$^{137}\text{Cs}$ Soil to Rice Transfer Factor and Soil Properties:
Fukushima and Kawauchi Case Study

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The long-term migration of $^{137}\text{Cs}$ in the environment is mainly through the $^{137}\text{Cs}$ adsorbed on the dispersed soil particles of various sizes. However, the transfer of $^{137}\text{Cs}$ from soil to plant, especially rice plant, remains questionable. The objective of this study is to determine the relation among soil characteristics, $^{137}\text{Cs}$ distribution and transfer factor (TF) of $^{137}\text{Cs}$ from soil to rice. In this study paddy fields in Kawauchi and Fukushima were chosen. This is because more studies have focused only on one sampling field and there have not been much discussion comparing various fields as envisaged in this study. The results have shown that TF for Kawauchi is 5-fold higher than that of Fukushima. Physicochemical properties of the soils showed that Fukushima soil has less percentage of exchangeable $^{137}\text{Cs}$ and high percentage of exchangeable K in contrast to Kawauchi soil. These factors likely disturbed the transfer of $^{137}\text{Cs}$ from soil into the rice plant. Powder X-ray diffraction has shown that Fukushima soil is rich in micaceous minerals which also release a lot of K$^+$ to distract the $^{137}\text{Cs}$ transfer. This study suggests that the presence of micaceous minerals in the soil would be a good amendment for radiocesium-contaminated rice paddy fields in enhancing adsorption of $^{137}\text{Cs}$ in the soil. However, there is still a need to investigate adsorption kinetics of $^{137}\text{Cs}$ to ascertain higher values of TF in Kawauchi soil.

Key Words: exchangeable cations, $^{137}\text{Cs}$ transfer factor, Kawauchi, Fukushima, adsorption

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1. Introduction

The earthquake which triggered tsunami on 11 March 2011 led radionuclides to escape from three boiling water reactor (BWR) units of Fukushima Daiichi Nuclear Power Plant (FDNPP) in Japan which are earmarked as the main source of radiocesium expelled into the surrounding environment. Apart from nuclear disasters, distribution of $^{134+137}\text{Cs}$ in the environment also relies on other sources such as nuclear weapon tests, submarines and leaching from radioactive waste disposal facilities. Following Chernobyl (1986) and Fukushima (2011) disasters, large amount of radiocesium were discharged into terrestrial, aquatic, and marine environment worldwide. $^{137}\text{Cs}$ is a significant pollutant because of its large mass production during nuclear fission process and its longer half-life (30.07 years) compared to $^{134}\text{Cs}$ (half-life 2.06 years). The long-lived $^{137}\text{Cs}$ is an important indicator of radioactive pollution in terrestrial environments. Much of the $^{137}\text{Cs}$ from cold war era decades ago subsequently decayed away. Meanwhile the main concern


has been $^{137}$Cs expelled from the FDNPP and the Chernobyl accident.

Because of its chemical properties, $^{137}$Cs is readily carried through the environment and food chains. Cesium-137 is easily soluble in water, it can be absorbed by plants and assimilated by animals because it is chemically analogous to potassium and can cause long time internal irradiation. Foods such as rice contain detectable amount of radioactivity which goes into human body via the ingestion pathway. Cesium-137 and 134 and $^{90}$Sr are the common artificial radionuclides included in food and water.

The soil-to-plant transfer factor (TF), also called the concentration ratio, is related to the amount of an element in a plant under study to that in the source soil. The TF deals with long-term, chronic exposures and is ideally measured at equilibrium. Mainly transfer factors are used in risk assessments to estimate the amount of radioactivity that could be present in a food crop based on the concentration in the source soil. By determining the concentration in the food, the total intake, or a dose calculated from the annual intake, can be estimated. The TF is widely used to describe the soil-to-plant transfer of radionuclides through the plant roots.

