Effect of Structural Features of Plant Biomass as a Dewatering Aid for Digested Sludge from a Wastewater Treatment Plant

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Large amounts of plant biomass are produced by public work projects. This plant biomass was evaluated as an aid for the dewatering of sludge from a sewage treatment plant. The relationships were investigated between the different structural types of plant biomass (grass clippings, pruned branches of Japanese black pine, and bamboo powder) and their dewaterability potential in digested sludge. Microscopic observations revealed that grass fibrous materials and Japanese black pine needles had hollow structures. However, xylem, bark parts of Japanese black pine, and bamboo culms exhibited woody cell structures. The difference in water retention value of grass clippings after filtration and centrifugation was higher than that of Japanese pine and bamboo, indicating that the water present within the pores of grass fibrous materials could be easily removed. Plant biomass was captured inside the floc when digested sludge was mixed with plant biomass and flocculation was performed by adding a flocculant. The addition of grass clippings exhibited better dewaterability compared with both Japanese black pine and bamboo. The grass fibrous materials used as a dewatering aid effectively improved the dewaterability of the digested sludge because the water in a sludge floc may be drained from within the grass fibrous materials.

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Keywords: Water retention value; Digested sludge; Plant biomass; Dewaterability of filter cake

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INTRODUCTION

Large amounts of plant biomass are produced by public work projects, such as mowing and pruning activities along rivers, highways, pathways, and parks, in Japan; however, this plant biomass has remained an unused resource in the region. Plant biomass can be used as compost (Stabnikova *et al*. 2005; Alvarenga *et al*. 2015) and as a dewatering aid for sewage sludge (Lin *et al*. 2001a,b; Jaafarzadeh *et al*. 2016). Furthermore, it can be used in methane production *via* co-anaerobic fermentation with sludge (Koch *et al*. 2009; Hidaka *et al*. 2013) and combusting fuels in an incinerator (Hurskainen and Vainikka 2016; Gutiérrez-Acosta *et al*. 2021). Thus, a wastewater treatment plant (WWTP) with an intense treatment system using this plant biomass is desirable.

In Japan, the amount of sludge generated as dry solids from WWTP in 2015 was 2.3 million tons, and approximately 75% of it was used as composts, fuels, building materials, *etc*. (MLIT 2019). Reduction in the water content of sewage sludge is crucial for its effective transportation and combustion in an incinerator. Besides, this is also important for promoting sewage sludge recycling. The digested sludge produced from anaerobic fermenter includes colloidal particles (Kamimura 1973; Mikkelsen and Keiding 2002), which decreases dewaterability. Thus, an effective dewatering system of digested sludge is necessary. One of the feasible method is to add physical conditioners to the sludge before dewatering, which improves sludge filterability and increases the solid content of the cake (Zall *et al.* 1987).

Previous reports have focused on the use of plant biomass for aiding sewage sludge dewatering (Yamasaki and Shigemura 2017, 2019, 2020). Sewage sludge centrifugal dewatering with grass clippings exhibited an effective reduction in sludge water content, and its disposal cost is expected to be lowered by adding plant biomass (Yamasaki and Shigemura 2017). Likewise, when pruned branches of Japanese black pine and bamboo powder were used as the aid for sewage sludge dewatering during a quasi-belt press-dewatering test in the laboratory, the sludge's dewaterability improved (Yamasaki and Shigemura 2019). In addition, when a screw press dewatering test was conducted in the WWTP, the order of dewaterability by adding plant biomass was grass clippings > pruned branches of Japanese black pine > bamboo powder (Yamasaki and Shigemura 2020). Further, the sludge's dewaterability changed when different structural types of plant biomass were used as the aid for sewage sludge dewatering.

The chief function of a dewatering aid has been proposed that to give a filter cake a porous nature and hence a high permeability (Cogger and Merker 1940). Fibrous materials, such as synthetic fiber and used paper, are renowned for improving filter cake's dewaterability (Tochioka *et al*. 2019). Usui and Hosokawa (2016) assumed that fibrous materials could function as a skeleton builder for creating pores between sludge particles. We have another hypothesis that the water in filter cake can be drained through inside of the fibrous materials, which is similar in mechanism to a drainage using soft ground improvement (prefabricated vertical drain) methods (Chai and Miura 1999), one of the technologies in the civil engineering field. Alternatively, the collecting place, plant species, and crushing method influence the structural types of plant biomass. It has also been reported that adding grass clippings (Yamasaki and Shigemura 2017, 2020), pruned branches of Japanese black pine (Yamasaki and Shigemura 2019, 2020), bamboo powder (Yamasaki and Shigemura 2019, 2020), bagasse pith (Jaafarzadeh *et al*. 2016), wood chips, and wheat dreg (Lin *et al*. 2001b) can improve sludge-cake's dewaterability; however, no reports have been identified in which structural types of plant biomass influenced dewatering.

