

ORIGINAL ARTICLE

# Effect of structural difference on wastewater treatment efficiency in multi-soil-layering systems: Relationship between soil mixture block size and removal efficiency of selected contaminants

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## Abstract

Multi-soil-layering systems composed of soil mixture blocks (SMB) arranged in a brick-like pattern and surrounded by permeable zeolite layers (PL) were designed for domestic wastewater and polluted river water treatment. To investigate the efficiency of MSL systems in relation to structural differences, five MSL systems with different sizes and layers of SMB and PL were constructed in five 50 cm × 10 cm × 60 cm acrylic boxes. The SMB comprised sandy soil, charcoal, sawdust and iron on a dry weight ratio of 7:1:1:1. Diluted domestic wastewater with an average suspended solids (SS), biological oxygen demand (BOD<sub>5</sub>), total phosphorus (T-P) and total nitrogen (T-N) concentration of 73, 34, 1.3 and 15 mg L<sup>-1</sup>, respectively, was applied at a hydraulic loading rate (HLR) ranging from 1,000 to 3,000 L m<sup>-2</sup> day<sup>-1</sup>. At HLR of 1,000 and 2,000 L m<sup>-2</sup> day<sup>-1</sup>, systems with larger SMB surface area had higher removal rates for SS, BOD<sub>5</sub>, chemical oxygen demand (COD) and T-P because of the enhanced contact efficiency between wastewater and SMB. The structural difference was greatest at a HLR of 2,000 L m<sup>-2</sup> day<sup>-1</sup>, especially for COD and T-P removal. An increase in the top surface area of SMB was found to affect the efficiency of MSL systems more than an increase in side surface area. When the HLR was increased to 3,000 L m<sup>-2</sup> day<sup>-1</sup>, the effect of structural differences on MSL systems was not as great, probably because of preferential water flow into PL as well as the oxidation–reduction potential ORP change caused by the accumulation of SS at high HLR. For T-N removal, no structural difference was found at a low HLR of 1,000 L m<sup>-2</sup> day<sup>-1</sup> and when HLR increased to more than 2,000 L m<sup>-2</sup> day<sup>-1</sup>, a secondary effect of SS accumulation and ORP change appeared to influence the systems' performance more than the expansion of SMB surface area.

**Key words:** hydraulic loading rate, multi-soil-layering system, soil mixture block, structure, water permeable layer.

## INTRODUCTION

In ecosystems, soil is not only important as a medium for crop production, but also acts as an ecosphere for the disposal of wastes. Soil's high purification capacity comes from many of its environment-related features, including developed pore systems, co-existence of aerobic–anaerobic and hydrophilic–hydrophobic conditions as well as habitat for various kinds of microorganisms.

Soil has been widely researched as a medium for waste treatment because of its ubiquitous presence and special characteristics for purification (Bhamidimarri 1988; Reed *et al.* 1995). However, traditional soil-based wastewater treatment systems display several limitations. Clogging is one of the major limitations even in on-site tank and soil leachline systems (Ho and Mathew 1993). Although soil exhibits a high purification capacity, the function of soil wastewater treatment systems strongly depends on the properties of the respective soil type. Therefore, even similar systems do not always perform with the same level of treatment efficiency (Sato *et al.* 2005a).

To fully exploit the environmental purification function of soil, a new type of water treatment system, multi-soil-layering (MSL) system, has been developed and studied.

