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Greywater treatment by slanted soil system

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ABSTRACT

Slanted soil system is a low cost, simple system suitable for greywater treatment. Performance of the slanted soil system for greywater was evaluated in light of required water quality for irrigation reuse. Removal rate of particle COD and BDOC, those may cause clogging of irrigation facility, were 94–97% and 88–89%, respectively. LAS removal rates were more than 90% and final concentrations (2.3–3.3 mg L^{-1}) were sufficiently lower than proposed target level for irrigation use (8 mg L^{-1}). Only fine soil (1–4 mm) performed 5 $\log_{10}$ and 3 $\log_{10}$ reductions of *Escherichia coli* and MS2 phage, while coarse soil could not remove those pathogens. Clogging was observed in fine soil after 3–5 weeks operation, however combination of coarse soil chamber and fine soil chamber could extend it to 8 weeks. Reductions of total COD and LAS were described by 1st order reaction model and reaction coefficient k was described by equation of per area discharged rate.

1. Introduction

Naked dry soil with no plant is difficult to keep rich soil ecosystem and it can be easily lost by wind or rain erosion. This kind of soil deterioration has considerable effect on ecosystem and agricultural productivity in arid or semi-arid zone (Lal, 1998; Visser et al., 2005). Planting through a year can reduce this soil deterioration; however, water limitation does not allow it in these areas. For example, in rural area of Burkina Faso, which belongs to semi-arid zone, farmers can cultivate their main farmland only during rainy season. Only small garden which located in shoreline of reservoir or near the well, are able to be cultivated in dry season (Ushijima et al., 2012). Distribution and time periods of available water greatly affect the agricultural activity in this area, and most farmers are facing poverty problem due to such low productivity. On the other hand, people in this area use some amount of water for daily life even in dry season, and its wastewater is just disposed (Ushijima et al., 2012). Effective wastewater reuse has a potential to increase the cultivatable area and season, and it provides not only reduction of soil deterioration but also increase of productivity.

The concept of onsite wastewater differentiable treatment system (Lopez Zavala et al., 2002) can be one of suitable system for above-mentioned situation. It proposes onsite treatment of greywater, urine and feces separately, in order to achieve effective resource recycling system. Separated greywater has low concentration of pollutant load (Gajurel et al., 2003) and its treatment would be easier than mixed wastewater. For example, WHO (2006) wastewater reuse guideline stated that 2–7 $\log_{10}$ pathogen reduction by treatment is required for irrigation use, however separated greywater contains 2 $\log_{10}$ or more lower bacterial pathogen than mixed wastewater which WHO assumed (Ottoson and Stenström, 2003) and therefore we are able to set 5 $\log_{10}$ as a target level of bacterial pathogen reduction for separated greywater treatment. Furthermore, if reuse purpose was focused on irrigation only, advanced treatment technology for nitrogen, phosphorus removal would not be necessary. The most important point is to be low cost and simple, because most of those who need greywater reuse are low income people.

The slanted soil system is one of the promising treatment systems for this concept. It consists of several chambers containing soil (Fig. 1). These chambers are able to be stacked vertically, therefore its footprint is very small (e.g. approximately 1.0 m × 0.5 m). This system accepts direct discharge of greywater (Kondo et al., 2011) therefore no pump and no septic tank are required. Itayama et al. (2006) and Kondo et al. (2011) performed continuous monitoring of slanted soil system used by real household in Japan. Itayama et al. (2006) reported averaged removal ratio of the COD, the SS, the TN and the TP as 85%, 78%, 78% and 86%. Li et al. (2009) referred this result and concluded that the treated water is not suitable for reuse because it remains high in organic load and suspended solids, which can limit the chemical disinfection. These are however not the discussion for irrigation use but for avoiding eutrophication (Itayama et al., 2006) or for potable reuse (Li et al., 2009).

