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Multi-Soil-Layering Systems for Wastewater Treatment in Small and Remote Communities

C. J. An[1,2], E. McBean[1,3], G. H. Huang[4,*], Y. Yao[2], P. Zhang[2], X. J. Chen[2], and Y. P. Li[4]

[1]*Institute for Energy, Environment and Sustainability Research, UR-NCEPU, North China Electric Power University, Beijing 102206, China*
[2]*Institute for Energy, Environment and Sustainability Research, UR-NCEPU, University of Regina, Regina S4S 0A2, Canada*
[3]*School of Engineering, University of Guelph, Guelph N1G 2W1, Canada*
[4]*China-Canada Institute of Energy and Environmental Research, North China Electric Power University, Beijing 102206, China*

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ABSTRACT. Large portions of domestic wastewater in small and remote communities are discharged into the environment without effective treatment. In areas with low population densities and dispersed households, wastewater system strategies are needed which are environmentally, socially and economically sustainable. A wastewater treatment technique known as a multi-soil-layering (MSL) system is shown to be a promising wastewater treatment and disposal method. A full-scale, land-based approach developed from the most recent efforts in this emerging field is described. A brief description of the mechanisms in the treatment process within the MSL system, as well as the design and operation for the MSL system, are provided. The state-of-the-art and development trends of MSL process for the wastewater treatment are further introduced.

Keywords: multi-soil-layering system, wastewater treatment, removal mechanisms, design and operation

1. Introduction

Water safety has received increased attention over the past decades (Yin et al., 1999; Motiee et al., 2006; Li et al., 2015). In small and remote communities, a large portion of domestic wastewater is discharged into the environment without effecttive treatment and/or no treatment (Molinos-Senante et al., 2012; Sorensen and McBean, 2015; Tan et al., 2015). Although the characteristics of wastewater from different communities vary significantly in quality and quantity, wastewater is able to be generalized as having high content of particulate matter, dissolved organic matter, nutrients and microbes. The receiving water bodies may be heavily polluted, resulting in serious environmental and ecological problems (Boluwade and Madramootoo, 2015; Brennan and McBean, 2011a; Tan et al., 2015). This issue is particularly poignant in villages and remote regions of developing countries. It is a challenge to provide reliable and affordable wastewater treatment in such areas around the world (Massoud et al., 2009; Zhang et al., 2014). In response, centralized wastewater treatment plants have been used as common practice to remove pollutants from wastewater with high efficiency and loading rate (Garcia et al., 2013). However, it requires a well-designed sewage network to collect wastewater. The construction, operation and maintenance of wastewater treatment plant are also costly. In areas with low population densities and dispersed households, of interest are strategies for dealing with wastewater which can be environmentally, socially and economically sustainable.

Traditional and modern technologies have been used for decentralized sewage treatment (Moussavi et al., 2010; Sabry, 2010). For example, many individual residences in rural areas rely on septic tanks to dispose of their wastewater. Although septic tanks are an easy and safe technique, the concentration of suspended solids (SS), biochemical oxygen demand (BOD), total nitrogen (TN) and total phosphorus (TP) in effluents from septic tanks can hardly meet the discharge requirements (Liang et al., 2010). It is also noted that septic tanks are not correctly designed, built and operated in many situations. Failing septic systems are regarded as the third most frequently cited source of groundwater contamination in the United States (USEPA, 1998). Engineered lagoons are also widely used to treat domestic wastewater generated from rural communities in North America and Europe. Sewage treatment lagoons usually contain at least one artificial aerated lagoon plus additional aerated and/or anaerobic lagoons in series, in parallel, or both (Li et al., 2013). Sewage treatment lagoons account for more than 50% of the wastewater treatment facilities in the U.S. (USEPA, 2011). In addition, many other on-site systems, such as soil trenches, constructed wetlands, high-rate algal ponds and compound media filter beds, have been used to treat wastewater

* Corresponding author. Tel.: +1061773889; fax: +1061773885.
E-mail address: guohe.huang@outlook.com (G. H. Huang).

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when dealing with small quantities (Matamoros and Bayona, 2013; Ma et al., 2015). All of these methods have their own unique principles, advantages and limitations and can be applied to treat decentralized sewage with different efficiencies.

An alternative technique that holds interesting potential for decentralized sewage treatment is multi-soil-layering (MSL) system. MSLs have been successfully used for treatment of several types of wastewater (Attanandana et al., 2000; Pattnaik et al., 2008; Guan et al., 2012). MSLs are characterized by their ability to handle higher hydraulic load rates and pollutant loads compared with some conventional land treatment systems (Guan et al., 2014). The environmental cleanup capability of soil is maximized in MSL systems, while avoiding many problems encountered in the previous soil-based sewage treatment systems. The MSL system shows good performance in the reduction of organic matter and nutrients (Sato et al., 2010). Removal of pollutants from wastewater through MSL is a complicated process involving various chemical, physical and biological processes. As a promising treatment technology and a cost-effective solution for sustainable water management, the need exists to develop increasingly deeper insight into the performance aspects of MSL systems. This article presents a full-scale review on the most recent efforts in this emerging field. Process fundamental, design, operation and field practice and future development needs are discussed in detail, motivating consideration of MSL as a viable approach for resolving wastewater issues in small and remote communities.

2. Mechanisms of MSL System

2.1. Previous On-site Wastewater Treatment Methods

Soil is a special media which includes organic matters, inorganic minerals, moisture, animals, plants and microorganisms which also describes an ecosystem. Adsorption on soil particles, ion-exchange, oxidation-reduction, migration and precipitation, uptake by animals and plants and biodegradation can occur in the soil matrix as wastewater passes through. Land filtration using soil as a filter is a traditional on-site wastewater treatment approach. This soil treatment process include several types such as slow rate, overland flow and soil aquifer treatment. In slow rate treatment, wastewater is applied to a vegetated soil surface and the wastewater is remediated as it flows through the plant root/soil matrix. Hydraulic pathways of the applied water include vegetation irrigation, evapotranspiration and percolation (USEPA, 1984). In overland flow treatment, wastewater is applied to relatively impermeable soils on gentle grass covered slopes (Smith and Schroeder, 1985). Vegetation in the system can contribute to slope stability, erosion protection and wastewater treatment. The process of overland flow treatment is similar to that of tricking filters and other attached growth processes. In soil aquifer treatment, wastewater is applied to earthen basins with permeable soils (Amy and Drewes, 2007). Water-tolerant grasses are often used due to their relatively high hydraulic loading rate (HLR). Soil aquifer treatment is accomplished by active soil matrices near the surface. A trench system improves the soil aquifer treatment. The soil layers consist of composite soil, air layer, composite layer, filter layer and storage layer from top to bottom. Air permeability in soil layer can be increased due to the existence of the air layer.

Constructed wetlands are typically proposed based on traditional soil filtration. In constructed wetland, gravels are used as permeable filters to improve water flow. Nutrient uptake by plants plays an important role and microorganisms near plant roots may induce specific biodegradation of contaminants. The processes in constructed wetlands can be classified as free water surface (FWS) and subsurface flow (SF) constructed wetlands. FWS contains free-floating, emergent or submerged aquatic vegetation dominated systems and can be applied for ecological restoration of polluted rivers. However, a FWS constructed wetland has limited capacity for nutrient reduction. Removal efficiencies typically range from 40 to 50% for nitrogen and from 40 to 90% for phosphorus (Zhang et al., 2015a). SF constructed wetlands typically consist of a rectangular bed planted with common reed or other higher aquatic plants and lined with an impermeable membrane on the bottom. SF constructed wetlands include both types of horizontal and vertical flow systems. BOD_5 and COD removal can be attributed to filtration and sedimentation of SS as well as degradation by microorganisms. Nitrogen removal in SF constructed wetlands can be impacted by hydraulic retention time (HRT), tempera-

Table 1. Comparison of Requirements for Treatment Techniques

Technique	Pretreatment	Area (m^2)	Loading rate (m/day)	Vegetation	Temperature response	Average value in after treatment (mg/L)					Reference
						BOD_5	SS	NH_3-N	TN	TP	
Slow rate	Primary sedimentation	(23 - 280) ×10^4	4×10^{-3}	Required	Sensitive	< 2	< 1	< 0.5	3	< 0.1	(USEPA, 2006)
Overland flow	Screening	(6.5 - 44) ×10^4	2.7×10^{-2}	Required	Sensitive	10	10	<4	5	4	
Soil aquifer	Primary sedimentation	(3.0 - 23) ×10^4	8.1×10^{-2}	Optional	Not critical	5	2	0.5	10	1	
Free surface constructed wetland	Screening	(0.0025 - 1.07) ×10^4	7.5×10^{-3}	Required	Sensitive	19.24	19.85	2.28	7.95	5.54	(Zhang et al., 2015a)
Subsurface constructed wetland	Primary sedimentation	(0.0001 - 0.32) ×10^4	5.6×10^{-2}	Required	Sensitive	24.66	26.56	22.12	36.56	3.24	

ture, vegetation type and properties of soil media (Akratos and Tsihrintzis, 2007). Phosphorus is removed primarily through ligand exchange reactions in which phosphate is displaced by water or hydroxyls from the surface of Fe and Al hydrous oxides (Faulkner and Richardson, 1989).

