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Communication

Practical Removal of Radioactivity from Soil in Fukushima Using Immobilized Photosynthetic Bacteria Combined with Anaerobic Digestion and Lactic Acid Fermentation as Pre-Treatment

Ken SASAKI,[1,†] Hiroyo MORIKAWA,[1] Takashi KISHIBE,[1] Kenji TAKENO,[1] Ayaka MIKAMI,[2] Toshihiko HARADA,[3] and Masahiro OHTA[2]

[1]*Materials Science and Engineering, Graduate School of Engineering, Hiroshima Kokusai Gakuin University, 6-20-1 Nakano, Aki-ku, Hiroshima 739-0321, Japan*
[2]*Ohta Koukan Co., Ltd., 6-2-30 Shoko Center, Nishi-ku, Hiroshima 733-0833, Japan*
[3]*RCO Co., Ltd., 2-5-7 Honkawacho, Naka-ku, Hiroshima 730-0802, Japan*

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Practical removal of radioactivity from polluted soil in Fukushima, Japan was done using a photosynthetic bacterium, *Rhodobacter sphaeroides* SSI, immobilized in alginate beads. The beads were put in a mesh bag and soaked in which soil was suspended (5 kg of soil/10 L of tap water). The radioactivity of the broth decreased by 31% after 15 d of aerobic treatment. When lactic acid bacterial culture broth was added to the suspend broth, about 50% of the radioactivity was transferred to a suspend broth fraction consisting of small particles from the soil after 3 d of fermentation and 20 s of sedimentation. The results suggest that organic matter in the soil was decomposed by anaerobic digestion and lactic acid fermentation simultaneously, and was then transferred into the liquid as small particles. With combined treatment by anaerobic digestion and lactic acid fermentation for 5 d and immobilized bead aerobic treatment for an additional 19 d, the radioactivity of suspend broth decreased by 66%. The radioactivity of the original soil (10.56 μSv/h) ultimately decreased by 67% (3.52 μSv/h) after the combined treatment.

Key words: radioactive soil; radioactive Cs removal; photosynthetic bacteria; anaerobic digestion; lactic acid fermentation

The pollution of drinking and agricultural water, sediment mud, and soil by radioactive materials due to the spread of depleted uranium (DU) during the Iran–Iraq War and the Gulf War, and in uranium mine wastewater, cause severe health problems among local inhabitants.[1,2] For more than 10 years, we have studied the removal of radionuclides such as uranium (U), strontium (Sr), and cobalt (Co) using a photosynthetic bacterium, *Rhodobacter sphaeroides* SSI, immobilized on porous ceramic beads. Almost 95% of U, 82% of Sr, and 58% of Co were removed from water containing artificial sewage wastewater after 6 d of aerobic treatment.[3] In addition, SSI immobilized ceramic beads can remove toxic heavy metals such as mercury (Hg), chromium (Cr), arsenate (As), and cadmium (Cd) in 2–4 d of treatment.[3,4] Furthermore, almost 100% of the cesium (Cs) was removed from the contaminated water using immobilized SSI ceramic beads after 4 d of treatment.[5,6]

The March 2011 nuclear accident spread radioactive materials throughout local and regional environments from the Fukushima Electric Power Plant. Radioactive materials contaminated the area's soil, water, and sediment mud. The main radioactive materials that must be removed from the water, sediment mud, and soil in the Fukushima area are Cs radionuclides. ^{137}I has already disappeared due to its short half life (about 8 d) and the amount of radioactive Sr diffusion was small.[7] Radioactive Cs removal from the water, sediment mud, and soil must be done. Rapid purification is necessary to recover from the disaster.

Radioactive Cs removal from water and soil is being done mainly by physical and chemical approaches such as using zeolite and clay and treatment with chemicals.[8–10] Adsorption treatment using solvents has also been proposed,[11] but more efficient, convenient, and low-cost technologies must be developed in view of the long-term need for practical purification. Biological treatment using plants such as sunflowers have been tried, but the removal effects were insufficient.[8]