Water retention value (WRV) can be used to evaluate the degree of fibrillation of the fibrous materials, such as pulp fibers (Stana-Kleinschek *et al*. 2001; Hubbe and Heitmann 2007). The WRV is measured by the amount of water retained by a material after centrifuging at a given condition (Cheng *et al*. 2010). If the WRV measurement is conducted by filtration under normal pressure, the water-filled in the plant biomass would remain in the fibrous material's pores. In this study, the difference in WRV after filtration and centrifugation was thought to be a relevant reference to evaluate the possibility of water draining from plant tissues during the dewatering process.

In this study, the relationships between the different structural types of plant biomass (grass clippings, pruned branches of Japanese black pine, and bamboo powder) and their dewaterability potential in digested sludge were investigated. First, microscopic observations of the plant biomass were conducted, and their structural features and WRV were studied. Second, the flocculation properties of digested sludge with plant biomass by adding flocculant were studied. Third, the effect of plant biomass structures on the dewaterability of flocculated digested sludge was studied.

EXPERIMENTAL

Materials

Plant samples used in this study were the same as described in previous study (Yamasaki and Shigemura 2020). Grass (Poaceae family) clippings and pruned branches of Japanese black pine (*Pinus thunbergii*) were obtained from an area in Public Work Research Institute. Then, they were treated using a crusher (Ohashi Inc., GS131GH equipped with a 10-mm screen). Bamboo (*Phyllostachys* spp.) powder was purchased from the market, and subsequently, it was treated using a crusher (Ohashi Inc., GS121GB). The prepared samples were kept in a desiccator (20 ± 5 °C and 30 ± 10%) for over 12 months.

Digested sludge was obtained from the WWTP in Japan. The total solid (TS), volatile solid (VS), and pH of this sludge were 1.13%, 0.84%, and 7.4, respectively.

Analysis of Plant Biomass

TS and VS were measured at 110 and 600 °C, respectively, based on a standard method (Baird and Bridgewater 2017) with minor modifications. Moisture content was calculated by subtracting TS from 100%. Plant samples (oven-dried) of 0.3 g were soaked in 30-mL water in a 100-mL graduated cylinder for 13 days. The density of the samples was calculated by dividing the dry weight (g) of the plant samples with the increase in water volume (mL) after soaking.

The plant samples were filtered using a wire mesh (100 mesh) after soaking them in water, and the weight of the samples was measured after filtered by gravity. The same samples were centrifuged at 15,000 G for 15 min, and then their weight was measured again. These samples were further dried at 110 °C, and their dried weight was measured. The WRV of plant samples was calculated using the following formula (TAPPI UM256 1981),

$$\text{WRV}\ (\%) = A/B \times 100 \tag{1}$$

where *A* represents the sample weight (g) after filtration or centrifugation and *B* represents the sample weight (g) after drying at 110 °C, respectively. ΔWRV was calculated by subtracting WRV after centrifugation from that after filtration.

Air-dried plant samples were spread in a plastic tray (10 cm × 5 cm) and photographed with a camera having a scale meter. Thirty parts from each plant tissues were randomly selected from the photograph; their length and width were measured using image J software. The measured tissues include fibrous materials from grass clippings, needles, xylem, barks from pruned branches of Japanese black pine, and column parts from bamboo powder.

Microscopic Observation

An optical microscope (Biotools Inc., UA310 CA, Takasaki, Japan) equipped with the camera was used for observation. The microscope was operated at magnifications of 100 and 400 folds, and the obtained photographs were further magnified by 3- to 12-fold. The pore size of plant samples were measured using image J software.

Dispersion Test

Plant samples (0.8 g) were added in 100-mL water or digested sludge in a 100-mL graduated cylinder. The top of the graduated cylinder was closed and inverted three times, and then left to stand for 3 min. Afterward, a 30-mL dispersion was obtained from the upper and bottom parts as the floating and precipitating parts, respectively. The collected dispersion was dried at 110 °C, and the weight of plant biomass was measured by subtracting the solid weight of water or digested sludge from the TS weight of the dispersion.

