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Treatment of rural domestic wastewater using multi-soil-layering systems: Performance evaluation, factorial analysis and numerical modeling

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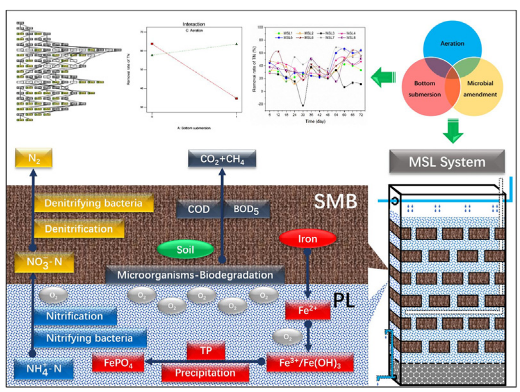
HIGHLIGHTS

- Investigated the rural wastewater treatment using multi-soil-layering (MSL) systems.
- Explored the effects of operating factors on the performances of MSL systems.
- Analyzed the complicated interactions based on interactive factorial analysis.
- Develop a stepwise-cluster inference model for simulating contaminant removal.
- Provided a sound strategy for optimal operation of MSL systems in applications.

GRAPHICAL ABSTRACT



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ABSTRACT

The discharge of wastewater in rural areas without effective treatment may result in contamination of surrounding surface water and groundwater resources. This study explored the wastewater treatment performance of multi-soil-layering (MSL) systems through interactive factorial analysis. MSL systems showed good performances under various operating conditions. The COD and BOD_5 removal rates in MSL systems could reach 98.53 and 93.66%, respectively. The performances of MSL systems in TP removal stayed at high levels ranged from 97.97 to 100% throughout the experiments. The $NH_4^+ - N$ removal rates of the well performed MSL systems reached highest levels ranging from 89.96 to 100%. The TN removal rates of aerated MSL systems ranged from 51.11 to 64.44% after 72 days of operation. The independent effects of bottom submersion, microbial amendment and aeration, as well as most interactions were significant. The performance of MSL systems was mainly affected by bottom submersion and aeration as well as their interactions. Aeration was the most positive factor for the removal of organic matter, TP and $NH_4^+ - N$. However, oxygenated environment was unfavorable for $NO_3^- - N$ removal. In the submerged area with limited oxygen, the microbial transformation of $NO_3^- - N$ still occurred. A stepwise-cluster inference model was developed for tackling the multivariate nonlinear relationships in contaminant removal processes. The results can help obtain a better understanding of the complicated processes among contaminant removal in MSL systems.

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1. Introduction

Water pollution in rural areas of developing countries has received increasing attention in recent years (Blum et al., 2017; Gan et al., 2012; Koundouri et al., 2016; Omar et al., 2017; Xin et al., 2018). Especially, the economic development and population growth lead to the generation of a large amount of domestic wastewater (An et al., 2016b; Di Battista et al., 2016; Huang et al., 2006; Yu et al., 2017). In small and remote communities, many wastewater treatment technologies associated with potential secondary pollution and excessive energy consumption are unsuitable for household application (An et al., 2016a; Latrach et al., 2018). There are few sewage treatment plants and the capability for treating wastewater is limited (Wang et al., 2011). The discharge of wastewater without effective treatment has resulted in the contamination of surrounding surface water and groundwater resources (Gan et al., 2006; Khan and Valeo, 2017; Latrach et al., 2016). How to deal with this problem through eco-friendly, economical and easy-to-construct (3E) approaches has become a urgent issue in these areas.

To address this issue, multi-soil-layering (MSL) system has been developed as a sound 3E wastewater treatment approach for decentralized domestic wastewater treatment in rural areas (Pattnaik et al., 2008a; Zhang et al., 2015). Removal of contaminants by MSL system is a complicated process involving precipitation, filtration, adsorption and biodegradation processes (Luo et al., 2014; Sato et al., 2011b). This technology has many advantages, such as good environmental suitability, long service lifespan, reduced land-space requirement, flexible operation modes, low construction and maintenance cost (Chen et al., 2009; Guan et al., 2014; Luanmanee et al., 2002a). Its performance is satisfied even under high hydraulic load rates (HLR) and pollutants loads. MSL system consists of soil mixture blocks (SMBs) and permeable layers (PLs) (Masunaga et al., 2007a). With the unique characteristics in structure, permeability, and water distribution, SMBs and PLs can work as saturated zone (anaerobic) and unsaturated zone (aerobic), respectively. The whole MSL system is like a miniature soil ecosystem with good performance in removing pollutants.

