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ARTICLE

Agricultural Approaches of Remediation in Rice Fields near the Fukushima Daiichi Nuclear Plant

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To evaluate the environmental contamination by radioactive materials and the technologies for environmental restoration of contaminated areas after the Fukushima Daiichi Nuclear Power Station (FDNPS) accident, a cleanup subcommittee was established in the Atomic Energy Society of Japan. We have investigated the migration behavior of cesium from the soil to brown rice by paddy field testing in an area contaminated with radioactive cesium. This paper outlines approaches to agricultural remediation used by the committee in contaminated areas near the FDNPS.

KEYWORDS: migration, cesium, brown rice, paddy field, radioactive cesium pollution

I. Introduction

This project was conducted by the Cleanup Subcommittee of the Fukushima Support Project established in the Atomic Energy Society of Japan (AESJ) in April, 2011. The objectives of this subcommittee include the evaluation of environmental pollution by radioactive materials and recommendations for technologies for environmental restoration of contaminated areas after the FDNPS accident.

The first activity of this subcommittee was an investigation into decontamination methods, and the second was the creation of a catalog of decontamination methods; the results of these investigations were compiled into a report and published as a decontamination method catalog by the AESJ in 2011[1,2]. In addition, a demonstration test was conducted on a decontamination method for hydroponic rice fields in Minamisouma City, Fukushima Prefecture. An actual test was also carried out to verify the migration of radioactive cesium from the soil to the rice grown in this area. The present paper presents the results of the actual verification test conducted over 11 years.

II. Paddy Field Work

1. Procedures for Rice Cultivation

The procedure for rice cultivation in paddy fields is shown in **Fig. 1**. Standard cultivation procedures were supplemented by the addition of zeolite and additional potassium fertilization. When cultivating rice in a paddy field on site, initial fertilization containing nitrogen, phosphate and potassium was first carried out based on the concentrations of these elements in soil. Zeolite was then spread over the field, followed by plowing. After flooding the field with water, rice planting was carried out. Potassium fertilizer was applied again after planting. Over the rice was grown, it was harvested and threshed to obtain brown rice. If necessary, the brown rice was polished to produce white rice.

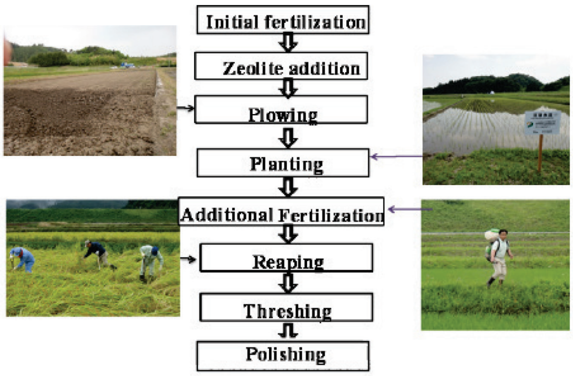

Fig. 1 Procedure of paddy field work

2. Application of Additional Potassium Fertilizer and Feolite

Table 1 shows the amounts of additional potassium fertilizer and zeolite applied from 2012 to 2022. Because farming did not resume in Minamisouma City in 2012 and 2013, we borrowed paddy fields from local farmers during this period and cultivated rice using varying amounts of additional zeolite and potassium fertilizer as parameters.

Farming resumed in Minamisouma City in 2014. Since then, we have continued to collect and evaluate rice grown in the area and tracked additional zeolite and potassium fertilization when applied. Because the effectiveness of the addition of zeolite in suppressing the transfer of cesium to brown rice was unclear, the addition of zeolite was discontinued from 2016.

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Additional potassium fertilization was also discontinued from 2021.