According to the wastewater types, land and location characteristics, treatment targets and cost requirement, different treatment approaches may show different performance. Some previous techniques are compared in Table 1. Slow rate infiltration requires a large area to treat wastewater which cannot be applied in regions with scarce land. Overland flow and soil aquifer infiltration have higher hydraulic loading rates than slow rate infiltration, while a better quality of effluent can be obtained in slow rate infiltration processes due to the larger treatment land area and longer HRTs. Constructed wetlands combine the features of soil treatment and plant uptake and require relatively smaller areas. However, this technique is also associated with large investment costs and maintenance. Moreover, BOD_5 and SS removal efficiencies of the FWS constructed wetland are better than SF constructed wetland. After a long term of operation, removal rates may decrease due to clogging of SS, which is a critical limitation of these techniques.

2.2. Fundamentals of MSL System

An MSL system is an innovative wastewater treatment technique (Wakatsuki et al., 1990). MSL systems not only require both low investment and minimal land, but also can address the risk of clogging associated with land-based wastewater treatment systems. As shown in Figure 1, the MSL system utilizes soil mixture blocks (SMBs) and permeable layers (PLs), which is different from traditional soil percolation systems. SMBs, including components such as soil, sawdust, charcoal, rice straw, and iron particles, are arranged as bricks and play a key role in the MSL system. Different materials in SMBs respond to different functions. Soil can work as both a filter and as habitat for microorganisms. Organic matter such as sawdust, rice straw and jute supply carbon source for denitrification processes. Charcoal can adsorb a vast array of contaminants from wastewater. Furthermore, iron particles can facilitate the formation of ferric ions, leading to the precipitation of phosphates (Brennan and McBean, 2011a). The common components and functions of soil mixtures in the MSL system are shown in Table 2. PLs are composed of materials such as gravel, pumice and zeolite. PLs surround SMBs like cement, which can improve water dispersion and distribution and reduce the clogging risk. In addition, materials with porous structure in PLs can also adsorb contaminants and provide benefit to microorganisms. Due to the differences in structure, permeability, and water distribution, SMBs and PLs can work as saturated zone (anaerobic) and unsaturated zone (aerobic), respectively. The MSL system is not only a hybrid reactor including aerobic and anaerobic processes, but also a miniature soil ecosystem. The mechanisms of pollutant removal in MSL are shown in Figure 2. An MSL system is characterized by low cost and easy maintenance and can be a viable option to treat wastewater for small communities.

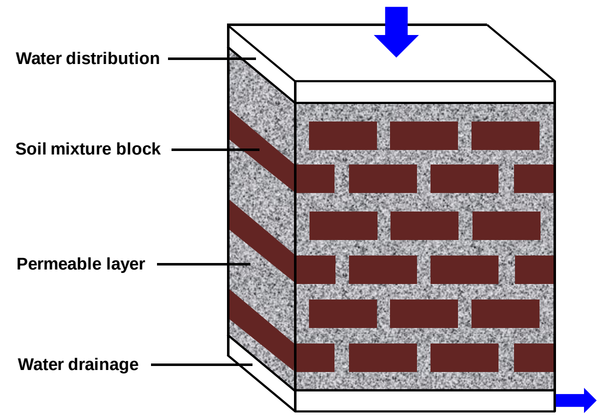

Figure 1. Schematic configuration of a MSL system.

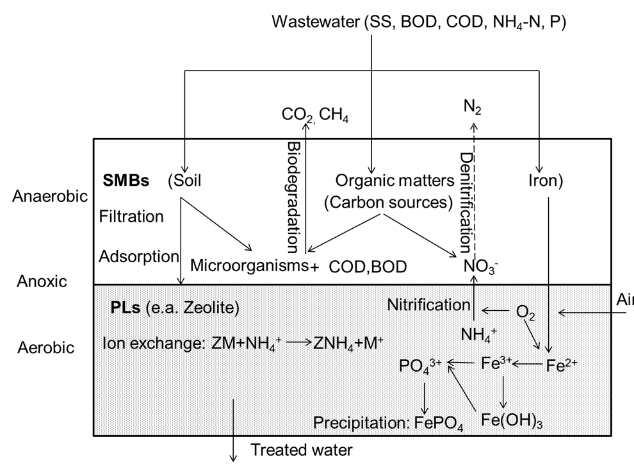

Figure 2. Mechanisms of the MSL system (Chen et al., 2009; Luo et al., 2014).

Table 2. Components and Functions of Soil Mixture in MSL

Component	Function	Mechanism
Soil	Provide the microorganisms and the pore space	Soil can work as filter and habitat for microorganisms.
Iron	Increase the phosphate-adsorption capacity	The adsorption capacity of a soil to phosphate is positively related to its composition of active Fe and Al.
Jute, saw dust	Enhance microbial activity and function as hydrogen suppliers during the denitrification process	The efficiency of the MSL system in nitrogen removal via the denitrification process can be limited if the amount of organic carbon is insufficient.
Charcoal, activated charcoal	Provide carbon sources and enhance the biological decomposition and adsorption capacity of the system	Charcoal or activated charcoal itself has a quite larger surface area and adsorption capacity.

2.3. Contaminant Removal in MSL Systems

2.3.1. Organic Matter Removal

The large size organic contaminants or particles are retained by size exclusion in SMBs. A portion of small size contaminants may form larger size contaminants through collision and amalgamation with soil colloids. In addition, soluble organic contaminants may adsorb to soil particles when wastewater penetrates into SMBs. The organic contaminants retained in SMBs can be further degraded by microorganisms. The organic matters, charcoal and jute of SMBs may supply adequate carbon sources. The MSL system has high BOD removal rates, which can perform at rates which are 10 - 50 times higher than natural soil treatment systems and subsurface flow wetlands. MSL systems have 80 - 160 times higher loading rates than those of soil trench systems and wetlands (Unno et al., 2003; Chen et al., 2009). Since COD includes not only biodegradable but also slowly decomposable organic matter, the removal rate of COD is not as high as that of BOD in MSL systems.

2.3.2. Nitrogen Removal

Ammonia nitrogen is removed by nitrification and denitrification in the MSL system (Sato et al., 2005a). On the one hand, ammonia nitrogen is transformed to nitrite through nitrification by nitrifiers in PLs which are in the aerobic zone. Then, the nitrite is further transformed to stable nitrate. On the other hand, nitrate can be transformed to nitrite through denitrification by denitrifiers in SMBs which are in the anaerobic zone and have adequate carbon sources. Then, the nitrite is transformed to nitrogen gas. Consequently, the ammonia nitrogen could be removed as wastewater passes the SMBs and the PLs alternatively. Since zeolites are characterized by high cation exchange capacity (CEC), the ammonium ions can also adsorb to zeolites in PLs through ion exchange. MSL systems show higher nitrogen removal rate than that of constructed wetlands and compact filter systems.

2.3.3. Phosphorus Removal

In the MSL system, iron particles within SMBs are dissolved and leached to PLs. Fe is oxidized to Fe (III) and then forms Fe (III) hydroxides. Phosphates may bond with such hydroxides or form precipitates with ferric ions. Compared to the removal rate of organic matters, the removal rates of phosphorrus are more dependent on flow rate in SMBs (Sato et al., 2011b). The removal of phosphorus in constructed wetlands is mainly dependent on uptake of plants. The corresponding removal of phosphorus by constructed wetlands can be signifycantly influenced by climate conditions.

3. Structure and Material Design for MSL System

3.1. Structure Design for MSLs

In MSL systems, SMBs are surrounded by PLs and they are arranged in a brick-like pattern. The structure of the MSL system facilitates the infiltration and distribution of wastewater and makes higher treatment loading rates possible compared with conventional land-based systems, which are limited by permeability and clogging problems (Sato et al., 2011b). A typical MSL system also includes pipes to distribute water, and aeration pipes. The dimension of MSL systems including SMBs and PLs varies in different studies. Ho & Wang (2015) studied the efficiency of an MSL system for wastewater treatment using environment-friendly filter materials. MSL blocks were stacked in an overlapping manner within the 50 × 10 × 70 cm (L × W × H) chamber. The soil blocks, 10 × 10 × 4 cm (L × W × H) and 10 × 5 × 4 cm (L × W × H) in size, were prepared. The horizontal intervals between the SMB were 2.5 cm and PLs between soil block layers was 4 cm in height. Masunaga et al. (2007b) investigated the characteristics of CO_2, CH_4 and N_2O emissions from MSL systems during wastewater treatment. The soil block was 10 × 20 × 10 cm (L × W × H) in size. A 2-cm thick layer of powder charcoal was used in each soil block. The horizontal intervals between the SMBs were 5 cm and PL between SMB was 7 cm in height. Latrach et al. (2015) investigated the performance of MSL systems to remove fecal contamination bacteria indicators and pathogens from domestic wastewater. The MSL system (36 × 30 × 65 cm, L × W × H) was used. The soil block was 10 × 30 × 5 cm (L × W × H) in size. The horizontal intervals between the SMBs were 5 cm and PL between SMBs was 5 cm in height.

