Strontium in the Ecosystem: Transfer in Plants via Root System

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Introduction

Strontium (symbol Sr, atomic no. 38) is a natural and commonly occurring alkaline earth metal (lying in group IIa, period 5, sandwiched vertically between calcium and barium). The mineral was discovered in 1790 by Adair Crawford and William Cruickshank at Strontian (Scotland). Sr ore is usually found in nature in the form of minerals like celestite ($SrSO_4$), and strontianite ($SrCO_3$); however, it can form a variety of compounds, which are either water soluble or not. Naturally occurring stable (non-radioactive) Sr exists in four stable isotopes, viz.^{84}Sr, ^{86}Sr, ^{87}Sr and ^{88}Sr (ATSDR 2004a; Therapeutic Goods Administration 2014; Qi et al. 2015). Furthermore, some 30 radioactive strontium isotopes are known, the most important one being ^{90}Sr, which is formed during nuclear weapons explosions or in nuclear reactors and was released into the environment by fallouts following accidents like Chernobyl Nuclear Power Plant (NPP) in 1986 and Fukushima NPP in 2011 (Sanzharova et al. 2005; Lipscy et al. 2013). ^{90}Sr is a β-radiation emitter with a radioactive half-life of 28.8 years and hazardous to health as it resembles calcium and creates metabolic imbalance (Merz et al. 2016). The radioactive decay through β emission of ^{90}Sr subsequently produces ^{90}Y (yttrium) and ^{90}Zr (zirconium). Once absorbed inside the body, ^{90}Sr causes bone cancer, leukaemia and softening of tissues situated around the bone and bone marrow and has lasting effects (ATSDR 2004b). Because of high toxicity and capability to be readily involved in geochemical and biological migration processes, ^{90}Sr is a particularly hazardous radionuclide

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(Sanzharova et al. 2005). However, strontium also finds application in treating and preventing diseases like postmenopausal osteoporosis and resultant bone fractures (O'Donnell et al. 2008; Bolland and Grey 2014; Nakano 2016), but the use has been somewhat reduced due to significant safety concerns, particularly the risk of using Sr with patients having a history of ischemic heart disease or venous thromboembolism (Sowa et al. 2014; www.tga.gov.au/alert/strontium-ranelateprotos-and-risk-adverse-events-0; accessed on: 1 Mar 2016). Humans get exposed to radionuclides either directly or indirectly by diverse pathways like consumption of contaminated food or water (Ruttenber et al. 1984; Fowler et al. 1987; Eisenbud and Gesell 1997; Arora et al. 2008). ^{90}Sr, due to rather high solubility in water, once inside the body, gets deposited in bones and teeth (Volkle et al. 1989). Similarly, ^{90}Sr also gets accumulated within plants depending on factors like soil properties, climate, biosphere, and particular species and populations (subspecies, cultivars) etc. (Yablokov et al. 2008).

^{90}Sr in Soil: Its Behaviour and Consequences

Varying meteorological conditions enhance airborne transport of radioactive aerosols from one place to another followed by deposition from atmosphere to soil. After precipitation, the fate of ^{90}Sr is affected by different physico-chemical processes in soil-water-plant compartments (Ehlken and Kirchner 2002). The global precipitation rate varies strongly but has a significant correlation with levels of ^{90}Sr in soil and grass (Bolsunovsky and Dementyev 2011). ^{90}Sr has a greater mobility and migrates faster downward into the soil (especially in mineral (sandy) and organic soils) as compared to other radionuclides like ^{241}Am (Americium), $^{239+240}$Pu (Plutonium) and ^{137}Cs (Cesium) (Gastberger et al. 2000; Solovitch-Vella et al. 2007; Chawla et al. 2010). Soil particles are a very important reservoir of ^{90}Sr in the terrestrial environment (Lee and Clark 2005). Sr is also known to compete with its macrohomologue calcium for exchange sites in minerals (Strebl et al. 2007). Five to tenfold increased mobility and bioavailability of ^{90}Sr has been observed in the non-remediated ecosystems close to Chernobyl (Warner and Harrison 1993). This increase in ^{90}Sr with passage of time may be attributed to the ion-exchange mechanism by soil components and the relatively high concentrations of the radionuclide within the soil (Maskalchuk et al. 2014). Therefore, ^{90}Sr distribution in ecosystems includes transfer into the food chain and entering the human body. Next to ^{137}Cs, ^{90}Sr has the potential to significantly contribute to internal ingestion dose (Gupta et al. 2016a).

The migration of ^{90}Sr in the solid phase of the soil–soil solution–plant system is computed by a concentration factor (CF) defined as CF = $[^{90}\mathrm{Sr}]_p/[^{90}\mathrm{Sr}]_s$, where $[^{90}\mathrm{Sr}]_p$ and $[^{90}\mathrm{Sr}]_s$ are the equilibrium specific activities of ^{90}Sr in plant and soil, respectively, expressed in Bq kg^{-1} (Sanzharova et al. 2005). The CF depends on a number of parameters like the properties of soil, plant and calcium (macrohomologue of Sr) (1983). Maskalchuk et al. (2014) derived an equation to estimate the migration of ^{90}Sr from soil to plants, which includes key characteristics of soil, content of exchangeable Ca^{2+} and fraction of exchangeable $^{90}Sr^{2+}$ in soil and an exchange selectivity coefficient for the $^{90}Sr^{2+}$–Ca^{2+} cation pair. The model suggests reduction of ^{90}Sr migration in the soil–plant system by liming (in case of acidic soils; depending on the cation-exchange capacity of the soil in question) and also by introducing soil sorbents with high sorption potential like organozeolites (Maskalchuk et al. 2014). Thus, long-term soil uptake of ^{90}Sr is strongly influenced by the pedological and agronomic characteristics of the soil and agricultural practices (Koranda and Robison 1978).

Claus et al. (1990) reported a ^{90}Sr transfer factor (TF; mean value 0.18) in ten rye fields with podzolic soils near Bremen, Germany, correlated positively with organic content of soil and negatively with Ca and P content. Further, Rabideau et al. (2005) performed real-time performance studies and consequent modelling of a permeable reactive barrier constructed of a natural zeolite material at the West Valley Demonstration Project in western New York State. Changes in soil temperature and moisture content have a considerable impact on the oxidation states (speciation) and consequently, the geochemical forms of ^{90}Sr in soil (Kovacheva et al. 2014). The concept of "effective half-life" as an indicator of long-term decay kinetics of a radionuclide in an environmental compartment (soil/water/plant) is also being reviewed recently (Corcho-Alvarado et al. 2016). The effective half-life may be expressed as close to ecological half-life and is calculated by using a regression analysis of the specific activity (expressed in mBq kg^{-1} dry weight of soil), assuming that the specific activity in the environmental compartment decreases exponentially with time. The effective half-life integrates all processes that potentially affect the activity and decay of the radionuclides in the compartment including physical radioactive decay (Pröhl et al. 2006; IAEA 2009).