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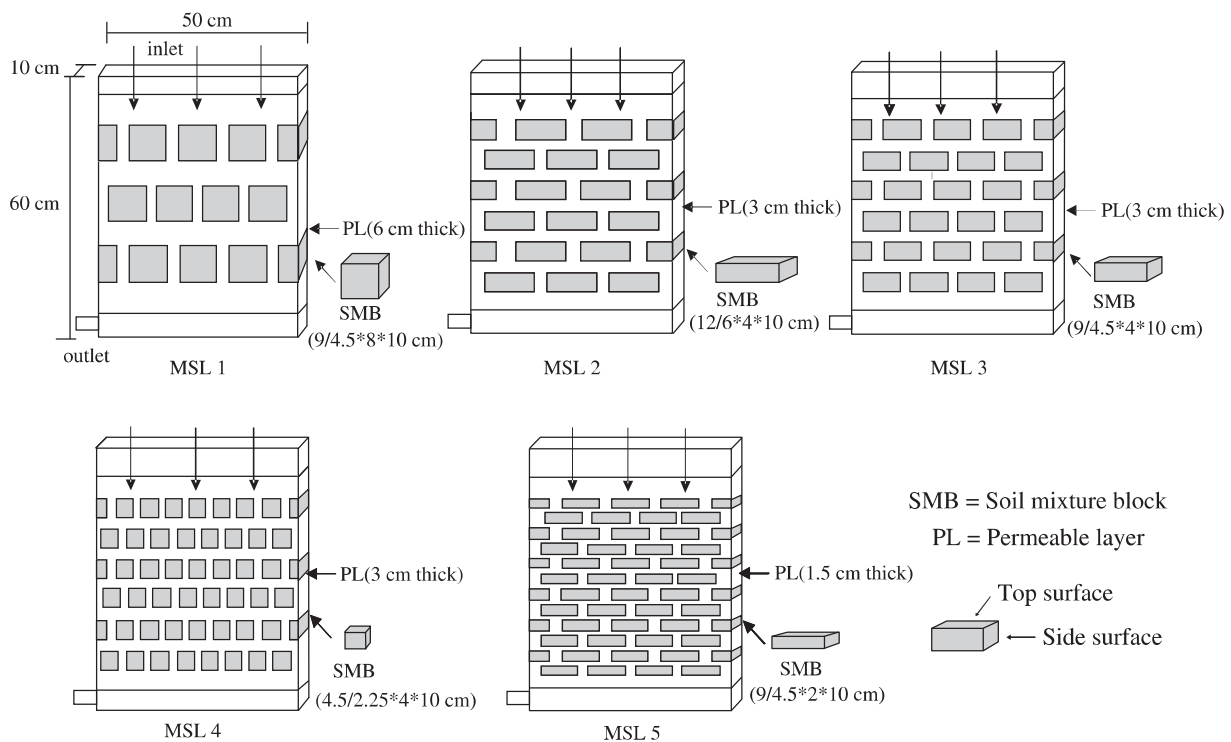
The MSL system is typically composed of soil mixture blocks (SMB) arranged in a brick-like pattern and surrounded by water-permeable particles, such as zeolite and gravel. MSL systems are cheap because they can be developed mainly from local resources, such as soil, sawdust, iron, charcoal, zeolite and alternative materials (Boonsook *et al.* 2003; Luanmanee *et al.* 2001). Various studies have been conducted on MSL systems to examine performance characteristics. In a previous study, we found that we could modify the structure of SMB depending on the water quality and treatment target to control and optimize the treatment efficiency of MSL systems. The contact of wastewater with SMB decreased with increasing hydraulic loading rate (HLR), while the process for organic matter, phosphorus and nitrogen removal depended, to a large degree, on physicochemical reactions, such as filtration and adsorption. Thus, it was suggested that effective contact between the wastewater and SMB was a major factor for MSL performance (Masunaga *et al.* 2003; Sato *et al.* 2005b) and increasing the surface area of the SMB might enhance the removal efficiency of MSL systems. However, to date, there has been no quantitative research on the effect of structural difference on MSL system performance. Therefore, we conducted a laboratory-scale experiment to analyze quantitatively the relationship between size and surface

area of SMB and the treatment efficiencies of selected parameters in MSL systems that can contribute to the optimal design of MSL structures suitable for different treatment conditions.

## MATERIAL AND METHODS

### Structure and components of the MSL systems

Figure 1 shows a detailed description of the structures of the five MSL systems used in this study, with different sizes and layers of SMB. The five MSL systems evaluated in this study were packed in five individual W50 cm × H60 cm × D10 cm acrylic boxes. The SMB was placed in the acrylic boxes in an alternating brick-like pattern. Zeolite with a diameter ranging from 3 to 5 mm was used to fill in the void spaces between adjacent SMB. The SMB was composed of soil (humus poor granite sandy soil), charcoal, sawdust and granular metal iron (20 mesh) at a ratio of 7:1:1:1 on a dry-weight basis and packed at a density of 1.2 g cm<sup>-3</sup>. MSL 1 had three layers and the height of the SMB was 8 cm. MSL 2, MSL 3 and MSL 4 had six layers and the height of the SMB was 4 cm. MSL 5 had 12 layers and the height of the SMB was 2 cm. MSL 2, MSL 3 and MSL 4 differed mainly in the width of the SMB, 12 cm, 9 cm and 4.5 cm,



**Figure 1** Structure and components of the five multi-soil-layering (MSL) systems (W50 cm × H60 cm × D10 cm) used for wastewater treatment. The size of the soil mixture block (SMB) is shown in parentheses (W cm × H cm × D cm).

**Table 1** Top surface area (cm<sup>2</sup>), side surface area (cm<sup>2</sup>) and total volume (cm<sup>3</sup>) of the soil mixture blocks in the five multi-soil-layering (MSL) systems

	MSL systems				
	1	2	3	4	5
Top surface area (cm <sup>2</sup> )	1080	2160	2160	2160	4320
Side surface area (cm <sup>2</sup> )	1920	1440	1920	4320	1920
Top and side surface area (cm <sup>2</sup> )	3000	3600	4080	6480	6240
Total volume (cm <sup>3</sup> )	8640	8640	8640	8640	8640

**Table 2** Operation period, time, multi-soil-layering (MSL) systems, hydraulic loading rate (HLR) and temperature during the three experimental periods

Period	Experimental Time	Operation of MSL	HLR (L m <sup>-2</sup> day <sup>-1</sup> )	Temperature (°C)
1	29 Oct.–3 Dec. 2003	1,2,3,4,5	1000	11–16
2	25 Dec.–30 Jan. 2004	1,2,3,4,5	2000	5–15
3	7 Apr.–13 Jun. 2004	1,3,4,5	3000	20–27

respectively. When SMB became thinner and narrower, its top and side surface area also increased, thus, a better contact between the wastewater and the SMB was expected even though the total volume of SMB remained the same (Table 1). Side surface area of the SMB didn't include the two sides against the acrylic box walls because it could not enhance the contact of wastewater with SMB.