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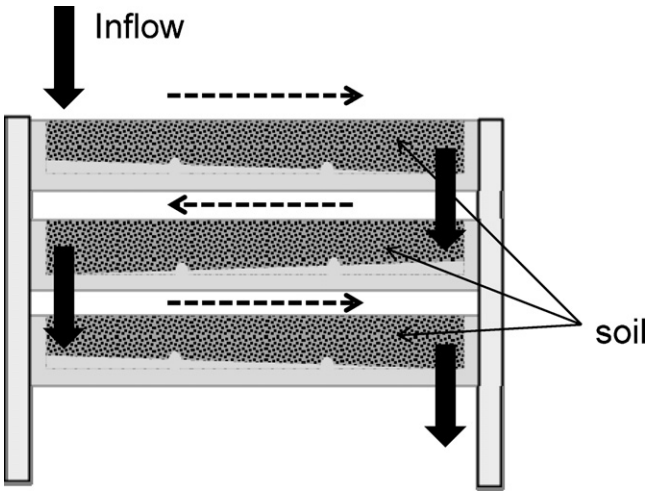

Fig. 1. Structure of slanted soil system.

Fig. 2. Picture of slanted soil system for this experiment.

Therefore, in this study, we evaluated the performance of the slanted soil system as a treatment facility for irrigation reuse, and proposed its design criteria for arid or semi-arid zone.

2. Materials and methods

2.1. Experimental apparatus and operation

Full scale slanted soil system was installed inside of laboratory; four soil chambers were connected as shown in Fig. 2, the size of each chamber was 0.10 m of depth, 0.145 m of width, and 0.94 m of length, chamber bed has gradient of 1/20. We performed 6 cases of experiments, in variety of soil type, soil particle size and amount of discharged wastewater (Table 1). In all experiments, greywater was discharged to first chamber 3 times in a day because actual discharge pattern of greywater shows 2 or 3 peaks in a day (Funamizu et al., 2002; Kondo et al., 2011). In this study, 5 h intervals were set between 3 discharges; morning, noon and evening. Volume and components of each discharge were listed in Table 1. The volume ratio of kitchen sink wastewater, laundry wastewater and shower wastewater in daily total was fixed at 3:2:5, which was determined with referring observed data in developing countries (Otaki, 2007; Ushijima et al., 2008).

Each greywater was prepared synthetically. Kitchen sink wastewater was prepared following the method which was described in detail by Huelgas (2009). The components listed in Table 2 were well mixed in 5 L of water solution. After 30 min settling, 4 L of supernatant was diluted with water until 94 L. Incubated *Escherichia coli* (NBRC13168) and MS2 phage (NBRC 102619) was added to this solution as an indicator of bacterial and virus pathogen, respectively. Reported concentrations of *E. coli* in real greywater were $10^{1.2}$ to $10^{5.4}$ mL^{-1} (Ottoson and

Table 1
Variation of greywater discharge, experimental period and soil type.

		Greywater discharge	Total discharge	Experimental period	Soil type
Case 1	Morning Noon Evening	KSWW 6 L + LWW 12 L KSWW 6 L KSWW 6 L + SWW 30 L	60 L d^{-1}	6 weeks	Kanuma soil (4–11 mm)
Case 2	Morning Noon Evening	KSWW 6 L + LWW 12 L KSWW 6 L KSWW 6 L + SWW 30 L	60 L d^{-1}	6 weeks	Crushed baked mud brick (4–11 mm)
Case 3	Morning Noon Evening	KSWW 6 L + LWW 12 L KSWW 6 L KSWW 6 L + SWW 30 L	60 L d^{-1}	5 weeks[a]	Crushed baked mud brick (1–4 mm)
Case 4	Morning Noon Evening	KSWW 3 L + LWW 6 L KSWW 3 L KSWW 3 L + SWW 15 L	30 L d^{-1}	8 weeks[b]	Crushed baked mud brick (1–4 mm)
Case 5	Morning Noon Evening	KSWW 3 L + LWW 6 L KSWW 3 L KSWW 3 L + SWW 15 L	30 L d^{-1}	8 weeks[c]	Crushed baked mud brick (1st chamber 1–4 mm, 2nd–4th chamber 4–11 mm)
Case 6	Morning Noon Evening	KSWW 1.5 L + LWW 3 L KSWW 1.5 L KSWW 1.5 L + SWW 7.5 L	15 L d^{-1}	8 weeks[b]	Crushed baked mud brick (1–4 mm)

KSWW: kitchen sink wastewater; LWW: laundry wastewater; SWW: shower wastewater.
[a] Experiment was ended at 5th week because overflow due to clogging was observed.
[b] The soil in 1st chamber was replaced by new soil at 3rd week, when overflow was observed.
[c] Experiment was ended at 8th week because overflow due to clogging was observed.