Limited data are available on distribution of artificial radionuclides in meadow soils. However, radionuclide behaviour in the forest environment is becoming an important area of research in radioecology. Pourcelot et al. (2007) pointed out that ^{90}Sr activity concentrations in milk samples from cows that grazed in Alpine pastures are more elevated and show lower variability than that in soil and grass samples from the same area. Lukšienė et al. (2015) studied the spatial distribution of ^{90}Sr and other artificial radionuclide activity and concentration in the top layer (0–10 cm) of undisturbed meadow soils in Chernobyl NPP fallout affected areas of Lithuania. Therefore, milk might be a more sensitive indicator of ^{90}Sr contamination than soil or grass samples (Pourcelot et al. 2007; Kamenova-Totzeva et al. 2017). As early as in 1959, Lee (1959) reported estimated ^{90}Sr in soil, runoff and wheat. Gustafson (1959) reported ^{90}Sr accumulation of radioactivity in the kernels of Thatcher wheat which was about one-tenth of that in leaves and stems. Subsequently, Menzel (1960) found that only a small portion of ^{90}Sr (10%) deposited on cultivated soils were removed in runoff. Other than small plants (crops, etc.) seasonal and multi-year dynamics of Chernobyl-derived ^{90}Sr accumulation in woods are investigated by Shcheglov and Tsvetnova (2004).

Seasonal variation is more regular and predictable than multiyear variation (Fellows et al. 2009). The multi-year dynamics of ^{90}Sr within the plant body depends on type of landscape, kinetics of plant-available forms of ^{90}Sr and irreversible fixation of ^{90}Sr in the root-abundant soil layer (Shcheglov and Tsvetnova 2004).

Mahmoud and El-Hemamy (2005) studied the leakage pattern and consequent hydrological and geological effect of leaking of old (functional since 1961) underground settling tanks at the Egyptian Atomic Energy Authority (EAEA) Inshas site, where the tanks contained ^{90}Sr among other radionuclides. The migration of ^{90}Sr through the unsaturated zone (soil between tank and aquifer) was observed, that depends on soil type, thickness of the unsaturated zone, water velocity and retardation factor, which is a function of the specific distribution coefficient of ^{90}Sr (Mahmoud and El-Hemamy 2005). These studies may be termed as "mini radiological fallouts" as compared to Chernobyl and Fukushima (Maloshtan et al. 2017).

^{90}Sr in Water: Uptake and Interactions

Environmental ^{90}Sr deposited on soil and vegetation likely gets transported into freshwater ecosystems because of washout by spring high waters. Some reports of ^{90}Sr in the food chain and accumulation records are available on Russian, Belorussian and Ukrainian water bodies in post-Chernobyl accident, where the speed of vertical migration of ^{90}Sr was around 2–4 cm year^{-1} (Outola et al. 2009; Saxen and Koskelainen 2002; Fesenko et al. 2011). The vertical migration in soil resulted in higher absorption of ^{90}Sr in plants having deep root systems (Yablokov et al. 2008) finally leading to increased internal irradiation exposures of people in the contaminated territories (Yablokov et al. 2008).

The concentration of radionuclides in non-human biota is usually defined by biota-to-water concentration ratio (CR) (IAEA 2014) and used to subsequently estimate radiation dose to organisms or humans. For aquatic organisms especially for fishes, CR is usually defined as the ratio between the radionuclide concentration in the fish muscle (as mostly consumed) and the concentration in the surrounding water (Yankovich et al. 2010). For environmental risk assessment, CR^{muscle} values can be converted to $CR^{whole\text{-}organism}$ using conversion coefficients (Yankovich et al. 2010). However, calculating the conversion factor is difficult, hence predicting the elements/radionuclides (like Sr/^{90}Sr), that accumulate in tissues other than muscle. Sr uptake mechanism resembles the ions of Ca (Kryshev 2006; Outola et al. 2009), with Ca^{+2} and Sr^{+2} competing for receptor sites on biological membranes (Van Leeuwen and Koster 2004). According to Saxen and Koskelainen (2002), 95% of ^{90}Sr accumulates in fish skeleton, scales and fins and only 2–5% accumulates in muscles.

Although the CR may ideally be defined as the concentration equilibrium of radionuclides in organisms with its surrounding media, practically, radionuclides in the environment and in organisms vary in a dynamic manner (Batlle et al. 2016). Moreover, to evaluate risk assessment, data on spatio-temporal variation (like data from various sites, longitudinal variation, etc.) must be considered (Avila et al. 2013; Beresford et al. 2016). Hence, it is very difficult accurately predicting risks related to radionuclide contamination from water to aquatic organisms in case of ^{90}Sr. The Fukushima Daiichi NPP (FDNPP) liquid release has given us insight of what may happen to seawater and marine biota after such an accident. Marine mussels (*Septifer virgatus*) provide an important animal system to assess the status of ^{90}Sr uptake and accumulation in marine biota on a spatio-temporal basis (Karube et al. 2016). Nelson (1962) studied ^{90}Sr concentration in freshwater clams and their shells; the study may be used as indicators of the ^{90}Sr contamination of their environment and helpful in predicting the concentrations within the organisms. Studies on the dispersion of ^{90}Sr from FDNPP site along the Pacific coast of eastern Japan (north direction by coastal current) and radiostrontium activity in coastal areas have revealed the environmental aspects related to aquatic ecosystems human safety assessments (Fujimoto et al. 2015; Castrillejo et al. 2016; Konovalenko et al. 2016). Fujimoto et al. (2015) reported correlation of fish contamination by beta emitting radionuclides and their concentration in marine water in and around Fukushima FDNPP harbour. The investigations include Japanese rockfish (*Sebastes cheni*), brown hakeling (*Physiculus maximowiczi*) and fat greenling (*Hexagrammos otakii*).

However, according to the study by Tomilin et al. (1987), the accumulation of radiostrontium in mammals is surprisingly low as evident from experiments being conducted on pigs fed with contaminated mine water to their food ratio as a salt additive. Degteva et al. (1994) accounted the dose received by individuals residing on the adjoining banks of Techa river (Russia) and its flood plains due to release of fission products (primarily ^{90}Sr) from the plutonium production facility “Mayak” from 1949 to 1956. The medium dose to the red bone marrow was about 250 mSv and the mean dose about 400 mSv (Degteva et al. 1994, 1996, 2000). Yablokov et al. (2008) studied the secondary ^{90}Sr contamination of freshwater ecosystems and found that the vertical migration velocity of ^{90}Sr in flood plains, lowland moors, peat bogs, etc. is about 2–4 cm year^{-1}, where plants play a major role in absorption and subsequent taking it to the surface again. This soil to surface transfer leads to a persisting activity in the upper soil horizons and consequently to doses of internal irradiation in the contaminated territories. Delistraty and Van Verst (2009) measured the tissue radiostrontium levels in water bird which are compared to upland birds from two time periods (1971–1990 vs. 1991–2009) and different locations (on-site and off-site). On-site median concentration of ^{90}Sr in bones of water birds was significantly higher than those in on-site upland birds (1991–2009) and on-site median concentrations in 1971–1990 were significantly higher than those in 1991–2009 for ^{90}Sr in water bird muscle (Delistraty and Van Verst 2009). Median concentrations of ^{90}Sr in bone were significantly higher than those in muscle for both avian groups (water and upland) and both locations. This study undoubtedly proves that the absorption mechanism of ^{90}Sr in the body is very similar to calcium (Delistraty and Van Verst 2009).

In soil and water, plants are the first links in the transfer chain of ^{90}Sr from the environment to human food (Moyen and Roblin 2010). Vose and Koontz (1959) have compared the Ca and ^{90}Sr absorption by different species of clover and grass grown in pots in three distinct soil types to distinguish species differences in uptaking strontium from the soil.