Previous studies have reported that the plant uptake of radionuclides especially for $^{137}$Cs depends on factors such as soil pH, clay type, exchangeable K, Ca, Mg, organic matter content, particle size distribution and time itself and that the TFs are independent of the level of radionuclide contamination in the soil but are declined with time after contamination. However, it is still necessary to investigate the factors that determine the $^{137}$Cs uptake by plant such as oxidation state of the soil using Mössbauer spectroscopy and chemical composition of the soil using X-ray diffractometry. Yamaguchi et al. noted that soil chemical and physical properties significantly affect Cs$^+$ uptake while Zhu and Smolders found that exchangeable K$^+$ can play a strong counter-elemental activity for Cs uptake by rice and other plants while the uptake process of $^{134+137}$Cs depends on the type of circumstances. For example dissolved radiocesium is readily taken by rice roots via osmosis process, while it is difficult for adsorbed radiocesium in soil minerals to be transferred to rice plants via roots. Choi et al. noted that since rice normally grow in flooded fields, they tend to have a plant base uptake of the $^{137}$Cs in addition to root uptake of which base is the part of the plant immersed in the standing water. Further, the study by D’Souza and Mistry demonstrated that the uptake of radiocesium via the plant base was very efficient in flooded rice plants.

In this study we investigated the relation between soil characteristics (soil particle distribution, exchangeable cation and $^{137}$Cs, mineral composition, Fe oxidation state and $^{137}$Cs transfer factor) by analyzing the soil and rice samples from Fukushima and Kawauchi. The finding reveals complex factors that might influence the state of $^{137}$Cs released from the soil and its uptake by rice plant, that is important for evaluating the risk of radiological hazard through food chain. This study ensured the comparison of two study areas unlike other studies which have only focused on one particular area.

2. Materials and Methods

2.1. Study area

The samples were collected from two locations: Fukushima city and Kawauchi village within Fukushima Prefecture, Japan. There were 25 soil and 10 rice samples that were gathered. The first 5 soil and 5 rice samples from Kawauchi (longitude, latitude: 37.32087, 140.83568; 37.32090, 140.83600; 37.32068, 140.83585; 37.32042, 140.83571; 37.32047, 140.83607) 20 km away, southwest of FDNPP were taken on 22 August 2017. Later 20 soil samples and 5 rice samples were collected from Fukushima city 60 km away, northwest of FDNPP on 23 August 2018. The soil and rice samples were taken from a single field (K) in Kawauchi village and 4 paddy fields (F1, F2, F3 & F4) in Fukushima city (Fig. 1). Each sampling point covered an area of roughly 10 cm $\times$ 20 cm ranging from 0–5 cm depth.

2.2. Methodology

The soil samples were air dried at room temperature for 2 weeks and unwanted materials such as dead vegetation and large rocks were removed before sieving through 2 mm sieve. The samples were then oven dried at 110°C for 24 hours then packed into the U8 vessel (100 mL, 5 cm height, 5 cm diameter). The dried mature rice samples (10 in total) were each also packed into distinct vessel for radioactivity measurement. The activity of $^{134}$Cs, $^{137}$Cs and $^{90}$K in soil were analyzed by High Purity Germanium (HPGe) detector and multichannel analyzer (GEM 30–70, ORTEC) at gamma energy peak of 605, 662 and 1461 keV for $^{134}$Cs, $^{137}$Cs and $^{90}$K, respectively. Calibration of gamma spectrometer was conducted by using a set of standard sources (MX033U8PP) manufactured by the Japan Radioisotope Association.

Exchangeable major cations (Na$^+$, K$^+$, Mg$^{2+}$, Ca$^{2+}$) in soil samples were analyzed by using CH$_3$COONH$_4$ (1 M ammonium...
acetate) adjusted to pH 7, which was used as extractant. To each 5 g soil 25 mL of 1 M ammonium acetate was added. The mixture was then shaken by shaker (EYELA UNI THERMO SHAKER NTS-1300) for 24 h then extracted by centrifugation at 3000 rpm for 10 min. The supernatant from each sample was filtered using 0.45 μm filter paper. The clear solution of each sample was analyzed immediately using ICP-AES (SPS 3500, Hitachi). To determine exchangeable $^{137}$Cs and percentage of exchangeable $^{137}$Cs, $^{137}$Cs activity in soil samples were analyzed before and after treatment with 1 M ammonium acetate. The radioactivity of $^{137}$Cs was measured by HPGe and the difference in $^{137}$Cs radioactivity before and after treatment with 1M ammonium acetate was considered as exchangeable $^{137}$Cs.

