Review Paper

Accumulation of Radiocesium in Mushrooms

Young-Keun Lee and Chandran Sathesh-Prabu*

Advanced Radiation Technology Institute, Korea Atomic Energy Research Institute, Jeongeup 580-185, Korea

Abstract − In spite of colossal efforts taken for safe handling and storage of radioactive waste, the uncontrolled release of radiocesium (^{137}Cs and ^{134}Cs isotopes) into the natural environment is inevitable. ^{137}Cs is of particular concern because of its long half-life, ability to transfer into biota through food chains, as well as its great mobility, bioavailability, and chemical and ecophysiological similarity with potassium. Radiocesium is released anthropogenically into the environment. Mushrooms are known for their ability to accumulate radionuclides, particularly radiocesium, which is heterogeneously distributed in the individual parts of mushrooms, and it is found that mushrooms are a hyper-accumulator of radiocesium from their environment than other vegetation. Mushrooms play a major role in the mobilization, accumulation, and translocation of cesium, i.e., decontamination of soils (mycoextraction) polluted with cesium radioisotopes, and this capacity appears to be a relevant bioindicator of cesium contamination in the environment. Moreover, the extension of mycelium into the soil makes the use of mushrooms as bioindicators of radiocesium possible. This paper reviews the potential of mushrooms in the accumulation of radiocesium from the environment, and dissertates the salient features to support the employment of mushrooms in environmental biomonitoring as a sensitive bioindicator of radiocesium contamination.

Key words : Radiocesium, Mushroom, Bioindicator, Bioaccumulation, Radionuclide contamination

INTRODUCTION

Fungi, the greatest living biomass in the organic layers of forest soil (Gaso *et al.* 2007; Karadeniz and Yaprak 2010), are considered to be the most important agents responsible for the decomposition of litter because they are the primary sources of enzymes required for decomposition. The organic layer of soil is said to be a major pool of radiocesium (^{137}Cs and ^{134}Cs) in forest ecosystems, which is evident from various data derived from sampling at areas contaminated by the Chernobyl nuclear power accident in 1986 (Ruhm *et al.* 1996; Linkov and Schell 1999). Peplow (2006) mentioned that the contamination of soils with radiocesium is still a major cause for alarm within the global society. Fungal mycelium may act as a sink for radiocesium (Olsen *et al.* 1990; Dighton *et al.* 1991), as it contains 20～30% ^{137}Cs in soil inventories (Vinichuk *et al.* 2011). Mushrooms belonging to macrofungi have been identified as one of the potent bioaccumulators of heavy metals, amongst which are most of the radionuclides (Kalac and Svoboda 2000). Compared to green plants, the high radionuclide accumulating ability, in addition to the accumulation of many trace elements and heavy metals, of mushrooms has been explored (Karadeniz and Yaprak 2011). The concentrations of ^{137}Cs in forest mushrooms are markedly higher than those in autotrophic plants (Yoshida and Muramatsu 1998; Ban-nai *et al.* 2005). Fungi can either directly precipitate radionuclides or indirectly affect radionuclide speciation and mobility in forest soils (Gadd 1996). As many mushroom species absorb and concentrate radionuclides from the substrate in which they grow, it is confirmed that they

* Corresponding author: Chandran Sathesh-Prabu, Tel. +82-63-570-3301, Fax. +82-63-570-3309, E-mail. immunesathesh@yahoo.co.in

may be highly useful bioindicators of the concentration fluctuations of the radioactive elements (Gaso *et al.* 1996; Baeza *et al.* 2000; Grdovi *et al.* 2010; Karadeniz and Yaprak 2010). High accumulating ability in several mushroom species promoted their screening as bioindicators, and fruiting bodies can be useful to distinguish between polluted and unpolluted areas (Kalac and Svoboda 2000). Giovani *et al.* (1990), Ingaro *et al.* (1992), and Ruhm *et al.* (1997) demonstrated that the long life and wide extension of mycelium make the mushrooms very good bioindicators. Therefore, their bioaccumulation properties can be used to detect even low contamination levels (Marzano *et al.* 2001). Even 25 years after the Chernobyl accident, the presence of ^{137}Cs can be determined in some samples due to its long half-life (30.17 years), and ^{134,137}Cs from the Fukushima nuclear accident (2011) has contaminated several environmental samples in North America (USA), Europe, and Asia (Russia) (Bolsunovsky and Dementyev 2011). Therefore, it is of great importance to investigate the bioindicators of radiocesium contamination.

Radionuclides

Radionuclides, unstable forms of chemical elements, decay radioactively with the emission of nuclear radiation such as alpha, beta or gamma rays. Radionuclides are released into the environment primarily from mining and milling of uranium and thorium minerals, manufacturing and exploitation of fertilizers and coal, production of oil and gas, transportation of nuclear material, nuclear power plants, reprocessing of nuclear waste, and disposal of spent nuclear fuel. Naturally occurring radionuclides migrate from the ground to the air, soil, water, and biota without human action (Tornivaara and Kauppila 2011).