MSL system used in wastewater treatment was first proposed by Wakatsuki (1993). Its performance in wastewater treatment has been proved in some previous studies (Attanandana et al., 2000; Chen et al., 2007a; Latrach et al., 2014; Luanmanee et al., 2002b; Masunaga et al., 2007b; Pattnaik et al., 2008a; Sato et al., 2011a; Sato et al., 2005). Some efforts have been made to investigate the wastewater treatment in MSL systems in these years. Luanmanee et al. (2001) reported the removal rates of BOD_5 and TP in MSL systems were up to 95.2 and 89.0%, respectively. Chen et al. (2007b) investigated structural differences among MSL systems and found that MSL systems with large top surface area of SMBs had higher removal rate for COD, BOD_5 and TP because of the improved contact efficiency. Sato et al. (2011b) found that SMBs and PLs presented different treatment performances and the removal rate of TP was significantly influenced by flow rate. Ho and Wang (2015) investigated the efficiency of MSL system with different materials in PLs. It was found that the systems using zeolite and granular activated carbon showed stable ammonia nitrogen removal rate at 92.3–99.8%, while the TP removal rate was not directly correlated with material change in PLs. Latrach et al. (2016) developed a hybrid system including MSL and sand filter, which showed high efficiency in the removal of organic matter and nutrients at low HLR.

MSL system shows good potential for removing organic matters and nutrients from rural domestic wastewater at small and remote communities (An et al., 2016a; Guan et al., 2012; Latrach et al., 2018). Although the findings in previous studies are encouraging, the performances of MSL system under some important conditions such as exogenous microorganism from microbial amendment and invisible bottom submersion from field construction are unclear. The processes involved in MSL systems are complicated and they may interact with each other. However, the interactions among influencing factors in the operation of MSL systems remain unknown. Factorial analysis can help better explore such internal interactive effects (Wang et al., 2018; Zhou and Huang, 2011). In addition, there is also a lack of effective modeling approach for tackling discrete and nonlinear complexities of contaminant removal in MSL systems. The stepwise-cluster analysis (SCA) method can help tackle the nonlinear relationships among multiple factors. A cluster could be cut into two sub-clusters, while two could be merged into a new cluster during the iterative training process. Step by step, a classification tree in the sense of probability can be established when no clusters can be further cut or merged, which was based on a series of cutting or mergence processes under given statistical criteria (Huang et al., 2006). SCA has been applied in some environmental fields such as air quality prediction (Huang, 1992) and petroleum pollution control (Qin et al., 2007). However, the report of SCA application in the analysis of wastewater treatment processes is limited.

To address these challenges, this research aims to obtain insights from the treatment of rural domestic wastewater using MSL systems based on interactive factorial analysis. In detail, the study will (i) explore the effects of aeration, bottom submersion and microbial amendment on the performances of MSL systems, (ii) analyze the interactions of multiple state variables in treatment process, and (iii) develop a stepwise-cluster inference model for simulating the contaminant removal in MSL systems. This is the first study to reveal the complicated pollutant removal processes in MSL through interactive and simulation analyses. The results can provide a sound strategy for optimal operation of MSL systems in both laboratory and field applications.

2. Materials and methods

2.1. MSL systems

As shown in Fig. 1, the lab-scale MSL systems made of acrylic were designed with the dimensions of 52 × 10 × 85 cm (L × W × H). There were two 3-cm holes on the top for influent distribution pipe and 2-cm outlet hole at bottom for effluent pipe. In SMBs, the mixed planting soil, charcoal, sawdust and iron powder were packaged in jute bags with a ratio of 7:1:1:1 (dry weight). The soil samples were collected in the campus of North China Electric Power University. The bulk density of SMBs was 0.9 g/cm^3. 4–6 mm homogeneous zeolites in PLs were obtained from Shengwei Water Treatment Materials Co., Ltd. (Dengfeng, China). SMBs had the dimensions of 10 × 10 × 5 cm (L × W × H) to 5 × 10 × 5 cm (L × W × H). The horizontal distance between SMBs was 3–4 cm and each PL between SMBs was 5 cm in height. SMBs were surrounded by PLs to form a brick-like pattern. In the bottom of MSL apparatus, there was the 10 cm-height bedding filled with pebbles in the diameter of 2–4 cm. The plastic plates with holes were put above pebble bedding course.

2.2. Synthetic wastewater

In this experiment, synthetic wastewater was prepared according to the real wastewater characteristics in rural areas (Latrach et al., 2014; Luo et al., 2014; Yu et al., 2012; Zhang et al., 2015). Table S1 showed the quantity of required chemicals for preparing synthetic wastewater, and the related influent water quality. The wastewater was continuously fed into MSL systems through a perforated pipe on the top of the MSL systems by peristaltic pumps (Longer ZT600-1J, China).

2.3. Operation of MSL systems

Continuous aeration in MSL systems was supplied by air pumps at a rate of 26,000 L/(m^3 d). It is expected that MSL systems can be operated without bottom submersion. However, bottom submersion often exists in real MSL systems due to insufficient discharge of treated water, increase of flow rate, and potential system clogging. Therefore, it will be interesting to investigate the performance of MSL system under the