Furthermore, to determine percentage of exchangeable $K^+$ which means exchangeable $K^+$ divided by total $K^+$ in soil, the total $K^+$ in soil based on total activity of $^{40}$K in soil measured by Gamma spectrometry was calculated. The following equations were used:

$$A = \lambda N$$  \hspace{1cm} (1)

where $A$ is activity concentration, $\lambda$ is the decay constant (s$^{-1}$) and $N$ is number of $^{40}$K. The decay constant was calculated based on the following equation:

$$\lambda = \frac{\ln 2}{t_{1/2}}$$  \hspace{1cm} (2)

where $t_{1/2}$ is half-life of $^{40}$K which is $1.248 \times 10^9$ y ($= 3.936 \times 10^{16}$ s). The mol of $^{40}$K was calculated based on the calculation result of equation (1) by the following expression:

$$N = N' \cdot m$$  \hspace{1cm} (3)

where $N'$ is Avogadro constant ($= 6.022 \times 10^{23}$ mol$^{-1}$) and $m$ is the moles of element ($^{40}$K). The mol of total K in soil was
finally calculated based on the natural abundance of $^{40}$K (0.0117%).

$$\text{Mol of Total K} = \frac{\text{mol of } ^{40}\text{K}}{0.0117\%} \quad (4)$$

Particle size distribution of the soil samples was determined through the horizontal shaking column of 2 mm, 850 μm, 250 μm, 75 μm sieves sequentially for 2 hours repeatedly.

Soil sample analysis for oxidation state of iron was conducted using the $^{57}$Fe Mössbauer spectroscopy. The measurement was set at 25°C with a $^{57}$Co (Rh) radiation source moving in a constant acceleration mode on Wissel MB-500. The Mössbauer parameters were obtained by least-squares fitting to Lorentzian peaks. The calibration of the spectra was achieved by the six lines of α-Fe, whose center was considered as zero isomer shift.

To determine the nature of soil component in Kawauchi and Fukushima, soil specimens were mounted on glass slides and the structure was determined by X-ray diffraction pattern acquired by Rigaku PXRD using Cu Kα radiation ($\lambda = 1.54059$ Å) at 40 kV and 44 mA, 2θ range from 3 ~ 80°, at room temperature. The PXRD data of each soil sample were analyzed by Match software by which the diffraction pattern could be compared with the patterns stored in the ICDD (International Centre for Diffraction Data) PDF database, resulting in phase identification. Studies using Match software are numerous.13–15)

### 3. Results and Discussion

#### 3.1. Radionuclides proportion decay-corrected to release day

Figure 2(a) and (b) show the radioactivity concentration decay-corrected to the release day for Fukushima and Kawauchi soil, respectively. Figure 2(a) depicts the results of Fukushima soil. $^{134}$Cs ranged from 2500 ± 50 to 3660 ± 130 Bq/kg with a mean value of 3160 ± 150 Bq/kg, $^{137}$Cs gave values of 2460 ± 60 to 3560 ± 110 Bq/kg with mean of 3100 ± 150 Bq/kg, and $^{40}$K was 286 ± 27 to 413 ± 18 Bq/kg with the average of 376 ± 23 Bq/kg.

On the other hand, Kawauchi soil (Fig. 2(b)) gave the following results: $^{134}$Cs from 505 ± 12 to 810 ± 19 Bq/kg with average of 638 ± 15 Bq/kg; $^{137}$Cs from 583 ± 15 to 877 ± 24 Bq/kg and mean of 720 ± 18 Bq/kg, and $^{40}$K from 548 ± 26 to 708 ± 37 Bq/kg with average of 622 ± 30 Bq/kg. The results show that the Fukushima soil was more contaminated by $^{137}$Cs and $^{134}$Cs than Kawauchi soil. One of the possibilities to explain the difference is maybe the difference in the direction of radioactive plume just after the accident or the difference in decontamination activity.

#### 3.2. Source of radiocesium in Fukushima

The release day ratios of $^{134}$Cs to $^{137}$Cs were as follows, F1: 1.01, F2: 1.01, F3: 1.03 and F4: 1.02 for Fukushima (Fig. 2(a)) while K1: 0.87, K2: 0.83, K3: 0.93, K4: 0.88, K5: 0.90 for Kawauchi (Fig. 2(b)). Nishihara et al. found that the $^{134}$Cs to $^{137}$Cs ratios of inventories in Units 1 to 3 at the shutdown time (March 11, 2011) were estimated as the highest for Unit 2.
portrays that the transfer factor of $^{137}$Cs is higher in Kawauchi paddy field compared to that of Fukushima despite the soils of Fukushima being more radioactive than that of Kawauchi.