Table 2
Components of synthetic kitchen sink wastewater.

Components	Amount
Kitchen detergents	5.12 g
Soybean flower	34.6 g
Fish powder	34.6 g
Dextrine	6.9 g
Powder cream for coffee	21.6 g
Beef extract	5.2 g
Carrot	34.6 g
Cabbage	34.6 g
Banana peel	25.9 g
Apple	25.9 g
Grapefruit peel	25.9 g
Dried horse mackerel	25.9 g
Cooked rice	25.9 g
Tea leaves	7.6 g

Table 3
Characteristics of each greywater.

	KSWW	LWW	SWW
T-COD ($mg\,L^{-1}$)	600–1000	500–600	200–400
SS ($mg\,L^{-1}$)	150–250	70–100	40–70
pH	7.0	10.1	7.3
EC ($mS\,cm^{-1}$)	0.69	1.15	0.28
E. coli ($CFU\,mL^{-1}$)	10^5	–	–
MS2 phage ($PFU\,mL^{-1}$)	10^3	–	–
LAS ($mg\,L^{-1}$)	–	50	–

Abbreviations: KSWW: kitchen sink wastewater; LWW: laundry wastewater; SWW: shower wastewater.

Stenström, 2003) therefore we set the concentration of *E. coli* as 1.0×10^5 CFU mL^{-1}. Regarding MS2 phage, we set the concentration of 1.0×10^3 PFU mL^{-1}, which is same level as wastewater not separated with toilet wastewater (WHO, 2006). Laundry wastewater was prepared by washing one new labo apron in automatic laundry machine with 25 g of laundry detergents. Total water use in the laundry machine was 60 L. Shower wastewater was prepared by mixing 5 g of shampoo, 5 g of rinse, 5 g of liquid soap and 3 g of toothpaste in 30 L of tap water. Table 3 represents characteristics of synthetic greywater.

Two types of soil were used in this study. Kanuma soil, which was used in Case 1, consists of alumina and hydrated silica (Itayama et al., 2006). Performance of Kanuma soil had already been examined by previous studies (Kondo et al., 2011, Itayama et al., 2006), however it is very unique soil and available only in Japan. As alternative soil, which is available in the world, crushed baked mud brick was applied in Cases 2–6. It was prepared by crushing baked mud brick and sieving into 1–4 mm and 4–11 mm. In Cases 4 and 6, soil in first chamber was replaced with new same soil after 3 weeks because clogging was observed at that time. After replacement, experiment was continued under same condition as before replacement.

2.2. Sampling and analysis

Effluent of each chamber was sampled every 1 or 2 weeks. Total COD (T-COD), suspended solid (SS), *E. coli*, and MS2 phage were measured for those samples. Additional to these items dissolved COD (D-COD), biodegradable dissolved organic carbon (BDOC) and liner alkilbenzene sulfonate (LAS) were also measured in Cases 4, 5, and 6.

COD and suspended solid was measured in standard method of (APHA, 1985). *E. coli* in the sample was incubated on "Compact Dry EC (NISSUI PHARMACEUTICAL CO.LTD)" 24 h under 37 °C, and blue colored *E. coli* colonies were counted. MS2 phage was measured in PFU method with the double-layer method (Adams, 1959). *E. coli* (NBRC 13965) is used as bacterial host. Bacteriophage was propagated for 22–24 h at 37 °C in *E. coli*. LAS was measured by liquid chromatography mass spectrometry (LC–MS). Targeted LAS was C10–C14. Eluents was methanol and water, containing ammonium acetate. Solid-phase extraction as the pretreatment for LAS measurement was done using BOND ELUT PPL (500 mg) cartridge. The operation conditions of LC–MS were listed in Table 4. Filtered samples were incubated in BOD bottles at 20 °C for 7 days and 14 days, and dissolved organic carbon was measured by TOC analyzer (TOC-5000A, Shimazu corp.). Decrease from initial TOC to 7 or 14 days were regarded as $BDOC_7$ and $BDOC_{14}$ in this study.