Regarding microbiological removal of radioactive Cs, many reports have described the use of a fungus, *Paxillus involutus*,[12] and cyanobacteria, *Synecchocystis* PCC 6803,[13] and *Rhodococcus erythripolis* and *Rhodococcus* sp.[14] Recently, radioactive Cs removal using a blue-green alga, *Parachlorella binos*, has been reported[15] in a flask-level experiment, but practical Cs removal using these means has not been reported. Hence, we attempted practical radioactive Cs removal from sediment mud using a photosynthetic bacterium immobilized on SSI beads with alginate. The experiment used water from a swimming pool in Fukushima. About 90% of the radioactive Cs in the sediment mud was removed during 4 d of treatment in an outdoor 55 L scale experiment.[7] After treatment, immobilized beads containing radioactivity can be incinerated at low temperature, achieving 97–99% reduction in biomass volume and weight, without radioactive Cs release into the air.[7] These results appear to promise important benefits

† To whom correspondence should be addressed. Fax: +81-82-820-2560; E-mail: sasaki@hkg.ac.jp

considering the built-up stocks of radioactive waste materials that require disposal now.

This report describes practical radioactive Cs removal from Fukushima soil, done with SSI immobilized beads by a procedure reported earlier.[7] In addition, anaerobic digestion and lactic acid fermentation were newly applied as a pre-treatment to enhance radioactive Cs removal from the soil.

A photosynthetic bacterium, *Rhodobacter sphaeroides* SSI, was used. Strain SSI produces extracellular polymeric substances (EPSs) on the cell surface, which can absorb radioactive Cs as a Cs^+ cation.[3,7] It also incorporates Cs with a potassium (K) transport system.[16]

The cultivation and immobilization procedures for SSI, with approximately 2-cm alginate beads, are described in a previous paper.[17,18] The beads were packed into a mesh bag (1.0×1.0 mesh, 15 cm in diameter, 30 cm long), as described previously. One mesh bag contained about 210 beads and 10.0 mg of SSI cells (dry base).[7]

Radioactive Cs polluted soil contain muck was harvested from the Yokogawa Dam site in Haramachi-ku, Minami-Soma City, Fukushima, which is immediately outside the 20-km radius from the Fukushima Electric Power Plant. The soil in this area has high radioactivity, 7.0–15 μSv/h. The radioactivity in the air around the dam-site was 5–10 μSv/h. The harvested soil was a typical clay forest soil including the muck found in this forest area (moisture 32.0%, COD 11.7 mg/g of dry weight, NO_3–N 0.55 mg/g, NH_4–N 0.10 mg/g, PO_4^{3-} 4.20 mg/g). The radioactive materials were almost entirely ^{137}Cs and ^{134}Cs.^{131}I, and ^{89}Sr and ^{90}Sr were almost nonexistent in the environment as of September 2011.[7]

Four glass water vessels (23 L, $40 \times 25 \times 28$ cm) were prepared. Then 5 kg of clay soil (wet base) and 10 L of tap water (radioactivity less than 0.3 μSv/h) were added. After thorough mixing, 0–3 bags of SSI immobilized beads were soaked in the broth. The designation zero bags is for a control experiment without the addition of a bead mesh bag. Aeration (0.2–0.3 vvm) was continued under dark conditions after the addition of nutrients (glucose 4 g, peptone 0.15 g, thiamine-HCl 0.05 g, nicotinic acid 0.05 g, and biotin 0.01 g/15 kg of broth). The temperature was maintained at $30\,^{\circ}C \pm 1.0$. The broth pH was adjusted every day by hand after thorough mixing between 6.0–7.5 pH with a concentrated NH_4OH solution. At 3–4 d intervals, broth radioactivity was measured and nutrients were added. The SSI strain grows well under both anaerobic light (photosynthesis) and aerobic dark (respiration) conditions.[3,4,6]

Radioactivity was measured using a survey meter (Aloka TGS121; Aloka, Tokyo) and two different models of dosimeters (Dose RAE2, PRM-1200; Rae System, Boston, MA), as described in an earlier report.[7] The sensor was covered with a waterproof vinyl bag and immersed in 2–5 cm of liquid to measure radioactivity, as described previously.[7] For soil radioactivity measurements, sensor was put in a small hole from which soil had been removed to 1–2 cm depth to cover the sensor moiety completely. In an evaluation of radioactivity, Becquerel (Bq) units are preferred for accurate quantitative evaluation. However, in practical removal of Cs, analysis by Bq unit is expensive and requires time for accurate evaluation. It is not convenient for practical tasks.[6,7]

The SSI immobilized beads used had no radioactivity, because cultivation and SSI cell immobilization were done in a laboratory in Hiroshima, Japan where only trace radioactivity (0.12 μSv/h) was detected in the air. Radioactivity removal in the soil purification experiments was conducted in our branch laboratory in Minami-Soma City, Fukushima, where the radioactivity in the air was 0.3–0.4 μSv/h.