Cesium-137 TF of Kawauchi that is 5 times larger than that of Fukushima is probably related to the exchangeable $^{137}$Cs and K$^+$ in those soils and the soil characteristics. The higher exchangeable $^{137}$Cs will result in higher $^{137}$Cs TF. For K$^+$ having quite similar chemical behavior with Cs$^+$, the higher exchangeable K$^+$ will reduce the $^{137}$Cs TF.

### 3.4. Exchangeable $^{137}$Cs and K$^+$ in Fukushima and Kawauchi soil

Figure 4 outlines the exchangeable $^{137}$Cs and K$^+$ in Fukushima and Kawauchi soil. Figure 4(a) shows $^{137}$Cs in Fukushima and Kawauchi soils before and after treatment with 1M ammonium acetate at pH 7. Concentration of $^{137}$Cs for Kawauchi soil before treatment with ammonium acetate ranged from 369 ~ 879 Bq/kg with an average of 620 ± 6 Bq/kg, while Fukushima soil was 2160 ~ 3140 Bq/kg with an average value of 2640 ± 10 Bq/kg. Then after the extraction, it reduced to 1980 ~ 2940 Bq/kg with the average value of 2330 ± 10 Bq/kg for Fukushima soil, while Kawauchi soil was 337 ~ 700 Bq/kg with the average of 527 ± 4 Bq/kg. Figure 4(b) shows ammonium acetate solution had impact on $^{137}$Cs in Kawauchi and Fukushima soil by which there was a decrease in $^{137}$Cs activity concentration for both soils.

Figures 4(c) and (d) show that Fukushima soil contains lesser percentage of exchangeable $^{137}$Cs and more percentage of exchangeable K$^+$ in contrast to Kawauchi soil. That is, exchangeable $^{137}$Cs is low and exchangeable K$^+$ is high in Fukushima soil while the exchangeable $^{137}$Cs is high and the exchangeable K$^+$ is low in Kawauchi soil. This could be the reason behind higher TF for Kawauchi rice compared to Fukushima (Fig. 3). This agrees well with other studies, for example, Kondo et al. and Tsumura et al. noted that $^{137}$Cs in plants tends to decrease with decreasing exchangeable $^{137}$Cs in soil although there was no clear relationship is found between $^{137}$Cs concentration in plants and total $^{137}$Cs in soil. It was also observed that the relationship between exchangeable K and $^{137}$Cs concentration in plants indicate that low exchangeable K increases $^{137}$Cs uptake in rice.

Figure 5 shows the exchangeable cations of different soil fraction of Fukushima and Kawauchi soil. The rates of each size of the soils are shown in Fig. 6. Na$^+$ is almost similar in Fukushima and Kawauchi soil size fraction 75 µm < x < 850 µm
while Na$^+$ of Kawauchi is higher in size portion of $< 75 \mu m$ (Fig. 5(a)). K$^+$ has tendency of exhibiting higher exchangeable cation in larger particles of Fukushima soil. Cs is in the same group (Alkali metal element) with K. K$^+$ of Fukushima soil is higher in size fraction of $75 \mu m < x < 850 \mu m$ than Kawauchi soil. The higher K$^+$ in the larger grain size of Fukushima is probably caused by the fertilizer input, while the higher K$^+$ in the finer grains in Kawauchi is probably caused by clays. Moreover, it is well known that the higher the K$^+$ content the lower will be the TF.$^{21,23,24}$ This agrees well with this study (Figs. 4(d) and 5(b)) on average Fukushima soils which contain more exchangeable K$^+$ than Kawauchi soil, thus its TF is lower compared to that of Kawauchi. In addition, Fukushima soil contains significantly higher amount of Mg$^{2+}$ and Ca$^{2+}$ compared to Kawauchi (Figs. 5(c) and 5(d)). There is a possibility of Mg$^{2+}$ and Ca$^{2+}$ high concentration effect for reducing $^{137}$Cs TF in Fukushima soil.

3.5. Fukushima and Kawauchi soil particle size distribution

Soil particle distributions of Kawauchi and Fukushima are quite different (Fig. 6). Despite Kawauchi having more $< 75 \mu m$ fine particle fractions compared to that of Fukushima yet combination of fine and medium sand ($850 - 75 \mu m$) for Fukushima surpasses that of Kawauchi. Much abundant fine and medium sand, which have much exchangeable K$^+$ (Fig. 5(b)), causes smaller TF of $^{137}$Cs soil to rice grain in Fukushima. If soil has a good proportion of clay, silt and sand, it makes the soil become more cemented when mixed with water,$^{25}$ probably this might be applied to Fukushima soil.