### Quality of the wastewater and operating conditions

The wastewater used in this study was from a local community disposal plant and was diluted fourfold before flowing into the systems. In practical terms, we hoped to apply the results from the experiment to the advanced treatment of sewage plant wastewater, individual house wastewater after septic tank treatment or polluted river water treatment. The degree of dilution was decided by using the biological oxygen demand (BOD<sub>5</sub>) level of approximately 30 mg L<sup>-1</sup> that was often observed in the released water from septic tanks of individual houses (Aoyama 2001, unpubl. data). The average properties of the inflow water were as follows: suspended solids (SS) 73 mg L<sup>-1</sup>, BOD<sub>5</sub> 34 mg L<sup>-1</sup>, chemical oxygen demand (COD) 63 mg L<sup>-1</sup>, total phosphorus (T-P) 1.3 mg L<sup>-1</sup> and total nitrogen (T-N) 15 mg L<sup>-1</sup>. The water quality did not fluctuate greatly and the coefficient of variation was less than 20% for all parameters during the experimental period. The study was conducted over three periods. The HLR increased from 1,000 to 3,000 L m<sup>-2</sup> day<sup>-1</sup> and the air temperature ranged from 11–16, 5–15 and 20–27°C, respectively, during the three experimental periods (Table 2). In each period, the experiment was conducted for more than 4 weeks, and this was considered

empirically to be long enough to obtain average data for the discussion of structure influence on water contact efficiency with SMB separately from other factor influences. According to the results from a previous study, MSL systems under similar treatment conditions could keep stable treatment efficiency continuously for 212 days' operation at a HLR of 1,000 L m<sup>-2</sup> day<sup>-1</sup> (Sato *et al.* 2005a). However, when the HLR was increased to 3,000 L m<sup>-2</sup> day<sup>-1</sup>, the treatment efficiency of some parameters, such as BOD<sub>5</sub> and NH<sub>4</sub><sup>+</sup>-N, tended to gradually decrease and the period was extended to 8 weeks to follow the change. New MSL systems with the same structure and composition were re-constructed during Period 3 to avoid the possible influence of accumulated organic matter on the systems' treatment efficiency. For the same reason, calculation of the mean treatment efficiency was based on data from the first 5 weeks of Period 3 as the removal rates dropped sharply from week six, which might be because of the accumulation of SS. In Period 3, MSL 2 was stopped because the amount of wastewater applied every day was beyond the experimental facility capacities (i.e. pumps and the transportation of wastewater).

### Water samples and laboratory analysis

To investigate the effects of structural differences in MSL systems, wastewater and treated water were sampled once per week during the three experimental periods. The oxidation–reduction potential (ORP) was analyzed using the electrometric method, BOD<sub>5</sub> using the standard method of the American Public Health Association (1992), COD using the potassium dichromate method, PO<sub>4</sub><sup>3-</sup>-P using the ascorbic acid method, NH<sub>4</sub><sup>+</sup>-N using the Nessler method, NO<sub>2</sub><sup>-</sup>-N and NO<sub>3</sub><sup>-</sup>-N using the ion

chromatography method (DIONEX DX-120 Suanyvale, USA). T-P and T-N were determined as  $\text{PO}_4^{3-}\text{-P}$  and  $\text{NO}_3\text{-N}$  after potassium peroxodisulfate digestion.

### Statistical analysis of the experimental data

To analyze the structural influence on MSL treatment efficiency for different parameters, we used a logarithmic equation to express the experimental data. The equation was expressed as follows:

$$Y = a \ln(X) + b$$

where  $Y$  refers to the average removal rates (%) of SS,  $\text{BOD}_5$ , COD, T-P by the MSL system at different HLR,  $X$  refers to the top or side surface area of SMB, and  $a$  and  $b$  are constants.

Statistical significance of the structural effect on MSL system performance was subjected to a uni-variant analysis using Tukey's honestly significant difference (HSD) method in SPSS (version 12.0) (Ishimura 2001).