Table 1 Fertilization of the additional potassium and the zeolite spraying conditions from 2012 to 2022

Test Condition for Paddy Field		
Year	Additional Potasium Fertilization	Zeolite Addition
2012	Zero, 60kg/1000m2	Zero,100,200kg /1000m2
2013	Zero,60kg /1000m2	Zero,100,200kg /1000m2
2014	60kg /1000m2	100kg /1000m2
2015	60kg /1000m2	100kg /1000m2
2016	50kg /1000m2	Zero
2017	50kg /1000m2	Zero
2018	50kg /1000m2	Zero
2019	50kg /1000m2	Zero
2020	50kg /1000m2	Zero
2021	Zero	Zero
2022	Zero	Zero

III. Result and Discussion

1. Concentrations of Radioactive Cesium in the Soil

Figure 2 shows the change over time in the concentrations of radioactive cesium in the soil of paddy fields where rice was grown.

By 2017, the concentrations had decreased to about one-fifth of their initial levels, likely due to the decay of Cs-134.

Since 2018, Cs-137 has been the main radioactive cesium isotope in the soil, and no significant decrease in its concentrations has been observed.

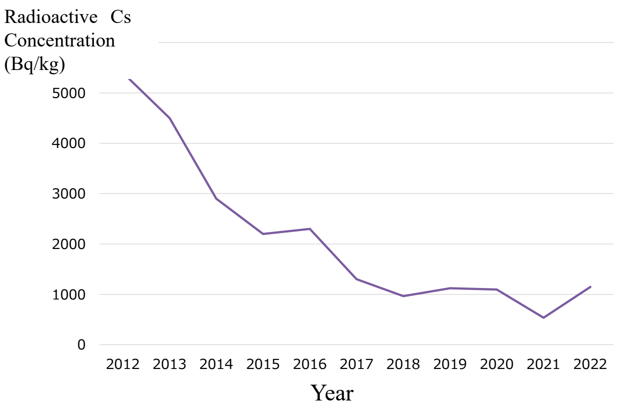

Fig. 2 Radioactive cesium concentration of paddy soil used in this test from 2012 to 2022

2. Cesium Transfer to Rice Plants

(1) Rice Cultivation in Paddy Fields in 2012

A schematic drawing of the paddy test field in 2012 is shown in **Fig. 3**. The 1000m^2 paddy field was divided into six sections, and additional potassium fertilizer and zeolite were applied on each section in the amounts given in **Table 2**.

The radioactive cesium concentrations in the chaff, straw, and roots of the rice plants collected from each section in 2012 are given in **Table 3**.

Given that radioactive cesium concentrations in the soil at that time were 5,400 Bq/kg, the migration rate of radioactive cesium to straw and chaff was determined to be about 2.0 to 3.5%. However, the values for migration rate of radioactive cesium to roots were more than 10 times higher than those values for straw and chaff.

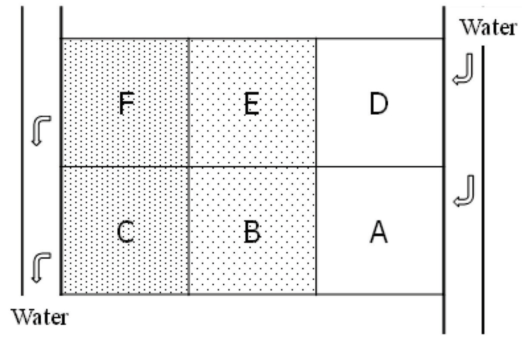

Fig. 3 Schematic drawing of the paddy test field (2012)

Table 2 Fertilization of the additional potassium and the zeolite spraying conditions in 2012

Section	Additional K fertilization	Zeolite Add.
A	60kg/1000m^2	Zero
B	60kg/1000m^2	100kg/1000m^2
C	60kg/1000m^2	200kg/1000m^2
D	Zero	Zero
E	Zero	100kg/1000m^2
F	Zero	200kg/1000m^2

Table 3 Radioactive Cs Concentration for Rice Plant ; 2012 Test(Bq/kg)

Section	Chaff	Straw	Root
A	140	190	2800
B	120	140	2700
C	110	160	1800
D	190	190	2100
E	120	180	2000
F	150	150	1900

Figure 4 shows the concentrations of radioactive cesium and radioactive potassium in brown rice after harvesting and processing. Radioactive cesium concentrations in the brown rice were between 17 and 33 Bq/kg, well below the food standard value of 100 Bq/kg. The radioactive concentrations of natural radioactive K-40 were below 74 Bq/kg, which were also below the food standard value.