Furthermore, the present study has found that Kawauchi soil contains more silt and clay and less coarse and gravel than Fukushima. Nguyen et al. noted that radioesium is strongly adsorbed to the clay particles and that cesium adsorbed to large sized soil is a bit easily desorbed and absorbed by the rice plant.$^{26}$ Tsujimoto et al. observed that the rate of medium sand in soil is one of the factors to determine the migration of $^{137}$Cs.
from soil to rice plant. 27) The medium and coarse sand have large pore sizes which ensure that $^{137}$Cs moves more readily than in soil having more proportion of clay and silt compared to the sand particles. However, Kawauchi soil that contains more silt and clay has higher percentage of exchangeable $^{137}$Cs than Fukushima soil that contains more fine and medium sands (Fig. 4(c)). This could be due to difference in mineral composition between the two soils. Other studies have shown that the $^{137}$Cs migration within the soil layer may be affected by the adsorption kinetics. 28) The finding in this study shows that the $^{137}$Cs exchangeable rate cannot be easily explained only based on the soil particle size distribution.

3.6. Mössbauer spectral data for Fukushima and Kawauchi soil

On Mössbauer spectroscopy, there was no significant magnetic component (e.g., hematite) in Kawauchi soil (Fig. 7(a)) compared
to other soils from Fukushima (Fig. 7(b)). The ratio of Fe(II)/(Fe(III) + Fe(II)) of Kawauchi soil happens to be larger than that of other Fukushima soils. This is the opposite result to Nguyen et al.\textsuperscript{26} which shows the lower \(^{137}\text{Cs}\) transfer when the ratio is high. The difference between Fe(II) and Fe(III) in the soil samples shows the difference of the redox potential of the soils. Other studies have shown that microbially mediated reduction of Fe(III) in chlorite and biotite by \textit{Shewannella oneidensis} MR-1 leads a significant reduction in sorption of both Cs and Sr compared to the abiotic system.\textsuperscript{29} Taking into the consideration the various factors overall, we have to also consider the role of magnetic component.

3.7. Powder X-ray diffraction analysis of soil samples

Figure 8 displays diffraction pattern of Fukushima and Kawauchi soils. Table 1 shows the soil component of Fukushima and Kawauchi based on powder X-ray diffraction pattern (PXRD) analysis using Match software.\textsuperscript{30} Kawauchi soil contains more quartz constituents and slightly less mica minerals than Fukushima soil. Fukushima soil contains more vermiculite, zeolite and phlogopite. Study by Kondo \textit{et al.} showed that soils in some parts of Fukushima contained around 90% crystalline constituents with some kaolin, vermiculite, mica, zeolite and phlogopite.\textsuperscript{21}

Fukushima soil \(^{137}\text{Cs}\) is adsorbed to the clay particles more strongly compared to Kawauchi probably because Fukushima soil is rich in vermiculite, mica and zeolite which possibly retard \(^{137}\text{Cs}\) transfer from the soil to rice plant. Studies by Fujimura \textit{et al.} indicated that the level of radiocesium in rice plant was decreased by applying potassium or clay minerals rich in zeolite and vermiculite.\textsuperscript{31} Fujimura \textit{et al.} and Eguchi \textit{et al.} have shown that these minerals reduce the \(^{137}\text{Cs}\) migration in the soil.\textsuperscript{31,32} In addition, study by Nakao \textit{et al.} noted that one crucial factor in enhancing \(^{137}\text{Cs}\) adsorption is the presence of rough or weathered edges of some minerals, such as mica, in
3.8. Comparison of TF, exchangeable cations with other studies

Table 2 compares the transfer factors for rice grain observed in the present study in Kawauchi and Fukushima with previous studies in Japan, South Korea, India, China, Taiwan and the world. The present results are within the range of previously reported values both before and after Chernobyl and Fukushima accidents.