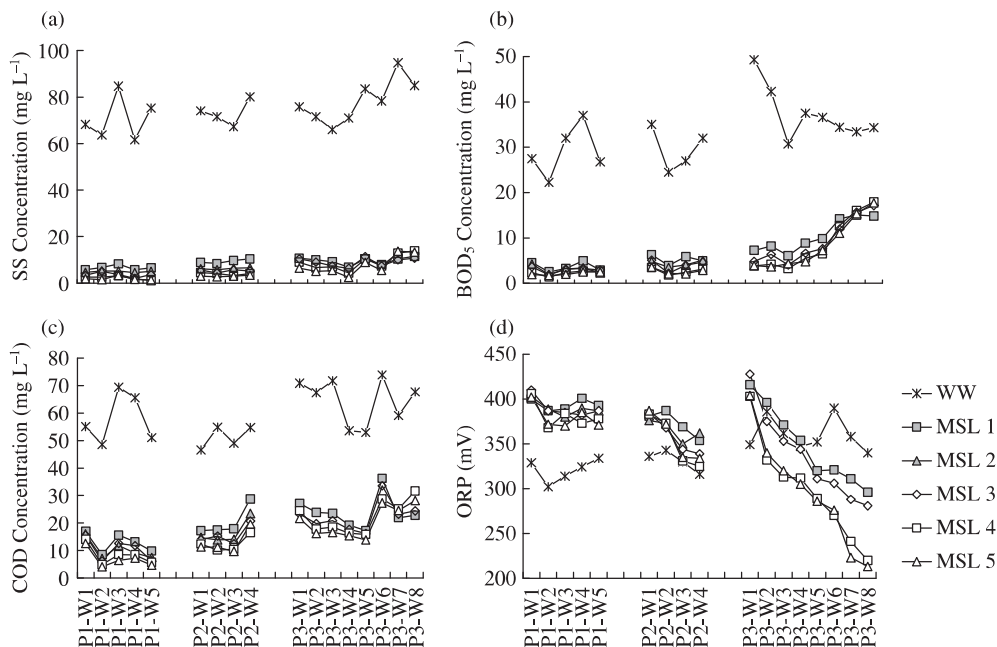
## RESULTS AND DISCUSSION

### Effect of structural difference on SS, $\text{BOD}_5$ and COD removal

Figure 2a–c shows the effect of MSL structural differences on the treatment efficiency of SS,  $\text{BOD}_5$  and COD during the study period. The analysis for wastewater

quality at each period showed a coefficient variation of less than 20% for the different parameters (Table 3), which means that the wastewater quality did not vary substantially. The MSL systems were quite effective in SS removal, and the removal rates ranged from 90.6% to 97.2% during Period 1 and from 87.1% to 95.8% during Period 2, resulting in the following order: MSL 5 > MSL 4 > MSL 3 > MSL 2 > MSL 1 (Table 3). Table 3 showed that SS removal efficiency differed significantly among the MSL systems as the main mechanism for SS removal was through physical adsorption and filtration by the SMB layers (Wakatsuki *et al.* 1990). An increase in surface area could enhance the contact efficiency of the wastewater with the SMB as well as the filtration capacity of the systems. However, when the HLR increased to  $3,000 \text{ L m}^{-2} \text{ day}^{-1}$  during Period 3 (Fig. 2a), the difference for SS removal efficiency among the systems became smaller. This was probably caused by the increasing ratio of water flow into the permeable layers (Sato *et al.* 2005b).

The trend for  $\text{BOD}_5$  removal was similar to that of SS when the systems had a HLR of  $1,000$  and  $2,000 \text{ L m}^{-2} \text{ day}^{-1}$ . Average  $\text{BOD}_5$  removal rates were 87.5–92.6% during Period 1 and 82.2–91.0% during Period 2 (Table 3). At a HLR of  $2,000 \text{ L m}^{-2} \text{ day}^{-1}$ , structural difference among the five MSL systems became clearer than the difference among them during Period 1 at a HLR of  $100 \text{ L m}^{-2} \text{ day}^{-1}$  (Fig. 2b). MSL 5 and MSL 4 were better



**Figure 2** Concentration of (a) suspended solids (SS), (b) biological oxygen demand ( $\text{BOD}_5$ ) and (c) chemical oxygen demand (COD), and (d) the value of the oxidation–reduction potential (ORP) in the wastewater (WW) and in the treated water of the five multi-soil-layering (MSL) systems as affected by hydraulic loading rate. P, period; W, week.

**Table 3** Average concentrations (mg L<sup>-1</sup>) and removal efficiency (%) of suspended solids (SS), biological oxygen demand (BOD<sub>5</sub>), chemical oxygen demand (COD), total phosphorus (T-P) and total nitrogen (T-N) in the multi-soil-layering (MSL) systems during the three experimental periods

	SS	BOD <sub>5</sub>	COD	T-P	T-N
	mg L <sup>-1</sup> (%)				
Period 1 ( <i>n</i> = 5)					
WW (CV)	70.7 (13)	29.1 (19)	57.9 (16)	1.44 (18)	11.4 (13)
MSL 1	6.6 (90.6) a <sup>†</sup>	3.6 (87.5) a	12.9 (77.7) a	0.60 (53.6) a	5.1 (55.2) a
MSL 2	5.0 (92.9) b	3.0 (89.7) ab	10.4 (82.0) b	0.50 (58.9) ab	5.2 (54.6) a
MSL 3	3.6 (94.9) b	3.0 (89.7) ab	10.5 (81.9) b	0.47 (61.1) b	4.9 (56.7) a
MSL 4	2.3 (96.8) c	2.3 (92.1) b	8.4 (85.5) c	0.42 (66.7) b	5.2 (54.9) a
MSL 5	2.0 (97.2) c	2.1 (92.6) b	7.5 (87.0) c	0.41 (67.1) b	5.3 (54.2) a
Period 2 ( <i>n</i> = 4)					
WW (CV)	73.3 (7)	29.6 (18)	51.3 (18)	1.20 (12)	10.0 (13)
MSL 1	9.4 (87.1) a	5.3 (82.2) a	20.4 (60.2) a	0.58 (51.9) a	6.7 (34.8) a
MSL 2	6.3 (91.4) b	4.4 (85.2) ab	16.6 (67.5) b	0.50 (57.3) b	6.8 (34.0) a
MSL 3	6.0 (91.8) b	4.0 (86.7) b	17.2 (66.5) b	0.49 (58.2) bc	6.4 (37.1) a
MSL 4	3.3 (95.5) c	2.7 (91.0) c	14.1 (72.6) c	0.43 (63.9) cd	6.0 (40.9) a
MSL 5	3.1 (95.8) c	2.7 (91.0) c	12.9 (74.9) c	0.42 (65.0) d	5.6 (44.5) a
Period 3 ( <i>n</i> = 5) <sup>‡</sup>					
WW (CV)	72.7 (12)	38.5 (13)	65.0 (13)	0.99 (19)	8.7 (18)
MSL 1	9.2 (87.1) a	9.3 (75.7) a	24.3 (62.6) a	0.44 (50.6) a	5.4 (40.7) a
MSL 3	8.7 (88.0) a	7.2 (81.4) b	21.8 (66.5) b	0.40 (55.4) ab	5.0 (45.6) ab
MSL 4	7.5 (89.8) b	6.3 (83.7) c	20.2 (68.9) bc	0.39 (59.7) ab	4.0 (55.4) ab
MSL 5	5.7 (92.4) c	6.1 (84.1) cd	18.5 (71.6) c	0.39 (57.9) b	3.3 (62.7) b