Moreover, K-40 concentrations were higher than the radioactive cesium concentrations. Radioactive cesium concentrations in brown rice tended to be slightly lower when additional potassium was added as fertilizer. In addition, the application of zeolite also tended to slightly lower radioactive cesium concentrations.

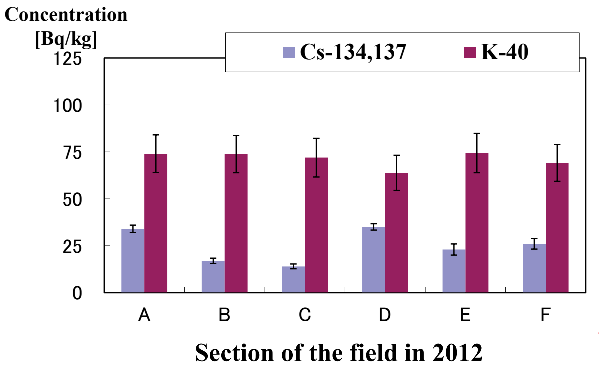

Fig. 4 Radioactive cesium and potassium concentration of brown rice (2012 Test)

(2) Rice Cultivation in Paddy Fields in 2013

The condition of the rice paddy in 2013 is shown **Fig. 5**. The 1000m^2 rice paddy was divided into four sections this year. Potassium fertilization and zeolite application were conducted on each section in the amounts shown in **Table 4**.

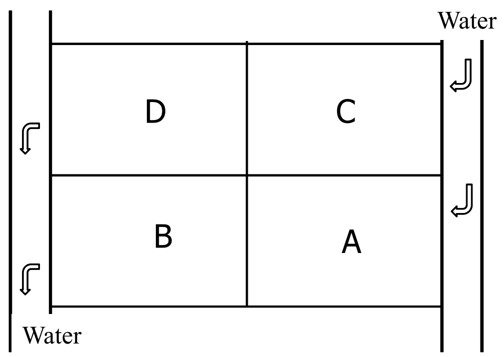

Fig.5 Schematic drawing of the test field in 2013

Table 4 Fertilization of the additional potassium and the zeolite spraying conditions in 2013

Section	Additional K fertilization	Zeolite Add.
A	Zero	Zero
B	Zero	200kg/1000m^2
C	Zero	100kg/1000m^2
D	60kg/1000m^2	100kg/1000m^2

Figure 6 shows radioactive cesium and potassium concentrations in brown rice harvested in each section in 2013. The levels of radioactive materials in both brown rice and polished rice were well below the food standard limit (100 Bq/kg), as seen in the results for 2012. In both cases, K-40 concentrations were higher than the radioactive cesium concentrations. Zeolite application seemed to be effective in suppressing the transfer of cesium from soil to brown rice. There also appeared to be a slight tendency for this to occur when additional potassium fertilizer was applied.

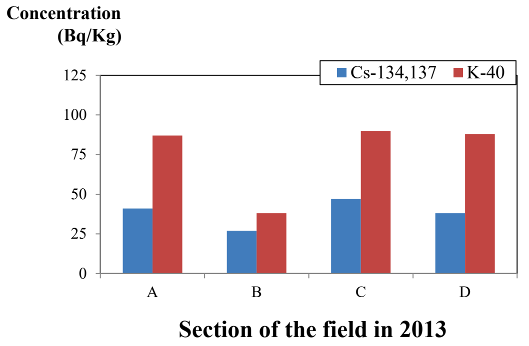

Fig. 6 The radioactive cesium and potassium concentration of brown rice in 2013

The transfer factors of cesium and potassium from soil to brown rice obtained in the 2013 test are shown in **Fig. 7**. The transfer factors of cesium to brown rice were very small, at most about 1%, while those of potassium were 5.8 to 12 times larger. The transfer factors of cesium were found to be smaller than those of potassium under all conditions.