To remove radioactivity from the soil, 1–3 bags of SSI immobilized beads were put in soil suspend broth with continuous aeration. As shown in Fig. 1, when 2 and 3 bags were soaked in the broth, the initial radioactivity of suspend broth of 7.26 μSv/h decreased to 5.81 (2 bags) and 5.63 (3 bags) after 9 d of aerobic treatment (about 20–22% removal). Then fresh SSI immobilized beads were substituted and radioactivity was further reduced, to 5.30 μSv/h (2 bags) and 5.04 (3 bags) after 15 d (maximum 31% reduction for 3 bags). When one bag was soaked in the broth, radioactivity decreased only 11% after 15 d. The control experiment, in which only nutrient addition and aeration were continued without SSI immobilized beads, showed almost no reduction in the radioactivity of the soil suspend broth. These results indicate that SSI immobilized beads absorbed or incorporated radioactive Cs from the soil suspend broth.

This was an unexpected result when compared with our previous results, in which about 90% radioactivity of sediment mud decreased after 3 d in water from a swimming pool in Fukushima.[7] SSI cells attract Cs^+ from sediment mud *via* water by the negative charge of EPS on the surfaces of cells and the K transport

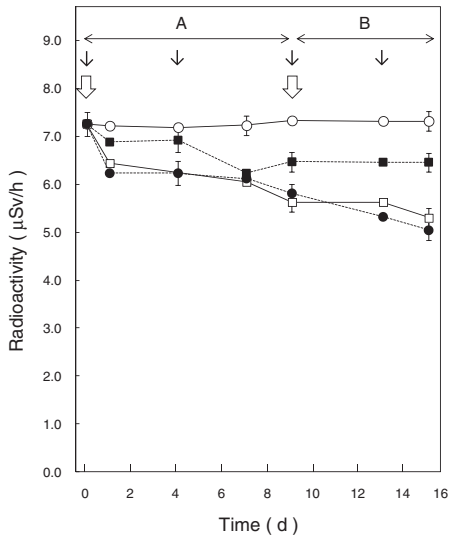

Fig. 1. Removal of Radioactivity by *Rhodobacter sphaeroides* SSI Immobilized Beads from Polluted Soil Suspend Broth in Fukushima.

Bags (n = 1–3) containing beads (about 210 pieces per bag) were put in soil suspend broth (5 kg of soil and 10 L of tap water). Nutrients (glucose, peptone, and vitamins) were added and aeration 0.2–0.3 vvm continued. Temperature and pH were maintained at 30 ± 1.0 and 6.0–7.5. A, first treatment; B, second treatment after fresh SSI immobilized beads bags were added. Solid arrows and hollow arrows respectively indicate nutrient and SSI immobilized mesh bags replaced: ○ control (no mesh bag of SSI immobilized beads); ■ one mesh bag; □ 2 mesh bags; ● 3 mesh bags.

system.[7] Radioactive Cs apparently strongly combines with soil compared with sediment mud. Fujikawa[19] reported that Cs generally combines strongly with silt and clay soil. In addition, Hashimoto reported that radiocesium strongly combines with organic muck, with soil components such as fumic and fulvic acids.[20] It is also difficult to release Cs into water even when strong acids such as HNO_3 are mixed with radioactive polluted soil.[8] The National Institute of Advanced Industrial Science and Technology, Japan reported that heat treatment (95 °C) with 0.5 mol/L of HNO_3 is necessary to release, at most, 70% of radioactive Cs from soil in the Fukushima area.[8] Thus, it is apparently difficult to reduce the radioactivity of soils as compared with sediment mud by SSI immobilized bead treatment.[7]

For more than 20 years, we have been studying purification (COD and phosphate and nitrate reduction) in sediment mud in Hiroshima Bay using photosynthetic bacteria[21] and lactic acid bacteria.[22] Recently, a report stated that a lactic acid bacterium, *Lactobacillus casei*, decomposed organic matter in sediment mud, and that the COD of the sediment mud was reduced about 30% by the addition of lactic acid bacteria over 4 weeks of static treatment, which suggests that lactic acid bacteria strongly decompose high molecular weight organic matter in the surface of sediment mud to low molecular weight organic acids and lactic acid.[18] Hence, we tried to bring about the release of radioactive Cs by lactic acid bacterial action from organic matter of forest soil containing muck in the Fukushima area, expecting Cs release in the form of small molecule organic matter into the liquid.