Table 4
Operation condition of LCMS for LAS measurement.

Items	Condition
Column	Wakopak WS AS-Aqua (4.6 mm × 250 mm)
Mobile phase	(A) 0.2 mM ammonium acetate in acetonitrile (B) 0.2 mM ammonium acetate in water
Flow rate	$0.25\,mL\,min^{-1}$
Injection volume	10 μL
Ionization method	ESI (electrospray ionization)
Measurement mode	Negative
Capillary voltage	4.5 kV
Drying gas temperature	350 °C
Column temperature	40 °C

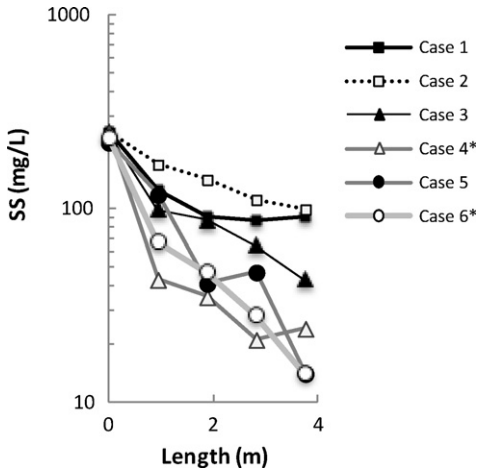

Fig. 3. Concentration of suspended solid (SS) at influent and effluent from each chamber on 4th week (Cases 1, 2, 3, and 5) and 2nd week (Cases 4 and 6).

3. Results

3.1. SS removal and clogging

SS removal by treatment length was almost linear in logarithmic graph (Fig. 3). Total removal rates through 4 chambers were 60–94%, and these were higher in finer particle and lower discharge (Fig. 4). Discharged water was overflowed from the chamber due to clogging in Cases 3, 4, 5 and 6 at the 5th, 3rd, 8th and 3rd week, respectively. Time periods until clogging (T) were longer in coarser soil and higher discharge. In Case 5, combination of fine and coarse soil, T was longer than those using fine soil only (Cases 3, 4, and 6). However, no relationship was observed between T and estimated cumulative amount of SS removal.

3.2. Removal of organic materials and LAS

T-COD at the outlet of 4th chamber on 4th week were 154–394 $mg\,L^{-1}$, while the results of Cases 4 and 6 were at 2nd

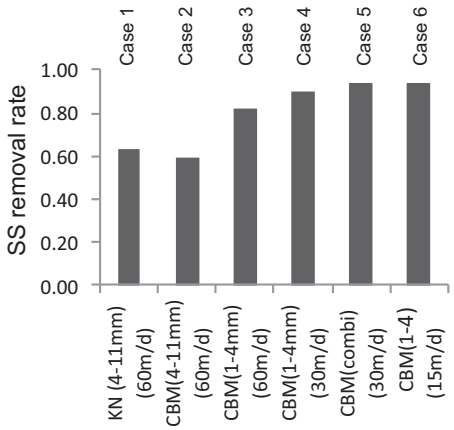

Fig. 4. Removal rate of suspended solid (SS) at the outlet of 4th chamber on 4th week (Cases 1, 2, 3, and 5) and 2nd week (Cases 4 and 6).

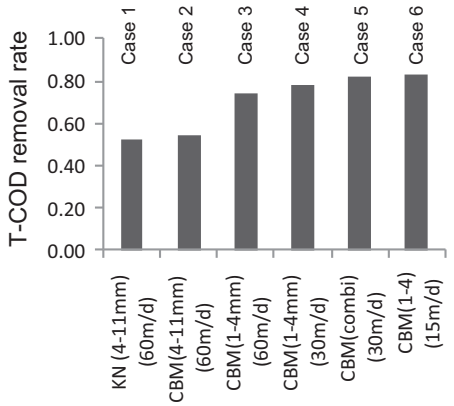

Fig. 5. Total COD (T-COD) removal rate at the outlet of 4th chamber on 4th week (Cases 1, 2, 3, and 5) and 2nd week (Cases 4 and 6).

