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An introduction of a multi-soil-layering system: a novel green technology for wastewater treatment in rural areas

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Abstract

Multi-soil-layering (MSL) systems are designed for municipal wastewater, livestock wastewater and polluted river water treatments. They are mainly composed of soil mixture block layers and water-permeable layers (PL). The MSL system overcomes many of the shortcomings of conventional soil treatment systems such as easy clogging, large land requirement and low hydraulic loading rate. This paper summarizes the structure, purification mechanism and practical application of the systems for different kinds of wastewater treatment. The paper also compares MSL systems with other decentralized systems such as wetland and compact filter systems in their respective structures and treatment efficiencies. Finally, the paper gives a rough evaluation of the lifespan and cost of an MSL system based on its material composition.

Introduction

High-technology wastewater treatment plants such as centralized sewage plants involve large capital investments and operating and running costs, and for economical reasons such systems are not applicable for wastewater treatment for small communities and livestock farms in rural areas, especially in developing countries like China. Recently, natural decentralized wastewater treatment systems have been gaining importance as an effective and low-cost alternative for the rural area wastewater treatment. In the United States, such systems serve approximately 25% of the population nationwide and about one-third of new construction uses this type of treatment today (Jantrania & Gross 2006). In response to Congress On Use of Decentralized Wastewater Treatment Systems, The United States Environmental Protection Agency (USEPA) states that adequately managed decentralized wastewater treatment systems are a cost-effective and long-term option to meet public health and water quality goals, particularly in less densely populated areas (Jantrania & Gross 2006). The rural population in the United States is about 64 million, contributing to 24% of the total population. For comparison, in China, there are about 850 million people living in the rural areas, approximately representing 67% of the total population of China. Therefore, it can be concluded that the wastewater generated in the rural area of China should be much greater than that of America. As economic reform and development continues and environmental awareness is being raised in China, water environmental pollution is gaining increasing attention in both urban and rural areas. Consequently, natural decentralized systems will be widely installed and used in the rural communities across China.

Natural decentralized wastewater treatment systems include conventional land treatment systems, septic tank–soil trench systems (unify the term in the text) and alternative technologies such as constructed wetlands, sand filters, etc., most of which are soil-based systems with a leach or a drain field (Crites & Tchobanoglous 1998). The high purification capacity of soil arises 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. However, the above soil-based natural wastewater treatment systems display several limitations. Clogging is one of the major limitations even in a septic tank–soil trench system (Ho & 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 types. Therefore, even for similar systems, they do not always perform with the same level of treatment efficiency (Sato *et al.* 2005).

Recently, a new kind of wastewater treatment system, multi-soil-layering (MSL) system, has been developed and studied to exploit the environmental purification function of soil completely. High treatment efficiency by the MSL system for municipal wastewater, livestock wastewater and polluted river water treatment has been reported (Wakatsuki *et al.* 1993; Masunaga & Wakatsuki 1999; Luanmanee *et al.* 2002). This paper summarizes the application result of this new technology so that it can be better understood and practiced, especially in developing countries, where a large need for this technology can be anticipated in the future to protect public health and for environmental sustainability in the future.

Structure and mechanism of MSL systems for wastewater treatment

Structure and material composition of MSL systems

Figure 1 shows the structure of an MSL system constructed for a municipal wastewater treatment for a family in Matsue City, Japan, which is mainly composed of soil mixture block (SMB) layers arranged in a brick-like pattern and water-permeable layers (PL). The MSL system can be constructed either above or underground. However, to keep warm during the winter period in some area, the underground construction would be a better choice. The SMB consists of soil mixed with 20–30% of other materials such as charcoal, sawdust, iron, etc. The addition of charcoal in SMB could enhance the biological decomposition and adsorption capacity of the system. Organic materials such as sawdust, rice straw, kenaff, corncob and so on added to SMB could enhance microbial activity and function as hydrogen suppliers during the denitrification process. As the adsorption capacity of a soil to phosphate is positively related to its composition of active Fe and Al, the addition of Fe in the form of an iron pellet or scrap in SMB could considerably increase the phosphate-adsorption capacity of MSL systems. After all the materials are weighed and mixed together, they can be filled in jute bags and fixed between the (PL).

