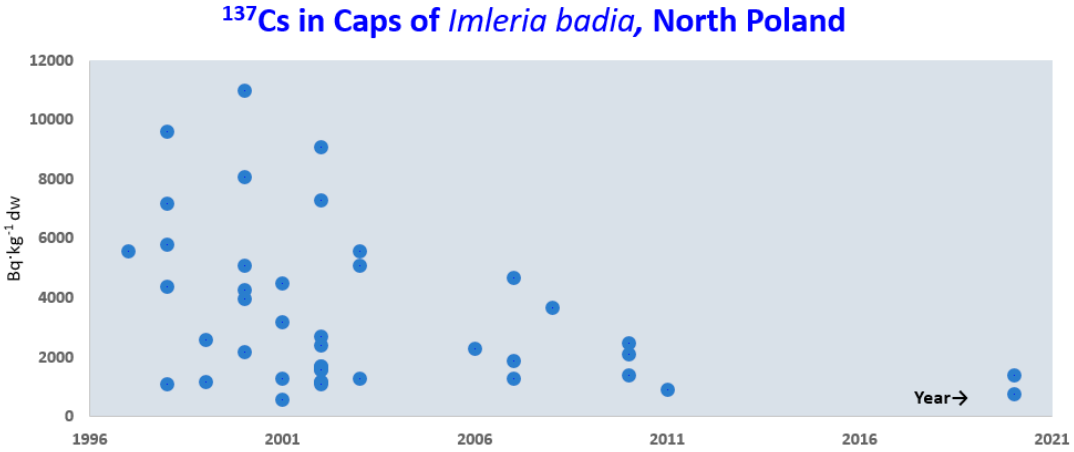

Figure 3. Temporal trend in ^{137}Cs activity in the caps of *I. badia* sampled from locations (Pomerania, Masuria and Warmia regions) in Northern Poland

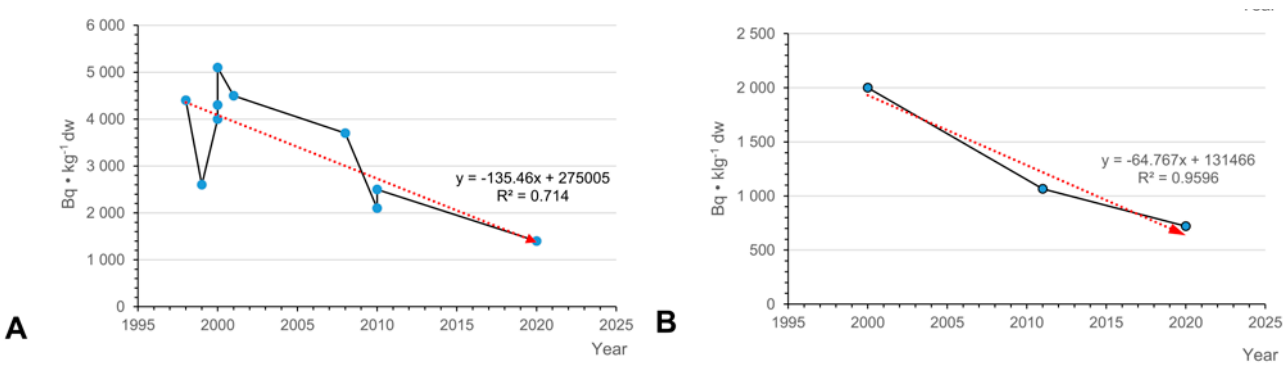

Figure 4. Time trend data of ^{137}Cs in caps of *I. badia* collected from the Tuchola Pinewoods complex (A) and in the whole fruiting bodies of this species collected from Sobieszewo Island (B)

Forty years after the Chernobyl accident, the temporal trend in mean ^{137}Cs activity showed a decline from 5617 $Bq \cdot kg^{-1}$ dw in the 1990s to 1095 $Bq \cdot kg^{-1}$ dw in 2020 – a trend that is consistent with the longer half-life of this radioisotope. Although genotoxic carcinogens like ^{137}Cs have no safe limit of exposure, the observed temporal decline in radionuclide content in this widely foraged and popular mushroom, points to a gradually reducing risk from dietary intake. Consumers should however be aware of the risk from this species, particularly given the high values of the BCF calculated in this study (up to 134), which underline the propensity of *I. badia* to accumulate harmful ^{137}Cs.

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Disclosure conflict of interest

The authors declare that have no relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript.

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