The structure of MSLs has an important impact on the performance of MSLs in wastewater treatment. MSL systems with thinner and narrower SMB showed a higher removal efficiency for SS, BOD_5, COD and phosphorus because of the improved contact between wastewater and SMB (Chen et al., 2007). An increase in the top surface area of SMBs could affect the efficiency of MSL systems more than an increase in side surface area. The effective height of MSL systems varies between 50 and 120 cm. Adequate SMB layers are required for the removal of COD and BOD (Sato et al., 2011b). The effect of structural differences on the performance of MSL systems was more obvious at a low HLR (Chen et al., 2007). Vertical flow patterns in MSL systems have been used in most of the previous studies. It was reported that horizontal flow could be used in MSL systems, which is similar with the horizontal SF constructed wetlands. Zhang et al. (2015b) developed a two-stage hybrid system, consisting of a vertical flow trickling filter (VFTF) and a horizontal flow multi-soil-layering (HFMSL) bioreactor. VFTF (32 × 16 × 60 cm, L × W × H) was packed with gravel and zeolite. HFMSL (120 × 16 × 32 cm, L × W × H) was designed in horizontal configurations including inlet pool, outlet pool and MSL bioreactor. The MSL bioreactor included SMB layers surrounded by PLs in a horizontal brick-like pattern.

3.2. Material Design for MSLs

In general, the SMB consists of soil mixed with 5 - 40% of other materials such as charcoal, sawdust, iron, etc. Song et al. (2015) added sludge which was collected from sewage treatment plants to SMBs to improve the microbial activity of MSL system. It was found that the MSL system with 20% sludge showed significantly improved ammonium removal efficiency. Latrach et al. (2015) applied local materials to build an MSL system to treat rural wastewater in Morocco. The SMBs were composed of local sandy soil mixed with sawdust, metal iron and charcoal at a ratio of 7:1:1:1, and the PLs were filled by gravel. The sawdust was derived from some species of Moroccan trees such as *Quercus* sp. and *Fraxinus* sp., and the charcoal was made from *Eucalyptus* sp. trees.

Modification of the SMB composition based on the wastewater quality and treatment target can help to control and optimize the treatment efficiency of MSL systems. Luanmanee et al. (2002c) constructed five MSL systems to evaluate the effects of different organic materials on wastewater treatment efficiencies. The organic materials were mixed with sandy clay soil and iron scraps at a ratio of 1:6:1 based on dry weight. The rice straw, kenaf and corncob were found to be more appropriate than Thai sawdust and Japanese sawdust, which could result in compaction and subsequent clogging due to their fine particle size and low biodegradability. Masunaga et al. (2003b) used the SMBs composed of soil (Andisol or Entisol), saw dust, granular iron and charcoal at weight ratios of 67.5 (78.3), 11.25 (7.5), 11.25 (7.5), and 10 (6.7)%, respectively. The results indicated that Entisol was more efficient for TN and TP removal than Andisol. Entisol might contribute more effective contact of inlet water with various components in the MSL system. In later research, the SMBs were composed of Andisol, sawdust, and granular metal iron at a volume ratio of 75, 12.5 and 12.5%, respectively. The SMBs were covered with a 2 cm thick layer of powdered charcoal. In this way, the mean pollutant removal rate increased in comparison with the tests with Andisol alone (Masunaga et al., 2007a; Masunaga et al., 2007b).

Besides the material selection, the mixing ratio of materials is also an important factor for MSL design. The ratio can be adjusted based on the characteristics of soil and wastewater to optimize treatment efficiency. Guan et al. (2012) constructed a modified MSL system to treat leachate from rural unsanitary landfills in southern China. Their preliminary test proved that the MSL system suffered severely from the oxygen deficiency and its performance deteriorated rapidly, in absence of aeration. Therefore, they modified the bulk density of SMB to 0.56 g/cm^3, using soil, saw dust, iron and charcoal in ratios of 50, 30, 10, and 10% on a dry weight basis, respectively. Better oxygen diffusion was obtained in the modified SMB and there was an enhanced NH_4-N removal capacity. Sato et al. (2005a, b) built an MSL system in which the mixing ration of Andisol, saw dust, granular iron, and charcoal was 71.6:10.5:11.9:6.0. The COD removal rate reached 90% in the last layer of the system. Later, Sato et al. (2011a, b) developed another MSL system when the dry weight ratio of soil, saw dust, granular iron and charcoal were changed into 70, 10, 10, and 10% in SMB. Although the COD removal rate could not reach 90%, the BOD removal rate may exceed 80% in an MSL system.

In most previous studies, zeolite was selected to fill the PLs in MSL systems. To investigate the treatment efficiency of other possible PL materials, Pattnaik et al. (2008) applied Perlite and Leilehua soil in PLs instead of zeolite to remediate dairy effluent in the Hawaiian Islands. Both materials were used separately for forming aerobic layers in the MSL system. The results revealed that the removal rates of inorganic N were similar in the Leilehua and Perlite MSL systems. However, the phosphate removal was higher in the Leilehua MSL system (64 - 99%) compared to the Perlite MSL system (9 - 97%). Ho and Wang (2015) studied three other materials in MSL systems which were comparatively cheaper and more environmentally friendly than zeolite, including expanded clay aggregates, oyster shells, and already-used granular activated carbon collected from water purification plants. All three substituted materials achieved favorable removal efficiencies at low HLR. The SS removal efficiencies of the materials decreased in an order of granular activated carbon > zeolite = expended clay aggregates > oyster shells. MSL systems using zeolite and granular activated carbon showed higher NH_3-N removal efficiency. There was no significant difference of TP removal efficiencies in systems using these materials. The structure and materials of the MSL system in previous studies are summarized in Table 3.

4. Operation of MSL System

4.1. Hydraulic Loading

Hydraulic loading is one of the most important parameters in the design and operation of MSL systems. The performance of MSLs under varying HLR was studied by Guan (2012). The HLRs in this experiment were set to 200, 400, 800, and 1600 $L/(m^2d)$, with corresponding nominal HRTs of, 63.8, 31.8, 15.9 and 7.8 h. It was found that the removal efficiency of MSLs was lower with a higher HLRs. Similar findings were also confirmed by Ho and Wang (2015), where different materials for permeable Layers was tested with the HLRs ranging from 0.5 to 3 $t/(m^2d)$. It was found that the removal of SS and COD were significantly affected by the HLR, while TP removal was not as sensitive. Masunaga (2007a) investigated the performance of MSL systems under various HLRs of 500-2000 $L/(m^2d)$. The removals of TN and SS were not appreciably influenced by changes in the HLR. The removals of COD and TP tended to be higher at lower HLRs. An increase in the HLR probably reduced the contact time in the MSL systems, which resulted in the decrease in the removal percentage. However, the removal rates of BOD, COD, nitrogen and phosphorus were higher at the higher HLR.

The gaseous emissions during MSL treatments under various HLRs were studied by Masunaga et al. (2007b). It was found that the flux of CO_2 was not appreciably different when the HLR differed widely. Methane was consumed in the MSL system during most of the study period, and the consumption tended to be more efficient in the treatments at high HLRs. Nitrous oxide emission decreased as the HLRs increased in the wastewater containing a high level of contaminants, while in the case of wastewater containing a low level of contaminants, such decreases in the emissions were not observed. Therefore, it can be speculated that more organic matters were retained in the system as biomass at higher HLR conditions, which could lead to clogging. This was confirmed in the study as at higher HLRs, clogging of the system during the early periods of operation was observed.

Table 3. Structure and Material of MSL Systems

System dimension (L × W × H cm)	Soil block dimension (L × W × H cm)	Horizontal intervals between soil blocks (cm)	Height of PL layer (cm)	Material of PL	Material of SMB	References
50 × 10 × 70	10 × 10 × 4	2.5	4	Zeolite, expanded clay aggregates, oyster shells used granular activated carbon	Sandy clay, powdered activated carbon, rice straws and iron scraps (75, 10, 5 and 10%)	(Ho and Wang, 2015)
30 × 36 × 65	10 × 5 × 30	5	5	Gravel	Sandy soil, charcoal, sawdust and metal iron (70, 10, 10, and 10%)	(Latrach et al., 2015)
32 × 16 × 60	16 × 8 × 16	5	5	Zeolite to iron scraps (5 - 95%)	Clayey soil, sawdust and iron scraps (75, 10 and 15%)	(Luo et al., 2014)
50 × 10 × 75	9 × 10 × 3.6	2.8	4.7	Zeolite	Soil, sawdust, iron, and charcoal (50, 30, 10 and 10%)	(Guan et al., 2012)
50 × 10 × 73	12 × 10 × 5	3.5	5	Zeolite layers (3 - 5 mm)	Andisol, sawdust, granular iron, and charcoal (70, 10, 10 and 10%)	(Sato et al., 2011a)
50 × 10 × 73	12 × 10 × 5	3.5	5	Zeolite	Andisol, sawdust, granular iron, and charcoal in ratios of 70, 10, 10 and 10%	(Sato et al., 2011b)c
45.7 (diameter) × 100	5 × 10 × 22, 5 × 10 × 38	0	5	Leilehua soil and perlite	Honouliuli soil, ground charcoal, fine sawdust, and 1mm diameter iron filings (70, 10, 10 and 10%)	(Pattnaik et al., 2008)
50 × 10 × 120	20 × 10 × 10	5	7	Zeolite (1-3 mm)	Andisol, sawdust and granular metal iron (75, 12.5 and 12.5%)	(Masunaga et al., 2007b)
50 × 10 × 120	20 × 10 × 10	5	7	Zeolite (1-3 mm)	Andisol, sawdust and granular metal iron (75%, 12.5% and 12.5%)	(Masunaga et al., 2007a)
50 × 10 × 73	12 × 10 × 5	5	5	Zeolite (3-5 mm)	Soil (Andisol), saw dust, granular iron and charcoal (71.6, 10.5, 11.9 and 6.0%)	(Sato et al., 2005a)
50 × 10 × 73	12 × 10 × 5	5	5	Zeolite (3-5 mm)	Soil (Andisol), saw dust, granular iron and charcoal (71.6, 10.5, 11.9 and 6.0%)	(Sato et al., 2005b)
50 × 15 × 100	14.5 × 15 × 4.6	3.5	2	Zeolite	Sandy clay soil, kenaf plus corncob and iron scraps (75, 12.5, 12.5%), charcoal cover	(Boonsook et al., 2003)
180 × 80 × 105	70 × 85 × 10	20	10	Zeolite (1 - 3 and 3 - 5 mm)	Soil (Andisol or Entisol), saw dust, granular iron and charcoal (67.5, 11.25, 11.25 and 10%, 78.3, 7.5, 7.5 and 6.7%)	(Masunaga et al., 2003b)
100 × 200 × 150	100 × 60 × 8	5	5	Zeolite	Clayey soil, sawdust and iron scraps (75, 10 and 15%), 2 cm charcoal cover	(Luanmanee et al., 2002b)
15 × 50 × 100	14.5 × 15 × 4.6		2	Zeolite	Sawdust, sandy clay soil and iron scraps (12.5, 75 and 12.5%), 1.6 cm charcoal cover	(Luanmanee et al., 2002c)
350 × 250 × 120	60 × 10 × 175	10	5	Zeolite	Sandy clay soil, iron, pelletized jute, forest floor litter (60, 15, 10, and 15)	(Sato et al., 2002)
100 × 200 × 150	100 × 60 × 8	5	5	Zeolite	Soil mixed, sawdust, iron scraps (75, 10 and 15%), 2-3 cm charcoal cover	(Attanandana et al., 2000)