Transfer factors in the present study are lower compared to TFs just after the Fukushima accident\(^36\) and slightly higher before Fukushima disaster.\(^37\) It may be because newly deposited \(^{137}\)Cs on the ground was in exchangeable form, resulting in higher \(^{137}\)Cs uptake by plant then it became more fixed in soil matrices with time. The notion that TFs before Fukushima disaster were lower than the present study might be due to the \(^{137}\)Cs fall out from nuclear weapon tests and it became aged in the soil and eventually TFs were diminished with time than the freshly deposited radioesium after Fukushima incident. Furthermore, contribution of Chernobyl disaster in \(^{137}\)Cs TF of Japan was very minimal.

On the other hand, a nuclear power plant site in South Korea showed the highest TF amongst all probably because most parameters were controlled by pot experiments unlike the rest which were based on field observations.\(^40,41\) Thus, it would not be appropriate to draw any conclusion of this study which was based on field samples versus the pot experiments.

4. Conclusion

This study has shown that soil to grain \(^{137}\)Cs transfer factor of Fukushima is lower than Kawauchi paddy fields. The Fukushima soil might resist the uptake of \(^{137}\)Cs more by rice plant compared to Kawauchi soil, despite the Fukushima soil having more \(^{137}\)Cs concentration, that probably due to its soil characteristics. Both X-ray diffraction pattern of the soils and the \(^{57}\)Fe Mössbauer spectrometry analysis showed that the soils are different in their composition and Fe (II)/(Fe (III) + Fe (II)) ratio. This study has shown that the presence of micaceous minerals, zeolite and vermiculite in Fukushima soil reduced the transfer of \(^{137}\)Cs in the soil to rice plant. In addition, relatively lower TF of Fukushima soil was in line with the slightly lower percentage of exchangeable \(^{137}\)Cs and slightly higher exchangeable K\(^+\) of Fukushima soil than that of Kawauchi soil. However, it would still be better for future research to look on how \(^{137}\)Cs transfer factor within the soil layer might be affected by the adsorption kinetics considering 5 folds values TF of Kawauchi compared to Fukushima.

Conflict of Interests

The authors have not declared any conflict of interests.
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References
1. Ashraf, M.A., Akib, S., Maah, M.J., Yusoff, I., Balkhair, K.S.: Cesium-137: Radiochemistry, Fate, and Transport, Remediation, and Future Concerns, Critical Reviews in Environmental Science and Technology, 44(15), 1740 (1993).
2. IAEA.: Nuclear and Industrial Safety Agency. Method for developing arrangements for response to a nuclear or radiological emergency, EPR Method, IAEA, Vienna (2011). http://ajw.asahi.com/article/0311disaster/analysis opinion/AJ2011101514679
3. Chino, M., Nakayama, H., Nagai, H., Terada, H., Katata, G., Yamazawa, H.: Preliminary estimation of release amounts of $^{131}$I and $^{137}$Cs accidentally discharged from the Fukushima Daiichi nuclear power, Journal of Nuclear Science and Technology 48, 1129 (2011).

Table 2 Comparison of TF, exchangeable cations with other studies.

| Country (Sampling location) | Experimental condition | Instrument | TF Cs-137 (Rice-grain) | Exchangeable cations (cmol·kg$^{-1}$) | Reference |
|-----------------------------|-------------------------|------------|-------------------------|--------------------------------------|------------|
|                             |                         |            |                         | K$^+$ | Na$^+$ | Mg$^{2+}$ | Ca$^{2+}$ |
| Japan (Kawauchi)            | Brown rice, field observation | HPGe, ICP-AES | 0.005 (0.0021–0.0058) | 0.30 | 0.30 | 0.02 | 0.29 | this study |
| Japan (Fukushima)           | Brown rice, field observation | HPGe, ICP-AES | 0.001 (0.0004–0.0018) | 0.48 | 0.17 | 1.43 | 3.01 | this study |
| Japan (Fukushima)           | Field observation soil | HPGe, ICP-AES | N.A. | 0.51 | 0.18 | 0.69 | 6.90 | Basuki et al., 2020(38) |
| Japan (Fukushima)           | Field observation soil | HPGe, ICP-AES | N.A. | 0.4 | 0.1 | 1.1 | 5.0 | Fujii et al., 2014(39) |
| South Korea a (Kori & Younggwang) | Rice, pot observation | HPGe, ICP-AES | $^{a}$0.001 (0.0012–0.011) | 0.81 | 1.7 | 1.95 | 4.52 | Choi et al., 2002(40), 2011(41) |
| South Korea b (Wolsung NPP) | Rice, pot observation | HPGe, ICP-AES | $^{b}$0.057 (0.022–0.15) | 0.41 | N.A. | 2.2 | 6.1 | |
| Japan (Minamisoma)          | Rice, field observation | HPGe | 0.023 (0.019–0.026) | N.A. | N.A. | N.A. | N.A. | Endo et al., 2013(36) |
| Japan (Fukushima)           | Brown rice, field observation | ICP-MS | 0.0026 | N.A. | N.A. | N.A. | N.A. | Komamura et al., 1994(27) |
| India (Kaigar)              | Rice, field observation | HPGe | 0.24 (0.07–0.8) | N.A. | N.A. | N.A. | N.A. | Karunakara et al., 2013(46) |
| China (Taiwan NPP)          | Rice, field observation | HPGe | 0.0022 | N.A. | N.A. | N.A. | N.A. | Lu et al., 2006(45) |
| Taiwan (Kaohsiung city)     | White rice, field | HPGe | 0.13 (0.07–0.27) | N.A. | N.A. | N.A. | N.A. | Wang et al., 1998(43) |
| Worldwide                   | Data gathering          | HPGe | 0.0083 (0.0047–0.012) | N.A. | N.A. | N.A. | N.A. | IAEA, 2010(44) |
4. Ciuffo, L., Maria, B., Pasquale, A., Menegon, S., Velasco, H.R.: 137Cs and 40K soil-to-plant relationship in a seminatural grassland of the Giulia Alps, Italy, The Science of the total environment. 295, 69 (2002).