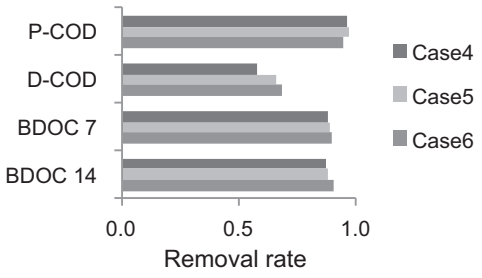

Fig. 6. Removal rate of particle COD (P-COD), dissolved COD (D-COD), and biodegradable dissolved organic carbon upon 7 days incubation ($BDOC_7$) and 14 days incubation ($BDOC_{14}$).

week because these were clogged at 3rd week. The removal rates (Fig. 5) were 52–83%, higher in finer particle and lower discharge. In Cases 4, 5, and 6, those measured D-COD and BDOC, more than 90% of particle COD (P-COD), derived by deducting D-COD from T-COD, was removed by this system (Fig. 6). Although the removal rates of D-COD were lower (58–68%), those of both $BDOC_7$ and $BDOC_{14}$ were removed 87–91% (Fig. 6). This is probably because biologically degradable organic matters in dissolved part were selectively removed and non-degradable or less degradable matters remained.

LAS at the outlet of 4th chamber on 3rd week (Cases 4 and 6) or 4th week (Case 5) were 2.3–3.3 mg L^{-1}, and removal rates were 93–96%.

3.3. Pathogens removal

Figs. 7 and 8 show *E. coli* and MS2 phage concentrations in each case, respectively. Most of *E. coli* and MS2 phage were not removed in all chambers containing coarse soil; Cases 1 and 2 and 1st chamber of Case 5. In contrast to those using coarse soil, 5 $\log_{10}$ reduction of *E. coli* and 3 $\log_{10}$ reduction of MS2 phage were performed through one or two chambers until 3rd or 4th week, in Cases 3, 4, 5, and 6, those used fine soil. After 4th or 5th week, breakthrough of *E. coli* and MS2 were observed in Cases 3 and 5. No breakthrough was observed in Cases 4 and 6, probably because experimental periods were only 3 weeks.

4. Discussion

4.1. Treatment performance

Fine soil presented better removal performance of pathogen, SS, and T-COD. Particularly, sufficient pathogen removals were performed only by fine soil chamber, while most part of pathogen passed through coarse soil chamber. Disadvantage of fine soil was shorter time periods until clog, however result of Case 5 represented that combination of coarse and fine soil can extend this time period to more than double. Most of previous studies used Kanuma soil, which is generally 10 mm or larger particle size (Itayama et al., 2006). Clogging was not observed in these previous studies (e.g. Itayama et al., 2006; Kondo et al., 2011), however they did not measure pathogens. Tada et al. (2007) used combination of several local soils; pumiceous soil (4–20 mm) for 1st and 2nd chambers, river sand (0.5–4 mm) for 3rd chamber, and limestone soil (0.25–2 mm) for 4th chamber, and its time period until clogging was half year. Two of coarse soil chambers (2 m), and too low per area discharged rate (0.06–0.36 $m^3\ m^{-2}\ d^{-1}$, which is 1/10 to 1/50 of our experiment) probably caused this longer period until clogging than our results.

Originally, slanted soil chamber system was developed to reduce environmental impact, and therefore focus of the previous studies was removal rate of organic matter and nutrients (Itayama et al., 2006; Kondo et al., 2011; Tada et al., 2007). In light of required water quality for irrigation reuse, removal of nutrient is not so important but removal of organic matters is important because they cause clogging of irrigation facilities such as drip irrigation system, and therefore particle COD (P-COD) and BDOC would be especially important. Fig. 6 implies that the slanted soil system in this study performed high removal rate in both P-COD (94–97%) and BDOC (88–89%), while removal rate of D-COD (58–68%) was comparatively low. Although BDOC levels in treated water (11–12 mg L^{-1}) were much lower than untreated greywater, these exceed 0.15–0.25 mg L^{-1} those were reported as maximum level to avoid bacterial regrowth (Servais et al., 1995; Niquette et al., 2001). Of course the volume of biofilm and increasing speed of biofilm volume are supposed to become smaller than untreated greywater, however farther practical study is needed for quantitative evaluation.