Metal Uptake by Plants: General Account

Metals in soil exist as a range of chemical species in a dynamic equilibrium; however, because of various factors like soil properties, solubility, ionic potential, biological constituents, etc. only a fraction of soil metal is readily available for plant uptake (Wenzel et al. 2003; Mitra et al. 2014). Therefore, plant-based remediation of contaminated soil (phytoremediation) can either be direct (where plants take up or absorb the metals through roots and subsequently translocate to the upper part of the plant) and rhizoremediation (where pollutants are confined to the rhizosphere only after transformation of the material either by enzymatic or root specific microbial actions) (Kuiper et al. 2004; Reboreda and Cacador 2008). Secretion of root exudates into the soil matrix plays a crucial role in heavy metal availability and uptake by plants (Mitra et al. 2014). However, the plant cell wall is functionally important in controlling metals uptake into the cytosol by immobilizing ions by providing histidyl groups, and extracellular carbohydrates such as callose and mucilage (Manara 2012). Admission of metals into plant tissue typically occurs through the root cellular membrane, where metals are directed towards the xylem through apoplast (Salt and Rauser 1995). Roots have high affinity chemical receptors to transport the ions into cells (Salt and Kramer 2000).

Effective reduction of heavy metals (HMs) in cytological active areas like cytoplasm and plasmids in the cells is mainly performed by common HM transporters involved in transportation to vacuole or in exclusion at plasma membrane. These HM transporters thereby help in reducing the levels of toxicity exerted by HMs as free radicals or indirect inducers of ROS in the sites (Inouhe et al. 2015). There are substantial evidences that many hyperaccumulator plants for various HMs are prevailed for these transportation mechanisms via xylem transport systems rather than their different detoxification mechanisms in the cells (Hossain et al. 2012; Socha and Guerinot 2014; Inouhe et al. 2015).

Strontium in Plants

Russell (1965) clarified the interactions of a typical vascular plant and radionuclide, which occurs at two levels: the first level is the aerial or shoot portion and the second level is the soil-root zone or rhizosphere of the plant. Accumulation of radionuclides by these two modes is interrelated, because radionuclides reaching the aerial part like foliage and shoot of the plant will ultimately be shed by the plant and eventually reach the soil (Russell 1965). However, two modes of radionuclide entry into plants are usually difficult to separate in practical scenario.

Significant portions of radionuclide solutions deposited on the leaf surfaces may get entry into the edible parts of plants (as for example, more than 40% of the cesium radioisotope in radishes) (Tukey et al. 1961; Oestling et al. 1989; Fortunati et al. 2004). Uptake of ^{90}Sr is also evident on leaf surfaces as it gets precipitated

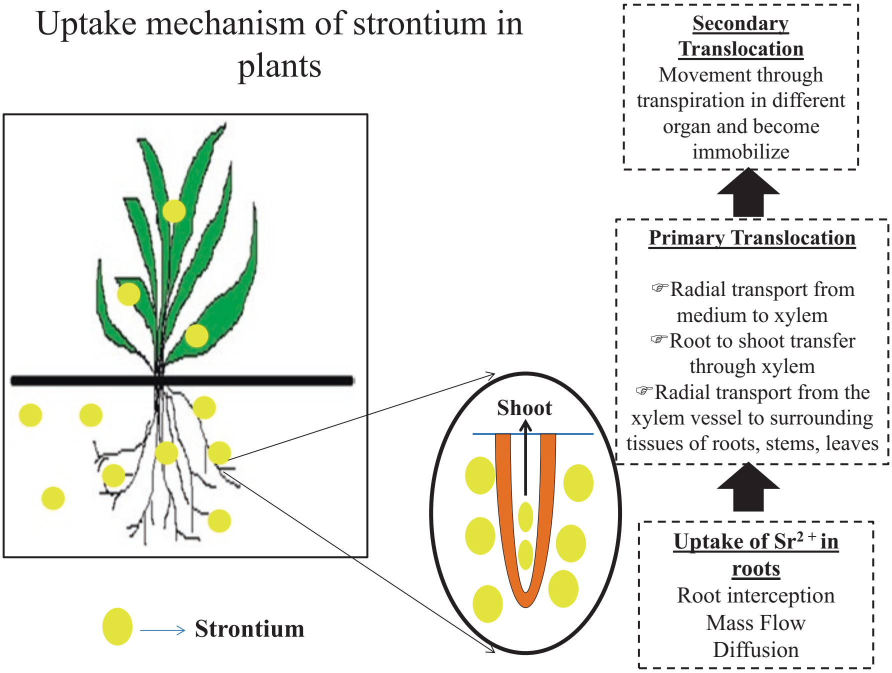

Fig. 1 Overview of uptake mechanism of strontium in plants

from atmospheric mist and contacting the leaf (cuticle and epidermis) (Fortunati et al. 2004). Both active and passive transport occurs for ^{90}Sr uptake via leaf epidermis, where it remains, as translocation from leafs to other plant parts is not common (Liu et al. 2016). According to Comar and Wasserman (1964), foliar uptake of Sr bears a non-specific competition with all the alkaline earth metals as compared to calcium alone for binding to sites on exchange compounds in case of passive transport, or on receptors in case of active transport. ^{90}Sr soil to root uptake depends on various physico-chemical factors of the soil components and the water-soluble form of the radionuclide (Fig. 1). Once the metal enters the body of the plant, it may get accumulated within the leaf tissues, while the accumulation of the metal in seeds and fruits is usually low (Asgari and Cornelis 2015). Even roots show lower activity in ^{90}Sr accumulation and translocation as compared to shoots (Wang et al. 2017). Willey (2014) has reported similar findings where plants showed more Sr in green shoots than woody parts, which is probably due to higher activity and flow of nutrients in green parts of the plants.

In 1950s, a study was conducted to assess the ^{90}Sr absorption in edible plants like wheat, rice, oats and barley. Lee (1959) studied the uptake of ^{90}Sr into wheat (Thatcher variety) and reported that the radioactivity in the kernels was about one-tenth in comparison with that of leaves and stems; milling of those kernels yielded flour with radioactivity lower than in brans. Ichikawa et al. (1962) reported the uptake of ^{90}Sr in rice due to root absorption from soil. Similar finding of root absorption of ^{90}Sr by rice was corroborated by Menzel et al. (1963), showing the definite observed pattern of radionuclide accumulation by field-grown crops.

Rickard and Price (1990) pointed out a positive correlation between ^{90}Sr concentrations in red canary grass grown near the nuclear reactor of the U.S. Department of Energy (Hanford site) in the eggshells of Canadian geese feeding on that red canary grass. This study was an important example of ^{90}Sr bioaccumulation across the food chain. Paasikallio et al. (1994) studied the soil to plant transfer of ^{90}Sr in different cereals and vegetables, where it was found that green leafy vegetables like lettuce and cabbage showed more accumulation, followed by cereals and tuberous vegetables (potato).

Strontium and Rhizosphere

Determining the plant-available fraction of a radionuclide is difficult considering the rhizospheric zone (Gupta et al. 2016a). The plant root-soil region is completely different from the bulk soil. Plants root exudates typically increase the richness of soil microflora (bacterial and fungal communities) by 1–4 orders of magnitude compared to the adjacent bulk soil that aids to degrade diverse pollutants (Anderson et al. 1994). The availability of metal to the plant depends upon the chemistries between soil fraction and variety of substances that a plant root exudes or releases that creates a micro-environment specific to the plants. Root exudates include: diffusates (e.g. organic or amino acids, inorganic ions, sugars, and water), excretions (e.g. bicarbonates, carbon dioxide, and protons), secretions (e.g. siderophores, mucilage, and allelopathic compounds) which help moderating soil microflora community structure to have a better variety of metabolic capabilities with unique gene pool (Hall 2002; LeDuc and Terry 2005; Mitra et al. 2014; Chatterjee et al. 2017a). As for instance, release of H^+ and HCO_3^- at root zone actively influences the pH in their immediate vicinity, thus increasing the accessibility of phosphorus and potassium (Gupta et al. 2016a).