PL are composed of coarse particles such as gravel, pumice, perlite or zeolite with a diameter of 1–5 mm, which could enhance water distribution, and the size should be as uniform as possible to reduce the risk of clogging. The water percolation coefficient of the MSL system was calculated using a model of 1 m^3, and 2000 m^3 water was flowed in during 1997. In a stable state, the value was around 1.0×10^{-1} cm/s. According to Reed *et al.* (1995), the maximum hydraulic loading rate (HLR) of the soil trench system is around 7–15% of the soil's water percolation coefficients; then the HLR of MSL systems could be 6–13 m^3/day (Wakatsuki *et al.* 1998). A mordenite-type zeolite has been utilized successfully as PL materials owing to its high cation exchange capacity (CEC) and adsorption capacity, which also prevents clogging caused by the dispersion of soil aggregate by Na-rich wastewater through Na reduction by cation exchange on the zeolite (a hard water softener induces Ca and Mg exchange to Na by Na-saturated zeolite). Besides, porous pipes can be set inside the system and air can be sent by the pump to control the aeration state of the system.

In conclusion, the MSL system has the following characteristics: (1) the PL considerably enhance the water permeability of the system and prevent clogging; (2) the addition of natural organic materials in the soil enhances the purification capacity of the system; and (3) the aeration state of the system can be controlled by on/off setting of the aeration pipe.

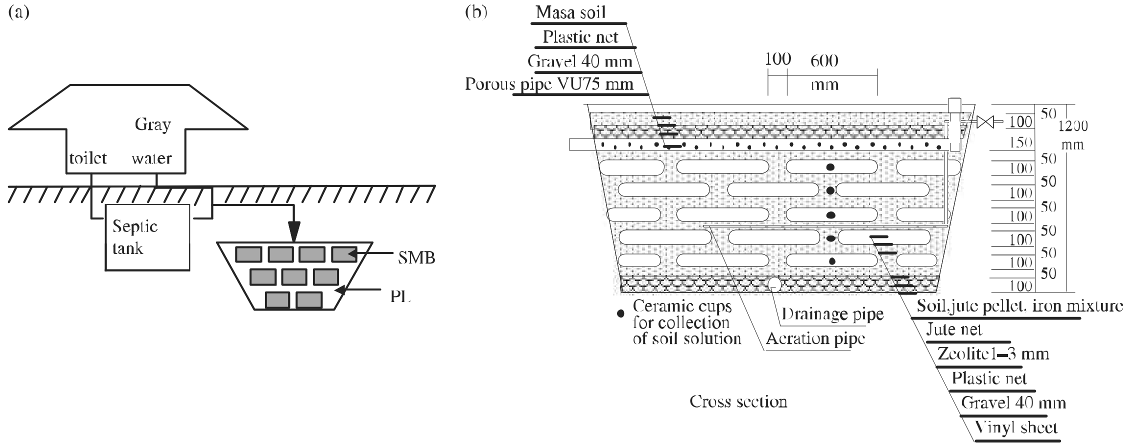

Fig. 1. Basic structure of a multi-soil-layering (MSL) system designed for municipal wastewater treatment for a single family in Matsue City, Japan. SMB, soil mixture block; PL, water-permeable layer.

Mechanism of MSL systems for wastewater treatment

Possible treatment mechanisms were well explained in Wakatsuki *et al.* (1993). The wastewater usually contains high concentrations of biological oxygen demand (BOD), chemical oxygen demand (COD), NH_4^+-N, organic nitrogen (Org-N) and PO_4^{3-}-P (Fig. 2). When wastewater is discharged into the MSL systems, organic matter from the wastewater is first physically and chemically adsorbed on the soil and zeolite-specific surface area and subsequently decomposed by microorganisms. Org-N is partly adsorbed on the soil and zeolite surface and partially mineralized to NH_4^+-N. Zeolite has a high capacity to adsorb NH_4^+-N owing to its high CEC. Under aerobic conditions, NH_4^+-N is oxidized to NO_2^--N and NO_3^--N. Then, NO_3^--N is translocated to SMB and reduced to nitrogen gas (N_2, NO, N_2O). Organic materials such as sawdust, kenaf or corncob added to the SMB are additional carbon sources for microorganisms to facilitate a smooth denitrification reaction. Therefore, the aerobic and anaerobic conditions in the system are the most important factors controlling the efficiency of the MSL system in removing N via nitrification and denitrification processes. Phosphorus can be adsorbed on the Al and Fe hydroxides in the soil. The iron added in the SMB is transformed into ferrous iron (Fe^{2+}), which is subsequently translocated to the zeolite interlayer and is oxidized to ferric ion (Fe^{3+}), which aids in associating coprecipitation of PO_4^{3-} from the percolating wastewater (Wakatsuki *et al.* 1993).