Flocculation Test

Plant biomass of 0.7 g was added to a 300-mL digested sludge (TS 1.13%), and then a 2.5 mL cationic polymer flocculant (Mitsubishi Chemical Corp., DIAFLOCK KP1200B, Tokyo, Japan) 1% solution was added. The dosage of plant biomass and flocculant was 20% and 0.74% on the sludge solid weight, respectively. The rapid mixing was conducted at 240 rpm for 3 min, followed by a slow mixing at 30 rpm for 5 min using a jar-tester. The mixture was left for 1 min after mixing. A portion of the floc was collected in a plastic tray (10 cm × 5 cm) and the obtained flocs were visually observed.

Filtration Test

The samples after the flocculation test were transferred to a graduated cylinder, whose total volume was adjusted to 500 mL. Filtration was conducted using an acrylic cylinder (108-mm diameter) and polyester filter cloth (Tokyo Metropolitan Sewerage Service Corp., dehydration test kit, Tokyo, Japan). The gravity filtration test was conducted by placing the samples in the acrylic cylinder with polyester filter cloth and they were left for 5 min. The amount of obtained filtrate and moisture content of the filter cake were measured. The gravity filtration test was followed by a pressurized filtration test using a 2-kg plumb, and the pressurization was conducted for 5 min using the same equipment. The additive amount of flocculant using gravity and pressurized filtration tests was 0.74% and 1.5% (on sludge solid weight), respectively.

RESULTS AND DISCUSSION

Physical Structural Features of Plant Biomass

Table 1 and Fig. 1 show the sizes and optical microscopic images of plant biomass, respectively. Grass clippings included fibrous materials, and the pruned branches of Japanese black pine included needles, xylems, and barks (Figs. 1A and D). The length and width of grass fibrous materials were smaller than Japanese black pine needles (Table 1). The size of the bamboo powder's culm parts was 2 mm (Fig. 1I).

Microscopic observations revealed that grass fibrous materials had hollow structures, and their pore size was approximately 80 to 150 μm (Table 1). Japanese black pine needles also had hollow structures (Fig. 1 F) with pore sizes of approximately 200 to 300 μm, which was larger than that of grass fibrous materials; a similar tendency was observed from the size measurement analysis presented in Table 1. However, the xylem and bark parts of Japanese black pine and bamboo culm exhibited woody cell structures (Figs. 1 G and K), and their pore sizes (less than 30 μm) were smaller than those of either grass fibrous materials or Japanese black pine needles. The bark parts of Japanese black pine exhibited smaller pore sizes compared with the xylem parts (Fig. 1 H). The bamboo powder contained culm parts and particulate materials (50 to 200 μm, Figs. 1 I and J); however, the origin of these particulate materials remains unknown. In addition, even when plant samples were stored in a desiccator (20 ± 5 °C and 30 ± 10%) for over 12 months, the decayed regions of plant cell walls by microorganisms could not be observed *via* microscopic investigations. Thus, plant biomass could be stored for a long time, provided the moisture content was maintained below 40% (Table 1).

Table 1 shows the WRV after filtration and centrifugation. The WRV after filtration of grass clippings (670%) was higher than that of the pruned branches of Japanese black pine (470%) and bamboo powder (380%). The WRV after centrifugation of grass clippings (260%) was similar to that of the pruned branches of Japanese black pine (260%) but higher than that of bamboo powder (190%). The higher WRV after filtration indicated that a large amount of water was retained in the plant tissues with hollow structures. The difference in WRV between after filtration and centrifugation (ΔWRV) of grass clippings was 410%, which was higher than that of the Japanese black pine pruned branches (210%) and bamboo powder (190%). These results showed that centrifugation can easily remove water from within the pores of plant tissues with hollow structures (such as grass fibrous materials and Japanese pine needles). The dewaterability of sewage sludge with hollow-structured plants could be improved by draining water from inside their pores during dewatering. However, because the ΔWRV of bamboo was low, a small amount of water can be drained from inside woody cell structures, such as bamboo culm, xylem, and bark parts of Japanese black pine.