Radiocesium

Cesium with atomic number 55 is thought to be an element occurring in the form of radioactive isotopes (^{137}Cs and ^{134}Cs) which circulate in the environment (Krajewski and Rosiak 2001) and significantly increase naturally occurring radioactivity (Bystrzejewska-Piotrowska and Urban 2003). Radiocesium is released into the environment anthropogenically, for example, through nuclear weapons testing, nuclear fuel reprocessing, and nuclear reactor accidents. Radiocesium is of particular concern because of its long half-life and its ability to transfer to living organisms through the food chain (Howard *et al.* 1991; Robison and Stone 1992; Boulois *et al.* 2008), great bioavailability (Malinowska *et al.* 2006), and its resemblance to the physical and chemical properties of potassium (K) (Kuwahara *et al.* 2011).

^{137}Cs can even be found far from the site of a nuclear accident due to its high mobility in the environment (Mukhopadhyay *et al.* 2007). It was recently reported that radioactive fallout (^{134}Cs, ^{137}Cs, ^{131}I) due to the Fukushima nuclear accident during March 2011 was detected in environmental samples collected at the city of Krasnoyarsk (Russia), situated in the center of Asia and Greece, which are very far from Japan (Bolsunovsky and Dementyev 2011). Muck (1997) observed that the total world-wide deposition of ^{137}Cs due to the weapon tests has been estimated to be 100-times higher than that from the Chernobyl accident. ^{137}Cs releases have been reported as 960 PBq from weapons testing and 85 PBq from the Chernobyl accident (OECD 1996; Gaso *et al.* 1998). The recent data implies that the amount of discharged ^{137}Cs (6.1 PBq) in the Fukushima accident is about one-fourteenth of that in the Chernobyl accident (85 PBq) (NISA 2011). However, it should be noted that the radionuclides release from the Fukushima accident will continue over a longer period of time compared to the Chernobyl accident (Hamada and Ogino 2011). Radiocesium migrates vertically in soil slowly (Pietrzak-Flis *et al.* 1996), and the organic layer holds the highest concentration of radiocesium (Vinichuk and Johanson 2003). The high ^{137}Cs activity in the top layer is probably due to a subsequent supply of the radionuclide through dropped needles and leaching from needles and bark (Kalac 2001).

Factors influencing the bioaccumulation of radiocesium in mushrooms

The bio-uptake and biotransfer of radionuclides are greatly influenced by various factors such as the concentration of total and available radionuclide in the soil/substrate where the mycelia grow (Eskander *et al.* 2011), pH-value (Kaduka *et al.* 2006), environmental factors (substrate composition and contamination by atmospheric deposition), characteristics of the soil and fungal factors (fungal structure, morphological portion, development of mycelium and fruit bodies, age and depth of mycelium, biochemical composition, decomposition activity, age of the fruiting body and its size) (Kalac and Svoboda 2000; Isiloglu *et al.* 2001; Randa and Kucera 2004; Melgar *et al.* 2009). Tsvetnova and Shcheglov (1994) deter-

mined that mushrooms growing under conditions of increased soil moisture accumulate significantly more radionuclides due to their increased mobility.

The nutritional type of mushroom species can affect the degree of cesium uptake (Calmon *et al.* 2009). Saprotrophic fungi generally accumulate more cesium than basidiomycete and non-basidiomycete mycorrhizal fungi (Clint *et al.* 1991; Gadd 1993), and this is probably due to a large surface-area effect (Clint *et al.* 1991; Avery 1996). It was found that fungal species whose mycelium takes part in such processes show generally high transfer factors of ^{137}Cs whereas nonmycorrhizal species accumulate radiocesium less intensively (Mietelski *et al.* 2010). Species whose mycelium grows within top layers commonly accumulate radiocesium (Kalac 2001).

Mushrooms from higher altitudes can have higher radiocesium levels than those at lower altitudes (Heinrich 1993). Coniferous forest mushrooms have higher levels of radioactivity than those from deciduous forests (Heinrich 1992). Additionally, the ratios of ^{137}Cs for above and below ground portions of mushrooms from conifer forests typically exceed those ratios for mushrooms in deciduous forests (Vinichuk and Johanson 2003).

Several authors have pointed to the relationship between radiocesium accumulation properties and the depth of location of mycelium as the most important factor (Mietelski *et al.* 2010). Gillett and Crout (2000) suggested that the depth of the mycelium and ecophysiological behaviour of the fungi play a key role in the uptake of ^{137}Cs by mushrooms. It was found that fungi with deeper penetrating mycelia have a propensity to accumulate increased levels of 'old' ^{137}Cs (Byrne 1988; Stijve and Poretti 1990). Studies have also observed that ^{137}Cs levels tend to be lower in the buried fungal mycelium than in the above ground fruiting bodies (Vinichuk and Johanson 2003). Heinrich (1993) found that approximately 59% of the examined basidiomycetes showed the highest radiocesium activity in the gills, followed by the flesh of the caps and then the stalks. The high transfers of cesium in some mushrooms species could be related to its existence in the carpophores of substances with a great affinity for cesium. *Xerocomus badius* is known to be a good accumulator of radiocesium because of the presence of a pigment (norbadione A) in the caps's skins that complexes cesium and potassium absorbed from the environment by mycelila and transports them to the fruit body. In addition, a low level of cesium accumulation in *Boletus edulis* was correlated with the absence of these pigments (Aumann *et al.* 1989). As described by Haselwandter and Berreck (1994), ^{137}Cs is complexed by cap pigments in some boletes, a type of fungal fruiting body characterized by the presence of a pileus that is clearly differentiated from the stipe, with a spongy surface of pores (rather than gills) on the underside of the pileus.