The flow patterns in the MSL as affected by the HLR were also investigated. Guan et al. (2014) investigated the flow patterns by the residence time distribution (RTD) method using pulse tracer. The extent of back-mixing extent in MSL systems was moderate dispersion under HLRs from 200 to 1600 L/(m^2d). Meanwhile, dead zones were significantly negative correlated with residence time. As well, the dead zone ratio of the MSL system were 41.0, 52.3, 59.6 and 38.8% under HLR 200, 400, 800 and 1600 L/(m^2d), respectively. Sato et al. (2005b) investigated characteristics of water movement in MSL system. Wastewater preferred to flow into the PLs while the HLR increased from 1000 to 5500 L/(m^2d), which dcreased the contact opportunities of the wastewater with the SMBs.

The hydraulic loading is considered as a contributing factor for the clogging of the MSL. Masunaga et al. (Masunaga et al., 2003b) showed that there was no clogging with hydraulic loading rates lower than 2000 L/(m^2d), but they caused clogging within 5 months after the loading rate was increased to 4000 L/(m^2d). According to Guan (2012), two MSLs with higher HLR (800 and 1600 L/(m^2d)) were found to be clogged after operating 48 days among four MSL reactors. Contrarily, the other two MSLs were not clogged under lower HLR, 200 and 400 L/(m^2d). This phenomenon was attributed to the imbalance between the input and output of organic matter. Therefore, the COD loading should be a more direct factor than hydraulic loading. It can also be speculated that with the same COD loading, the MSL with higher HLR is less likely to be clogged because of higher hydraulic disturbance (Ho and Wang, 2015).

4.2. Operation Cycles and Feeding Mode

Clogging of MSL systems has been a major problem that results in total system failure (Guan et al., 2015). It was suggested that clogging can be avoided by operation planning such as using two sets of operating systems or settling the rest period of the system during the season in which water is less polluted (Masunaga et al., 2003b). To reduce the risk of clogging, providing a periodic resting time in a system operation cycle and reduction of SS discharge into the system by pre-treatment of wastewaters could be recommended for the use of the MSL system. Net removal rates in operational cycles of 7-month working and 2-month rest for the L-2000 treatment and of 4-month work and 2-month rest cycle for the H-2000 treatment were the highest among the treatments (Masunaga et al., 2007a). The effect of water spraying frequency in a two-stage MSL system was studied (Zhang et al., 2015b). The frequency was set at 16 s/60 min, 8 s/30 min, 4 s/15 min. As the result, higher water spraying frequency benefited the removal of COD and TN.

4.3. Aeration

The performance of MSL systems can be influenced by the aerobic and anaerobic conditions. The purification capacity of MSL system can be maintained by adopting adequate aeration, even after 10 years of operation (Sato et al., 2002). Aeration at optimal intensity and duration can significantly enhance the removal of BOD_5, COD, TN and TP. As shown in Figure 3, aeration pipes can be set inside the MSL to control the aerobic and anaerobic states of the system by injections of air from outside the system (Sato et al., 2002; Masunaga et al., 2003b; Guan et al., 2015). Since BOD_5 represents easily decomposable organic matter, aeration can immediately increase its removal efficiency in an MSL system. COD includes more slowly decomposable organic matter, bordering on recalcitrant materials, so its removal requires more intensive aeration compared with BOD_5 removal. In the MSL system, TN is removed through nitrification and denitrification processes, and excessive aeration has an adverse effect on TN removal by hindering the denitrification processes. When nitrification occurs, hydrogen ions are released, thus the pH may decrease. In contrast, denitrification produces hydroxyl ions, and subsequently a higher pH is induced in MSL systems (Luanmanee et al., 2002c; Boonsook et al., 2003). Therefore, the rate and duration of aeration need to be adjusted depending on the quality of the wastewater and the components and structure of a given MSL system (Luanmanee et al., 2002c; Chen et al., 2009).

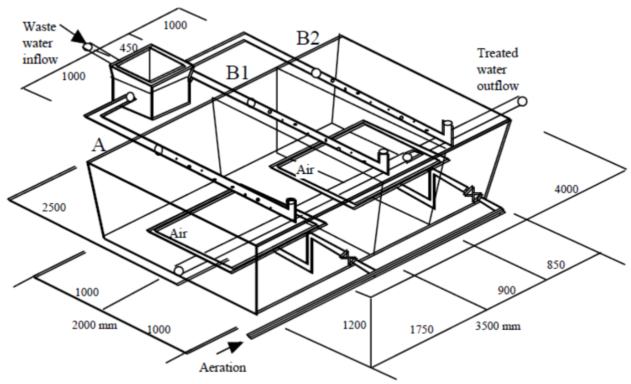

Figure 3. Typical setup of aeration pipes in MSL system (Sato et al., 2002).

Chen et al. (2007a) applied the MSL system to remove colored substances and COD from livestock wastewater and investigated the impacts of aeration on treatment efficiency. It was found that the different positions of aeration pipes did not have any significant influence on the removal efficiency. However, an increase in aeration intensity from 1000 to 2000 L/min per system increased decolourization rates by 3.0-12.1%. For COD removal, an increase in aeration intensity enhanced the removal rates by 23.0 - 43.3%. The decolouriza- tion and COD removal efficiencies of livestock wastewater reached 60.7 - 67.1% and 48.8 - 58.0%, respectively. Without aeration, the removal efficiencies of BOD_5, COD, TN and TP for cafeteria wastewater were only 48, 58, 83 and 53%, respectively (Attanandana, 1997). With continuous aeration supply for a month, the corresponding pollutants removal efficiencies increased substantially to 90, 70, 91 and 90% (Luanmanee et al., 2002c). Nevertheless, excessive aeration may negatively affect the normal metabolism of microorganisms. Excessive aeration may cause strong nitrification processes in an MSL system, and then inhibit the denitrification process as a result of the absence of reducing conditions following nitrification (Luanmanee et al., 2002c; Guan et al., 2012). Luanmanee et al. (2001) operated an MSL system for 10 years without aeration, the removals of

Table 4. Performance of MSL Systems under Various Hydraulic Loading and Aeration Conditions