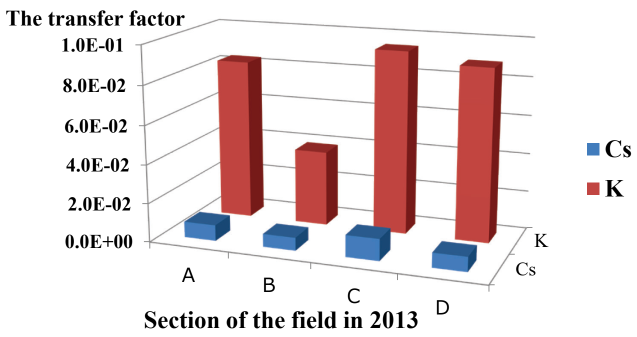

Fig. 7 The transfer factor from the soil of cesium and potassium to brown rice in 2013

(3) Resuming Farming and Rice Cultivation in Paddy Fields after 2014

In Minamisouma City, where rice had previously been grown hydroponically in paddy fields, farming resumed in 2014. Table 1 shows the conditions for potassium top dressing and zeolite application after farming resumed (from 2014 onwards). Zeolite application has been discontinued since 2016. From 2021 onwards, top dressing has been applied only when farming is resumed.

The radionuclide concentrations of radioactive cesium in the soil, chaff, and brown rice of paddy fields where rice was cultivated are shown in **Fig. 8**. The values for 2012 and 2013 are the average values for each section. In 2014, the recovered rice appears to have been eaten by wild boars during drying, and only a small amount of rice and other samples were recovered. Although there were some variations, cesium concentrations in all parts of a rice plant showed a deceasing trend. The radioactive cesium concentration in brown rice was much less than the food standard value (100Bq/kg). The cesium concentration of chaff is higher than the value of brown rice.

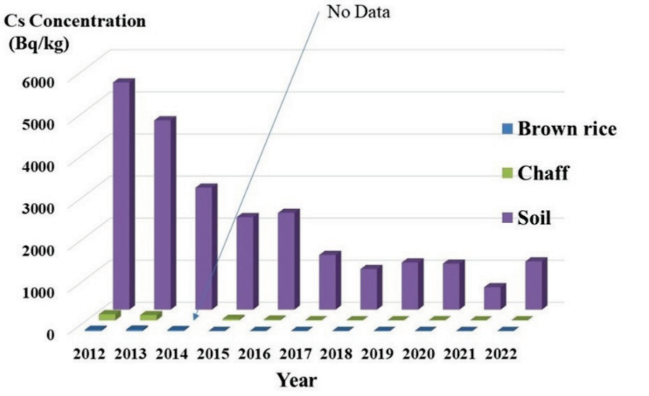

Fig. 8 Radioactive Cs Concentration for soil and Rice Plant (Chaff and brown rice) ; 2012-2022

(4) Transfer Factors from Soil to Brown Rice

Figure 9 shows the transfer factors of cesium from soil to brown rice obtained from 2012 to 2022. The values for 2012 and 2013 are the average values for each section. The cesium transfer factor is less than 1% for all years.

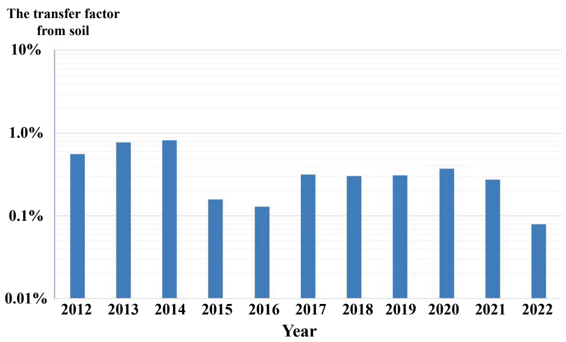

Fig. 9 The transfer factor of cesium from the soil to brown rice. (2012-2022)

Transfer factors of cesium and potassium from soil to rice plant samples obtained in 2022 are shown in **Fig. 10**. For all rice plant samples, the transfer factor of potassium was several times higher than that of cesium. The transfer factors for brown rice were the lowest among the rice plant samples.