<sup>†</sup>Means with the same letter within the same column of the same period are not significantly different at  $P < 0.05$ , determined using Tukey's honestly significant difference test. <sup>‡</sup>Means were calculated for the first 5 weeks of Period 3 when the treatment efficiency was relatively stable.

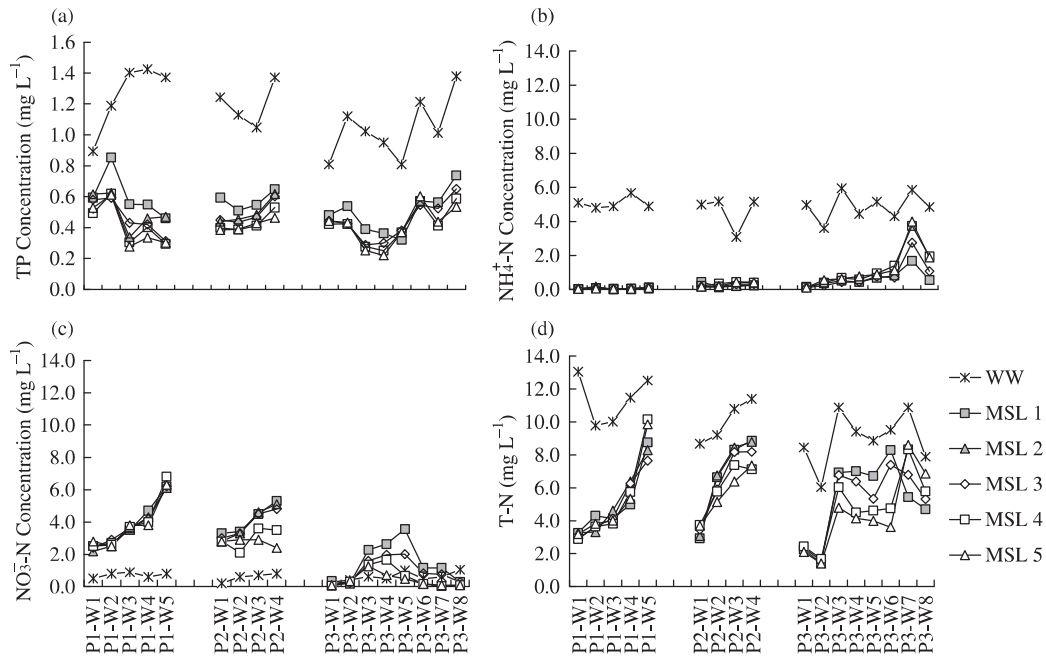
than the other systems because of the expanded surface area (Table 1). Table 3 showed a significant difference for BOD<sub>5</sub> removal among the systems as it represented easily decomposable organic matter and the effective contact between wastewater and SMB is important for microbial decomposition. The MSL systems' efficiency to remove BOD<sub>5</sub> gradually decreased towards the end of Period 3 at a high HLR of 3,000 L m<sup>-2</sup> day<sup>-1</sup>. This indicated that BOD<sub>5</sub> loaded into the systems started to accumulate and leach out into the treated water. A drop in ORP in the systems also suggested the accumulation of BOD<sub>5</sub> during Period 3 (Fig. 2d). In Table 3, the average removal rates of the parameters only includes data from the first 5 weeks of Period 3 to avoid the influence of dropping ORP on the treatment efficiency because BOD<sub>5</sub> removal rate showed a sudden decrease after 5 weeks operation.

The effect of structural difference on COD removal was greater than the effect on SS and BOD<sub>5</sub>. During Period 1, COD removal rates remained stable at 80–90% and the average removal rates for the five systems were 77.7–87.0% (Table 3). MSL 4 and 5 showed superiority over the other systems and the removal efficiency increased by 9.3% when the top plus side surface area of SMB increased from 3,000 cm<sup>2</sup> (MSL 1) to 6,240 cm<sup>2</sup>

(MSL 5), while the efficiency of SS and BOD removal increased by only 6.6% and 5.1%, respectively, over the same period. The removal of COD might need a more effective contact between the wastewater and the SMB because it represents slowly decomposable organic matter. Mbuligwe (2004) also reported that in an engineered wetland system, effective contact between the system and wastewater was necessary to achieve a high treatment for COD. When HLR increased during Period 2, the average removal rates of the MSL systems dropped to 60.2–74.9%, while that of SS and BOD<sub>5</sub> remained around the same level during Periods 1 and 2 (Table 3). COD removal efficiency was more influenced by the increase in HLR than that of SS and BOD<sub>5</sub>, possibly because the decomposition of COD requires a longer retention time, and retention time decreases as HLR increases (Sato *et al.* 2005b).