5. Yu, K.N., Mao, S.Y.: Assessment of radionuclide contents in food in Hong Kong, Health Phys. 77, 686 (1999).

6. Karunakara, N., Rao, C., Ujwal, P., Yashodhara, I., Kumara, S., Ravi, P.M.: Soil to rice transfer factors for 226Ra, 228Ra, 210Pb, 40K and 137Cs: a study on rice grown in India, J. Environ. Radioact. 118, 80 (2013).

7. Prister, B.S., Perepelyatnikov, G.P., & Pojarkov, V.A.: The classification of Ukrainian soil systems on the basis of transfer factors of radionuclides from soils to reference plants (IAEA-TECDOC–1497), International Atomic Energy Agency (IAEA) (2006).

8. Fesenko, S.V., Soukhova, N.V., Sanzharova, N.I., Avila, R., Spiridonov, S.I., Klein, D., Batod, P.M.: 137Cs availability for soil to understory transfer in different types of forest ecosystems, Science of The Total Environment, 269(1), 87–103 (2001). doi:10.1016/s0048-9697(00)00818-4.

9. Yamaguchi, N., Taketa, Y., Hayashi, K., Ishikawa, S., Kuramata, M., Eguchi, S., Yosikawa, A., Sakaguchi, A., Asada, K., Wagai, R., Makino, T., Akahane, I., Hiradate, S. Behavior of radio cesium in soil-plant systems and its controlling factor: a review, Rep. Natl. Inst. Agro. Environ. Sci. Jpn. 31(75), (2012) (in Japanese).

10. Zhu, Y.G., Smolders, E.: Plant uptake of radioisotopes: a review of mechanisms, regulation and application, J. Exp. Bot. 51, 1635 (2000).

11. Choi, Y.H., Lim, K.M., Park, H.G., Park, D.W., Kang, H.S., Lee, H.S.: Transfer of 137Cs to rice plants from various paddy soils contaminated under flooded conditions at different growth stages, Journal of Environmental Radioactivity 80, 45 (2005).

12. D’Souza, T.J., Mistry, K.B.: Absorption of gamma-emitting fission products and activation products by rice under flooded and unflooded conditions from two tropical soils, Plant and Soil 55, 189 (1980).

13. Singh, V., Agrawal, H.M.: Qualitative soil mineral analysis by EDSRF, XRD and AAS probes, Radiation Physics and Chemistry 81, 1796 (2012).