Similarly, ammonium (NH_4^+) mobilizes Sr on soil surface, leading to increased Sr concentration in soil solution, although it inhibits uptake by plants, like that of calcium. Thus, common ammonium fertilizers like diammonium phosphate (DAP) and NPK may act as inhibitor for the soil to plant transfer of ^{90}Sr after a radioactive fallout in agricultural fields, acting as a countermeasure (Guillén et al. 2017).

Plant growth-promoting rhizobacteria (PGPR) perform an important role in development by reducing the physiological stress in plants, when grown in contaminated soils. By stimulating the production of plant growth regulators like indole acetic acid, gibberellic acid, cytokinins and ethylene, PGPR helps in rhizospheric colonization. This microbial colonization contributes to plant health and better response. Rhizobacteria can also secrete antibiotics, hydrocyanic acid, phosphate solubilizing substances, siderophores and 1-aminocyclopropane-1-carboxylic acid (ACC) to increase bioavailability and root absorption of different metals (Meyer 2000; Davies et al. 2001; Gupta et al. 2016a). Burd et al. (1998) reported that after adding of *Kluyvera ascorbata* SUD165/26 a related rhizobacteria, germination and growth of Indian mustard (*Brassica juncea*) seeds was increased by 50–100% in a nickel-contaminated soil.

Number of metal transporter-proteins show significant roles in homeostasis of heavy metals at root cell plasma membranes. Amid diverse group of transporter-proteins, NRAMP (natural resistance-associated macrophage protein), CDF (cation diffusion facilitator) family, ZIP (Zinc importer) families (ZRT, IRT-like Protein; [ZRT—Zinc regulated transporter, IRT—iron regulated transporter]), heavy metal ATPases (HMAs) family like P1B-ATPases, ATP-binding cassette (ABC) transporters, copper transporter (COPT) family proteins, ABC transporters of the mitochondria (ATM), multidrug resistance associated proteins (MRP), Ca^{2+} cation antiporter (CAX), and yellow-stripe-like (YSL) pleiotropic drug resistance (PDR) transporters are well studied (Dubey 2011; Huang et al. 2012; Gupta et al. 2013, 2016a). A ZIP family transporter with histidine-rich domain is important in activated response and uptake to divalent metal ions (Kramer et al. 2007). Nishida et al. (2008) reported that IRT1 is responsible for transportation of metals like Fe^{2+}, Mn^{2+}, Zn^{2+} and Cd^{2+} in root cells of *A. thaliana*. Internal transporters like HMAs family transporters (P1B-type ATPases) help in loading of metals like Cd and Zn from the surrounding tissues into the xylem and performing as an efflux pump (Kramer et al. 2007). Sequestration of heavy metals at vacuole level is mainly carried out by AtHMA3 transporter present in the tonoplast membrane (Manara 2012; Gupta et al. 2013). Plants have their own general tactics that use vacuolar sequestration through proton pumps like vacuolar proton-ATPase (V-ATPase) and vacuolar protonpyrophosphatase (V-PPase) to isolate metals from metabolically active cytosol and cellular organelles (Dalcorso et al. 2010).

Sr Removal from Soil: Phytoremediation Approach

Removal of ^{90}Sr from soil is an interesting study carried out by different workers. As per the field study of Fuhrmann et al. (2002) on redroot pigweed (*Amaranthus retroflexus*), Indian mustard (*Brassica juncea*), and tepary bean (*Phaseolus acutifolius*) to determine the ability of extraction of ^{90}Sr from contaminated soil, it was found that the redroot pigweed was a most potent accumulator (estimated time required for removal of 50% of ^{90}Sr is 7 years, assuming two crops per year). *Calotropis gigantea* plants were also studied to remove ^{90}Sr from soil, where Eapen et al. (2006) demonstrated 90% of the radioactivity can be removed within 24 h. Broadley et al. (2003, 2004) and Willey and Fawcett (2006) identified the efficiency of Caryophyllidae (Eudicot plants, viz. amaranth, buckwheat, chards and beets; most of them being agriculturally important plants) clades for the transfer of alkali earth metals particularly ^{90}Sr from soil to roots.

Zheng et al. (2016) studied angiosperm *Tillandsia usneoides* (Bromeliaceae, known as Spanish moss, an established bio-monitor of air pollution) as a bio-indicator for ^{90}Sr, as this plant can tolerate Sr for an elongated period and has a very high uptake ratio which has a positive correlation with concentration of Sr in solution. It was also reported that high Sr concentration inhibits chlorophyll content due to oxidative stress, while low concentration promotes chlorophyll synthesis in Spanish moss (Zheng et al. 2016). Maxwell et al. (2010) and Amano et al. (2016) reported different methodologies to determine the concentration of ^{90}Sr in edible vegetation samples using liquid scintillation counting (LSC) and inductively coupled plasma (ICP)-mass spectrometry (MS).

Weed plants, in many a times, have been hyperaccumulators of metals or radionuclides (Wenzel et al. 1999; IAEA 2006). The soil-to-plant transfer factor accounts for the uptake of radionuclides via plant roots and represents the activity concentration ratio of the radionuclide per unit dry mass in the plant (Bq kg^{-1}) to that in the soil, designated as Fv (IAEA 2009, 2010). Attar et al. (2016) studied the effect of ageing on the transfer of ^{90}Sr to lettuce (*Lactuca sativa*) and winter wheat (*Triticum aestivum*) with respect to a clayey soil and semi-arid environment in Syria. Moderate accumulation of ^{90}Sr from soil may be compensated by high biomass and fast growth (Hernandez-Allica et al. 2008). Several authors have worked on the suitability of rice, wheat, rye and oat where existing data indicates that oats may be a better accumulator of ^{90}Sr as compared to wheat and rye (Krouglov et al. 1997; Soudek et al. 2006; Schimmack et al. 2007). In case of both rice and oats, it was also found that in the main plant where around 99% of ^{90}Sr is stored is the non-edible overground parts, i.e. leaves and stems as compared to roots because roots have lower biomass (Tsukada et al. 2005; Lin et al. 2015). As per the available reports, the activity concentration in a nutrient solution of 1 Bq L^{-1} of ^{90}Sr or ^{137}Cs corresponds to ca. 2×10^{-15} Moles L^{-1} however, the average concentrations of chemical homologues like K, Ca, and Mg, in soil solution are in the order of 1 mMoles L^{-1} . Uptake and co-precipitation of radionuclides like radioactive strontium by plants is therefore affected by many soil factors, where cation exchanges reactions regulate the concentration of a competitive ion, like Sr, in soil solution. Sorption of radiostrontium is governed by reversible exchange with major cations like Ca^{2+}. Although Sr is exchanged in preference to Ca in minerals, the preference of the same metal may get changed when organic matters are present (Chu et al. 2015).