It was found that the solubility and mobility of ^{137}Cs increase with a decrease in pH because the ^{137}Cs-ions bound by clay minerals can be exchanged for hydrogen-ions. With an increasing pH, ^{137}Cs remains bound and is therefore not available for the fungus (Eckl 1986). Not only the type of litter, but also the degree of degradation appeared to be an important parameter to determine the transfer factor values (Gaso *et al.* 1998). In addition, Malinowska *et al.* (2006) listed the characteristic soil properties of surface soil horizons in forests, such as low pH value, low clay content, and high organic carbon content, which can enhance radiocesium bioavailability (Thiry *et al.* 2000; Kruyts and Delvaux 2002) and may promote its uptake by mushrooms (Niesiobedzka 2000).

Baeza *et al.* (2005) investigated the influence of various uptake routes on accumulation of ^{134}Cs by *Pleurotus eryngii* and concluded that the most effective uptake route for ^{134}Cs is aerial deposition directly onto the cap of fruit bodies of *P. eryngii*. Their transfer values are one- or two-orders of magnitude greater than for the other two uptake routes such as contamination of the substrate on which the mycelium develops, and by deposition into the soil.

The influence of the degree of maturity on cesium uptake by *P. eryngii* was studied (Baeza *et al.* 2006). As the fruiting bodies matured, the percentage of the total activity of ^{134}Cs grew exponentially in the cap+gills, with a complementary decrease in the stem. This may be indicative of a translocation of these radionuclides during the development process of these parts of the fruiting body. It was concluded that the degree of maturity of fruiting bodies plays an important role in the uptake and distribution of radionuclides within the fruiting bodies of a given species.

Mushrooms: Bioaccumulation and bioindicator of radiocesium contamination

The persistent presence of cesium in mushrooms confirms their relevance as bioindicators for levels of radioactivity in the environment. *Xerocomus badius* has been employed as a potent bioindicator for radiocesium contamination of forests

in Poland (Mietelski *et al.* 1996). According to Duff and Ramsey (2008), mushrooms are generally of three main groups such as gilled, non-gilled, and puffballs, along with their relatives. Those mushrooms of interest as radiocesium accumulators are typically gilled or have pores or spines under their caps, and have stalks (Duff and Ramsey 2008). Cesium is accumulated into certain fungi by simple diffusion and facilitated transport (Johnson *et al.* 1991) and consequently most cesium ultimately becomes bound within tissue rather than at the organisms' surface (Dighton *et al.* 1991).

The transfer of the radionuclide concentrations from soil to mushrooms can roughly be described by aggregated transfer factors and transfer factors (Wichterey and Sawallisch 2002). Aggregated transfer factors (Tag) are defined as the ratio of activity in fungal fruit body (Bq kg^{-1} dry weight) divided by the total deposition in soil (Bq m^{-2}). Tag is a useful tool to estimate quickly the uptake of radionuclides, notably during the first time after an accidental release. Transfer factors (TF) or concentration ratios (CR) referring to standardized soil depths are defined as the ratio of the activity concentration in fungal fruit body (Bq kg^{-1} dry weight) divided by the activity concentration in soil (Bq kg^{-1} dry weight) within the uppermost layer of a standardized thickness (Steiner *et al.* 2002). TF is often used for natural radionuclides, whereas for artificial radionuclides, the Tag is more commonly used (Kostiainen 2011).

Higher concentrations of radiocesium in mushrooms are observed in comparison to other plants, but the reasons and mechanisms for the magnitude higher concentration of radiocesium in fungi are unclear (Vinichuk *et al.* 2011). It has been calculated that the fungal component of soils has the potential to immobilize between 10% and 100% (Dighton *et al.* 1991) of the total radiocesium content. Eckl (1986) compared the radionuclides uptake efficiency between mushrooms and lichens, and concluded that due to the large absorbing surface of the mycelium that grows in the upper parts of the soil, mushrooms take up higher amounts of ^{137}Cs than lichens. The extent depends on species and substrate. Korky and Kowalski (1989) revealed that cesium persists in fungi in an 'immobile' state for long periods of time, enabling the application of higher fungi as indicators of cumulative environmental radiocesium levels. Calmet *et al.* (1998) also reiterated that due to their cesium content, their ready availability, and their representative food matrix, mushrooms are ideal bioindicators of topsoil contamination.

Gaso et al. (1998) studied the accumulation of ^{137}Cs and ^{40}K in 21 wild edible mushroom species from a forest ecosystem located at the Nuclear Centre of Mexico. The local mushroom species that were found to show higher ^{137}Cs transfer factors were *Claariadelphus truncatus*, *Cortinarius caerulescens*, *Gomphus floccosus* and *Lyophyllum decastes*, and it was concluded that these species have the best capabilities as bioindicators of radioactivity contamination in the soil. The extension of mycelium into the soil makes mushrooms representative of the contamination of a large surface and makes possible their use as bioindicators of radiocesium (Mascanzoni 1990).