14. Aula, P., Little, N.D.: Analytical tests to evaluate pozzolanic reaction in lime stabilized soils, MethodsX 7, 100028 (2020). https://doi.org/10.1016/j.mex.2020.100028

15. Lutterotti, L., Pillière, H., Fontugne, C., Boullay, P., & Chatenier, D.: Full-profile search-match by the Rietveld method, Journal of applied crystallography, 52(3), 587 (2019). https://doi.org/10.1107/S1600576719000342

16. Nishihara, K., Iwamoto, H., Suyama, K.: Estimation of fuel compositions in Fukushima-Daiichi nuclear power plant, Japan Atomic Energy Agency, JAEA Data/Code 2012-018 (2012) [in Japanese].
30. Match software [https://match4.software.informer.com/download/ Version: 3.8.2.148 (x64)] downloaded 1 April 2021
31. Fujimura, S., Yoshioka, K., Saito, T., Sato, M., Sato, M., Sakuma, Y., Muramatsu, Y.: Effects of applying potassium, zeolite and vermiculite on the radioceium uptake by rice plants grown in paddy field soils collected from Fukushima prefecture, Plant Prod. Sci. 16(2), 166 (2013). https://doi.org/10.1626/pps.16.166
32. Eguchi, T., Ohta, T., Ishikawa, T., Matsumani, H., Takahashi, Y., Kubo, K., Yamaguchi, N., Kihou, N., Shinano, T.: Influence of the nonexchangeable potassium of mica on radioceium uptake by paddy rice, Journal of Environmental Radioactivity 147, 33 (2015).
33. Nakao, A., Takeda, A., Ogawara, S., Yanai, J., Sano, O., Ito, T.: Relationships between Paddy Soil Radioceium Interception Potentials and Physicochemical Properties in Fukushima, Japan, J. Environ. Qual. 44(3), 780 (2014).
34. Fujii, K., Yamaguchi, N., Imamura, N., Kobayashi, M., Kaneko, S., Takahashi, M.: Effects of radioceium fixation potentials on radioceium retention in volcanic soil profiles of Fukushima forests, Journal of environmental radioactivity 198, 126–134 (2019).
35. Ulrich, K.: Radiation Reloaded: Ecological Impacts of the Fukushima Daiichi Nuclear Accident.5 years later. Greenpeace Japan. Edited by Burnie S, Greenpeace Germany. www.greenpeace.org/japan/ERJ (accessed 2021/08/01).
36. Endo, S., Kajimoto, T., Shizuma, K.: Paddy-field contamination with radioceium and radiothorium from Fukushima Dai-ichi Nuclear Power Plant accident and soil-to-rice transfer coefficients, Journal of Environmental Radioactivity 116, 59 (2013).
37. Komamura, M., Tsumura, A.: The transfer factors of long-lived radionuclides from soil to polished rice measured by ICP-MS, Radioisotopes 43, 1 (1994).
38. Basuki, T., Bekelesi, W.C., Tsujimoto, M., Nakashima, S.: Investigation of radioceium migration from land to waterbody using radioceium distribution and soil to sediment ratio: A case of the steep slope catchment area of Ogi reservoir, Kawauchi Village, Fukushima, Radiation Safety Management 19, 23 (2020).
39. Fujii, K., Ikeda, S., Akama, A., Komatsu, M., Takahashi, M., Kaneko, S.: Vertical migration of radioceium and clay mineral composition in five forest soils contaminated by the Fukushima nuclear accident, Soil Science and Plant Nutrition, 60(6), 751 (2014).
40. Choi, Y.H., Lim, K.M., Yu, D., Park, H.G., Choi, Y.G., Lee, C.M.: Transfer pathways of Mn, Co, Sr, Ru and Cs in rice and radish plants directly contaminated at different growth stages, Annals of Nuclear Energy 29, 429 (2002).
41. Choi, Y.H., Lim, K.M., Keum, D.K., Han, M., Kim, G.: Transport behavior and rice uptake of radiostrontium and radioceium in flooded paddy soils contaminated in two contrasting ways, Science of the Total Environment, Volumes 412–413, 248–256 (2011). https://doi.org/10.1016/j.scitotenv.2011.09.063.
42. Lu, J., Huang, Y., Li, F., Wang, L., Li, S., Hsia, Y.: The investigation of Cs and Sr background radiation levels in soil and plant around Tianwan NPP, China, Journal of Environmental Radioactivity 90, 89 (2006).
43. Wang, J.J., Wang, C.J., Huang, C.C., Lin, Y.M.: Transfer factors of Sr and Cs from paddy soil to the rice plant in Taiwan, Journal of Environmental Radioactivity 39, 23 (1998). https://doi.org/10.1016/S0265-931X(97)00045-3
44. IAEA.: Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments, Technical Reports Series No. 472, IAEA, Vienna, Austria (2010).