LAS removal rates were more than 90% and final concentrations (2.3–3.3 mg L^{-1}) were sufficiently lower than 8 mg L^{-1} which was proposed as target level for irrigation use (Hijikata et al., 2011). However, this study could not cover byproduct of LAS degradation, which was found in treated greywater by another system (Huelgas,

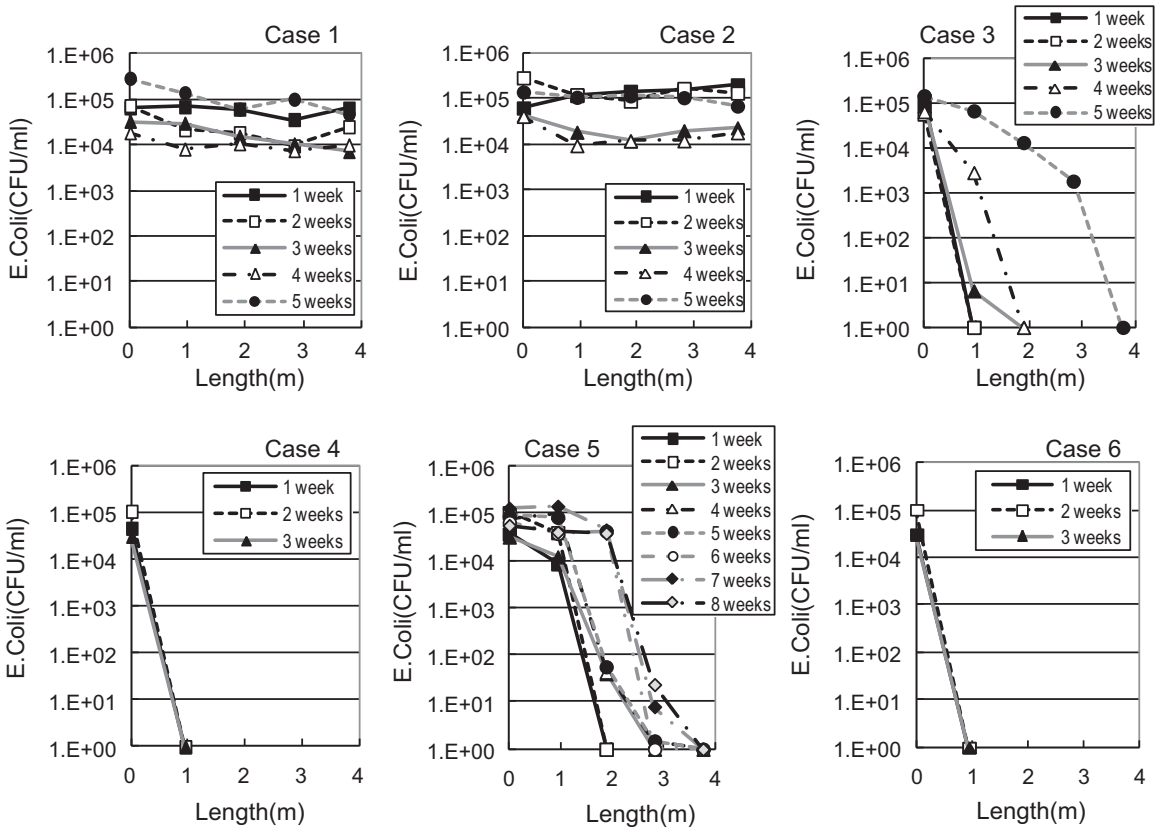

Fig. 7. *E. coli* concentration at influent and effluent from each chamber.

