Chapter 6
A Composting System to Decompose Radiocesium Contaminated Baled Grass Silage

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Abstract Due to the Fukushima Daiichi nuclear power plant accident, a tremendous amount of organic waste (e.g., baled grass silage) contaminated with radioactivity was generated in Tohoku region, northeastern Japan. To establish a safe and efficient way to treat cesium contaminated silage, we investigated the use of aerobic, high temperature composting. Radiocesium (^{137}Cs and ^{134}Cs) contaminated silage (2000 kg, approximately 2700 Bq/kg), water (4000 kg) and matured compost soil (as inoculum, 16,000 kg) were mixed by a wheel loader, and then the mixture was piled up. Air was supplied from the bottom of a compost pile continuously, and the fermentation continued for 7 weeks. The temperature at 100 cm below the surface reached approximately 100 °C. The water content decreased to less than 30% after 7 weeks. The level of radioactive cesium in the final product (18,000 kg) was 265 Bq/kg, which was below the tolerance value for fertilizer (400 Bq/kg) suggested by the Japanese government. The radioactive cesium within silage remained in the final products. We cultivated tomato (fruit), soybean (seed), carrot (root), Italian ryegrass (leaf feed for livestock), Swiss chard (leaf), cosmos (flower) and field mustard (seed) in an experimental farm fertilized with the matured compost made from the radiocesium contaminated silage, for 3 months. Radiocesium levels of edible parts and non-edible parts of each crop were lower than 20 Bq/kg, which was less than one-fifth of the Japanese government value for food (100 Bq/kg). This

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research demonstrated that the final product can be used safely as an organic fertilizer.

Keywords Aerobic · High temperature composting · Compost · Cultivation of crops · Fertilizer · Radiocesium · Silage · Waste treatment

6.1 Composting Organic Waste Contaminated with Radioactive Cesium

Due to radiation fallout at the Fukushima Daiichi nuclear power plant accident caused by the giant tsunami associated with the Tohoku earthquake on 11th March 2011, vegetation (e.g., baled grass silage) and carcasses of animals (e.g., livestock, wild boars) were contaminated with radioactive cesium. This contaminated organic matter has mostly remained untouched since 2011. Although the final treatment of organic waste from farms has yet to be been decided, it is essential to investigate the most optimum and safest way to do this to accelerate the recovery process.

Since radioactive cesium-contaminated waste is too large to remove and store, it is essential to reduce its physical weight and volume. Incineration is one solution, but this requires expensive equipment and is undesirable from the standpoint of the environment.

Instead, we have proposed to treat organic waste with microorganisms, that is, to decompose by composting, especially using aerobic, high temperature composting devised by Sanyu limited company (Kagoshima, Japan) (Oshima and Moriya 2008). We have already succeeded to treat contaminated carcasses of cows, pigs and wild boars in towns in Fukushima prefecture. In short, we could demonstrate the conversion of dead animal bodies into a smaller amount of compost soil.

In this article, we converted radioactive contaminated baled grass silage into compost soil which is less bulky. We also showed that the final product is usable as a fertilizer, with the resulting vegetables having a radioactivity level below 100 Bg/kg.

6.2 Reduction in the Volume and Weight of Silage Contaminated with Radiocesium by an Aerobic, High-Temperature Composting System