For anaerobic digestion and lactic acid fermentation, 5 kg of soil and 10 L of tap water were added to two cylindrical polyethylene vessels (20 L) and mixed well by hand after the addition of nutrients. One was for a control experiment on anaerobic digestion. Anaerobic digestion means static, dark incubation without aeration (dissolved oxygen 0). A vessel was sealed off with a lid, and the head air space was about 6 L. For another vessel, 1 L of lactic acid bacterial culture broth was added and mixed well. In both vessels, SSI immobilized beads were not soaked in the broth and no aeration was done (static condition). At 3–4 d, the broth was mixed well. After 20–60 s under static conditions, the sediment fraction (soil) of the bottom of the vessel and the turbid suspension fraction of the liquid (suspend broth) were separated. Then the radioactivity of each fraction was measured. In addition, the turbid suspend broth fraction was centrifuged (10,000 × *g*, 20 min), and the radioactivity of the clear supernatant, as the water fraction, was measured. Then, nutrients were added and the liquid (soil and suspend broth) was mixed well. Anaerobic digestion and lactic acid fermentation continued simultaneously for 14 d. The temperature was maintained at 35 °C ± 1.0 without aeration. The pH was maintained every day between 6.0 and 7.5 manually after complete-homogenization.

A lactic acid bacterial culture broth was prepared as described elsewhere.[18] Sterilized BCP liquid medium (1 L; glucose 1.0, yeast extract 2.5, peptone 5.0, polysorbate 80 1.0, L-cysteine 0.1, and bromocresol purple 0.06 g/L) was prepared in a 2-L conical flask. Lactic acid bacteria, *Lactobacillus casei*, isolated from a commercial environmental preservation materials (named Ehime AI),[23] was inoculated into the BCP liquid medium. After 4 d of cultivation under static dark conditions at 35 °C ± 1.0, this culture broth of lactic acid bacteria (OD_{660}, 0.6–0.7) was used as a seed for lactic acid bacterial culture broth. Ehime AI was made from a mixture of yogurt, baker's yeast, and *natto* (fermented soybeans).[23]

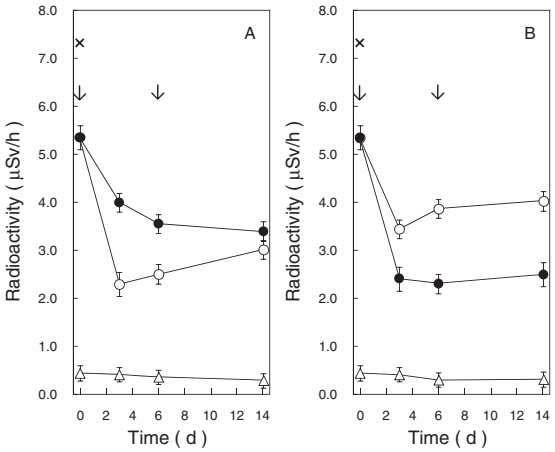

Fig. 2. Radioactivity Distribution in Soil and Suspend Broth Fraction during Anaerobic Digestion (A) and Anaerobic Digestion and Lactic Acid Fermentation (B) of Radioactive Cs Polluted Soil in Fukushima.

Soil suspend broth (5 kg of soil and 10 L of tap water) was incubated at 35 °C ± 1.0 after nutrient addition (solid arrows). pH was maintained at 6.0–7.5. A, anaerobic digestion; B, 1 L of lactic acid bacterial culture broth added; ○ suspend broth fraction after 20 s static condition; ● soil fraction after 20 s of static condition; △ clear water after centrifugation (10,000 × *g*, lactic acid bacterial broth and nutrients (glucose, peptone, and vitamins) 20 min); × original soil (7.32 μSv/h) used here.