Aeration pipes set inside the system can control the aerobic and anaerobic state of the system by sending air from outside the system with an on/off switch of the pump system. Aeration at an appropriate rate and for an optimum duration significantly enhances BOD, COD, total nitrogen (TN) and total phosphorus (TP) removal. However, excessive aeration has an adverse effect on TN removal by hindering the denitrification process. When nitrification occurs, hydrogen ions are released, thus reducing the pH of the treated water (Luanmanee *et al.* 2002; Boonsook *et al.* 2003), whereas denitrification produces hydroxyl ions and subsequently a higher pH is induced. Therefore, the changes in the pH of the treated water can be used to control aeration of the MSL system at an appropriate rate and duration. A study in Thailand showed that a pH between 6.5 and 7.0 is suitable to maintain the efficiency of the MSL system in treating municipal wastewater. Aeration at a rate of 20 000 L/m^3/day for 3 days alternated with 2 months of nonaeration was the appropriate operation regime for the MSL systems examined in Thailand for municipal wastewater treatment (Luanmanee *et al.* 2002).

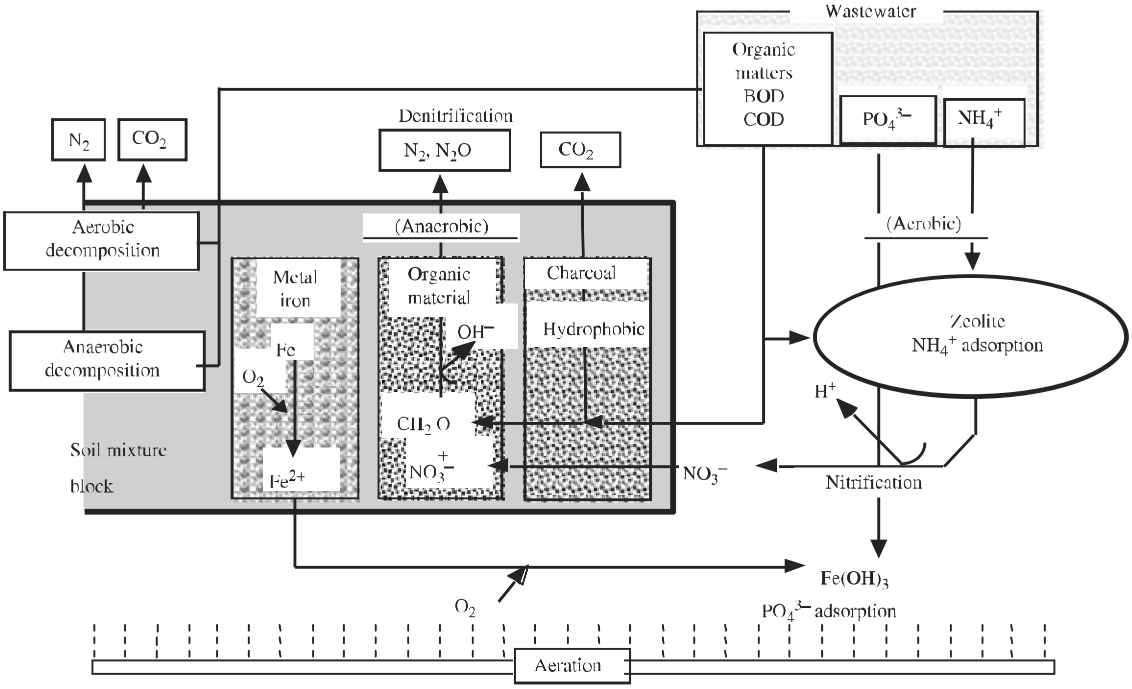

Fig. 2. Purification mechanism of a multi-soil-layering (MSL) system for municipal wastewater, livestock wastewater and polluted river water treatment.