For over 5 years after the Tohoku earthquake, approximately 2,600,000 kg of contaminated silage with low levels of radiocesium (mainly ^{137}Cs and ^{134}Cs) was left untouched on farms in Kurihara city, Miyagi prefecture, which is located about 150 km north of Fukushima Daiichi nuclear power plant (Fig. 6.1a). From May 2016, we began to compost contaminated silage after receiving a request from Kurihara city local government. The basic information on an aerobic, high-temperature compost system was reported by Manabe et al. (2016). Briefly, we set up two fermenters (4 m width × 3 m height × 6 m depth) in a temporary warehouse (165 m^2; 10 m × 16.5 m) covered with plastic sheets at Kurihara city (Fig. 6.1b, c). Two pipes for aeration were buried in the floor (Fig. 6.1c). The composting process is described in Fig. 6.1. We determined the quantities of radioactive cesium in each silage bale by using in-vehicle sodium iodide scintillator (Mirion Technologies-Canberra Japan Co. Ltd.; with ±10% accuracy). The mean concentration of radioactive cesium in silage was 2723 Bq/kg. Approximately 2000 kg of contaminated silage, 16,000 kg of mature compost (as inoculum) and 4000 kg of water were mixed in a fermenter in order to adjust water content to 45%. The temperature at 100 cm below the top of the compost pile reached 100 °C within 3 days. The compost pile was transferred to another fermenter using a wheel loader once a week and the mixing was repeated seven times. Although the dust and air moisture in the temporary warehouse were collected by circular sprinkling dust collector throughout the fermentation, radioactive cesium in the dust collector was not detected (<2 Bq/kg). The atmospheric radioactivity within a 200-m radius around the examination facility did not fluctuate during the composting process. Thus, the environmental effects of composting low levels of radiocesium contaminated silage appear not to be an issue. The end product of the silage composting became a powder-like substance and the water content was approximately 30%. The total weight of the end product was 18,000 kg. Assuming that the compost added as inoculum was not decomposed during the fermentation, it can be concluded that we can decomposed more than 90% of the contaminated silage by aerobic, high-temperature composting. We detected the presence of *Calditerricola satsumensis*, the genus *Geobacillus* and *Planifilum* as the dominant thermophiles in the composting process by using bacterial 16S rRNA gene targeting denatured gradient gel electrophoresis analyses. The radioactive cesium level of the end product was 265 Bq/kg, which indicated 100 Bq/kg less than the Japanese government tolerance value (400 Bq/kg).

Furthermore, we performed the dissolution test of radiocesium in contaminated silage and the compost. The elution rate of radiocesium from contaminated silage with water or 2% citrate were approximately 60% or 80%, respectively (Fig. 6.2) However, the radiocesium elution rate of the compost made from contaminated silage with water and 2% citrate were 30 and 40%, respectively. Therefore, it was conceivable that a part of radiocesium in the contaminated silage might be changed into an insoluble form by the composting process.

6.3 Dynamics of Radiocesium in Crops Grown with Radioactive Contaminated Silage Compost

In our earlier report, we cultivated seven different crops including soybean (seed), sweet corn (seed), eggplant (fruit), bitter gourd (fruit), potato (rhizome), cabbage (leaf) and ginger (root) on cubic holes filled with the radiocesium contaminated compost soil in a field of the experimental ranch of the University of Tokyo (Manabe

Fig. 6.1 Aerobic, high temperature composting process of radiocesium contaminated silage. Kurihara city is located about 150 km north of Fukushima Daiichi nuclear power plant (**a**).

et al. 2014a, b, c, 2016). The radiocesium levels in the roots, stems, leaves, and fruits of each crop were less than 20 Bq/kg (the Japanese government radiocesium limit in food is 100 Bq/kg).

The compost produced by composting of radiocesium contaminated silage in Kurihara city was 265 Bq/kg and can sell as commercial organic fertilizer. The results of the chemical composition of radiocesium contaminated silage compost indicated that amounts per weight of nitrogen (N) and phosphate (P_2O_5) were 2.6 and 4.6% respectively, which is higher than the compost of non-contaminated cattle feces in Kurihara city. However, the amount of potassium (K_2O) in the silage compost was 0.5%, which is one-quarter the amount of the compost made from non-contaminated cattle feces in Kurihara city (2.2%). Surplus potassium in soil is considered to compete against radiocesium crop absorption. In other words, radioactive cesium will be more easily transferred to plants from potassium deficient soil. We examined the movement of radiocesium into crops from soil when the contaminated silage compost was applied.

We built a greenhouse (5.4 m × 20.0 m) close to the composting facility in Kurihara city. We divided the greenhouse into four sections (4.0 m × 2.6 m) (Fig. 6.3a) before tilling the soil 20 cm deep (Fig. 6.3b). To fertilize the soil in each experimental section, a chemical fertilizer (as a control), 3 kg/m^2 of contaminated silage compost, 20 kg/m^2 of contaminated silage compost, and 2 kg/m^2 of non-contaminated cattle faces fermented compost (as an organic fertilizer control) were applied. Radiocesium concentrations in each soil identified by a germanium semiconductor detector was 39.8 Bq/kg in the chemical fertilizer applied-soil, 75 Bq/kg in the 3 kg/m^2 of contaminated-silage compost applied-soil, 87.6 Bq/kg in the 20 kg/m^2 of contaminated silage compost applied soil, and 76 Bq/kg in the 2 kg/m^2 of non-contaminated cattle feces fermented compost soil. We planted seven crops [tomato (fruit), soybean (seed), carrot (root), Italian ryegrass (leaf feed for livestock), Swiss chard (leaf), cosmos (flower) and field mustard (seed)] on each soil and conducted the cultivation for about 3 months. The effect of contaminated silage compost on the growth of tomato and Swiss chard were similar to that of chemical fertilizer treatment, and it was better than cattle feces-fermented compost. Radioactive cesium levels in the edible and non-edible parts of all harvesting crops were less than 20 Bq/kg. These results indicated that the radiocesium transfer rate to crops from soil applied with contaminated silage compost was very low.