As Fig. 2A shows, the radioactivity of the soil fraction after 20 s of sedimentation decreased to 3.40 μSv/h (7.32 to 3.40 μSv/h, 54% reduction) after 14 d of static incubation. The radioactivity of a 3.02 μSv/h was released in the suspend broth fraction after 14 d. Almost half of the radioactivity was released in the suspend broth fraction. Hence, the radioactivity of the water fraction, which was a clear supernatant of suspend broth, was almost nil because the radioactivity in ambient air of the laboratory in Minami-Soma was 0.3–0.5 μSv/h, which suggests that during incubation, anaerobic digestion proceeded by glucose and peptone addition, and then high molecular weight organic matter was decomposed to small particles of organic matter and organic acids. Organic matter containing Cs was suspended as low-molecular-weight materials in the liquid. We measured the radioactivity of the suspended broth after 20 s, 40 s, and 60 s of sedimentation. For instance, the radioactivity levels of the suspend broths at 20 s, 40 s, and 60 s after sedimentation at 14 d were 3.40, 3.20, and 3.50 μSv/h, respectively. High-molecular-weight soil materials deposited immediately during 20 s and low-molecular-weight materials remained suspended in the broth. The radioactivity of the suspend broth fraction increased gradually from 3 to 14 d, apparently as a result of the anaerobic digestion effect.

The radioactivity of original soil (7.32 μSv/h) was lower than the sum of the radioactivity of the suspend broth and the soil fraction. The reason is not clear. The

radioactivity measurements for the soil consisted of surface detection of the radioactivity of the soil mass. The radioactivity inside the soil mass may not detected due to the shield effect of the soil itself by our analytical approach. Germanium Semiconductor Detector analyses[7] are necessary in Becquerel units (Bq) to determine the quantitative fate of radioactivity from soil to suspend broth and soil fraction, but one can assess the fate of radioactivity by our analytical approach in practical terms.

When the lactic acid bacterial culture broth was added (Fig. 2B), the radioactivity of the suspend broth fraction was always higher than that for anaerobic digestion (Fig. 2A). The radioactivity of the suspend broth was almost 2 times greater than that of the soil fraction. The radioactivity of the soil fraction fell to 2.50 μSv/h after 14 d of treatment (7.32 to 2.50, a 66% reduction), which suggests that lactic acid fermentation functioned like organic matter decomposition and enhanced Cs release to the low-molecular-weight material moiety from the muck containing soil together with anaerobic digestion effects. Lactic acid fermentation is apparently more effective for release of radioactive Cs into a liquid than anaerobic digestion. However, radioactive Cs in the clear pure water fraction was invariably absent. Released radioactive Cs was combined with low-molecular weight-materials of the soil moiety including organic matter (fumic and fulvic acids) and was suspended in the broth. In addition, a possibility exists that the lactic acid produced by bacterial action enhanced Cs release into liquids such as oxalic acid. Another possibility is that nutrients in lactic acid bacterial broth enhance the decomposition of high-molecular-weight materials.

Our results (Fig. 2B) indicate that no radioactive Cs release into low-molecular-weight materials of the soil due to anaerobic digestion and lactic acid fermentation has been reported to date. Our results are apparently important observation. The radioactivity of the original soil at 7.32 μSv/h was reduced to 2.50 μSv/h at 14 d (66% reduction) by anaerobic digestion and lactic acid fermentation. Anaerobic digestion and lactic acid fermentation are simple and inexpensive. Mere substrate addition and mixture and temperature maintenance (30–50 °C) are sufficient for this process. Some organic wastes such as food industry wastes and stockbreeding wastes are available as nutrients. The lactic acid bacterium used here is a common bacterium isolated from commercial environment preservation materials.[23] Furthermore, reduction of radioactivity was effective after 3 d.

If better lactic acid bacteria or anaerobes are selected, then greater reduction of radioactive Cs from soil is to be expected. This report presents one example of microbiological effective removal of radioactive Cs from soil using lactic acid bacteria. Anaerobic digestion bacteria and lactic acid bacteria are popular microorganisms in the agricultural fields. This technology is potent for radioactive Cs purification of the soil for agricultural fields in Fukushima and the Tohoku region.

For removal of radioactive Cs, physical treatments such as zeolite and clay treatments[8,9] are frequently applied in the Fukushima area, but such treatments are difficult for agricultural fields because the release of Cs from soil is difficult and a large amount of treated radioactive waste comes to present another problem for built-up stock areas. Moreover, radioactive Cs removal using chemicals is difficult in agricultural fields because of the chemicals' chronic toxic effects on plants and human beings. Biological treatments such as plant bioremediation and microbiological proceses are applicable to agricultural fields.