Table 1. List of the Properties and Size of Plant Biomass

		Grass clippings	Pruned branches of Japanese black pine			Bamboo powder
Moisture content (%)		34.1	41.8			39.8
Density (g/cm^3)		0.22	0.55			0.39
WRV* (%)	Filtration	670	470			380
	Centrifugation	260	260			190
	ΔWRV**	410	210			190
Plant tissue		Fibrous material	Needle	Xylem	Bark	Culm
Length (mm)		3.8 ± 1.6	6.0 ± 2.4	4.9 ± 2.1	3.3 ± 2.0	2.2 ± 0.7
Width (mm)		0.5 ± 0.2	0.8 ± 0.2	1.6 ± 0.5	1.6 ± 0.6	0.6 ± 0.3
Pore size (μm)		80 - 150	200 - 300	<30	-	<30

*: Water retention value, **: Subtract WRV after centrifugation from WRV after filtration.

Dispersion Property of Plant Biomass

Table 2 shows the comparison of the dispersion property of plant biomass in water and digested sludge. When grass clippings and pruned branches of Japanese black pine were dispersed in water, they were mostly collected as the floating part (84% and 73%, respectively), as they easily floated on the water. Grass clippings with lower density than Japanese black pine and bamboo (Table 1) were particularly difficult to sink in water. In contrast, the bamboo powder was mostly collected as the precipitating part (83%), and it could easily sink in water. These difference of dispersion property might also be affected by plant biomass surface. Grass clippings and Japanese pine leaves have hydrophobic surface. In contrast, woody cell (bamboo and Japanese pine xylem) would have more hydrophilic surface due to their composition.

Alternatively, when grass clippings and pruned branches of Japanese black pine were dispersed in the digested sludge, the amount of the floating part decreased, whereas the precipitating part increased. In the case of bamboo powder, the amount of floating part in the digested sludge (31%) was similar to the precipitating part (33%). Plant biomass was more uniformly dispersed in the digested sludge than in water. In general, the digested sludge includes colloidal particles, which repel one another in the water (Kamimura 1973; Mikkelsen and Keiding 2002). These particles may adsorb to the surface of the plant biomass, preventing plant biomass from floating and precipitating in the digested sludge.