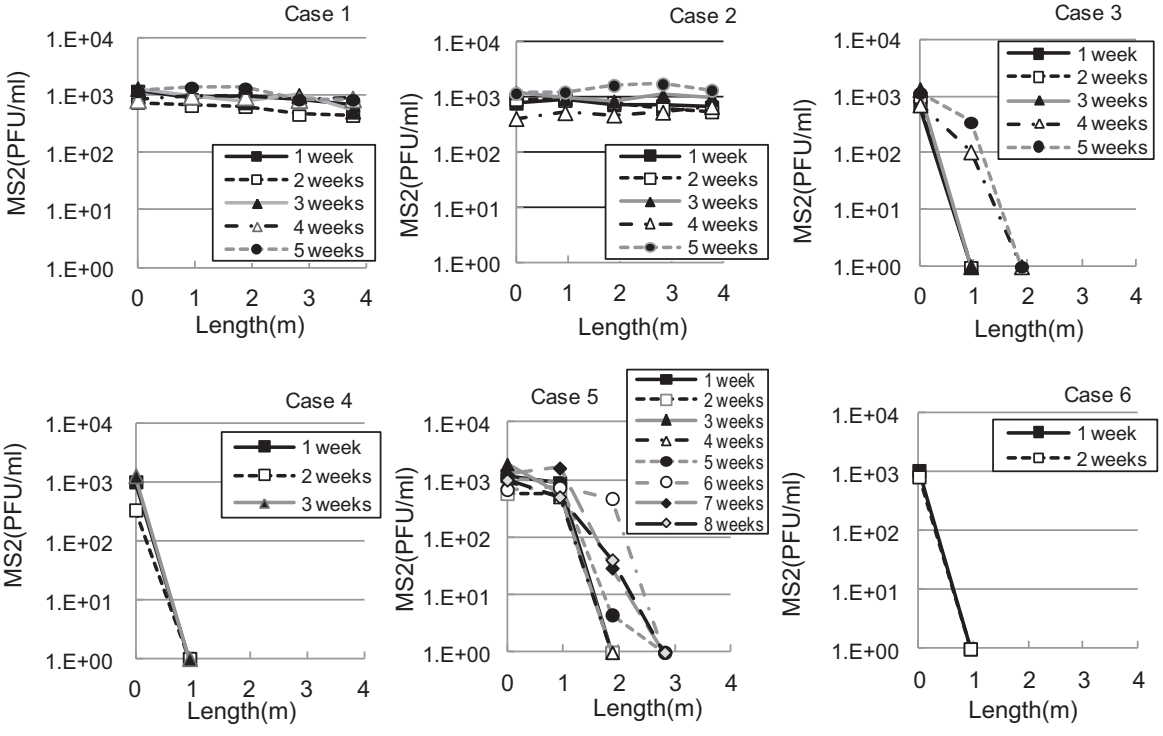

Fig. 8. MS2 phage concentration at influent and effluent from each chamber.

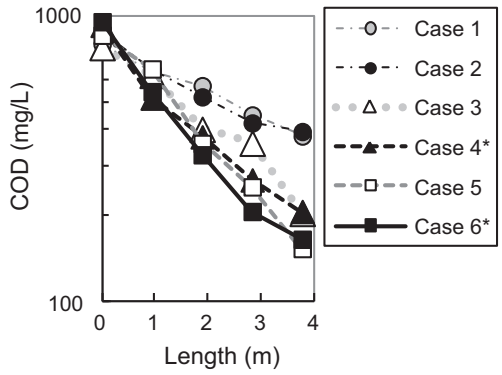

Fig. 9. Concentration of total COD (T-COD) at influent and effluent from each chamber on 4th week (Cases 1, 2, 3, and 5) and 2nd week (Cases 4 and 6).

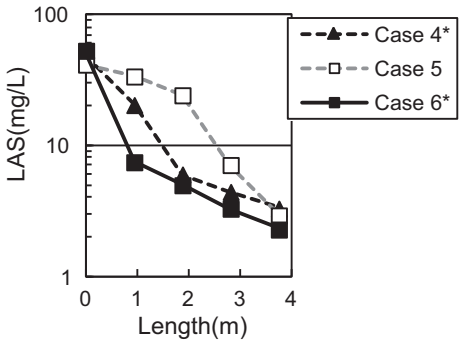

Fig. 10. Concentration of liner alkilbenzene sulfonate (LAS) at influent and effluent from each chamber on 4th week (Case 5) and 2nd week (Cases 4 and 6).

Table 5
Reaction coefficient k for T-COD reduction.

	Reaction coefficient k	R^2
Case 1	0.194	0.99
Case 2	0.213	0.96
Case 3	0.342	0.96
Case 4	0.388	0.98
Case 5	0.466	0.99
Case 6	0.475	0.98

2009). Direct toxicity assessment, such as germination test or plant growth test will give farther information about this issue.