Efficiency of MSL systems compared with other conventional soil-based systems

MSL system for municipal wastewater treatment

An MSL system was constructed and studied for municipal wastewater treatment of a single family in Matsue city from 1990 to 2000 (Wakatsuki *et al.* 1993; Luanmanee *et al.* 2001; Sato *et al.* 2002). The municipal wastewater was a mixture of toilet (pretreated with septic tank), kitchen and bathroom water with an average concentration of BOD_5 100 mg/L, TN 65 mg/L and TP 9.6 mg/L and flowed into the system at an HLR of 300–400 $L/m^2/day$ (two to five family members). The MSL system had an area of around $4.4 m^2$ (1.75×2.5 wide × 1.2 m deep). During the 10-year operation, the removal rates for BOD_5 and TP were higher than 80–90% (Fig. 3). The TN removal rates decreased to 50–70% after 3 years of operation and meanwhile the pH value of the treated water decreased to around 4, which suggested leaching of NO_3^--N from the system as NO_3^--N in the treated water increased. In 1996, aeration was applied to the system at a rate of $1.44 \times 24 m^3/m^3/day$ and it resulted in a lower pH value and a higher concentration of NO_3^--N in the treated water. From March to April 1997, aeration was stopped and TN removal rates increased gradually to over 80% again, which suggested that N removal could be adjusted and controlled by the aeration state in the system.

An MSL system constructed in Kasetsart University, Thailand, for food service wastewater treatment showed high removal rates of BOD 90%, TN 70% and TP 90% for wastewater with high concentrations of BOD 500 mg/L, TN 300 mg/L and TP 30 mg/L at a loading rate of 250 $L/m^2/day$. Thus, the purification efficiency ranges of the MSL system are 113 $g BOD/m^2/day$, 53 $g N/m^2/day$ and 6.8 $g P/m^2/day$. In the case of subsurface wetland, the general purification efficiency is not so different from those of natural soils, in which it is around 2–30 $g BOD/m^2/day$, 0.1–3 $g TN/m^2/day$ and 0.1–3 $g TP/m^2/day$ (Attanandana *et al.* 2000). These data suggest that MSL systems could also efficiently treat high-concentrated wastewater and the purification efficiency was about 10–50 times higher than natural soil systems and subsurface flow wetland (Knight *et al.* 2000).

MSL systems showed more efficient and stable wastewater treatment results than other soil-based systems such as constructed wetland or compact filter systems. During the first 2 years of operation, the MSL system in Matsue city, Japan, showed much higher reduction rates for BOD, P and N than constructed wetlands in the United States and N reduction rate than compact filter systems in Norway (Table 1). The high removal efficiency for N might be due to the co-existence of aerobic and anaerobic states inside the system and selection of materials that could adsorb and denitrify NH_4^+-N in the wastewater. The low N removal efficiency during 1996 was caused by overaeration in the whole system. In comparison, a study of 21 single-family constructed wetland systems in Ohio, USA, during 1994–2001 reported an average reduction of BOD_5 70 ± 48%, NH_3 56 ± 31% and P 80 ± 20%, with average concentrations of BOD_5, NH_3 and P of influent being 104.7, 47.7 and 8.36 mg/L; there were one to seven members in a family. All the wetlands had a three-stage design (septic tank plus two wetlands) and share a

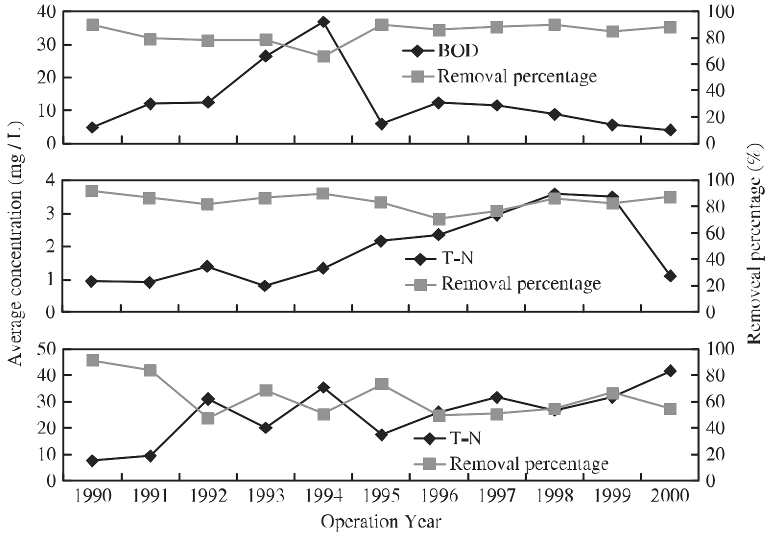

Fig. 3. Average concentration and removal percentage of biological oxygen demand (BOD), total phosphorus (TP), total nitrogen (TN) of a multi-soil-layering (MSL) system for municipal wastewater treatment during a continuous 10-year operation.