### Effect of structural difference on phosphorus removal

Figure 3a shows the change in T-P concentration during the study period and the average removal rates are presented in Table 3. During Period 1, T-P removal rates increased and remained stable at 60.8–83.4% after 3 weeks operation because the system needed a few



**Figure 3** Concentration of (a) total phosphorus (T-P), (b)  $\text{NH}_4^+\text{-N}$ , (c)  $\text{NO}_3^-\text{-N}$  and (d) total nitrogen (T-N) in the wastewater (WW) and treated water of the five MSL systems as affected by hydraulic loading rate. P, period; W, week.

weeks for the metal iron added to the SMB to be oxidized and actively adsorb phosphorus in the system. The average T-P removal rates were 53.6%, 58.9%, 61.1%, 66.7% and 67.1%, respectively, for MSL 1 to MSL 5. The T-P removal rates were mainly affected by increasing the surface area of SMB, which enhanced the physico-chemical reaction of phosphorus fixation by the active Al and Fe contained in the SMB (Wakatsuki *et al.* 1993). Thus, effective contact between the wastewater and the SMB is necessary to achieve high removal efficiency of T-P.

Increasing HLR to  $2,000 \text{ L m}^{-2} \text{ day}^{-1}$  decreased T-P removal rates in all systems to lower than 70%, and structural differences among the systems became more obvious than those observed in Period 1 (Fig. 3a.). The highest average T-P removal rate was found in MSL 5 (65.0%), followed by MSL 4 (63.9%), MSL 3 (58.2%), MSL 2 (57.3%) and MSL 1 (51.9%). MSL 4 and 5 were significantly different from MSL 1 and 2 in T-P removal because of the expanded surface area, which enhanced the contact efficiency of wastewater and SMB. Reducing sizes and increasing numbers of SMB achieved a more effective T-P removal result by increasing the adsorption sites in the surface of SMB.

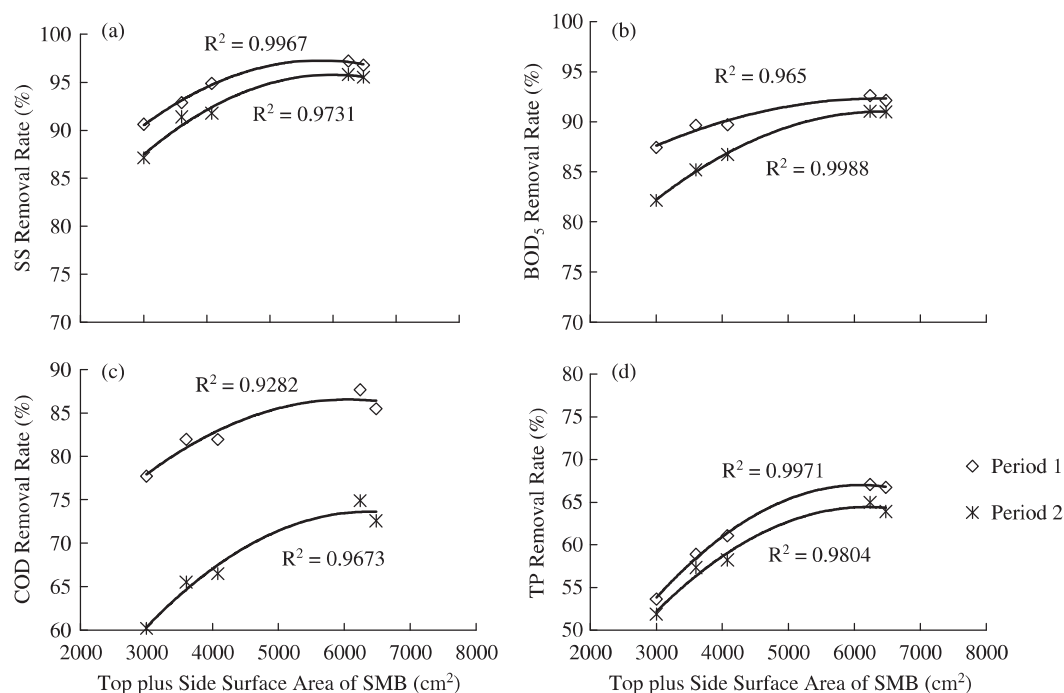
When HLR was set at  $3,000 \text{ L m}^{-2} \text{ day}^{-1}$  during Period 3, average removal rates for the systems became lower compared with the rates recorded during Periods 1 and 2 when the HLR was lower. The removal efficiency

difference became smaller among the systems and only MSL 1 and MSL 5 showed a significant difference (Table 3). The high HLR influenced the treatment efficiency and narrowed the effect of structural difference among the systems by hindering the fixation of phosphorus and oxidation of ferrous iron through loss of adsorption sites and a decrease in ORP as well as increasing the ratio of water flow into the PL (Sato *et al.* 2005b).