The transfer factors of cesium from soil to brown rice (tested in 2012) are shown in **Fig. 11**. The values used in the performance evaluation of radioactive waste disposal facilities are also shown in the figure for comparison. Transfer factor of cesium from soil to brown rice obtained by paddy field testing in Minamisouma City, Fukushima Prefecture, were much lower than the values given in studies performed overseas, as cited in **Fig. 11**.

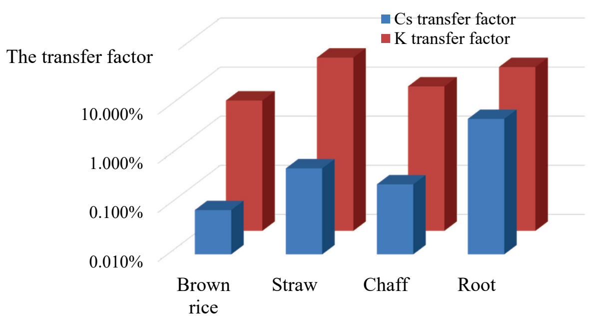

Fig. 10 Transfer factor of Cs and K from soil to rice plant samples obtained in 2022

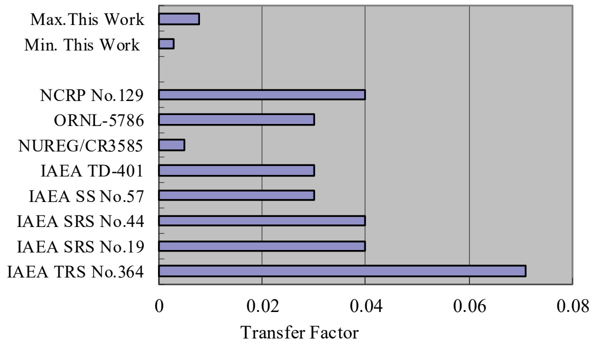

Fig. 11 Comparison of transfer coefficients of Cs obtained in this study with literature values[3-10)]

IV. Conclusion

The radioactive cesium concentration in brown rice grown in the paddy fields over the past 11 years has been very low, at less than 40 Bq/kg. This result is thought to be similar to the results of brown rice grown in other areas of Fukushima Prefecture.[11)] As reported in several studies, the effect of potassium fertilization is also thought to suppress the transfer of cesium to brown rice.[12,13)] Currently, even without potassium fertilization, the radioactive cesium concentration in brown rice is maintained at a level that does not exceed the food standard value of 100 Bq/kg.

Our research activities have revealed several key findings. First, cesium concentrations in brown rice harvested from a contaminated rice paddy field in Minamisouma City were well below food standards. In addition, transfer factors of cesium from soil to brown rice were very low compared with literature values for the performance evaluation of radioactive waste disposal facilities.

There was a tendency to reduce the transfer of cesium by increasing potassium fertilization, and the addition of zeolite was found to have a slight effect in suppressing cesium migration.

The transfer factor of cesium to brown rice was smaller than that of potassium, and radioactive cesium concentrations were lower than radioactive potassium concentration. Additionally, the transfer factor of cesium to brown rice was very low compared with that to other parts of the plant, such as roots or chaff.

According to results from examinations over 11 years, cesium concentrations have fallen each year. Furthermore, radioactive cesium concentrations of brown rice have remained below the detection limit during the 7 years, as measured with a 50,000 seconds.

-These research activities remain ongoing.

Acknowledgment

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