Table 1 Comparison of a multi-soil-layering (MSL) system with a constructed wetland, a compact filter system in area occupation, hydraulic loading rate (HLR), input concentration and reduction percentages of biological oxygen demand (BOD), total nitrogen (TN) and total phosphorus (TP) for municipal wastewater treatment

	Area (m^2)	Loading rate (L/day)	BOD		N		P	
			Input (mg/L)	Reduction (%)	Input (mg/L)	Reduction (%)	Input (mg/L)	Reduction (%)
Multi-soil-layering system[a]								
1990	4.38	573	64.5	84.5	64.9	88.9	8.17	87.5
1991	4.38	650	65.8	81.8	63.2	86.6	7.82	84.6
1996	4.38	760	113.2	92.4	77.2	53.1	11.31	76.9
Constructed wetland[b]								
1994–2001	24.75	ND	104.7	70.3	47.7	56.5	8.36	80.5
Compact filter system[c]								
2002–2004	9.40	450–864	174.0	97.0	67.0	30.0	ND	99.4

[a] Luanmanee *et al.* (2001).
[b] Steer *et al.* (2002).
[c] Heistad *et al.* (2006).

common design of 4.5 × 5.5 m width and 0.46 m depth for each cell with a substrate of riverbed gravel (Steer *et al.* 2002). In another study of a compact filter system to treat municipal wastewater in Norway, it was found that at a loading rate of 450–864 L/day, the system could reduce BOD_7 97.0%, N 30% and P 99.4% with three fundamental elements (a septic tank, an aerobic filter and an up-flow saturated filter reactor). The high BOD reduction rate was because of the aerobic and up-flow saturated filter reactors, which had a high BOD removal efficiency similar to the A/O process. The high P reduction rate was because of the up-flow filter medium FiltraliterP^{TM}, which has a grain size of 0–4 mm and a high phosphorus retention capacity (Heistad *et al.* 2006). Besides, wetland occupied a much larger area (24.8 m^2) than the MSL system (4.4 m^2) for municipal wastewater treatment with similar loading rates and concentrations.

MSL system for livestock wastewater treatment

Owing to the success in municipal wastewater treatment, natural systems such as constructed wetlands to treat livestock wastewater have been included as a component of the waste management strategy in many countries such as the United States and New Zealand (Knight *et al.* 2000; Tanner *et al.* 2005). Most existing designs for livestock wastewater treatment wetlands are based on estimated or measured BOD loadings. In the United States, the BOD_5 loading rate to a constructed wetland suggested by the Natural Resources Conservation Service (NRCS) is 73 kg/ha/day and the outflow should reach a water quality of $BOD_5 < 30$ mg/L, TSS 30 mg/L and $NH_3+NH_4^+$-N < 10 mg/L (Cronk 1996). It is difficult to compare these results because pretreatment, substrate, vegetation and climatic conditions vary widely among the wetland sites. A review of five constructed wetlands for dairy wastewater treatment by Cronk (1998) showed a retention capacity of BOD_5 of 0.9–24.3, TSS 1.9–95.4, NH_3 0.1–1.4 and TP 0.03–2.1 g/m^2/day. Furthermore, Knight *et al.* (2000) reported that the average inflow and outflow of BOD_5, SS and TN concentrations were 263 and 93 mg/L, 585 and 273 mg/L, 122.2 and 63.7 mg/L, with an average reduction efficiency of 65, 53 and 48%, respectively, for 68 sites with a total of 135 separate systems in the livestock wastewater database (LWDB).