The capability of *Pleurotus pulmonarius* to bioaccumulate ^{137}Cs during the biodegradation of a spiked mixture of cellulose-based organic solid waste simulate was investigated (Eskander *et al.* 2011). The process is based on the capability of *P. pulmonarius* to biodegrade the cellulose-based organic solid waste simulates, achieving acceptable weight reduction for the waste as well as a reasonable bioaccumulation of ^{137}Cs from the spiked mixture, within their cells. Up to 135 kBq kg^{-1} (based on the dry weight of the mushrooms) was accumulated from ^{137}Cs within a period of 54 ± 3 days. Irradiation of the *P. pulmonarius* spawn before their cultivation enhances the bioaccumulation of ^{137}Cs. It was found that the variation in the biodistribution of ^{137}Cs between the cap and stem of mature fruiting bodies referred to the behavior of the radionuclides within the organism. Cesium is a very soluble element, and hence it smoothly transpires to cap and bioconcentrate there. In contrary, other radionuclides such as cobalt requires certain enzymatic activities, e.g., alkaline phosphatase, in the organism (Wolfe and Hoehamer 2003).

Baeza *et al.* (2004) studied the uptake of alpha and beta emitters (^{134}Cs, ^{85}Sr, ^{239}Pu, $^{234,235,238}U$, and $^{228,230,232}Th$) by different mushrooms under laboratory and natural conditions. *Pleurotus eryngii* was cultured under controlled laboratory conditions, and it was found that ^{134}Cs was incorporated to a greater extent in the mushroom than the other radionuclides, and ^{239}Pu at least. The importance of the uptake of these radionuclides was in the following order: $^{134}Cs > {}^{85}Sr > {}^{234,238}U \sim {}^{228,230,232}Th > {}^{239}Pu$. These results were confirmed by the uptake under natural conditions: $^{137}Cs > {}^{228,230,232}Th \sim {}^{234,238}U \sim {}^{90}Sr \gg {}^{239,240}Pu$. Baeza *et al.* (2005) found that mushrooms preferentially accumulate ^{137}Cs, then ^{40}K, ^{90}Sr, and ^{226}Ra, but this does not apply to all mushroom species.

There are marked differences in the transfer factors among various radionuclides (Kostiainen 2011).

The uptake of ^{137}Cs, ^{40}K, stable elements, and heavy metals in 25 mushroom samples, covering 12 biological species, *Agaricus campestris, Lactarius semisanguifluus, Clitocybe bresadoliana, Tricholoma terreum, Lactarius* sp., *Sarcodon scabrosus, Lactarius deliciosus, Lepista nuda, Suillus bovinus, Tricholoma* sp., *Russula delica* and *Macrolepiota excoriate*, was evaluated. A significant positive relationship was found between the ^{137}Cs activity of mushrooms and ^{137}Cs activity concentration of soil (Karadeniz and Yaprak 2011).

Mukhopadhyay *et al.* (2007) first investigated the accumulation of radiocesium by *Pleurotus citrinopileatus*. The pileus (cap)/stipes (stem) ratio of a ^{134}Cs accumulated mushroom sample was determined and found to be 2.22, i.e., maximum accumulation took place in the cap portion. The protein and fat fractions of *P. citrinopileatus* were extracted separately after accumulation of radiocesium, and it was found that most of the radiocesium accumulation occurred in the protein fraction of the mushroom. The mushroom *P. citrinopileatus* which is white in color, turned completely black after radiocesium accumulation, and hence this black mushroom species may play an important role as a bioindicator of radioactive pollution caused by nuclear fallout containing ^{134}Cs or ^{137}Cs. Radiocesium is unevenly distributed within the fruiting bodies in the order gills > caps > stipes (Heinrich 1993). Bazala *et al.* (2008) concluded that radiocesium is mainly accumulated in fruitbodies, while vegetative hyphae of the underground mycelium only facilitate uptake and transport of this radionuclide. Vinichuk and Johanson (2003) investigated the accumulation of ^{137}Cs by mushrooms collected in a coniferous forest in the Ovruch region of the Ukraine, and it was found that the ^{137}Cs activity concentrations were usually higher in the fruit bodies (*Paxillus involutus* and *Sarcodon imbricatus, Xerocomus subtomentosus* and *Cantharellus cibarius*) compared with the mycelium, with ratios ranging from 0.1 to 66 and a mean of 9.9.

Mietelski *et al.* (2010) carried out a study on the accumulation of radiocesium in fruiting bodies of more than 70 species of mushrooms and concluded that *Lactarius helvus* was found to be a potent species that accumulates high amounts of radiocesium in its fruiting bodies. It was found that the species-depending radiocesium accumulation properties for different fungal fruiting bodies was not constant over time, as it is at least partially governed by the localization of the mycelium in the forest litter/soil system, which is specific for the given species.

Kalac (2001) ranked the selected mushroom species based on their ability to accumulate radiocesium such as high accumulators (*Xerocomus badius, Xerocomus chrysenteron, Suillus variegates, Cantharellus tubaeformis, Cantharellus lutescens, Rozites caperata, Hydnum repandum, Laccaria amethystine* and *Russula cyanoxantha*); medium accumulators (*Leccinum scabrum, Leccinum aurantiacum* and *Agaricus silvaticus*); and low accumulators (*Boletus edulis, Cantharellus cibarius, Macrolepiota procera, Armillariella mellea, Amanita rubescens, Laccaria laccata, Lycoperdon perlatum, Calocybe gambosa* and *Pleurotus ostreatus*). However, among the investigated edible mushrooms, special attention has been paid to *Boletus edulis* and *Cantharellus cibarius* as these mushrooms are not only widespread, but also a highly esteemed delicacy (Marovi *et al.* 2008). On the contrary, *Boletus* mushrooms are prized for their high affinity for cesium (Duff and Ramsey 2008). *Gomphidius glutinosus* has been reported to absorb and concentrate ^{137}Cs more than 10,000-fold over ambient background levels (Stamets 2005). *Paxillus involutus* can accumulate nearly one million Bq kg^{-1} of ^{137}Cs (Vinichuk and Johanson 2003). *P. involutus* mushrooms are fairly common as they are found in conifer or birch woodlands and in gardens and parks. Fortunately, *P. involutus* are poisonous and not consumed by humans (Duff and Ramsey 2008).