Strontium Exposure, Plant Responses and Phytoremediation

Irrespective of biological necessity, plants usually take up several cations present in their root region. When plants are exposed to radionuclide and ionizing radiation, cellular and molecular effects take place, involving direct damage of macromolecules or indirect radiolytic reactions producing reactive oxygen species (ROS) (Gupta et al. 2016b, 2017). Ionizing radiation can induce DNA strand breaks, lipid oxidation, or enzyme denaturation (Gupta and Walther 2014; Gupta et al. 2016a). Antioxidative defence system of plants having enzymes (e.g. superoxide dismutase (SOD) and catalase (CAT)) and metabolites (e.g. ascorbate and glutathione) controls the ROS within cellular systems (Gupta and Sandalio 2012). Plants employ complex coordinated mechanism for metal tolerance mechanisms involving both biochemical and physiological processes. To cope with toxic effects of radionuclides, plants may avoid (restricting the metal uptake) or tolerate (survive in the presence of high internal metal concentration) the stress condition (Chatterjee et al. 2017b). Avoidance mechanism of plants involves concentration reduction of metal entering into the cell by extracellular precipitation, biosorption to cell walls, reduced uptake, and/or by increased efflux (Gupta and Walther 2014; Gupta et al. 2016a). Elaborate physiological responses are also present in plants like intracellular chelation by synthesizing organic acids, amino acids, glutathione (GSH), and/or by metal-binding ligands such as phytochelatins (PCs) and metallothioneins (MTs), vacuolar compartmentalization, glyoxalase systems and up-regulation of antioxidant defence to defy the harmful effects rooted by ROS (Gupta and Sandalio 2012; Gupta et al. 2016a).

Sasmaz and Sasmaz (2009) studied Sr phytoremediation potential in *Euphorbia macroclada*, *Verbascum cheiranthifolium* and *Astragalus gummifer*, where they investigated the roots and shoots of the plants for distribution and accumulation of the metal. The Sr enrichment factors for root (ECR) and shoot (ECS) and mean translocation factors (TLF) of these plants were examined and the authors found that the shoots of these plant (*Euphorbia macroclada*, *Verbascum cheiranthifolium* and *Astragalus gummifer*) were competent Sr bioaccumulator (having high TLF) which may be used in amelioration of Sr-contaminated soil (Sasmaz and Sasmaz 2009). The probable use of coyote willow (*Salix exigua*) plants for phytoextraction of the soil Sr through the plant roots and into above-ground shoots is being tested by the Department of Energy (DOE), USA, to protect the environment contaminated with ^{90}Sr (Fellows et al. 2009). The study showed that, as plants take up ^{90}Sr from soil, the soil content of the ^{90}Sr is also being reduced. Further, the study also pointed out that the hazard for detectable transfer of ^{90}Sr through the food chain of herbivorous insects from willow trees grown in the Sr-contaminated soil is minor to nonexistent (Fellows et al. 2009). Wang et al. (2017) studied phytoremediation of Sr-contaminated soil by *Sorghum bicolor*. This study examined soil microbial community-level physiological profiles (CLPPs), where it was found that Sr-spiked soil is having enhanced soil-microbial diversity and activity with considerable augmentation in the height and the stem biomass weight of the plant (with Sr content in tissues decreased in the order of leaves > roots > stems) (Wang et al. 2017).

Conclusion

^{90}Sr is a fission product of uranium (U) and plutonium (Pu). Anthropogenic activities led to discharge and waste disposal of Sr in many places of the world that impacted soil and groundwater. There are certain factors for implementing specific plants for restoration of radionuclide-contaminated sites, which includes relative high levels uptake potential of plants for the radioactive material and growth or high biomass production. Potential plants must amass radionuclide in the above-ground parts at a proportion which significantly exceeds the soil concentration. Several factors limit the application of plant-based techniques that affect the Sr uptake by plants, which include clay/soil particle/minerals properties, and availability of organic matters. However, phytoremediation might be the appropriate and easy technique for restoration of radionuclide-contaminated soil if selected cultivars are used. Therefore, detailed research on plants selection, manipulation of diverse transporters, and explication of anti-stress physiology factors in plants are the area which will be useful to decontaminate Sr-contaminated soil in an eco-friendly manner.

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References

Amano H, Sakamoto H, Shiga N, Suzuki K (2016) Method for rapid screening analysis of Sr-90 in edible plant samples collected near Fukushima, Japan. Appl Radiat Isot 112:131–135

Anderson TA, Kruger EL, Coats JR (1994) Enhanced degradation of a mixture of three herbicides in the rhizosphere of a herbicide-tolerant plant. Chemosphere 28:1551–1557

Arora M, Kiran B, Rani S, Rani A, Kaur B, Mittal N (2008) Heavy metal accumulation in vegetables irrigated with water from diff sources. Food Chem 111:811–815

Asgari K, Cornelis WM (2015) Heavy metal accumulation in soils and grains, and health risks associated with use of treated municipal wastewater in subsurface drip irrigation. Environ Monit Assess 187:410

ATSDR-Agency for Toxic Substances and Disease Registry USA (2004a) Toxicological profile for strontium. Agency for Toxic Substances and Disease Registry Division of Toxicology/Toxicology Information Branch Atlanta, Georgia. https://www.atsdr.cdc.gov/toxprofiles/tp159.pdf. Accessed 11 May 2017

ATSDR-Agency for Toxic Substances and Disease Registry USA (2004b) Public health statement. Strontium CAS#: 7440–24-6. https://www.atsdr.cdc.gov/ToxProfiles/tp159-c1-b.pdf. Accessed 12 May 2017

Attar LA, Oudat MA, Safia B, Ghani BA (2016) Ageing impact on the transfer factor of ^{137}Cs and ^{90}Sr to lettuce and winter wheat. J Environ Radioact 164:19–25

Avila R, Kautsky U, Ekström PA, Astrand PG, Saetre P (2013) Model of the long-term transport and accumulation of radionuclides in future landscapes. Ambio 42:497–505

Batlle JVI, Beresford NA, Beaugelin-Seiller K, Bezhenar R, Brown J, Cheng JJ, Cujic M, Dragovic S, Duffa C, Fievet B, Hosseini A, Jung KT, Kamboj S, Keum DK, Kryshev A, LePoire D, Maderich V, Min BI, Perianez R, Sazykina T, Suh KS, Yu C, Wang C, Heling R (2016) Inter comparison of dynamic models for radionuclide transfer to marine biota in a Fukushima accident scenario. J Environ Radioact 153:31–50

Beresford NA, Wood MD, Batlle JVI, Yankovich TL, Bradshaw C, Willey N (2016) Making the most of what we have: application of extrapolation approaches in radioecological wildlife transfer models. J Environ Radioact 151:373–386

Bolland MJ, Grey A (2014) A comparison of adverse event and fracture efficacy data for strontium ranelate in regulatory documents and the publication record. BMJ Open 4:e005787

Bolsunovsky A, 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

Broadley MR, Bowen HC, Cotterill HL, Hammond JP, Meacham MC, Mead A, White PJ (2003) Variation in the shoot calcium content of angiosperms. J Exp Bot 54:1431–1446

Broadley MR, Bowen HC, Cotterill HL, Hammond JP, Meacham MC, Mead A, White PJ (2004) Phylogenetic variation in the shoot mineral concentration of angiosperms. J Exp Bot 55:321–336

Burd GI, Dixon DG, Glick BR (1998) A plant growth-promoting bacterium that decreases nickel toxicity in seedlings. Appl Environ Microbiol 64:3663–3668

Castrillejo M, Casacuberta N, Breier CF, Pike SM, Masqué P, Buesseler KO (2016) Reassessment of ^{90}Sr, 137Cs, and ^{134}Cs in the Coast off Japan derived from the Fukushima Dai-ichi Nuclear Accident. Environ Sci Technol 50:173–180

Chatterjee S, Deb U, Datta S, Walther C, Gupta DK (2017a) Common explosive (TNT, RDX, HMX) and their fate in the environment: emphasizing bioremediation. Chemosphere 184:438–451