4.2. Reduction characteristics of COD and LAS

Reduction curves of T-COD against chamber length seem linear in logarithmic graph (Fig. 9). When we assume uniform flow velocity inside of each system, these reductions can be regarded as first order kinetic reaction, which is described as

$$C_{COD} = C_{0COD}\ \exp(-k_{COD}L) \quad (1)$$

where C_{COD} is COD concentration, C_{0COD} is initial concentration, k_{COD} is the reaction coefficient with m^{-1} unit and L is length of soil (Table 5). Because of the assumption above, the k_{COD} values would change by different flow velocity. Therefore, correlations between k_{COD} and possible control factors of flow velocity; elapsed time, soil particle size and q defined by $Q/(W \times D)$ where Q is daily discharge ($m^3\ d^{-1}$), W is width of chamber, and D is depth of chamber, were accessed. Slope of chamber bed also affects flow velocity, but in this study it was fixed at 1/20. As a result, $k_{T\text{-}COD}$ shows linear correlation with q in the equation of

$$k_{T\text{-}COD} = -0.04q + 0.5 \quad (2)$$

by high correlation coefficient ($R^2 = 0.87$) but other factors does not show clear correlation.

As well as T-COD, first order kinetic reaction equation by length was applied for LAS reduction curve (Fig. 10).

$$C_{LAS} = C_{0LAS}\ \exp(-k_{LAS}L) \quad (3)$$

where C_{LAS} is LAS concentration, C_{0LAS} is initial concentration, k_{LAS} is the reaction coefficient with m^{-1} unit. k_{LAS} of Cases 4, 5, and 6 were 0.73 ($R^2 = 0.92$), 0.73 ($R^2 = 0.91$), and 0.76 ($R^2 = 0.83$), respectively. k_{LAS} shows linear correlation with q in the equation of

$$k_{LAS} = -0.02q + 0.8 \quad (4)$$

by high correlation coefficient ($R^2 = 0.99$), but other factors does not show clear correlation.

4.3. Design criteria

First of all, fine soil chamber is required in order to remove pathogen. According to the results of Cases 3 and 5, those observed breakthrough, removal capacity levels of *E. coli* and MS2 phage in one chamber (0.145 m width, 0.1 m height, and 0.94 m length) were estimated 10^{10} CFU and 10^8 PFU, respectively. When the capacity became full, it has to be replaced. Required replacement interval (INT) would be explained by

$$\mathrm{INT} = 6.9q^{-1}[d] \quad (5)$$

On the other hand, outlet concentrations of LAS are able to simulate by Eqs. (3) and (4). In case applying target level of 8 mg L^{-1} proposed by Hijikata et al. (2011), adequate q which satisfies $C_{LAS} < 8$ have to be set. Regarding organic matters, farther study is required in order to simulate outlet concentration, not only of T-COD but also of P-COD and BDOC. The q is determined by balance between chamber size and discharged volume of greywater, and therefore possible chamber size can be designed according to expected discharged volume.

Regarding clogging issue, combination of coarse and fine soil is preferable. According to result of Case 5, first 1 or 2 chambers were recommended to use coarse soil, and it extends time periods until clogging. Under the condition of Case 5, time period until clogging was longer than INT, however quantitative evaluation on clogging under different condition is difficult so far.

5. Conclusions

Performance of the slanted soil system for greywater was evaluated in light of required water quality for irrigation reuse. The slanted soil system performed high removal rate in both P-COD (94–97%) and BDOC (88–89%), while removal rate of D-COD (58–68%) was comparatively low. LAS removal rates were more than 90% and final concentrations (2.3–3.3 mg L^{-1}) were sufficiently lower than 8 mg L^{-1} which was proposed as target level for irrigation use (Hijikata et al., 2011). First order reaction equation of T-COD and LAS were determined and $k_{T\text{-}COD}$ and k_{LAS} were expressed by the equation of q. Fine soil (1–4 mm) presented better removal performance of pathogen, SS, and T-COD than coarse soil (4–11 mm). Particularly, sufficient pathogen removals were performed only by fine soil chamber, while most part of pathogen passed through coarse soil chamber. Disadvantage of fine soil was recognized in shorter time periods until clog, however result of Case 5 represented that combination of coarse and fine soil can extend this time period.

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