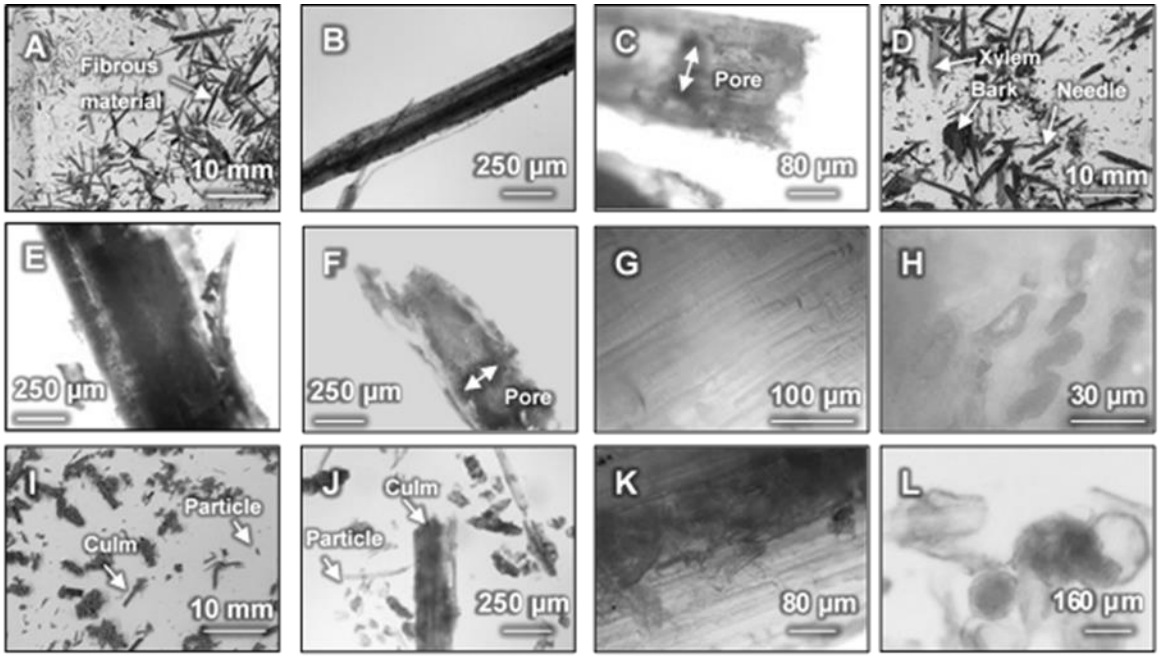

Fig. 1. Optical and microscopic images of plant biomass. A: grass clippings–appearance, B: grass clippings–fibrous material, C: grass clippings–fibrous material (cut surface), D: pruned branches of Japanese black pine–appearance, E: Japanese black pine–needle, F: Japanese black pine–needle (cut surface), G: Japanese black pine–xylem (fiber direction), H: Japanese black pine–bark (cross direction), I: bamboo powder–appearance, J: bamboo–culm and particle, K: bamboo–culm, and L: bamboo–particle.

Table 2. Comparison between Floating and Precipitating Parts of Plant Biomass Dispersed in Water and Digested Sludge

Dispersion Medium	Collecting Part	Grass Clippings	Japanese Black Pine	Bamboo Powder
Water	Floating (%)	84	73	12
	Precipitating (%)	13	19	83
Digested sludge	Floating (%)	53	54	31
	Precipitating (%)	19	30	33

Flocculation Property of Plant Biomass with Digested Sludge

Figure 2 shows the results of flocculation after the flocculant was added to the digested sludge with plant biomass. It was revealed that the plant biomass was captured within the floc. Plant biomass did not inhibit the flocculation of the digested sludge when the flocculant was introduced. Table 2 shows that the digested sludge was predicted as a function of dispersant for plant biomass. It was assumed that the complex floc containing sludge and plant biomass was obtained when digested sludge and plant biomass were mixed followed by the addition of flocculant to this mixture. This floc is expected to contribute to effective sludge dehyradtion.

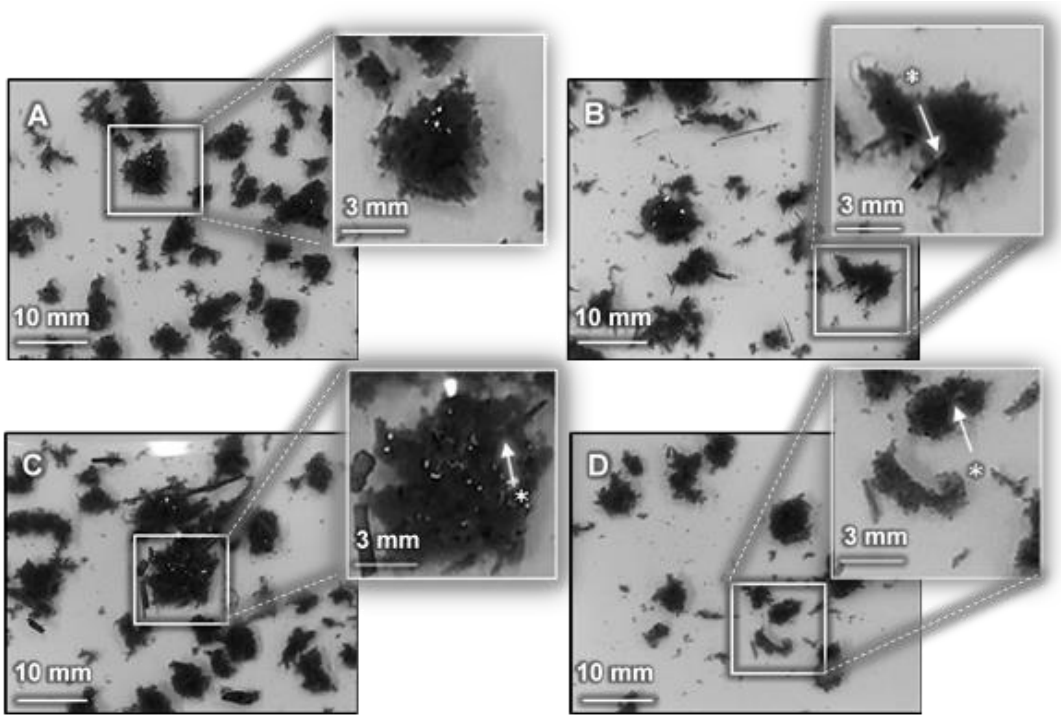

Fig. 2. Flocculation observation when the flocculant is added to the digested sludge with plant biomass. A: without biomass, B: grass clippings, C: pruned branches of Japanese black pine, and D: bamboo powder. *: plant biomass inside the flock