HLR (L/m²d)	Aeration	COD (mg/L) (Removal %)	BOD (mg/L) (Removal %)	TN (mg/L) (Removal %)	TP (mg/L) (Removal %)	SS (mg/L) (Removal %)	Clogging	Reference
660	No	417.47 ± 89.01 (92.5)	-	49.02 ± 7.74 (89.5)	4.22 ± 0.82 (91.0)	-	No	(Zhang et al., 2015b)
660	No	255.20 ± 65.12 (92.3)	-	49.31 ± 9.91 (89.4)	3.91 ± 0.41 (92.1)	-	No	
660	No	98.68 ± 35.22 (81.8)	-	49.58 ± 7.23 (73.6)	3.93 ± 0.31 (91.9)	-	No	
200	No	641 ± 12 (81)	201 ± 3 (86)	100.5 ± 1.5 (78)	3.6 ± 0.07 (80)	164 ± 3 (93)	No	(Latrach et al., 2015)
500	No	170.7 - 203.2 (54.6 - 76.9)	-	NH_3-N: 24.6 - 27.5 (77.9 - 99.7)	7.9 - 10.7 (97.8 - 99.1)	11.28 - 16.77 (63.2 - 94.5)	-	(Ho and Wang, 2015)
1000	No	(33.9 - 65.2)	-	(53.8 - 99.7)	(94.4 - 98.3)	(54.9 - 90.3)	-	
2000	No	(22.9 - 49.4)	-	(41.3 - 98.6)	(90.5 - 96.3)	(33.5 - 88.9)	-	
3000	No	(26.8 - 42.7)	-	(24.8 - 93.4)	(91.4 - 93.3)	(32.4 - 74.2)	-	
240	No	265 ± 17 (92.8)	-	60.0 ± 3.59 (63.5)	5.32 ± 0.46 (58.6)	-	No	(Luo et al., 2014)
440	No	210 ± 15 (79.0)	-	57.7 ± 3.69 (52.3)	4.61 ± 0.66 (47.3)	-	No	
200	No	218.4 ± 133.8 (72.0 ± 20.3)	-	73.7 ± 14.3 (66.5 ± 33.1)	1.1 ± 1.3 (84.1 ± 17.6)	-	No	(Guan et al., 2012)
400	No	(62.0 ± 18.4)	-	(44.0 ± 34.2)	(54.9 ± 40.8)	-	No	
800	Occasional	(45.3 ± 15.7)	-	(29.0 ± 39.5)	(33.9 ± 39.6)	-	Yes	
1600	Occasional	(35.3 ± 17.9)	-	(25.5 ± 29.8)	(26.1 ± 37.5)	-	Yes	
1000	No	65.7 (87.7)	28.1 (98.0)	9.8 (73.5)	1 (94.1)	14.9	Yes	(Sato et al., 2011b)
500	No	43.9 ± 21.5 (89)	32.1 ± 20.9 (94)	6.3 ± 1.7 (44)	0.76 ± 0.30 (73)	27.8 ± 21.9 (93)	No	(Masunaga et al., 2007a)
1000	No	(84)	(94)	(48)	(69)	(90)	No	
1250	No	(83)	(94)	(51)	(69)	(91)	No	
1500	No	(86)	(95)	(47)	(66)	(92)	No	
2000	No	(85)	(91)	(56)	(63)	(94)	Yes	
500	No	121.6 ± 96.7 (94)	69.5 ± 52.7 (98)	9.6 ± 2.7 (45)	1.47 ± 1.16 (89)	78.3 ± 75.3 (95)	No	
1000	No	(92)	(94)	(54)	(85)	(96)	No	
1250	No	(91)	(95)	(56)	(74)	(93)	Yes	
1500	No	(90)	(94)	(48)	(71)	(92)	Yes	
2000	No	(87)	(88)	(57)	(65)	(91)	Yes	
1000 - 3000	-	51.3 - 65 (60.2 - 87.0)	29.1 - 38.5 (75.7 - 92.6)	8.7 - 11.4 (34.0 - 62.7)	0.99 - 1.44 (50.6 - 61.7)	70.7 - 73.3 (81.7 - 97.2)	-	(Chen et al., 2007)
1000 - 4000	No	26 (63 - 85)	11 (72 - 84)	5.4 (22 - 39)	0.22 (52 - 67)	29 (72 - 84)	At 4000 HLR	(Masunaga et al., 2003b)
96 - 346	No	304 ± 150 (79.0 - 98.1)	55.6 ± 44.8 (80.0 - 99.6)	60.1 ± 28.8 (79.0 - 92.1)	8.6 ± 0.7 (97.1 - 100)	-	Partial	(Boonsook et al., 2003)
130 - 210	Yes	148 (95)	106 (90)	65 (62)	9.6 (91)		Partial	(Sato et al., 2002)
96 - 346	64000 $Lm^{-3}d^{-1}$, 7 in 21 d	-	575 ± 191 (88.0 - 99.8)	52.0 ± 9.1 to 60.1 ± 28.8 (75.2 - 95.1)	6.3 ± 2.3 to 8.6 ± 0.7 (92.5 - 100)	575 ± 191 (88.0 - 99.8)	At higher HLR	(Luanmanee et al., 2002c)
100 - 600	4000 $Lm^{-3}d^{-1}$, 7 in 21 d	287 ± 58 (53.2)	88 ± 31.8 (87.4)	43.5 ± 7.88 (-26.7)	9.13 ± 0.89 (80.3)	-	-	(Luanmanee et al., 2002c)
	20000 $Lm^{-3}d^{-1}$, 3 in 60 d	(73.30)	(92.20)	(15)	(74.70)	-	-	
	No	(27)	(82.10)	(65.30)	(83.00)	-	-	
850	No	326.7 ± 131.1 (57.6)	298.3 ± 260.8 (48.2)	280.0 ± 53.8 (68.1)	30.2 ± 0.96 (51.9)	86.3 ± 38.7 (53.0)	326.7 ± 131.1 (57.6)	(Attanandana et al., 2000)
850	When necessary	212.7 ± 36.7 (69.9)	228.3 ± 126.0 (90.3)	372.3 ± 57.1 (90.8)	39.6 ± 10.1 (90.1)	101.7 ± 22.4 (71.2)	212.7 ± 36.7 (69.9)	
850	Periodical	86.1 ± 51.3 (47.9)	153.3 ± 162.0 (52.6)	63.5 ± 20.4 (44.2)	4.9 ± 1.5 (30.5)	34.8 ± 35.1 (21.9)	86.1 ± 51.3 (47.9)	

BOD_5, TN and TP were 95.0, 54.0 and 82.9%, respectively; but under continuous air supply for 24 h, the removal of TN dropped 23 % while that of BOD_5 and TP increased slightly, and the TN removal recovered to 73%, following cessation of the air injection. Pattnaik et al. (2008) also developed two MSL systems with aeration systems to remediate dairy effluent. However, the supplemental aeration, which was applied in the second phase of the study, did not significantly improve the removal of inorganic N, but the removal of TP increased with additional aeration.

To balance the removal rates of BOD, COD, TN and TP in the MSL system, researchers have tried intermittent aeration. MSL systems was operated using intermittent aeration in a previous study (Luanmanee et al., 2002b). The results showed that a pH between 6.5 and 7.0 was suitable to maintain the efficiency of the MSL system in treating municipal wastewater. The changes in the pH of the treated water could be used to control aeration at an appropriate rate and duration (Luanmanee et al., 2002b; Luanmanee et al., 2002c; Chen et al., 2009). It was also found that the aeration at a rate of 20000 L/(m^3d) for 3 days alternated with 2 months of non-aeration was the appropriate operation approach for the operation (Luanmanee et al., 2002b). The results from additional research in southern China also proved that intermittent aeration was helpful to remove the clogging of the MSL system (Guan et al., 2012). The operation modes of MSL systems in previous studies are summarized in Table 4.

5. Cost and Space Requirement

Although information regarding the cost of MSL systems is very limited, a qualitative comparison between wastewater treatment alternatives for small communities is presented in Table 5. This comparison was based on available literature and the authors' previous successful projects. Conventional activated sludge based processes are considered as reliable and efficient in wastewater treatment, the cost-effectiveness becomes lower for small scale applications. In contrast, constructed wetlands, MSLs and lagoons offer low-tech options at the cost of land requirement and reliability. Compared with constructed wetlands and lagoons, MSL systems feature lower land requirement due to its tolerance for high organic loading and minimal negative aesthetical impacts. Moreover, MSL systems are often composed of local materials. Many studies have focused on the alternative materials for PLs and SMB (section 3.2). Therefore, the cost can be significantly reduced upon successful utilization of local resources. Environmental optimization is important for system design and operation (Cai et al., 2008; Huang and Cao, 2011). To optimize the operating costs, the periodic aeration is more suitable than continuous aeration. Chen et al. (2009) estimated the cost of MSL of 100 m^3/d at an HLR of 1000 L/(m^2d) in China. The cost for constructing such an MSL system can be less than US$10000 in China. 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 is rich in nutrients such as NH_4^+, P, Fe and Ca.

6. Challenges in Field Applications

MSL systems have been used in some previous field applications. In Matsue City of Japan, an MSL treatment system was operated to treat domestic wastewater from 1990 to 2000 (Luanmanee et al., 2001; Luanmanee et al., 2002a). The removal rates of BOD_5 and TP were higher than 80-90% and the removal rates for TN decreased to 50-70% after 3 years of operation. In Oki Island, Shimane prefecture, Japan, the MSL systems were constructed for direct treatment of polluted water from Uya River. About 1400 households were located along the river and water flow was 600 m^3/day on average. The removal rates of BOD_5, TN and TP were 72.2 - 83.5%, 22.4 - 50.0% and 51.9 - 66.8%, respectively (Masunaga et al., 2003a). At Kasetsart University of Thailand, the MSL system was built to treat toilet wastewater from catering outlets (Attanandana et al., 2000). The removal rates of SS, BOD_5, COD, TN, NH_4-N, total P and dissolved P were 53, 48, 58, 68, 53, 52 and 64%, respectively. When aeration was applied, the removal rates of SS, BOD_5, COD, TN, NH_4-N, total P and dissolved P could be further increased to 71, 90, 70, 91, 76, 90 and 89%, respectively.

Use of MSL for the wastewater treatment in small communities must be carefully designed so as to maximize the pollutant removal, while minimizing cost and the negative effects to the surrounding environment. Although extensive research has been done on the structure and function of these systems for treatment of various wastewaters, comprehensive guidelines and recommendations are not available and there are still many challenges for field applications.