### Effect of structure difference on nitrogen removal

Nitrogen in the wastewater was mainly in the form of  $\text{NH}_4^+\text{-N}$  and its concentration ranged from 3 to  $6 \text{ mg L}^{-1}$ . Concentration of  $\text{NH}_4^+\text{-N}$  in treated water remained low for all systems during Periods 1 and 2 (Fig. 3b) because of adsorption on zeolite, which had a high cation exchange capacity (CEC) of approximately  $110 \text{ cmolc kg}^{-1}$ . At the beginning of each period, the MSL systems showed a high capacity to remove T-N from wastewater for all the systems (Table 3). However, T-N concentration in the treated water increased with time because of the increase in  $\text{NO}_3^-\text{-N}$  in the treated water (Fig. 3c).

During Period 1, there was no significant difference in  $\text{NH}_4^+\text{-N}$ ,  $\text{NO}_3^-\text{-N}$  and T-N concentrations in the treated water among the five systems (Fig. 3b–d). Although during Period 2,  $\text{NO}_3^-\text{-N}$  and T-N concentrations were



**Figure 4** Relationship between average removal rates of (a) suspended solids (SS), (b) biological oxygen demand ( $BOD_5$ ), (c) chemical oxygen demand (COD) and (d) total phosphorus (T-P) and the top plus side surface area of the soil mixture blocks (SMB).

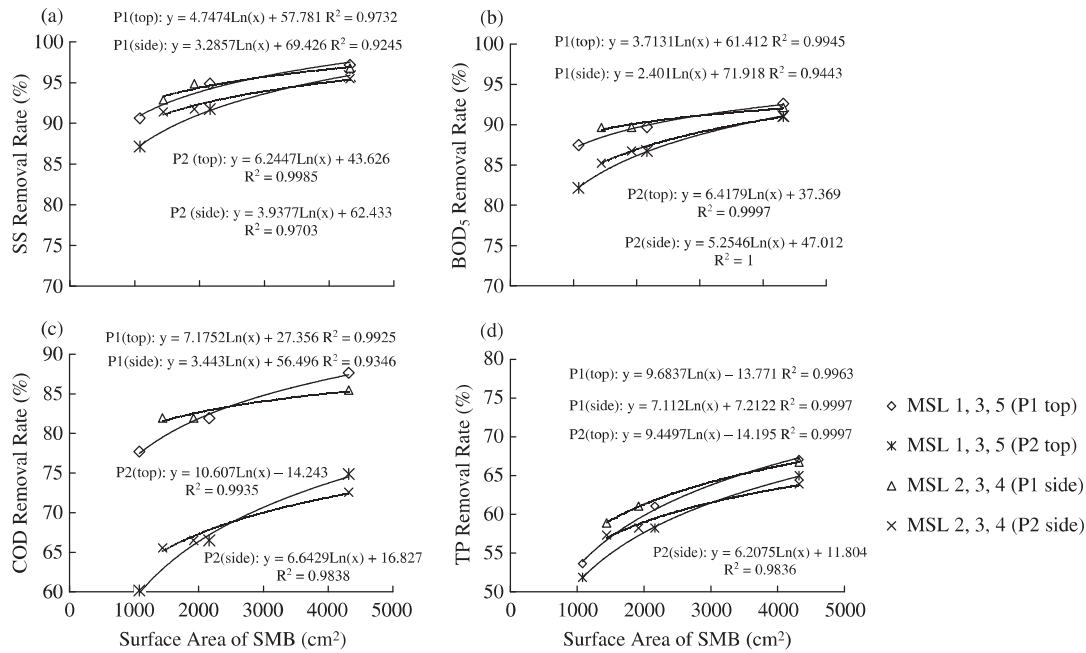
lower in MSL 4 and 5 than in the other systems. As  $NH_4^+-N$  concentration in the treated water was still low, as in Period 1, better T-N removal rates resulted from the lower  $NO_3^- -N$  concentration in MSL 4 and 5. This was possibly because of the high rate of denitrification that might be induced by lower ORP (Fig. 2d) because the higher removal rates of SS,  $BOD_5$ , COD in these two systems needed to consume more oxygen for organic decomposition. A similar trend was also found during Period 3. It is possible that the secondary effect caused by structural differences, such as ORP change and the accumulation of SS, influenced nitrogen removal more than the surface area change did as the process of nitrogen removal in MSL systems consists of mineralization of organic N and nitrification of  $NH_4^+-N$  under aerobic conditions followed by denitrification under anaerobic conditions. This is more complicated than the removal process of other parameters such as SS,  $BOD_5$ , COD or phosphorus, which are removed through adsorption and decomposition under aerobic conditions. Thus, the  $NH_4^+-N$ ,  $NO_3^- -N$  and T-N concentrations in treated water became unstable during Period 3 in the present study. To discuss the influence of structural difference on T-N removal we need to separately analyze the data in the two phases, aerobic and anaerobic, in which the different processes occur. Thus, further data analysis and discussion focused on

SS,  $BOD_5$ , COD and T-P removal efficiencies in relation to structural differences in MSL systems.