Grodzinskaya *et al.* (2011) conducted investigations on wild growing mushrooms of Ukrainian Polissya, such as *Cortinarius* sp., *Rosites caperata, Hebeloma crustuliniforme, Lactarius rufus, Boletus* sp., *Leccinum scabrum, Tylopilus felleus Suillus* spp., *Paxillus involutus, Sarcodon imbricatus, Hydnum repandum, Tricholoma flavovirens, Gomphidius glutinosus* and *G. rutilus*, and found out that among them, *L. rufus* and *P. involutus* may be regarded as the most convenient bioindicators since their inedibility and toxicity, respectively, allow a reduction in the influence of external factors in the estimation of environmental radiocesium contamination.

^{137}Cs does not correlate with K in mushrooms, which indicates that the mechanism of ^{137}Cs uptake is different from that of K, whereas, the uptake of Rb is closely related to the uptake of Cs (Vinichuk *et al.* 2011). ^{137}Cs uptake is affected by the presence of K, Rb and ^{133}Cs (Terada *et al.* 1998; Gyuricza *et al.* 2010). The incorporation of cesium

into fruit bodies of *Pleurotus eryngii* was not suppressed by Na^+ and Rb^+ or tetraethylammonium chloride. However, it was inhibited by Ca^{2+} and stimulated by high concentrations of K^+. These results suggest that two pathways of passive transport of cesium in mycelium may exist: (i) uptake mediated by a non-specific potassium channel localized in plasmalemma followed by the diffusive transport inside hyphae, and (ii) extracellular transport from the medium through interhyphal cavities into fruit bodies (Bystrzejewska-Piotrowska and Bazala 2008). Sugiyama *et al.* (2008) and Kuwahara *et al.* (2011) suggested that cesium in the mycelia is trapped by intercellular materials such as polyphosphate in vacuoles or other organelles.

Stamets (2005) documented that to decontaminate radiocesium contaminated sites, after cultivating potent mushrooms, those with concentrated activity should be removed continuously and incinerated. The resulting radioactive ash can be further refined and vitrified or stored using other state-of-the-art storage technologies.

CONCLUSION

Contamination of the environment by radiocesium is a critical concern because of its anthropogenic origin, long half-life, strong possibility for its incorporation in the food chain, great mobility, bioavailability, and chemical similarity with potassium. Mushrooms can accumulate high concentrations of ^{137}Cs than plants, and the uptake is governed by various environmental and fungal factors. Their hyper-accumulation, extension of mycelium into the soil, rapid growth of the aerial parts, ready availability, and representative food matrix make the mushrooms an ideal candidate for the bioindication of radiocesium contamination, and a highly useful element in an environmental biomonitoring program.

REFERENCES

Aumann DC, Clooth G, Steffan B and Steglich W. 1989. Kompexierung von cesium-137 durch die hutfarbstoffe des maronenrohrings (*Xerocomus badius*). *Angewandte Chemie* **101**: 495-496.

Avery SV. 1996. Fate of cesium in the environment: distribution between the abiotic and biotic components of aquatic and terrestrial ecosystems. *J. Environ. Radiact*. **30**:139-171.

Baeza A, Guillen FJ, Salas A and Manjon JL. 2006. Distribution of radionuclides in different parts of a mushroom: influence of the degree of maturity. *Sci. Total Environ*. **359**:255-266.

Baeza A, Guillen J and Bernedo JM. 2005. Soil-fungi transfer coefficients: importance of mycelium in soil and of the differential availability of radionuclides in soil fractions. *J. Environ. Radioact.* **81**:89-106.

Baeza A, Guillen J and Mietelski JW. 2004. Uptake of alpha and beta emitters by mushrooms collected and cultured in Spain. *J. Radioanal. Nucl. Chem*. **261**:375-380.

Baeza A, Guillen J, Paniagua JM, Hernandez S, Martin JL, Diez J, Manjon JL and Moreno G. 2000. Radiocesium and radiostrontium uptake by fruit bodies of *Pleurotus eryngii* via mycelium, soil and aerial absorption. *Appl. Radiat. Isotopes* **53**:455-462.

Ban-nai T, Yoshida S, Muramatsu Y and Suzuki A. 2005. Uptake of radiocesium by hypha of basidiomycetes-radiotracer experiments. *J. Nucl. Radiochem. Sci.* **6**:111-113.

Bazala MA, Golda K and Bystrzejewska-Piotrowska G. 2008. Transport of radiocesium in mycelium and its translocation to fruitbodies of a saprophytic macromycete. *J. Environ. Radioact*. **99**:1200-1202.

Bolsunovsky A and Dementyev D. 2011. Evidence of the radioactive fallout in the center of Asia (Russia) following the Fukushima nuclear accident. *J. Environ. Radioact.* **102**:1062-1064.