Table 5. Comparison of Requirements for Some Treatment Techniques

Techniques	Initial investment	Land requirement	Energy & material cost	Operational labor	Reliability	Aesthetics
MBR	High	Low	High	Technician	High	Noise
Constructed wetland	Intermedia	High	Low	Informed owner	Intermedia	Odor and insects
MSL	Intermedia	Intermedia	Low	Informed owner	Intermedia	Minimal
Lagoon	Low	High	Minimal	Minimal	Low	Odor and insects

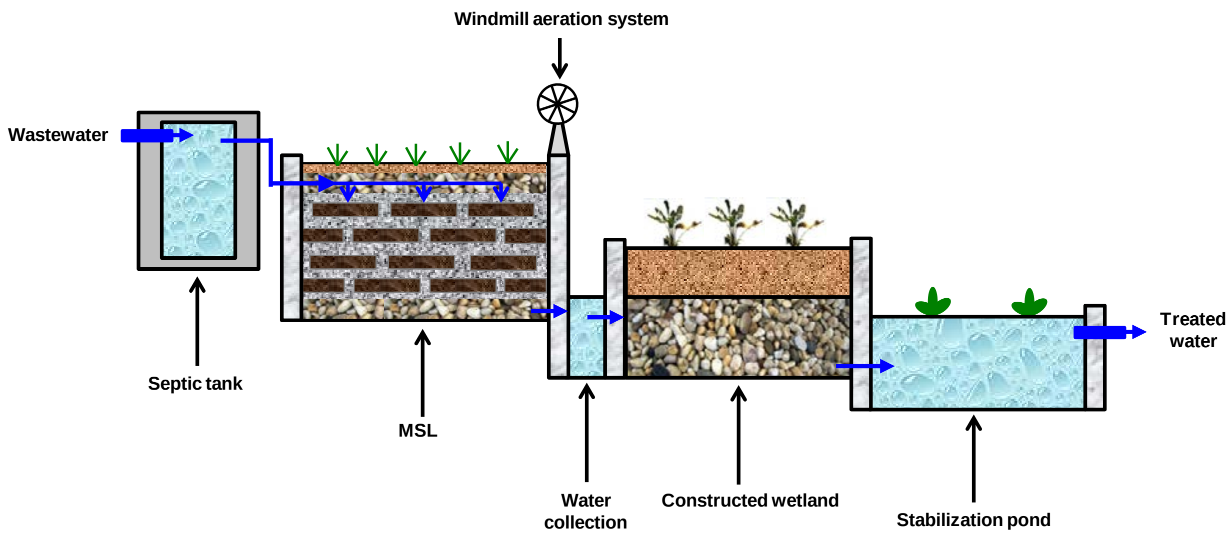

Figure 4. The schematic configuration of an integrated MSL treatment system (Huang et al., 2015).

(i) Availability of field application data

In the planning stage of MSL system design, quantitative evaluation is required in order to determine the system configuration and dimension. A target for treated water quality needs to be set against wastewater conditions such as contaminant concentrations. Although some studies of MSLs have been conducted, MSL systems reported in previous studies exhibited variability in the level of contaminant removal. That could be attributed to different structures, SMB and PL materials, and operation modes for these systems. For instance, soil can play an important role in the MSL system. But the soil texture and microorganisms may be different from case to case, resulting in different performance in pollutant removal. Some literature-derived results may not be directly transferable to engineering applications. Therefore, the engineering design of a new MSL system has to be more than simply applying identical results of HLR and other parameters from previous studies. For the field application, it is still required to build lab-scale MSL systems using the same components and conditions as those in on-site construction. In order to optimize the system performance, some techniques such as RTD can also help to predict the velocity distribution of liquids and hydraulic performance (short circuiting and dead zones) of MSL (Guan et al., 2014).

(ii) Combination with other treatment approaches

When designing MSL systems for wastewater treatment in small communities, both the treatment efficiency and socio-economic impacts based on the different treatment targets and site conditions need to be considered. For example, wastewater reuse is an important strategy for conserving water resources, particularly in areas suffering from water shortages. When treated water needs to be recycled in applications, some pre- or post-treatment methods can be used in order to improve the quality of the water. In some cases, therefore, it would not be recommended to implement MSL system as the sole practice in field application. Various types of treatment systems may represent combined MSL systems to achieve treatment targets. In hybrid processes, the advantages of various systems can be combined to complement each other. However, there is limited information on the development of MSL-related integrated treatment systems. In future, increasing attention can be paid to developing suitable combinations of different treatment technologies. For example, wastewater from tourist sites with many restaurants can be characterized by high-level of oils. Once entering the MSL system, this may cause serious problems such as the choking of water distribution pipes, and offensive smells due to putrefaction. To solve the problem, an effective system for removal of oil together with organic matter, can be applied prior to MSL system. In addition, the combination is also dependent upon some targets other than treatment performance. From the perspective of landscape design, the constructed wetland and aeration ponds with various land and aquatic vegetation can be used with MSLs to improve the visible attributes of treatment process. A better understanding of the complex interactions among different treatment processes can help to optimally combine the basic scientific aspects of available technical alternatives, enabling MSL technologies to be used on a broader scale. The value of land converted into MSL and other treatment systems can be examined, while weighing potentially ecological and economic benefits.

(iii) Requirement for power supply

Another problem to address is related to the power required in MSL systems. In order to achieve better treatment performance, aeration is required to provide oxygen to aerobic reactions within an MSL. However, the operation and maintenance of aeration equipment necessitates skilled labor, which is a critical obstacle in rural regions. Additionally, the electrical costs for aeration can also be a burden for the local residents. One energy-saving strategy would be the use of green power. Among various green power technologies, wind and solar power are the most promising approaches for MSL processes. Huang et al. (2015) reported the installation of a windmill aeration system in an integrated ecological system for the treatment of domestic sewage. The added aeration could increase the level of oxygen in an MSL system and improve the efficiency of wastewater treatment. The different sectors within the integrated system were built on a slope and gravity-driven flows could pass through these sectors without the requirement for addition power. The schematic configuration of this hybrid system is shown in Figure 4.

(iv) Performance at low temperatures

Temperature and seasonal conditions are the important components of local climate and weather (Huang et al., 1996; Rahmani and Zarghami, 2015). They may affect many biological activities within the MSL treatment system. MSL has an advantage in cold regions because treatment mainly occurs below the ground surface where biological activities are insulated somewhat from the frigid air. Although soil microbes in winter still have the capacity to decompose organic contaminants, the microorganisms are usually not as effective for pollutant removal at low temperatures as that at high temperatures. The performances of most types of MSL systems are not veryfied in winter. Winter performance of MSL can be achieved by effectively applying some approaches in design. When the outside temperature is comparably lower, bed insulation and higher influent wastewater temperature can make MSLs less susceptible to the influence of low temperatures. However, it should be also noted that pollutant removal in MSL can entail biological, physical and chemical mechanisms. Some removal processes could be enhanced as temperature decreases (e.g. the solubility of some organic compounds can decrease and assume a colloidal state, which are favorable for removal by filtration).

(v) Removal of emerging contaminants

Domestic wastewaters contain many organic compounds. Previous studies have mainly focused on the removal of conventional "priority" pollutants. Recently, there have been increasing concerns for emerging contaminants. For example, pharmaceutical and personal care products (PPCPs) constitute a large and diverse group of organic compounds which are discharged directly into the sewerage systems. The risks of PPCPs such as hormones, nonsteroidal anti-inflammatory drugs, lipid regulators, β-blockers, and psychiatric drugs to human health have been reported (Ellis, 2006). For wastewater treatment in MSLs, the removal of emerging pollutants has not yet investigated. It is still necessary to obtain more quantitative data and analyses for the removal of such pollutants in MSLs. Understanding the basic mechanisms and processes controlling the removal of emerging pollutants can increase the probability of success of MSL application.

7. Conclusions

MSL systems have been used to treat wastewaters from a variety of sources. MSL systems need little energy, have low operational cost and requires small land areas. MSLs represent a suitable solution for treatment of wastewater in small and remote communities. A good design of MSL before being built, is of paramount importance for the successful application of MSL techniques. The design should take into account the pollutant characteristics, loading rates, hydrological and climatelogical conditions, and the management needed for operation of MSLs. Although some field applications of MSL have been conducted, most of the previous studies have been based on lab-scale MSL systems. Only a few studies assessing the effects of long-time operation on the performance of MSL system have been investigated in this regard. Some challenges related to field applications of MSL systems must be taken into consideration. MSL depends on the interaction of many different components. A number of fundamental aspects of exactly how MSL systems function are not yet adequately understood. A better understanding of the entire mechanism can provide valuable insight into the overall MSL function and structure. Increasing knowledge about process optimization, temperature effects and removal of emerging pollutants should be a goal of ongoing and future research in this field. It is expected that guidelines for the design and operation of MSL system depending on the wastewater characteristics, treatment target and site conditions can be generated in the near future.