In experiments to assess combinations of anaerobic digestion, lactic acid fermentation, and SSI immobilized beads treatments, three glass vessels (23 L, described above) were prepared and 5 kg of soil and 10 L of tap water, and nutrients were added. To three vessels, 1 L of lactic acid fermentation broth was added. One was for a control experiment without added SSI immobilized beads (only for anaerobic digestion and lactic acid fermentation) and aeration. After 4 d of fermentation at 35 °C ± 1.0, simultaneous anaerobic digestion and lactic acid fermentation of the soil proceeded in the three vessels. Subsequently, 2–3 mesh bags of SSI immobilized beads were soaked in the two vessels and aeration at 0.2–0.3 vvm was started at 30 °C ± 1.0 in the three vessels. The pH of the broth was maintained at 6.0–7.5 manually every day. The broth was mixed well 2 times every day to produce homogeneous conditions to the extent possible.

To reduce suspend broth radioactivity after anaerobic digestion and lactic acid fermentation, SSI immobilized beads treatment was done. As depicted in Fig. 3, when two or three bags were soaked in soil suspend broth, the

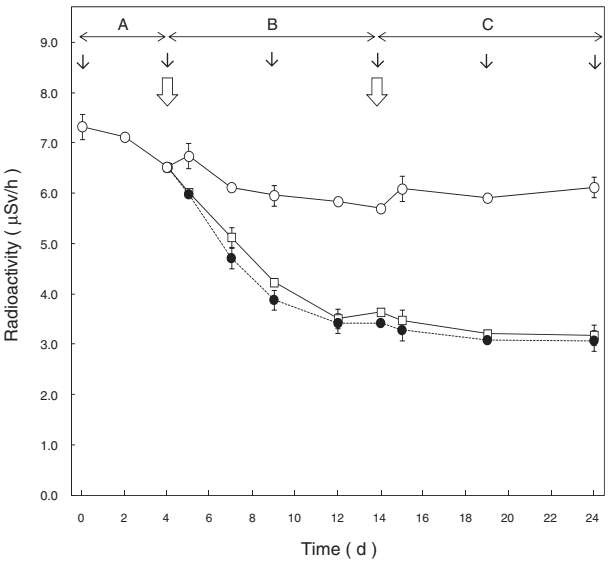

Fig. 3. Removal of Radioactivity of Soil Suspend Broth in Fukushima in Combination with Anaerobic Digestion and Lactic Acid Fermentation and *Rhodobacter sphaeroides* SSI Immobilized Beads Treatment from Polluted Soil Suspend Broth.

As pre-treatment, anaerobic digestion and lactic acid fermentation were conducted for 3 d (A) at 35 °C ± 1.0 after addition of lactic acid bacterial broth and nutrients (glucose, peptone, and vitamins) to the soil suspend broth (5 kg of soil and 10 L of tap water). Then 2–3 mesh bags were soaked in the broth and aeration at 0.2–0.3 vvm was continued under the same conditions as described in Fig. 1. Temperature and pH were maintained at 30 °C ± 1.0 and 6.0–7.5. A, pre-treatment, anaerobic digestion and lactic acid fermentation; B, first treatment after SSI immobilized bead addition; C, second treatment after fresh SSI immobilized beads bags were soaked in the broth. Solid arrows and hollow arrows indicate nutrient addition and SSI immobilized mesh bag addition: ○ control (no mesh bag of SSI addition); □ two mesh bags added; ● three mesh bags added.

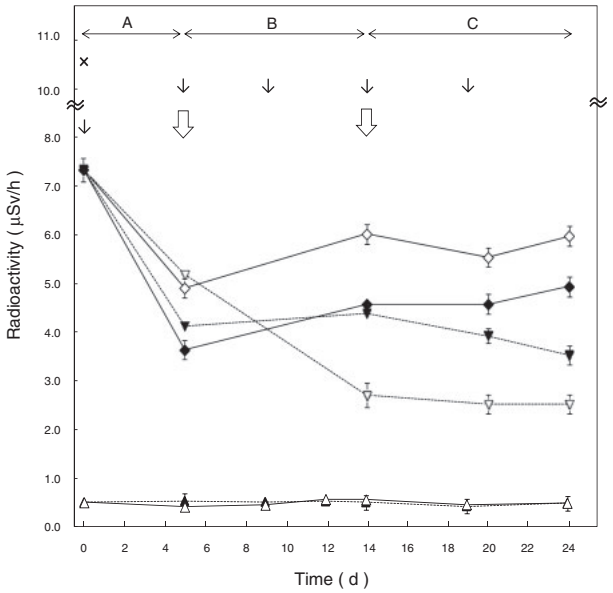

Fig. 4. Radioactivity Distribution in Soil, Suspend Broth, and Clear Water Fraction during Combined Treatment with Anaerobic Digestion and Lactic Acid Fermentation and SSI Immobilized Beads.