Boulois DH, Joner EJ, Leyval C, Jakobsen I, Chen BD, Roos P, Thiry Y, Rufyikiri G, Delvaux B and Declerck S. 2008. Role and influence of mycorrhizal fungi on radiocesium accumulation by plants. *J. Environ. Radioact*. **99**:785-800.

Byrne AR. 1988. Radioactivity in fungi in Slovenia, Yugoslavia, following the Chernobyl accident. *J. Environ. Radioact.* **6**:177-183.

Bystrzejewska-Piotrowska G and Bazala MA. 2008. A study of mechanisms responsible for incorporation of cesium and radiocesium into fruitbodies of king oyster mushroom (*Pleurotus eryngii*). *J. Environ. Radioact*. **99**:1185-1191.

Bystrzejewska-Piotrowska G and Urban PL. 2003. Accumulation of cesium in leaves of *Lepidium sativum* and its influence on photosynthesis and transpiration. *Acta Biol. Cracoviensia Series Botanica* **45**:131-137.

Calmet D, Boursier B, Bouisset P, Guiard A and Barker E. 1998. Mushrooms as a reference material for intercomparison exercises and as bioindicators of radiocesium deposition in soil (France and Central European Countries). *Appl. Radiat. Isotopes* **49**:19-28.

Calmon P, Thiry Y, Zibold G, Rantavaara A, Fesenko S and Orlov O. 2009. Radionuclide transfer in forest ecosystems. pp. 33-380. *In*: Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological

Assessments. IAEA-TECDOC-1616, Vienna.

Clint GM, Dighton J and Rees S. 1991. Influx of ^{137}Cs into hyphae of basidiomycete fungi. *Mycol. Res*. **95**:1047-1051.

Dighton J, Clint GM and Poskitt J. 1991. Uptake and accumulation of ^{137}Cs by upland grassland soil fungi: a potential pool of Cs immobilization. *Mycol. Res*. **95**:1052-1056.

Duff MC and Ramsey ML. 2008. Accumulation of radiocesium by mushrooms in the environment: a literature review. *J. Environ. Radioact*. **99**:912-932.

Eckl P, Hofmann W and Turk R. 1986. Uptake of natural and man-made radionuclides by lichens and mushrooms. *Radiat. Environ. Biophys*. **25**:43-54.

Eskander SB, Aziz ASM and El-saayed H. 2011. Bioaccumulation of cesium-137 and cobalt-60 from solid cellulosic-based radioactive waste simulates by *Plurotus pulmonarius. African J. Microbiol. Res*. **5**:2804-2811.

Gadd GM. 1993. Interactions of fungi with toxic metals. *Nemo Phytol*. **124**:25-60.

Gadd GM. 1996. Influence of microorganisms on the environmental fate of radionuclides. *Endeavour* **20**:150-156.

Gaso MI, Cervantes ML, Segovia N and Salazar S. 1996. Soil-fungi radiocesium transfer in forest ecosystems in Mexico. *Environ. Int*. **22**:365-368.

Gaso MI, Segovia UN, Herrerab T and Perez-Silva E. 1998. Radiocesium accumulation in edible wild mushrooms from coniferous forests around the nuclear centre of Mexico. *Sci. Total Environ*. **223**:119-129.

Gaso MI, Segovia N, Morton O, Lopez JL, Machuca A and Hernandez E. 2007. Radioactive and stable metal bioaccumulation, crystalline compound and siderophore detection in *Clavariadelphus truncatus. J. Environ. Radioact.* **97**:57-69.

Gillett AG and Crout NMJ. 2000. A review of ^{137}Cs transfer to fungi and consequences for modelling environmental transfer. *J. Environ. Radioact*. **48**:95-121.

Giovani C, Nimis PL and Padovani R. 1990. Investigation of the performance of macromycetes as bioindicators of radioactive contamination. pp. 485-491. *In*: Transfer of Radionuclides in Natural and Semi-natural Environments (Desmet G, Nassimbeni P and Belli M *eds.*), Elsevier Applied Science, London.

Grdovi S, Vitorovi G, Mitrovi B, Andri V, Petrujki P and Obradovi M. 2010. Natural and anthropogenic radioactivity of feedstuffs, mosses and soil in the Belgrade environment, Serbia. *Arch. Biol. Sci. Belgrade* **62**:301-307.

Grodzinskaya AA, Syrchin SA, Kuchma ND and Bilay VD. 2011. Radioactive contamination of Ukrainian wild-growing mushrooms. Proc. 7th Int. Con. Mushroom Biol. Mushroom Prod. 566-572.

Gyuricza V, Boulois DH and Declerck S. 2010. Effect of potassium and phosphorus on the transport of radiocesium by arbuscular mycorrhizal fungi. *J. Environ. Radioact.* **101**:482-487.

Hamada N and Ogino H. 2011. Food safety regulations: what we learned from the Fukushima nuclear accident. *J. Environ. Radioact*. In Press. doi:10.1016/j.jenvrad.2011.08.008.

Haselwandter K and Berreck M. 1994. Accumulation of radionuclides in fungi. pp. 259-277. *In*: Metal Ions in Fungi (Winkelmann G and Winge DR *eds*.), Dekker, New York.

Heinrich G. 1992. Uptake and transfer factors of ^{137}Cs by mushrooms. *Radiat. Environ. Biophys*. **31**:39-49.