Fig. 6.1 (continued) The outside appearance of the temporary warehouse and the fermenter (**b** and **c**). The circular sprinkling dust collection system (**d**). The contaminated baled grass silage with low levels of radiocesium contamination was left untouched since 2011 (**e**). Measurement of radiocesium level of each bale using an in-vehicle sodium iodide scintillator (**f**). Appearance of the compost after 2 weeks of fermentation (**g**). Mixing the compost pile using a shovel loader (**h**). The end product produced after 7 weeks of composting (**i**)

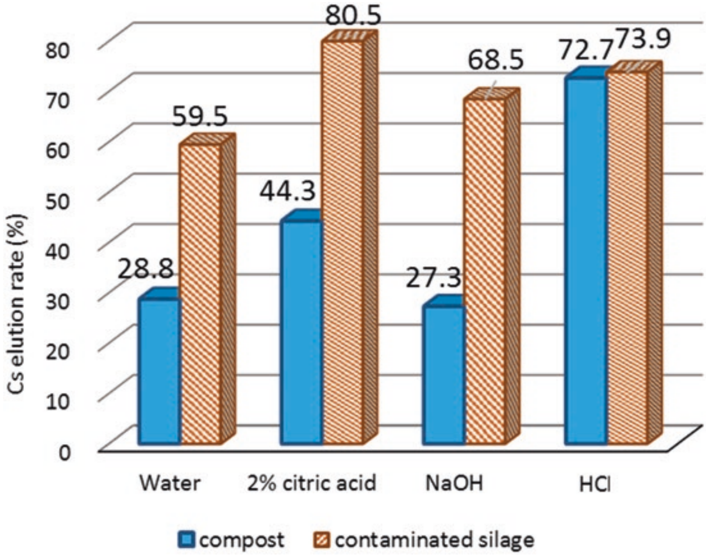

Fig. 6.2 The radioactive cesium elution rate of the contaminated silage and the compost. The silage or compost soil were mixed with ten times volume of water, 2% citrate, 1 N HCl or 1 N NaOH and then agitated for 6 h at room temperature. After centrifugation, the supernatant was filtered by suction through a 0.45-μm Millipore filter. The radiocesium elution rates were determined by measuring radioactivity in each fraction

6.4 Conclusion

Low levels of radioactive cesium contaminated silage were decomposed by aerobic, high-temperature composting system. The final product contained radioactivity of 265 Bq/kg, which was lower than the Japanese government maximum tolerable level in fertilizers (400 Bq/kg). Radiocesium in the silage compost might have changed into a more insoluble form during the composting process because radiocesium in the compost was less soluble in water and citrate solution than before. We cultivated crops fertilized with radiocesium-contaminated silage compost. Radiocesium levels in the edible and non-edible parts of each crop were less than 20 Bq/kg, which is below the Japanese government maximum tolerable level in food (i.e., 100 Bq/kg). These results strongly suggested that aerobic, high-temperature composting system was an extremely useful and safe way to treat low levels of radiocesium-contaminated organic waste. In addition, because the contaminated silage compost can be reused as organic fertilizer or soil conditioner safely, a final landfill site is not required. For reconstruction of sustainable agriculture in radiocesium-contaminated areas of Japan, it can be helpful to treat the organic waste contaminated with radioactive cesium by aerobic, high-temperature composting.

Fig. 6.3 The examination of cultivation of crops in soil fertilized radiocesium contaminated silage compost. Overview of the experimental sections in the greenhouse (**a**). We fertilized the soil with a chemical fertilizer (control treatment in the 1st section). In the 2nd and 3rd sections, the contaminated silage compost (265 Bq/kg) was applied to the soil (3 kg/m^2 and 20 kg/m^2, respectively). And cow feces compost (2 kg/m^2; non-contaminated) was applied to the 4th section. Mixing of compost in the 3rd section (**b**). Cultivation of crops in a greenhouse (**c**). Swiss chard (leaf), tomato (fruit), carrot (root), and cosmos (flower) were cultivated in soil fertilized with the contaminated silage compost 20 kg/m^2 (**d**, **e**, **f**, and **g**)

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