Chatterjee S, Sharma S, Gupta DK (2017b) Arsenic and its effect on major crop plants: stationary awareness to paradigm with special reference to rice crop. In: Gupta DK, Chatterjee S (eds) Arsenic contamination in the environment: The issues and solutions. Springer, New York, pp 123–143

Chawla F, Steinmann P, Pfeifer HR, Froidevaux P (2010) Atmospheric deposition and migration of artificial radionuclides in Alpine soils (Val Piora, Switzerland) compared to the distribution of selected major and trace elements. Sci Total Environ 408:3292–3302

Chu Q, Watanabe T, Sha Z, Osaki M, Shinano T (2015) Interactions between Cs, Sr, and other nutrients and trace element accumulation in Amaranthus shoot in response to variety effect. J Agric Food Chem 63:2355–2363

Claus B, Grahmann B, Hormann V, Keuneke S, Leder M, Müller H, Peters E, Rieger EM, Schmitz-Feuerhake I, Wagschal F (1990) Sr-90 transfer factors for rye in podzolic soils: dependence on soil parameters. Radiat Environ Biophys 29:241–245

Comar CL, Wasserman RH (1964) Strontium. In: Bronner F, Comar CL (eds) Mineral metabolism, vol. II, part A. Academic, New York

Corcho-Alvarado JA, Balsiger B, Sahli H, Astner M, Byrde F, Rollin S, Holzer R, Mosimann N, Wüthrich S, Jakob A, Burger M (2016) Long-term behavior of ^{90}Sr and ^{137}Cs in the environment: case studies in Switzerland. J Environ Radioact 160:54–63

Dalcorso G, Farinati S, Furini A (2010) Regulatory networks of cadmium stress in plants. Plant Signal Behav 5:1–5

Davies FT Jr, Puryear JD, Newton RJ (2001) Mycorrhizal fungi enhance accumulation and tolerance of chromium in sunflower (*Helianthus annuus*). J Plant Physiol 158:777–786

Degteva MO, Kozheurov VP, Vorobiova MI (1994) General approach to dose reconstruction in the population exposed as a result of the release of radioactive wastes into the Techa River. Sci Total Environ 142:49–61

Degteva MO, Kozheurov VP, Burmistrov DS, Vorobiova MI, Valchuk VV, Bougrov NG, Shishkina HA (1996) An approach to dose reconstruction for the Ural populations. Health Phys 71:71–76

Degteva MO, Vorobiova MI, Kozheurov VP, Tolstykh EI, Anspaugh LR, Napier BA (2000) Dose reconstruction system for the exposed population living along the Techa River. Health Phys 78:542–554

Delistraty D, van Verst S (2009) Tissue radionuclide concentrations in water birds and upland birds on the Hanford Site (USA) from 1971-2009. Ann N Y Acad Sci 1181:223–236

Dubey RS (2011) Metal toxicity, oxidative stress and antioxidative defense system in plants. In: Gupta SD (ed) Reactive oxygen species and antioxidants in higher plants. CRC Press, Boca Raton

Eapen S, Singh S, Thorat V, Kaushik CP, Raj K, D’Souza SF (2006) Phytoremediation of radiostrontium ((90)Sr) and radiocesium ((137)Cs) using giant milky weed (*Calotropis gigantea* R.Br.) plants. Chemosphere 65:2071–2073

Ehlken S, Kirchner G (2002) Environmental processes affecting plant root uptake of radioactive trace elements and variability of transfer factor data: a review. J Environ Radioact 58:97–112

Eisenbud M, Gesell T (1997) Environmental radioactivity from natural, industrial and military sources, 4th edn. Academic, New York

Fellows RJ, Fruchter JS, Driver CJ (2009) 100-N Area Strontium-90 Treatability Demonstration Project: food chain transfer studies for phytoremediation along the 100-N Columbia River Riparian Zone. U.S. Department of Energy (PNNL-18294), Pacific Northwest National Laboratory, Washington. http://www.pnl.gov/main/publications/external/technical_reports/PNNL-18294.pdf

Fesenko S, Fesenko J, Sanzharova N, Karpenko E, Titov I (2011) Radionuclide transfer to freshwater biota species: review of Russian language studies. J Environ Radioact 102:8–25

Fortunati P, Brambilla M, Speroni F, Carini F (2004) Foliar uptake of ^{134}Cs and ^{85}Sr in strawberry as function by leaf age. J Environ Radioact 71:187–199

Fowler SW, Buat-Menard P, Yokoyama Y, Ballestra S, Holm E, Nguyen HV (1987) Rapid removal of Chernobyl fallout from Mediterranean surface waters by biological activity. Nature 329:56–58

Fuhrmann M, Lasat MM, Ebbs SD, Kochian LV, Cornish J (2002) Uptake of cesium-137 and strontium-90 from contaminated soil by three plant species; application to phytoremediation. J Environ Qual 31:904–909

Fujimoto K, Miki S, Kaeriyama H, Shigenobu Y, Takagi K, Ambe D, Ono T, Watanabe T, Morinaga K, Nakata K, Morita T (2015) Use of otolith for detecting strontium-90 in fish from the harbor of Fukushima Dai-ichi Nuclear Power Plant. Environ Sci Technol 49:7294–7301

Gastberger M, Steinhäusler F, Gerzabek MH, Lettner H, Hubmer A (2000) Soil-to-plant transfer of fallout caesium and strontium in Austrian lowland and alpine pastures. J Environ Radioact 49:217–233

Guillén J, Muñoz-Muñoz G, Baeza A, Salas A, Mocanu N (2017) Modification of the 137Cs, ^{90}Sr, and ^{60}Co transfer to wheat plantlets by NH^{4+} fertilizers. Environ Sci Pollut Res Int 24:7383–7391

Gupta DK, Sandalio LM (2012) Metal toxicity in plants: perception, signaling and remediation. Springer, New York

Gupta DK, Walther C (2014) Radionuclide contamination and remediation through plants. Springer, New York

Gupta DK, Huang HG, Corpas FJ (2013) Lead tolerance in plants: strategies for phytoremediation. Environ Sci Pollut Res 20:2150–2161

Gupta DK, Chatterjee S, Datta S, Voronina AV, Walther C (2016a) Radionuclides: accumulation and transport in plants. Rev Environ Contam Toxicol 241:139–160

Gupta DK, Tawussi F, Hamann L, Walther C (2016b) Moderate uranium disturbs the nutritional status and induces oxidative stress in *Pisum sativum* L. J Plant Physiol Pathol 4:1

Gupta DK, Tawussi F, Hölzer A, Hamann L, Walther C (2017) Investigation of low level ^{242}Pu contamination on nutrition disturbance and oxidative stress in *Solanum tuberosum* L. Environ Sci Pollut Res. doi: 10.1007/s11356-017-9071-9

Gustafson PF (1959) Ratio of cesium-137 and strontium-90 radioactivity in soil. Science 130:1404–1405

Hall JL (2002) Cellular mechanism for heavy metal detoxification and tolerance. J Exp Bot 53:1–11

Hernandez-Allica J, Becerril JM, Garbisu C (2008) Assessment of the phytoextraction potential of high biomass crop plants. Environ Pollut 152:32–40

Hossain MA, Piyatida P, Teixeira da Silva JA, Fujita M (2012) Molecular mechanism of heavy metal toxicity and tolerance in plants: central role of glutathione in detoxification of reactive oxygen species and Methylglyoxal and in heavy metal chelation. J Bot 2012:872875. 37

Huang J, Zhang Y, Peng JS, Zhong C, Yi HY, Ow DW, Gong JM (2012) Fission yeast HMT1 lowers seed cadmium through phytochelatin-dependent vacuolar sequestration in Arabidopsis. Plant Physiol 158:1779–1788