#### Relationship between the treatment efficiency of selected parameters and the surface area of SMB in MSL systems

Figure 4 shows the relationship between treatment efficiency of SS,  $BOD_5$ , COD, T-P and the top plus side surface area of SMB at HLR of 1,000 and 2,000  $L\ m^{-2}\ day^{-1}$ . At a high HLR of 3,000  $L\ m^{-2}\ day^{-1}$ , the efficiency of the MSL systems was possibly influenced by the secondary effect of structural difference, such as change of ORP and accumulation of organic matter, but these data were not included in the figures so that we could concentrate on the direct influence of structural difference. As shown in Fig. 4, with the increase in the top plus side surface area of SMB (Fig. 1), the average removal efficiency for SS,  $BOD_5$ , COD and T-P increased at HLR of 1,000 and 2,000  $L\ m^{-2}\ day^{-1}$ . In general, MSL systems' removal efficiency for SS,  $BOD_5$ , COD and T-P was in the order of MSL 5 = MSL 4 > MSL 3 > MSL 2 > MSL 1, which was positively related to the top plus side surface area of the SMB in the systems.

In Fig. 5, the influence of an increase in the top surface area (MSL 1, 3, 5) or side surface area of SMB (MSL 2, 3, 4) on the treatment of SS,  $BOD_5$ , COD and T-P was shown separately. The decrease in SMB height



**Figure 5** Relationship between the average removal rates of (a) suspended solids (SS), (b) biological oxygen demand (BOD<sub>5</sub>), (c) chemical oxygen demand (COD) and (d) total phosphorus (T-P) and the top plus side surface area of the soil mixture blocks (SMB). P, period.

among MSL 1, 3 and 5 increased the top surface area of SMB, while the decrease of SMB width among MSL 2, 3 and 4 increased the side surface area of SMB. Increases in both top and side surface areas of SMB enhanced the contact of wastewater with SMB and resulted in higher treatment efficiency for SS, BOD<sub>5</sub>, COD and T-P by MSL systems. Logarithmic equations to express the relationship between SMB surface area and MSL system treatment efficiency are listed in Fig. 5.  $R^2$  is higher than 0.9 for all the data analyzed, suggesting that the equation explained the experimental data well. Constant  $a$  represents the degree of influence on removal efficiency of the change in SMB surface area. The higher constant  $a$ , the bigger the influence of structural difference on MSL treatment efficiency. When  $a$  is compared in each period for all parameters, it is higher for top surface area increases than for side surface area increases, which means that the treatment efficiency of MSL systems could be improved more by increasing the top surface area rather than increasing the side surface area of SMB. This was because the increase in top surface area could increase the vertical water flow into the SMB. Comparing Periods 1 and 2, it was found that the effect of structural difference is greater in period 2. The increase in HLR shortened the retention time of wastewater inside the system, thus, efficient contact of wastewater with SMB became more important. Among the different pollutants, constant  $a$  was higher for COD and T-P removal than

for SS and BOD<sub>5</sub> removal, which implies that COD and T-P removal rates were more influenced by the change in SMB surface area. This was because phosphorus needs an efficient contact with the SMB, which is where the phosphorus is adsorbed. COD includes non-biodegradable components and certainly needs to be retained longer in the system. Efficient contact of wastewater and SMB probably increased COD retention time in the MSL systems and contributed to its efficient removal.

It is clear from the present study that MSL systems with smaller (thinner and narrower) SMB are better for SS, BOD<sub>5</sub>, COD and T-P removal because of the enhanced contact efficiency. This result agreed with the findings of Sato *et al.* (2005c), which indicated that MSL systems with narrower SMB had a larger side surface area and resulted in higher efficiency in BOD<sub>5</sub> and T-P removal. However, if the HLR and pollutant concentration were high, systems with smaller SMB might exert influence on the treatment efficiency of the systems, especially on nitrogen removal, by changes in ORP and accumulation of SS. Therefore, we need to consider this secondary effect when designing MSL system structures. In order to generalize the findings from this research and apply it for optimal MSL structural design in the future, we need to conduct further study and collect more data on different water quality and treatment conditions.



## Conclusion

Multi-soil-layering systems with thinner and narrower SMB showed a higher removal efficiency for SS, BOD<sub>5</sub>, COD and T-P treatment at HLR from 1,000 to 2,000 L m<sup>-2</sup> day<sup>-1</sup> because of the better contact efficiency between wastewater and SMB caused by the expansion of the top and side surface areas of the SMB. The effect of structural difference on the performance of MSL systems was more obvious at a HLR of 2,000 L m<sup>-2</sup> day<sup>-1</sup>, especially for COD and T-P, which require more efficient contact with SMB for adsorption and decomposition. When HLR was increased to 3,000 L m<sup>-2</sup> day<sup>-1</sup>, the difference among the systems became smaller probably because of preferential water flow into PL as well as ORP change caused by SS accumulation within the systems. This type of secondary effect of structural difference influenced T-N removal more than the expansion of SMB surface area did, although detailed discussion could not be conducted based on the present study. When designing MSL systems for wastewater treatment, we need to evaluate both the first and secondary effects of structural differences based on the different treatment targets and conditions, especially at high HLR and pollutant concentrations.

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