This is the same experiment as that depicted in Fig. 3. ◆ control (no mesh bag of SSI addition), soil fraction after 40 s of static condition; ◇ control (no mesh bag of SSI addition), suspend broth fraction after 40 s of static condition; ▲ control (no mesh bag of SSI addition), clear water fraction after centrifugation (10,000 × *g*, 20 min); ▼ soil fraction after 40 s of static condition with three mesh bags of SSI immobilized beads added; ▽ suspend broth fraction after 40 s of static condition with three mesh bags of SSI immobilized beads added; △ clear water fraction after centrifugation (10,000 × *g*, 20 min); × original soil (10.56 μSv/h) used here.

initial radioactivity of the broth (7.33 μSv/h) decreased to 3.64 (two bags) and 3.42 (three bags) (an approximately 53% reduction) after 14 d. The approximately 53% reduction in the soil suspend broth was greater than for SSI immobilized beads treatment alone (Fig. 1, 31% reduction after 15 d). Furthermore, the radioactivity decreased to 3.18 (two bags) and 3.02 (three bags) (a maximum 59% reduction after 24 d). Radioactivity was slightly reduced by the addition of fresh SSI immobilized beads. Radioactive Cs was almost absorbed, and was incorporated as low-molecular-weight material that were easily absorbed and incorporated by SSI cells at the first SSI immobilized bead soaking. As for enhancement of radioactivity removal by soil suspend broth as compared with SSI immobilized beads alone, anaerobic digestion and lactic acid fermentation enhanced the release of radioactive Cs into small particles of soil and enhanced adsorption and incorporation by SSI cells.

It has been inferred by us that Cs removal by SSI cells proceeds by two processes: adsorption of Cs^+ by the negative charge of EPS on the surfaces of cells,[3,7] and incorporation of Cs by a potassium transport system.[7,16]

For this experiment as shown in Fig. 3, the radioactivity distribution in soil, the suspend broth, and the clear water fraction are portrayed in Fig. 4. Only the results of the three bags treatment are shown, because the results obtained for two bags were almost identical. The radioactivity of the suspend broth decreased to 2.52 μSv/h after 24 d of treatment, a 66% reduction. The radioactivity of the original soil, 10.56 μSv/h, decreased to 3.52 after 24 d (a 67% reduction). This soil (shown in Figs. 3 and 4) was obtained from different place in the Yokogawa Dam site in Minami-Soma compared with the soil (7.32 μSv/h) used for the experiments in Fig. 2. This 67% reduction in radioactivity is almost the same level as those for anaerobic digestion and lactic acid fermentation (Fig. 2B). The SSI immobilized beads reduced the radioactivity of the suspend broth, but it is difficult to remove radioactive Cs from soil that is strongly combined with the soil structure.[20] Pre-treatment such as anaerobic digestion and lactic acid fermentation appeared enhance Cs removal from the soil.

An important benefit of using SSI immobilized beads was reduction in the polluted biomass of the beads after Cs removal by drying and incineration. The maximum reduction is 97% and 99% (volume and weight, respectively) without release of radioactivity into air.[7] This technology can be used to reduce the radioactivity of other sandy soils, incinerated ash from wastewater treatment sludge, and other trash and debris in the Fukushima area containing radioactive Cs. Furthermore, it can be used for removal of radionuclides from wastewater by post anaerobic digestion, bioethanol production, and lactic acid fermentation from radioactive biomass and debris and large amounts of biomass including radioactive materials from forests in Fukushima.

The reduction in soil radioactivity was about 70%. Better lactic acid bacteria or anaerobes might improve the process. About 30% of the original radioactivity remained in the soil, and the remaining Cs was strongly combined with the soil matrix structure. Thus it is difficult to transfer radioactive Cs to plants, crops, and vegetables, once biological treatment by photosynthetic bacteria is finished. In connection with this, sunflower plantations cannot remove radioactive Cs from the soil in Fukushima because Cs is strongly combined with the soil structure in the clay soils of the region.[8] In addition, radioactive Cs, which is biologically easily transferred to plant cells, will have already transferred to photosynthetic bacteria. Therefore, soil treated using our technology might be applicable to agriculture and gardening without any accumulation of radioactive Cs in grown plants. This possibility is under investigation.

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