IAEA (2006) Classification of soil systems on the basis of transfer of radionuclides from soil to reference plants. IAEA-TECDOC-1497, pp 250

IAEA (2009) Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments. IAEA, Vienna. TecDoc-1616

IAEA (2010) Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments. IAEA, Vienna. Technical Report Series No. 472

IAEA (2014) Handbook of parameter values for the prediction of radionuclide transfer to wildlife. IAEA, Vienna. Technical Reports Series No. 479

Ichikawa R, Eto M, Abe M (1962) Strontium-90 and Cesium-137 absorbed by rice plants in Japan, 1960. Science 135:1072

Inouhe M, Sakuma Y, Chatterjee S, Datta S, Jagetiya BL, Voronina AV, Walther C, Gupta DK (2015) General roles of phytochelatins and other peptides in plant defense mechanisms against oxidative stress/primary and secondary damages induced by heavy metals. In: Gupta DK, Palma JM, Corpas FJ (eds) Reactive oxygen species and oxidative damage in plants under stress. Springer, Berlin, pp 219–245

Kamenova-Totzeva RM, Totzev AV, Kotova RM, Badulin VM (2017) Radionuclides content in pasteurized cow milk: Dose estimation. Radiat Prot Dosim 174:464–470

Karube Z, Inuzuka Y, Tanaka A, Kurishima K, Kihou N, Shibata Y (2016) Radiostrontium monitoring of bivalves from the Pacific coast of eastern Japan. Environ Sci Pollut Res 23:17095–17104

Konovalenko L, Bradshaw C, Andersson E, Lindqvist D, Kautsky U (2016) Evaluation of factors influencing accumulation of stable Sr and Cs in lake and coastal fish. J Environ Radioact 160:64–79

Koranda JJ, Robison WL (1978) Accumulation of radionuclides by plants as a monitor system. Environ Health Perspect 27:165–179

Kovacheva P, Slaveikova M, Todorov B, Djingova R (2014) Influence of temperature decrease and soil drought on the geochemical fractionation of ^{60}Co and ^{137}Cs in fluvisol and cambisol soils. Appl Geochem 50:74–81

Kramer U, Talke IN, Hanikenne M (2007) Transition metal transport. FEBS Lett 581:2263–2272

Krouglov SV, Filipas AS, Alexakhin RM, Arkhipov NP (1997) Long-term study on the transfer of ^{133}Cs and ^{90}Sr from Chernobyl-contaminated soils to grain crops. J Environ Radioact 34:267–286

Kryshev AI (2006) ^{90}Sr in fish: a review of data and possible model approach. Sci Total Environ 370:182–189

Kuiper I, Lagendijk EL, Bloemberg GV, Lugtenberg JJ (2004) Rhizoremediation: a beneficial plant-microbe interaction. Mol Plant Microbe Int 17:6–15

LeDuc DL, Terry N (2005) Phytoremediation of toxic trace elements in soil and water. J Ind Microbiol Biotechnol 32:514–520

Lee CC (1959) Distribution of radioactivity in wheat plants grown in the presence of strontium-90. Science 129:1280

Lee MH, Clark SB (2005) Activities of Pu and Am isotopes and isotopic ratios in a soil contaminated by weapons-grade plutonium. Environ Sci Technol 39:5512–5516

Lin Q, Xiaoliang Q, Li F-M, Kadambot H, Siddique M, Brandl H, Xu J, Li X (2015) Uptake and distribution of stable strontium in 26 cultivars of three crop species: oats, wheat, and barley for their potential use in phytoremediation. Int J Phytorem 17:264–271

Lipscy P, Kushida K, Incerti T (2013) The Fukushima disaster and Japan's Nuclear Plant vulnerability in comparative perspective. Environ Sci Technol 47:6082–6088

Liu HC, Chung CH, You CF, Chiang YH (2016) Determination of ^{87}Sr/^{86}Sr and $\delta^{88/86}$Sr ratios in plant materials using MC-ICP-MS. Anal Bioanal Chem 408:387–397

Lukšienė B, Puzas A, Remeikis V, Druteikienė R, Gudelis A, Gvozdaitė R, Buivydas Š, Davidonis R, Kandrotas G (2015) Spatial patterns and ratios of ^{137}Cs, ^{90}Sr, and Pu isotopes in the top layer of undisturbed meadow soils as indicators for contamination origin. Environ Monit Assess 187:268

Mahmoud NS, El-Hemamy ST (2005) On the possible leakage of ET-RR1 liquid waste tank: hydrological and migration modes studies. Sci World J 5:234–252

Maloshtan I, Polishchuk S, Kashparov V, Yoschenko V (2017) Assessment of radiological efficiency of countermeasures on peat-bog soils of Ukrainian Polissya. J Environ Radioact 175–176:52–59

Manara A (2012) Plants and heavy metals. In: Furini A (ed) Springer briefs in molecular sciences. Springer, New York, pp 27–53

Maskalchuk LN, Baklaia AA, Konoplevb AV, Leontievaa TG (2014) Migration of ^{90}Sr in the solid phase of the soil–soil solution–plant systems and ways to reduce It. Radiochemistry 56:222–225

Maxwell SL, Culligan BK, Noyes GW (2010) Rapid separation of actinides and radiostrontium in vegetation samples. J Radiol Nucl Chem 286:273–282

Menzel RG (1960) Transport of Strontium-90 in runoff. Science 31:499–500

Menzel RG, Roberts H Jr, Stewart EH, Mackenzie AJ (1963) Strontium-90 accumulation on plant foliage during rainfall. Science 142:576–577

Merz S, Shozugawa K, Steinhauser G (2016) Effective and ecological half-lives of ^{90}Sr and ^{137}Cs observed in wheat and rice in Japan. J Radioanal Nucl Chem 307:1807–1810

Meyer JM (2000) Pyoverdines: pigments siderophores and potential taxonomic markers of fluorescent *Pseudomonas* species. Arch Microbiol 174:135–142

Mitra A, Chatterjee S, Datta S, Sharma S, Veer V, Razafindrabe BHM, Walther C, Gupta DK (2014) Mechanism of metal transporters in plants. In: Gupta DK, Chatterjee S (eds) Heavy metal remediation. Nova Science, New York, pp 1–28

Moyen C, Roblin G (2010) Uptake and translocation of strontium in hydroponically grown maize plants, and subsequent effects on tissue ion content, growth and chlorophyll a/b ratio: comparison with Ca effects. Environ Exp Bot 68:247–257

Nakano T (2016) Potential uses of stable isotope ratios of Sr, Nd, and Pb in geological materials for environmental studies. Proc Jpn Acad Ser B Phys Biol Sci 92:167–184

Nelson DJ (1962) Clams as indicators of Strontium-90. Science 137:38–39

Nishida S, Mizuno T, Obata H (2008) Involvement of histidine-rich domain of ZIP family transporter TjZNT1 in metal ion specificity. Plant Physiol Biochem 46:601–606

O'Donnell S, Cranney A, Wells GA, Adachi JD, Reginster JY (2008) Strontium ranelate for preventing and treating postmenopausal osteoporosis. Cochrane Database Syst Rev (4):CD005326.