Heinrich G. 1993. Distribution of radiocesium in the different parts of mushrooms. *J. Environ. Radioact*. **18**:229-245.

Howard BJ, Beresford NA and Hove K. 1991. Transfer of radiocesium to ruminants in natural and semi-natural ecosystems and appropriate countermeasures. *Health Phys*. **61**:715-725.

Ingaro G, Belloni P and Santaroni GP. 1992. Mushrooms as biological monitors of trace elements in the environment. *J. Radioanal. Nucl. Chem*. **161**:113-120.

Isiloglu M, Merdivan M and Yilmaz F. 2001. Heavy metal contents in some macrofungi collected in the northwestern part of Turkey. *Arch. Environ. Contam. Toxicol*. **41**:1-7.

Johnson EE, Odonnell AG and Ineson P. 1991. An autoradiographic technique for selecting Cs-137-sorbing microorganisms from soil. *J. Microbiol. Meth.* **13**:293-298.

Kaduka MV, Shutov VN, Bruk GY, Balonov MI, Brown JE and Strand P. 2006. Soil dependent uptake of ^{137}Cs by mushrooms: experimental study in the Chernobyl accident areas. *J. Environ. Radioact.* **89**:199-211.

Kalac P. 2001. A review of edible mushroom radioactivity. *Food Chem*. **75**:29-35.

Kalac P and Svoboda L. 2000. A review of trace element concentrations in edible mushrooms. *Food Chem*. **69**:273-281.

Karadeniz O and Yaprak G. 2010. ^{137}Cs, ^{40}K, alkali-alkaline earth element and heavy metal concentrations in wild mushrooms from Turkey. *J. Radioanal. Nucl. Chem*. **285**:611-619.

Karadeniz O and Yaprak G. 2011. Soil-to-mushroom transfer of ^{137}Cs, ^{40}K, alkali-alkaline earth element and heavy metal in forest sites of Izmir, Turkey. *J. Radioanal. Nucl. Chem*. **288**:261-270.

Korky JK and Kowalski L. 1989. Radioactive cesium in edible mushrooms. *J. Agric. Food Chem*. **37**:568-569.

Kostiainen E. 2011. Uptake of radionuclides by mushrooms and berries. pp. 8-9. *In*: ERACedu Workshop Proceedings on Naturally Occurring Radioactive Materials (NORM) in the Environment-Geochemical and Biological Behaviour, Tools for Risk Assessment (Kauppila PM, Tornivaara A and Makkonen S *eds*.), September 14-15. Kuopio, Finland.

Krajewski P and Rosiak L. 2001. Transfer of radioceasium to

crops from different soil types in Poland as a function of radioceasium interception potential and soil characteristics. *Postepy Techniki Jadrowej* **44**:32-50.

Kruyts N and Delvaux B. 2002. Soil organic horizons as a major source for radiocesium biorecycling in forest ecosystems. *J. Environ. Radioact.* **58**:175-190.

Kuwahara C, Fukumoto A, Nishina M, Sugiyama H, Anzai Y and Kato F. 2011. Characteristics of cesium accumulation in the filamentous soil bacterium *Streptomyces* sp. K202. *J. Environ. Radioact*. **102**:138-144.

Linkov I and Schell WR. 1999. Contaminated forests: recent developments in risk identification and future perspectives. 430pp. Kluewer, Amsterdam.

Malinowska E, Szefer P and Bojanowski R. 2006. Radionuclides content in *Xerocomus badius* and other commercial mushrooms from several regions of Poland. *Food Chem.* **97**:19-24.

Marovi G, Frani Z, Senar J, Bituh T and Vugrinec O. 2008. Mosses and some mushroom species as bioindicators of radiocesium contamination and risk assessment. *Coll. Antropol*. **32**:109-114.

Marzano FN, Bracchi PG and Pizzetti P. 2001. Radioactive and conventional pollutants accumulated by edible mushrooms (*Boletus* sp.) are useful indicators of species origin. *Environ. Res. Sec. A* **85**:260-264.

Mascanzoni D. 1990. Uptake of ^{90}Sr and ^{137}Cs by mushrooms following the Chernobyl accident. pp. 459-467. *In*: Transfer of Radionuclides in Natural and Seminatural Environments (Desmet G, Nassimbeni P and Belli M *eds*.), Elsevier Applied Science, London.

Melgar MJ, Alonso J and Garcia MA. 2009. Mercury in edible mushrooms and underlying soil: bioconcentration factors and toxicological risk. *Sci. Total Environ*. **407**:5328-5334.

Mietelski JW, Dubchak S, Blazej S, Anielska T and Turnau K. 2010. ^{137}Cs and ^{40}K in fruiting bodies of different fungal species collected in a single forest in southern Poland. *J. Environ. Radioact*. **101**:706-711.

Mietelski JW, Jasinska M, Kozak K and Ochab E. 1996. The Method of measurement used in the investigation of radioactive contamination of forests in Poland. *Appl. Radiat. Isot.* **47**:1089-1095.

Muck K. 1997. Long term effective decrease of cesium concentration in foodstuffs after nuclear fallout. *Health Phys.* **72**: 659-673.

Mukhopadhyay B, Nag M, Laskar S and Lahiri S. 2007. Accumulation of radiocesium by *Pleurotus citrinopileatus* species of edible mushroom. *J. Radioanal. Nucl. Chem*. **273**:415-418.