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Abbreviations

BOD	Biochemical oxygen demand
CEC	Cation exchange capacity
COD	Chemical oxygen demand
FWS	Free water surface
HFMSL	Horizontal flow multi-soil-layering
HLR	Hydraulic loading rate
HRT	Hydraulic retention time
MSL	Multi-soil-layering
PLs	Permeable layers
RTD	Residence time distribution
SMBs	Soil mixture blocks
SS	Suspended solids
SF	Subsurface flow
TN	Total nitrogen
TP	Total phosphorus
VFTF	Vertical flow trickling filter

References

Akratos, C.S. and Tsihrintzis, V.A. (2007). Effect of temperature, HRT, vegetation and porous media on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands. *Ecol. Eng.,* 29(2), 173-191. http://dx.doi.org/10.1016/j.ecoleng. 2006.06.013

Amy, G. and Drewes, J. (2007). Soil aquifer treatment (SAT) as a natural and sustainable wastewater reclamation/reuse technology: fate of wastewater effluent organic matter (EfOM) and trace organic compounds. *Environ. Monit. Assess.,* 129(1-3), 19-26. http://dx.doi.org/10.1007/s10661-006-9421-4

Attanandana, T., Luanmani, S., Saitthiti, B., and Thongpae, S. (1997). Treatment of wastewater from cafeteria by multi-soil layering system. *Thai J. Soils Fertilizers,* 19(1), 28-41. http:// aims. fao.org/serials/c_48080886

Attanandana, T., Saitthiti, B., Thongpae, S., Kritapirom, S., Luanmanee, S., and Wakatsuki, T. (2000). Multi-media-layering system for food service wastewater treatment. *Ecol. Eng.,* 15(1-2), 133-138. http://dx.doi.org/10.1016/S0925-8574(99) 00041-5

Boluwade, A. and Madramootoo, C. (2015). Determining the influence of land use change and soil heterogeneities on discharge, sediment and phosphorus. *J. Environ. Inf.,* 25(2), 126-135. http://dx.doi.org/ 10.3808/jei.201500290

Boonsook, P., Luanmanee, S., Attanandana, T., Kamidouzono, A., Masunaga, T., and Wakatsuki, T. (2003). A comparative study of permeable layer materials and aeration regime on efficiency of multi-soil-layering system for domestic wastewater treatment in Thailand. *Soil Sci. Plant Nutr.,* 49(6), 873-882. http:// dx.doi. org/10.1080/00380768.2003.10410350

Brennan, R. and McBean, E. (2011a). A performance assessment of arsenic-iron removal plants in the Manikganj District of Bangladesh. *J. Water Health,* 9(2), 317-329. http://dx.doi.org/ 10.2166/wh.2011. 107

Brennan, R. and McBean, E. (2011b). The role of orthophosphate and dissolved oxygen in the performance of arsenic-iron removal plants installed by space in the Manikganj District of Bangladesh. *J. Environ. Sci. Health Part A,* 46, 1-10. http://dx. doi.org/10.1080/ 10934529.2011.549409

Cai, Y.P., Huang, G.H., Yang, Z.F., Lin, Q.G., Bass, B., and Tan, Q. (2008). Development of an optimization model for energy systems planning in the Region of Waterloo. *Int. J. Energy Res.,* 32(11), 988-1005. http://dx.doi.org/10.1002/er.1407

Chen, X., Luo, A.C., Sato, K., Wakatsuki, T., and Masunaga, T. (2009). An introduction of a multi-soil-layering system: a novel green technology for wastewater treatment in rural areas. *Water Environ. J.,* 23(4), 255-262. http://dx.doi.org/10.1111/j.1747-6593.2008. 00143.x

Chen, X., Sato, K., Wakatsuki, T., and Masunaga, T. (2007). 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. *Soil Sci. Plant Nutr.,* 53(2), 206-214. http://dx.doi.org/10.1111/j.1747-0765.2007. 00126.x

Chen, X., Sato, K., Wakatsuki, T., and Masunaga, T. (2007a). Effect of aeration and material composition in soil mixture block on the removal of colored substances and chemical oxygen demand in livestock wastewater using multi-soil-layering systems. *Soil Sci. Plant Nutr.,* 53(4), 509-516. http://dx. doi.org/10.1111/j.1747-0765.2007. 00156.x

Ellis, J.B. (2006). Pharmaceutical and personal care products (PPCPs) in urban receiving waters. *Environ. Pollut.,* 144(1), 184-189. http:// dx.doi.org/10.1016/j.envpol.2005.12.018

Faulkner, S.P. and Richardson, C.J. (1989). Physical and chemical characteristics of freshwater wetland soils. *Constr. Wetlands wastewater treat.,* 41-72.

Garcia, S.N., Clubbs, R.L., Stanley, J.K., Scheffe, B., Yelderman Jr, J.C., and Brooks, B.W. (2013). Comparative analysis of effluent water quality from a municipal treatment plant and two on-site wastewater treatment systems. *Chemosphere,* 92 (1), 38-44. http:// dx.doi.org/10.1016/j.chemosphere.2013.03.0 07

Guan, Y., Chen, X., Zhang, J., and Luo, A. (2012). Performance of multi-soil-layering system (MSL) treating leachate from rural unsanitary landfills. *Sci. Total Environ.,* 420, 183-190. http://dx.doi. org/10.1016/j.scitotenv.2011.12.057

Guan, Y., Xu, D., Chen, X., Luo, A., Fang, H., and Song, Y. (2014). Flow patterns of multi-soil-layering systems. *Desalination Water Treat.,* 52(22-24), 4165-4169. http://dx.doi.org/10.1080/19443994. 2013.801791

Guan, Y., Zhang, Y., Zhong, C., Huang, X., Fu, J., and Zhao, D. (2015). Effect of operating factors on the contaminants removal of a soil filter: multi-soil-layering system. *Environ. Earth Sci.,* 74(3), 2679-2686. http://dx.doi.org/10.1007/s12665-015-4288-8

Ho, C.C. and Wang, P.H. (2015). Efficiency of a multi-soil-layering system on wastewater treatment using environmentfriendly filter materials. *Int. J. Environ. Res. Public Health,* 12(3), 3362-3380. http://dx.doi.org/10.3390/ijerph120303362

Huang, G.H., Cohen, S.J., Yin, Y.Y., and Bass, B. (1996). Incorporation of inexact dynamic optimization with fuzzy relation analysis for integrated climate change impact study. *J. Environ. Manage.,* 48(1), 45-68. http://dx.doi.org/10.1006/je ma.1996.0065

Huang, G.H. and Cao, M.F. (2011). Analysis of solution methods for interval linear programming. *J. Environ. Inf.,* 17(2), 54-64. http:// dx.doi.org/10.3808/jei.201100187

Huang, G.H., An, C.J., Yao, Y., and Zhang, P. (2015). Development of an integrated ecological system for the treatment of rural domestic sewage. Submitted to United Nations Development Programme, Beijing, China.

Latrach, L., Masunaga, T., Ouazzani, N., Hejjaj, A., Mahi, M., and Mandi, L. (2015). Removal of bacterial indicators and pathogens from domestic wastewater by the multi-soil-layering (MSL) system. *Soil Sci. Plant Nutr.,* 61(2), 337-346. http://dx.doi.org/10.1080/ 00380768.2014.974480

Li, X., Zheng, W., and Kelly, W.R. (2013). Occurrence and removal of pharmaceutical and hormone contaminants in rural wastewater treatment lagoons. *Sci. Total Environ.,* 445-446, 22-28. http:// dx.doi.org/10.1016/j.scitotenv.2012.12.035

Li, Z., Huang, G.H., Fan, Y.R., and Xu, J.L. (2015). Hydrologic risk analysis for nonstationary streamflow records under uncertainty. *J. Environ. Inf.,* 26(1), 41-51.

Liang, H., Liu, J., Wei, Y., and Guo, X. (2010). Evaluation of phosphorus removal from wastewater by soils in rural areas in China. *J. Environ. Sci.,* 22(1), 15-22. http://dx.doi.org/10.1016/S1001-0742(09) 60069-3

Luanmanee, S., Attanandana, T., Masunaga, T., and Wakatsuki, T. (2001). The efficiency of a multi-soil-layering system on domestic wastewater treatment during the ninth and tenth years of operation. *Ecol. Eng.,* 18(2), 185-199. http://dx.doi. org/10.1016/S0925-8574 (01)00077-5

Luanmanee, S., Attanandana, T., Masunaga, T., and Wakatsuki, T. (2002a). Treatment of domestic wastewater with a multi-soillayering (MSL) system in a temperate and a tropical climate. *Food and Fertilizer Technology Center*.

Luanmanee, S., Boonsook, P., Attanandana, T., Saitthiti, B., Panichajakul, C., and Wakatsuki, T. (2002b). Effect of intermittent aeration regulation of a multi-soil-layering system on domestic wastewater treatment in Thailand. *Ecol. Eng.,* 18(4), 415-428. http:// dx.doi.org/10.1016/S0925-8574(01)00103-3

Luanmanee, S., Boonsook, P., Attanandana, T., and Wakatsuki, T. (2002c). Effect of organic components and aeration regimes on the efficiency of a multi-soil-layering system for domestic wastewater treatment. *Soil Sci. Plant Nutr.,* 48(2), 125-134. http://dx.doi.org/ 10.1080/00380768.2002.10409182

Luo, W., Yang, C., He, H., Zeng, G., Yan, S., and Cheng, Y. (2014). Novel two-stage vertical flow biofilter system for efficient treatment of decentralized domestic wastewater. *Ecol. Eng.,* 64, 415-423. http://dx.doi.org/10.1016/j.ecoleng.2014.01. 011

Ma, L., He, F., Sun, J., Huang, T., Xu, D., Zhang, Y., and Wu, Z. (2015). Effects of flow speed and circulation interval on water quality and zooplankton in a pond-ditch circulation system. *Environ. Sci. Pollut. Res.,* 22(13), 10166-10178. http://dx.doi. org/10.1007/s11356-015-4195-2

Massoud, M.A., Tarhini, A., and Nasr, J.A. (2009). Decentralized approaches to wastewater treatment and management: Applicability in developing countries. *J. Environ. Manage.,* 90(1), 652-659. http://dx.doi.org/10.1016/j.jenvman.2008.07.001