Oestling O, Kopp P, Burkart W (1989) Foliar uptake of cesium, iodine and strontium and their transfer to the edible parts of beans, potatoes and radishes. Intl J Rad Appl Instrum C Radiat Phys Chem 33:551–554

Outola I, Saxen RL, Heinavaara S (2009) Transfer of ^{90}Sr into fish in Finnish lakes. J Environ Radioact 100:657–664

Paasikallio A, Rantavaara A, Sippola J (1994) The transfer of cesium-137 and strontium-90 from soil to food crops after the Chernobyl accident. Sci Total Environ 155:109–124

Pourcelot L, Steinmann P, Froidevaux P (2007) Lower variability of radionuclide activities in upland dairy products compared to soils and vegetation: implication for environmental survey. Chemosphere 66:1571–1579

Pröhl G, Ehlken S, Fiedler I, Kirchner G, Klemt E, Zibold G (2006) Ecological half-lives of ^{90}Sr and ^{137}Cs in terrestrial and aquatic ecosystems. J Environ Radioact 91:41–72

Qi L, Qin X, Li F-M, Siddique KHM, Brandl H, Xu J, Li X (2015) Uptake and distribution of stable strontium in 26 cultivars of three crop species: oats, wheat, and barley for their potential use in phytoremediation. Int J Phytoremediation 17:264–271

Rabideau AJ, Van Benschoten J, Patel A, Bandilla K (2005) Performance assessment of a zeolite treatment wall for removing Sr-90 from groundwater. J Contam Hydrol 79:1–24

Reboreda R, Cacador I (2008) Enzymatic activity in the rhizosphere of *Spartina maritime*: potential contribution for phytoremediation of metals. Mar Environ Res 65:77–84

Rickard WH, Price KR (1990) Strontium-90 in Canada goose eggshells and reed canary grass from the Columbia River, Washington. Environ Monit Assess 14:71–76

Russell RS (1965) Interception and retention of airborne material on plants. Health Phys 11:1305

Ruttenber AJ, Kreiss K, Douglas RL, Buhl TE, Millard J (1984) The assessment of human exposure to radionuclides from a uranium mill tailings release and mined watering effluent. Health Phys 47:21–35

Salt DE, Kramer U (2000) Mechanisms of metal hyperaccumulation in plants. In: Raskin I, Ensley BD (eds) Phytoremediation of toxic metals: using plants to clean up the environment. Wiley, New York, pp 231–245

Salt DE, Rauser WE (1995) Mg ATP-dependent transport of phytochelatins across the tonoplast of oat roots. Plant Physiol 107:1293–1301

Sanzharova NI, Sysoeva AA, Isamov NN (2005) Ross Khim Zh 49:26–34

Sasmaz A, Sasmaz M (2009) The phytoremediation potential for strontium of indigenous plants growing in a mining area. Environ Exp Bot 67:139–144

Saxen R, Koskelainen U (2002) Distribution of ^{137}Cs and ^{90}Sr in various tissues and organs of freshwater fish in Finnish lakes. Boreal Environ Res 7:105–112

Schimmack W, Gerstmann U, Schultz W, Sommer M, Tschopp V, Zimmermann G (2007) Intra-cultivar variability of the soil-to-grain transfer of fallout ^{137}Cs and ^{90}Sr for winter wheat. J Environ Radioact 94:16–30

Shcheglov AI, Tsvetnova OB (2004) Basic features of seasonal and multi-year dynamics of Cs-137 and Sr-90 in wood. Radiats Biol Radioecol 44:113–117

Socha AL, Guerinot ML (2014) Mn-euvering manganese: the role of transporter gene family members in manganese uptake and mobilization in plants. Front Plant Sci 5:106

Solovitch-Vella N, Pourcelot L, Chen VT, Froidevaux P, Gauthier-Lafaye F, Stille P, Aubert D (2007) Comparative migration behaviour of ^{90}Sr, $^{239+240}$Pu and ^{241}Am in mineral and organic soils of France. Appl Geochem 22:2526–2535

Soudek P, Valenova S, Vavrıkova Z, Vanek T (2006) ^{137}Cs and ^{90}Sr uptake by sunflower cultivated under hydroponic conditions. J Environ Radioact 88:236–250

Sowa I, Wójciak-Kosior M, Strzemski M, Dresler S, Szwerc W, Blicharski T, Szymczak G, Kocjan R (2014) Biofortification of Soy (*Glycine max* (L.) Merr.) with Strontium Ions. J Agric Food Chem 62:5248–5252

Strebl F, Ehlken S, Gerzabek MH, Kirchner G (2007) Behaviour of radionuclides in soil/crop systems following contamination. In: Baxter MS (ed) Radioactivity in the environment. Elsevier, Amsterdam, pp 19–42

Therapeutic Goods Administration (2014) Strontium ranelate (Protos) and risk of adverse events: safety advisory. Australian Government Department of Health, Canberra, 3 Apr 2014. www.tga.gov.au/alert/strontium-ranelateprotos-and-risk-adverse-events-0 [cited 1 Mar 2016]

Tomilin IA, Vinitsukevich NV, Minin VL (1987) Preliminary radiation hygiene evaluation of the meat of animals whose feed was supplemented with mine water. Vopr Pitan 1:61–64

Tsukada H, Takeda A, Takahashi T, Hasegawa H, Hisamatsu S, Inab J (2005) Uptake and distribution of ^{90}Sr and stable Sr in rice plants. J Environ Radioact 81:221–231

Tukey HB, Wittwer SH, Bukovac MJ (1961) Absorption of radionuclides by aboveground plant parts and movement within the plant. J Agric Food Chem 9:106–113

Van Leeuwen HP, Koster W (2004) Physicochemical kinetics and transport at biointerfaces.V-9. Series on Analytical and Physical Chemistry of Environmental Systems. © IUPAC.

Volkle H, Murith C, Surbeck H (1989) Fallout from atmospheric bomb tests and releases from nuclear installations. Radiat Phys Chem 34:261–277

Vose PB, Koontz HV (1959) Uptake of strontium by pasture plants and its possible significance in relation to the fall-out of Strontium-90. Nature 183:1447–1448

Wang X, Chen C, Wang J (2017) Phytoremediation of strontium contaminated soil by *Sorghum bicolor* (L) Moench and soil microbial community-level physiological profiles (CLPPs). Environ Sci Pol Res 24:7668–7678

Warner F, Harrison RM (1993) Radioecology after chernobyl: biogeochemical pathways of artificial radionuclides. Wiley, Chichester

Wenzel WW, Lombi E, Adriano DC (1999) Biogeochemical processes inthe rhizosphere: role in phytoremediation of metal-polluted soils. In: Prasad MNV, Hagemejer J (eds) Heavy metal stress in plants: from molecules to ecosystems. Springer, New York, pp 273–303

Wenzel WW, Bunkowski M, Puschenreiter M, Horak O (2003) Rhizosphere characteristics of indigenously growing nickel hyperaccumulator and excluder plants on serpentine soil. Environ Pollut 123:131–138

Willey NJ (2014) Soil to plant transfer of radionuclides: predicting the fate of multiple radioisotopes in plants. J Environ Radioact 133:31–34

Willey N, Fawcett K (2006) A phylogenetic effect on strontium concentrations in angiosperms. Environ Exp Bot 57:258–269

Yablokov AV, Nesterenko VB, Nesterenko AV (2008) Atmospheric, water, and soil contamination after Chernobyl. Radiat Prot Dosim 128:146–158

Yankovich TL, Beresford NA, Wood MD, Aono T, Andersson P, Barnett CL, Uchida S (2010) Whole-body to tissue concentration ratios for use in biota dose assessments for animals. Radiat Environ Biophys 49:549–565

Zheng G, Pemberton R, Li P (2016) Bioindicating potential of strontium contamination with Spanish moss *Tillandsia usneoides*. J Environ Radioact 152:23–27