In comparison, four laboratory-scale MSL systems constructed for a 45 × 10 cm wide × 90 cm deep livestock wastewater treatment showed an average reduction efficiency for BOD_5, SS, NH_4-N and PO_4-P of 96–99, 95–97, 75–99 and 80–99%, respectively, at a loading rate of 220 L/m^2/day from April to June 1995 (Harada & Wakatsuki 1997). As the original concentrations of livestock wastewater for BOD_5, SS, NH_4-N and PO_4-P were 1666, 342, 604 and 41.8 mg/L, the MSL systems' nutrient retention capacity for BOD_5, SS, NH_4-N and PO_4-P were 35.2–36.3, 7.1–7.3, 10.0–13.2 and 0.74–0.91 g/m^2/day. This showed that the nutrient removal capacities for BOD and N by MSL systems were much higher than those by constructed wetlands. Actually, for livestock wastewater treatment, the maximum reduction by the MSL system for BOD and TN removal could reach 600 g BOD/m^2/day and 57.8 g N/m^2/day with a loading rate from 30 to 290 L/m^2/day (Masunaga *et al.* 2002).

MSL system for polluted river water treatment

A demonstration experiment for the treatment of Kumazoi river in Kyushu, Japan, was conducted and operated for 1 year from December 2000. The polluted river water was pumped into two pretreatment septic tanks and then

Table 2 Comparison of a multi-soil-layering (MSL) system with a constructed wetland in area occupation, hydraulic loading rate (HLR), input and output concentrations of biological oxygen demand (BOD), total nitrogen (TN) and total phosphorus (TP) for polluted river water treatment

	Area (m^2)	Loading rate (l/m^2/day)	BOD		TN		TP	
			Input (mg/l)	Reduction (%)	Input (mg/l)	Reduction (%)	Input (mg/l)	Reduction (%)
Multi-soil-layering system[a]								
MSL1	12	4000	16.0	86.3	2.8	41.2	0.56	60.7
MSL2	12	4000	16.0	88.1	2.8	41.2	0.56	55.4
MSL3	12	4000	16.0	83.8	2.8	71.4	0.56	64.3
Constructed wetland[b]								
Alexander (FWS)	200	20–80	36.3–97.5	74.3–96.9	45.6–56.7	45.0–94.9	12.2–16.1	6.5–95.4
Alexander (SSF)	200	20–80	36.3–97.5	63.3–97.0	45.6–56.7	34.7–95.3	12.2–16.1	3.5–95.5

[a] Unno *et al.* (2003).

[b] Green *et al.* (1996).

flowed into three parallel MSL systems. The SMB were composed of on-site alluvial soil, sandy soil, bark compost and charcoal at a volume ratio of 4 : 4 : 1 : 1. As the P concentration in the river water was low and not set as a treatment target, iron was not added to the systems. The PL of MSL 1 and 2 were composed of pumice while MSL 3 was a mixture of pumice and zeolite of the same size. Table 2 shows the removal efficiency of the three MSL systems. The MSL systems were able to treat BOD of 16 mg/L on average in the pretreated water up to 2 mg/L stably all year round without clogging, at a loading rate of 4000 L/m^2/day, which was 80–160 times higher than that usually applied to soil trench systems: 25–50 L/m^2/day (Unno *et al.* 2003). The amount of BOD discharged into MSL systems was 64 g/m^2/day, which was six to 12 times higher than that discharged into conventional soil trench systems. Although TN and TP was not an objective of this study, 41–68% of TN and 58–66% of TP were removed by MSL systems. Another study with six MSL systems for river water treatment was conducted along Uya River, Japan, from 1999 to 2000 at an HLR of 1000–4000 L/m^2/day. Similar results of 72.2–83.5% BOD reduction, 22.4–50.0% for TN reduction and 51.9–66.8% for TP reduction rates were reported (Masunaga *et al.* 2003).

Application of constructed wetlands was also reported for river water reclamation. A research project carried out at the Alexander River basin in Israel showed that the wetlands could remove BOD to <20 mg/L at a loading rate of 20–80 L/m^2/day and the BOD loading rate was around 1–5.5 g/m^2/day. As the pollutant concentrations in Alexandra river water were much higher than those in Uya river water, the loading rate was much lower than that applied to MSL systems. The removal efficiencies for TN and TP in Alexandra river water fluctuated considerably, from 0 to over 90% (Green *et al.* 1996). It can be concluded that MSL systems could receive a loading rate around 50 times that of wetland with a BOD amount more than 10 times higher than that flowed into wetlands.