Niesiobedzka K. 2000. Mobile forms of radionuclide ^{137}Cs in sandy soils in northeastern Poland. *Polish J. Environ. Stud*. **9**:133-136.

NISA-Nuclear and Industrial Safety Agency. 2011. International nuclear and radiological event scale rating on the events in Fukushima Dai-ichi nuclear power station by the Tohoku district e off the pacific ocean earthquake. http://www.nisa.meti.go.jp/english/files/en20110412-4.pdf. accessed on 17 January 2012.

OECD-Organisation for Economic Co-operation and Development. 1996. Chernobyl, ten years on radiological and health impact. 112pp. Paris.

Olsen R, Joner E and Bakken L. 1990. Soil fungi and the fate of radiocesium in the soil ecosystem - a discussion of possible mechanisms involved in the radiocesium accumulation in fungi, and the role of fungi as a Cs-sink in the soil. pp. 657-663. *In*: Transfer of Radionuclides in Natural and Semi-natural Environment (Desmet G, Nassimbeni P and Belli M. *eds*.), Elsevier Applied Science, Luxemburg.

Peplow M. 2006. Counting the dead. *Nature* **440**:982-983.

Pietrzak-Flis Z, Radwan I, Rosiak L and Wirth E. 1996. Migration of ^{137}Cs in soils and its transfer to mushrooms and vascular plants in mixed forest. *Sci. Total Environ.* **186**:243-250.

Randa Z and Kucera J. 2004. Trace elements in higher fungi (mushrooms) determined by activation analysis. *J. Radioanal. Nucl. Chem*. **259**:99-107.

Robison WL and Stone EL. 1992. The effect of potassium on the uptake of ^{137}Cs in food crops grown on coral soils: coconut at Bikini Atoll. *Health Phys*. **62**:496-511.

Ruhm W, Kammerer L, Hiersche L and Wirth E. 1996. Migration of ^{137}Cs and ^{134}Cs in different forest soil layers. *J. Environ. Radioactivity* **33**:63-75.

Ruhm W, Kammerer L, Hiersche L and Wirth E. 1997. The Cs-137/Cs-134 ratio in fungi as indicator of the major mycelium location in forest soil. *J. Environ. Radioact.* **35**: 129-148.

Stamets P. 2005. Mycelium running: how mushrooms can help save the world. 356pp. Ten Speed Press, Berkeley, California.

Steiner M, Linkov I and Yoshida S. 2002. The role of fungi in the transfer and cycling of radionuclides in forest ecosystems. *J. Environ. Radioact*. **58**:217-241.

Stijve T and Poretti M. 1990. Radiocesium levels in wild-growing mushrooms from various locations. *Mushroom the Journal* **Summer**:5-9.

Sugiyama H, Takahashi MN, Terada H, Kuwahara C, Maeda C, Anzai Y and Kato F. 2008. Accumulation and localization of cesium in edible mushroom (*Pleurotus ostreatus*) mycelia. *J. Agric. Food Chem.* **56**:9641-9646.

Terada H, Shibata H, Kato F and Sugiyama H. 1998. Influence of alkali elements on the accumulation of radiocesium by mushrooms. *J. Radioanal. Nucl. Chem.* **235**:195-200.

Thiry Y, Kruyts N and Delvaux B. 2000. Respective horizon

contributions to cesium-137 soil-to-plant transfer: a pot experiment approach. *J. Environ. Quality* **29**:1194-1199.

Tornivaara A and Kauppila PM. Introduction to naturally occurring radioactive materials. pp. 8-9. *In*: ERACedu Workshop Proceedings on Naturally Occurring Radioactive Materials (NORM) in the Environment-Geochemical and Biological Behaviour, Tools for Risk Assessment (Kauppila PM, Tornivaara A and Makkonen S *eds*.), September 14-15. Kuopio, Finland.

Tsvetnova OB and Shcheglov AI. 1994. Cs-137 content in the mushrooms of radioactive contaminated zones of the European part of the CIS. *Sci. Total Environ*. **155**:25-29.

Vinichuk M, Rosen K, Johanson KJ and Dahlberg A. 2011. Correlations between potassium, rubidium and cesium (^{133}Cs and ^{137}Cs) in sporocarps of *Suillus variegates* in a Swedish boreal forest. *J. Environ. Radioact.* **102**:386-392.

Vinichuk MM and Johanson KJ. 2003. Accumulation of ^{137}Cs by fungal mycelium in forest ecosystems of Ukraine. *J. Environ. Radioact.* **64**:27-43.

Wichterey K and Sawallisch S. 2002. Naturally occurring radionuclides in mushrooms from uranium mining regions in Germany. *Radioprot*. **37**:C1-353-C1-358.

Wolfe NL and Hoehamer CF. 2003. Enzymes used by plants and microorganisms to detoxify organic compounds. pp. 159-187. *In*: Phytoremediation: Transformation and Control of Contaminants (McCutcheom SC and Schnoor SJ *eds*.), John Wiley and Sons, Inc, USA.

Yoshida S and Muramatsu Y. 1998. Concentrations of alkali and alkaline earth elements in mushrooms and plants collected in a Japanese pine forest, and their relationship with ^{137}Cs. *J. Environ. Radioact.* **41**:183-205.

Manuscript Received: January 26, 2012
Revised: February 17, 2012
Revision Accepted: February 29, 2012