Masunaga, T., Sato, K., Mori, J., Shirahama, M., Kudo, H., and Wakatsuki, T. (2007a). Characteristics of wastewater treatment using a multi-soil-layering system in relation to wastewater contamination levels and hydraulic loading rates. *Soil Sci. Plant Nutr.,* 53(2), 215-223. http://dx.doi.org/10.1111/j.1747-0765.2007.00128.x

Masunaga, T., Sato, K., Senga, Y., Seike, Y., Inaishi, T., Kudo, H., and Wakatsuki, T. (2007b). Characteristics of CO_2, CH_4 and N_2O emissions from a multi-soil-layering system during wastewater treatment. *Soil Sci. Plant Nutr.,* 53(2), 173-180. http://dx.doi.org/10.1111/ j.1747-0765.2007.00118.x

Masunaga, T., Sato, K., Zennami, T., Fujii, S., and Wakatsuki, T. (2003a). Direct treatment of polluted river water by the multisoil-layering method. *J. Water Environ. Technol.,* 1(1), 97-104. http://doi.org/10.2965/jwet.2003.97

Masunaga, T., Sato, K., Zennami, T., Fujii, S., and Wakatsuki, T. (2003b). Direct treatment of polluted river water by the multisoil-layering method. *J. Water Environ. Technol.,* 1(1), 97-104. http://dx.doi.org/10.2965/jwet.2003.97

Matamoros, V. and Bayona, J.M. (2013). Removal of pharmaceutical compounds from wastewater and surface water by natural treatments. *Analysis, Removal, Effects and Risk of Pharmaceuticals in the Water Cycle: Occurrence and Transformation in the Environment,* 62, 409.

Molinos-Senante, M., Garrido-Baserba, M., Reif, R., Hernández Sancho, F., and Poch, M. (2012). Assessment of wastewater treatment plant design for small communities: Environmental and economic aspects. *Sci. Total Environ.,* 427-428, 11-18. http://dx.doi.org/10.1016/j.scitotenv.2012.04.023

Motiee, H., McBean, E., Semsar, A., Gharabaghi, B., and Ghomashchi, V. (2006). Assessment of the contributions of tradetional qanats in sustainable water resources management. *Int. J. Water Resour. Dev.,* 22(4), 575-588. http://dx.doi.org/10. 1080/07900620600551304

Moussavi, G., Kazembeigi, F., and Farzadkia, M. (2010). Performance of a pilot scale up-flow septic tank for on-site decentralized treatment of residential wastewater. *Process Saf. Environ. Prot.,* 88(1), 47-52. http://dx.doi.org/10.1016/j.psep. 200 d9.10.001

Pattnaik, R., Yost, R.S., Porter, G., Masunaga, T., and Attanandana, T. (2008). Improving multi-soil-layer (MSL) system remediation of dairy effluent. *Ecol. Eng.,* 32(1), 1-10. http://dx.doi.org/10.1016/j.ecoleng.2007.08.006

Rahmani, M.A. and Zarghami, M. (2015). The Use of Statistical Weather Generator, Hybrid Data Driven and System Dynamics Models for Water Resources Management under Climate Change. *J. Environ. Inf.,* 25(1), 23-35. http://dx.doi.org/10.3808/jei.201400285

Sabry, T. (2010). Evaluation of decentralized treatment of sewage employing Upflow Septic Tank/Baffled Reactor (USBR) in developing countries. *J. Hazard. Mater.,* 174(1-3), 500-505. http://dx.doi.org/10.1016/j.jhazmat.2009.09.080

Sato, K., Iha, Y., Luanmanee, S., Masunaga, T., and Wakatsuki, T. (2002). Long term on-site experiments and mass balances in waste water treatment by multi-soil-layering system. *Proc. of the 17th World Congress of Soil Science,* Symposium, Citeseer, pp. 14-21.

Sato, K., Iwashima, N., Matsumoto, T., Wakatsuki, T., and Masunaga, T. (2010). Wastewater treatment processes and mechanisms of organic matter, phosphorus, and nitrogen removal in a multi-soil-layering system. *Proceedings of the 19th World Congress of Soil Science: Soil solutions for a changing world,* Brisbane, Australia, 1-6 August 2010. Working Group 3.3 Soils in urban and industrial areas. International Union of Soil Sciences (IUSS), c/o Institut für Bodenforschung, Universität für Bodenkultur, pp. 85-88.

Sato, K., Iwashima, N., Wakatsuki, T., and Masunaga, T. (2011a). Clarification of water movement properties in a multi-soil-layering system. *Soil Sci. Plant Nutr.,* 57(4), 607-618. http://dx.doi.org/10.1080/00380768.2011.594966

Sato, K., Iwashima, N., Wakatsuki, T., and Masunaga, T. (2011b). Quantitative evaluation of treatment processes and mechanisms of organic matter, phosphorus, and nitrogen removal in a multi-soil-layering system. *Soil Sci. Plant Nutr.,* 57(3), 475-486. http://dx.doi.org/10.1080/00380768.2011.590944

Sato, K., Masunaga, T., and Wakatsuki, T. (2005a). Characterization of treatment processes and mechanisms of COD, phosphorus and nitrogen removal in a multi-soil-layering system. *Soil Sci. Plant Nutr.,* 51(2), 213-221. http://dx.doi.org/10.1111/j.1747-0765.2005.tb00025.x

Sato, K., Masunaga, T., and Wakatsuki, T. (2005b). Water movement characteristics in a multi-soil-layering system. *Soil Sci. Plant Nutr.,* 51(1),75-82.http://dx.doi.org/10.1111/j.1747-07 65.2005.tb00009.x

Smith, R.G. and Schroeder, E.D. (1985). Field studies of the overland flow process for the treatment of raw and primary treated municipal wastewater. *J. (Water Pollut. Control Fed.)*, 57(7), 785-794. http://www.jstor.org/stable/25042699

Song, Y., Huang, Y.T, Ji, H.F., Nie, X.J., Zhang, Z.Y., Ge, C., Luo, A.C., and Chen, X. (2015). Treatment of turtle aquaculture effluent by an improved multi-soil-layer system. *J. Zhejiang Univ. SCIENCE B,* 16(2), 145-154. http://dx.doi.org/10.1631/ jzus.B1400090

Sorensen, I. and McBean, E. (2015). Beyond appropriate technology: Social considerations for the sustainable use of Arsenic-iron removal plants in rural Bangladesh. *Technol. Soc.,* 41, 1-9. http://dx.doi.org/10.1016/j.techsoc.2014.10.003

Tan, X., Xia, X.L., Li, S.Y., and Zhang, Q.F. (2015). Water quality characteristics and integrated assessment based on multistep correlation analysis in the danjiangkou reservoir, China. *J. Environ. Inf.,* 25(1), 60-70. http://dx.doi.org/10.3808/jei.20150 0296

Unno, S., Wakatsuki, T., Masunaga, T., and Iyota, K. (2003). Study on direct treatment of river by multi-soil-layering method and its characteristics of water purification. *J. Jpn. Coc. Civil Eng.,* 726, 121-129.

USEPA (1984). Process design manual: land treatment of municipal waste water. Supplement on rapid infiltration and overland flow, Cincinnati, OH.

USEPA (1998). National water quality inventory: 1998 report to congress. EPA 305(b) report, Washington, DC.

USEPA (2006). Process design manual: land treatment of municipal wastewater effluents, Cincinnati, OH.

USEPA (2011). Principles of design and operations of wastewater treatment pond systems for plant operators, engineers, and managers, Cincinnati, OH.

Wakatsuki, T., Omura, S., Abe, Y., Izumi, K., and Matsui, Y. (1990). Treatment of domestic wastewater by Multi-Soil-Layering system (Part 3) Role and life of purification abilities of soil materials in the systems. *Jpn. J. Soil. Sci. Plant Nutr,* 61, 74-84.

Wang, Y.C., Niu, F.X., Xiao, S.B. et al. (2015). Phosphorus fractions and its summer's release flux from sediment in the China's Three Gorges Reservoir. *J. Environ. Inf.,* 25(1), 36-45. http://dx.doi.org/10.3808/jei.201400260

Yin, Y.Y., Huang, G.H., and Hipel, K.W. (1999). Fuzzy relation analysis for multicriteria water resources management. *J. Water Resour. Plann. Manage.,* 125(1), 41-47. http://dx.doi.org/10.1061/(ASCE) 0733-9496(1999)125:1(41)

Zhang, D.Q., Jinadasa, K.B., Gersberg, R.M., Liu, Y., Tan, S.K., and Ng, W.J. (2015a). Application of constructed wetlands for wastewater treatment in tropical and subtropical regions (2000-2013). *J Environ Sci (China),* 30, 30-46. http://dx.doi.org/10.1016/j.jes.2014.10.013

Zhang, N., Li, Y.P., Huang, W.W., and Liu, J. (2014). An inexact two-stage water quality management model for supporting sustainable development in a rural system. ***J. Environ. Inf.,*** 24(1), 52-64. http://dx.doi.org/10.3808/jei.201400274

Zhang, Y., Cheng, Y., Yang, C., Luo, W., Zeng, G., and Lu, L. (2015b). Performance of system consisting of vertical flow trickling filter and horizontal flow multi-soil-layering reactor for treatment of rural wastewater. ***Bioresour. Technol.,*** 193, 424-432. http://dx.doi.org/10.1016/j.biortech.2015.06.140