The lifespan and cost evaluation of MSL systems

The lifespan of MSL systems

A mass balance study for MSL systems after 10 years of application for municipal wastewater treatment in Matsue, Japan, showed that MSL systems could remove 60–70% of TN even in the eighth to 10th year. In addition to the organic materials added to SMB, organic matter such as BOD and COD also contributed to the carbon source for denitrification. A significantly negative correlation ($r = -0.56$) was found between the COD/TN ratio in wastewater and the TN concentration in treated water and it was estimated that a suitable COD/TN ratio in the wastewater should be around 4 and 5 to ensure efficient TN removal (Sato *et al.* 2002). Organic materials such as jute added to MSL systems also contribute to efficient TN removal. The jute used in the system was about 150 kg. However, in practical applications, jute was most likely to be decomposed completely within a few years. Consequently, effective use of organic matter in wastewater appeared to be a good option for TN removal in the long run by means of proper management of aeration to the system.

For TP removal, no precise data were available for the life of metal iron added in MSL systems. The result of a mass balance study on the above-mentioned MSL system in Matsue city, Japan, showed that during the 10-year operation, 19 kg of P was removed from the system and 11 kg of Fe was consumed. In this case, the soluble rate of the metal iron initially added to the system was the key factor for the calculation of the P fixation life of the MSL. If we assume that the efficiency of iron was 10%, i.e., 10% of added iron in the system functioned to precipitate 19 kg of P from the waste water, then 110 kg of metal iron were supposed to be dissolved during the 10 years period in this study. As the initial addition of metal iron to the system was around 300 kg, the durability of the MSL system should be 27 years for P fixation in this study.

The cost evaluation of MSL systems

As MSL systems are mainly composed of local materials such as soil, charcoal, sawdust and iron, the cost of construction is comparatively low. To construct an MSL system with a municipal wastewater treatment capacity of 100 m^3/day at an HLR of 1000 L/m^2/day, the area required is around 100 m^2, with a depth of 1 m. If we assume that half of the system is composed of zeolite (100 m^3), around 60 tonnes of zeolite would be required at a price of US$25/tonne, at a total price of US$1500 in China. The normal bulk density of SMB is around 1.2 g/cm^3 with sandy soil (Entisol) as the main material. The weight of SMB is around 120 tonnes, out of which 70% is soil (around 84 tonnes). Charcoal, iron and sawdust comprise the other 30% of SMB. The price for charcoal is around US$60/tonne, sawdust US$25/tonne and iron US$250/tonne in China. Therefore, the whole cost for constructing such an MSL system can be less than US$10 000 in China. The operation of the MSL system is easy, requires little maintenance and consumes little energy. In addition, most of the sludge can be decomposed inside the system. Soil and zeolite from used MSL systems can be applied for agricultural addition as it does not contain any harmful substance, while it is rich in nutrients such as NH_4^+, P, Fe and Ca (Wakatsuki *et al.* 1990).

Conclusions

It is important to choose suitable wastewater treatment systems according to the local natural and economic conditions. MSL systems provide another option for rural wastewater treatment as they have been constructed and applied in countries like Japan, America, Indonesia and Thailand and were stable and showed high treatment efficiency. A complete understanding of soil's purification mechanism and proper management of the system could contribute towards environment protection causes, especially in developing countries like China, as the system has the following advantages compared with other wastewater treatment technologies:

(1) It can control and enhance soil's purification functions and overcome the shortcomings of conventional soil systems. MSL systems proved to be highly efficient for different kinds of wastewater treatment, especially for removal of nutrients such as N and P, which could contribute towards solving the ever increasing serious eutrophication problems in rivers and lakes.

(2) The system needs little energy, has low operational cost and requires small land occupation, which is quite suitable for wastewater treatment in rural areas of developing countries.

(3) Based on the local condition, the system could make use of natural waste resource, which can contribute towards the construction of ecologically sustainable regional economics.

(4) Treated water could be recycled for landscape or toilet flushing and could lessen the serious water shortage conditions in most of the areas.

(5) The system needs little or no maintenance during operation. This kind of a 'low-technology' system is more appropriate for rural areas where few professional experts are available.

(6) The lifespan of MSL systems should be able to last for more than 20 years in case of a system used for municipal wastewater treatment, although it depends on the treatment condition. After application, the materials of the system could be recycled for agricultural addition because no toxic chemical substances are added during the treatment process.

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