Estimation of Plant Biomass as Dewatering Aid

Table 3 shows the filtration test results. The filter cake's water content was reduced in the order of adding grass clippings, pruned branches of Japanese black pine, bamboo powder, and control (without plant biomass), which was obtained by both gravity and pressurized filtration tests. Similar results were obtained using the screw press dehydration test in a previous study (Yamasaki and Shigemura 2020). In addition, the amount of filtrate obtained by the gravity filtration test increased in the same order. It was confirmed that the grass clippings as a dewatering aid for digested sludge were more effective than the other samples.

Figure 3 shows the proposed dewatering mechanism. The water in the floc might be drained from within the plant tissues if the plant biomass with hollow structures, such as grass fibrous materials and Japanese black pine needles, were captured within the floc with the digested sludge (Fig. 3A), as suggested by the obtained WRV (Table 1). Alternatively, the water in the plant with woody cell structures (such as bamboo culm, Japanese black pine xylem, and bark) was difficult to drain. Thus, the plant biomass would create a gap between sludge flocs (Fig. 3B) for this type of structure, as suggested by several previous reports (Cogger and Merker 1940; Usui and Hosokawa 2016).

The plant biomass with hollow structures, such as grass fibrous materials and Japanese black pine needles, was a suitable dewatering aid for improving dewaterability because the water in the complex floc might be drained from within them. Particularly, grass clippings which were mostly composed of fibrous materials (Fig. 1A) showed the highest dewaterbility (Table 3) and ΔWRV (Table 1) compared with other plant biomass. Thus, grass clippings were effective dewatering aid for enhancing the dewaterability of digested sludge.

Table 3. The Estimated Water Content of the Filter Cake and the Amount of Filtrate Obtained After Filtration

	Gravity Filtration		Pressurized Filtration	Screw Press Dewatering *
	Filtrate (mL)	Water content of filter cake (%)	Water content of filter cake (%)	Water content of filter cake (%)
Grass clippings	425	94.8	91.0	77
Japanese black pine	415	95.0	91.7	79
Bamboo powder	410	95.6	92.0	82
Control	385	96.5	93.0	84
*: This data was obtained by Yamasaki and Shigemura 2020.				

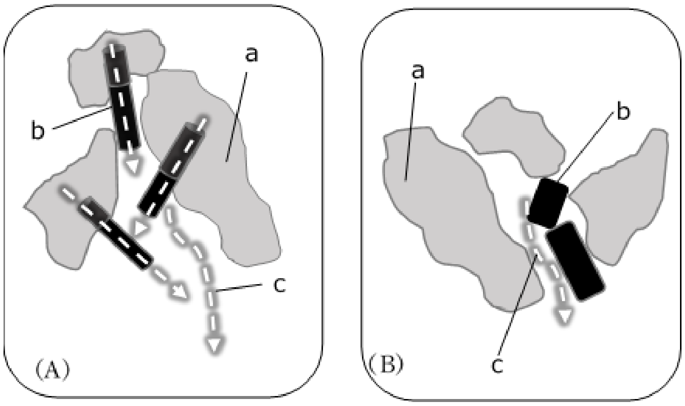

Fig. 3. Proposed mechanism of the improved dewaterability of digested sludge by adding biomass with hollow structure (A) and woody cell structure (B). a: flock, b: biomass, and c: water transfer

CONCLUSIONS

1. Microscopic observation revealed that grass fibrous materials and Japanese black pine needles had hollow structures. However, the xylem and bark parts of Japanese black pine and bamboo culm showed woody cell structures, and their pore sizes were smaller than those of either grass fibrous materials or Japanese black pine needles.
2. The ΔWRV of grass clippings (410%) was higher than that of Japanese black pine pruned branches and bamboo powder (210% and 190%, respectively). The higher ΔWRV indicated that the water inside the plant biomass could be easily drained from within their pores.
3. A uniform dispersion of plant biomass was confirmed when it was mixed in the digested sludge. Plant biomass was captured inside the floc after the flocculation was completed with the addition of a flocculant.
4. Grass fibrous materials were effective dewatering aid for enhancing the dewaterability of digested sludge.The water in the floc complexed with digested sludge and plant biomass may be drained from within the plant biomass with hollow structures.

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