Wastewater treatment processes and mechanisms of organic matter, phosphorus, and nitrogen removal in a multi-soil-layering system

Kuniaki Sato[A], Noriko Iwashima[B], Takuya Matsumoto[C], Toshiyuki Wakatsuki[D] and Tsugiyuki Masunaga[E]

[A]Faculty of Life and Environmental Science, Shimane University, Matsue 690-8504, Japan, Email ksato@life.shimane-u.ac.jp
[B]Faculty of Life and Environmental Science, Shimane University, Matsue 690-8504, Japan, Email iwashima@life.shimane-u.ac.jp
[C]Faculty of Life and Environmental Science, Shimane University, Matsue 690-8504, Japan, Email d06a2005@life.shimane-u.ac.jp
[D]Faculty of Agriculture, Kinki University, Nara City 631-8505, Japan, Email wakatuki@nara.kindai.ac.jp
[E]Faculty of Life and Environmental Science, Shimane University, Matsue 690-8504, Japan, Email masunaga@life.shimane-u.ac.jp

Abstract

The treatment processes inside a Multi-Soil-Layering system (MSL) were investigated by using a laboratory-scale system, which was set up in a D10×W50×H23-73cm acrylic box enclosing “soil mixture blocks” alternating with permeable zeolite layers. Six MSL systems consisted of 1~6 layers of soil mixture layers were constructed. For the study of the treatment processes inside the system, wastewater, with mean concentrations (mg/L) of BOD: 28.1, COD: 65.7, T-N: 9.8, T-P: 1.0, was introduced into the system at a loading rate of 1000 L/m^2/day. In the both of BOD and COD, the concentrations in soil mixture layers (SML) were lower than those in permeable layers between SML (PLb). As the flow rate in SML decreased and the rate in PLb increased, the concentrations in the PLb increased in each system. Phosphorus concentration was lower in the SML than in the PLb, probably because P was adsorbed mainly by soil and mixed iron particles. Therefore, phosphorus removal efficiency was strongly influenced by the flow rate in SML. The ammonia adsorption and nitrification were almost completed up to 3rd layer in this study. However, the removal of nitrogen did not so much proceed below 4th layer because of low denitrification efficiency.

Key Words

Multi-Soil-Layering system, processes of wastewater treatment, organic matter removal, nitrogen removal, phosphorus removal, soil-based wastewater treatment system.

Introduction

The physical, chemical, and biological properties of soil have been used for wastewater treatment systems all over the world for a long time. To bring out the water purifying function of soil as much as possible, the author’s group has been addressed the study of Multi-Soil-Layering (MSL) system. The MSL system consists of soil units (soil mixture layers : SML) arranged in a brick-like pattern surrounded by layers of zeolite or alternating particles of homogeneous sizes (permeable layers : PL) that allow a high hydraulic loading rate (HLR). The MSL system is effective for the prevention of clogging and shortcuts which are the main constraints in the conventional soil-based wastewater treatment systems (Masunaga *et al*. 2003, Sato *et al*. 2002, 2005, Wakatsuki *et al*. 1993). Although a large number of basic and applied researches have been investigated, it has not been clear the processes of wastewater treatment in the MSL system. So far, some settings such as the number of layers and the apparatus size and height have been established empirically. In this research, six laboratory-scale MSL systems consisted of SML of 1~6 layers were made for the purpose to evaluate the treatment processes. In addition, treated water from SML and PLb at the bottom of each system was separately collected. We attempted to reveal the wastewater treatment mechanisms in SML and PLb of each layer by the analysis of both the quantities and qualities in treated water.

Materials and methods

Appearance of the MSL systems in the present study

Figure 1 shows the structure of the laboratory-scale MSL system used in this study. For the MSL system, an acrylic box D10 × W50 × H23-73cm in size, forming an alternate brick layer-like pattern with zeolite and SML, was used. Six MSL systems consisted of SML of 1~6 layers were constructed. To collect the outflow water from SML and PLb separately, plastic divider plates were installed at the bottom part of the systems as shown in Figure 1. A 1.2cm diameter hole was made at the bottom of each partition part and a vinyl tube was attached to each hole. The SML consisted of volcanic ash soil (rich in organic materials classified as Andisol), saw dust, approximately 1mm diameter granular iron, and charcoal in ratios of 70, 10, 10, and 10%, respectively, on a dry weight basis. The bulk density of SML was 0.84g/ml. The void spaces (PL) between each block and block sides were filled with zeolite 3-5mm in diameter. In Addition, to measure oxidation-reduction potential inside the system, the ten platinum electrodes were installed from the side in system No.VI, as shown in Figure 1.

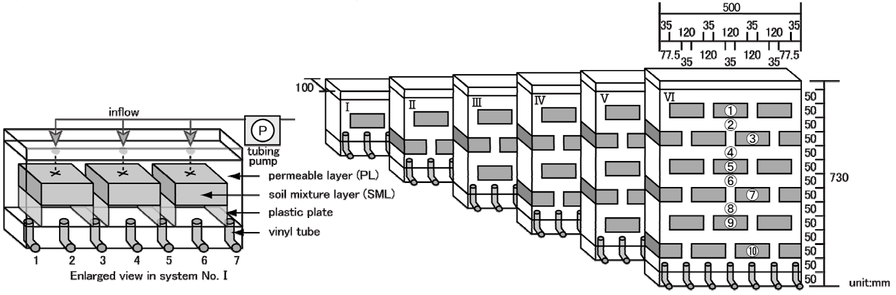


Figure 1. Structure of Multi-Soil-Layering (MSL) system for studies on characterization of treatment processes inside system. Numbers in system No.VI show setting places of Eh electrode.

Evaluation of wastewater treatment processes in respective layers of the system

Domestic wastewater from a nearby community disposal plant was diluted three times with well water and introduced into these systems for evaluation of wastewater treatment processes. Average characteristics of the diluted wastewater were as follows: pH 7.71, SS 14.9 mg/L, BOD 28.1 mg/L, COD 65.7 mg/L, T-N 9.8 mg/L and T-P 1.0 mg/L. HLR was set at 1000 L/m^2/d. The inflow water was divided into three points by using peristaltic pump. The three points were positioned right above centers of three SML in top layer of the systems, as shown Figure 1.This experiment was started on Aug 12, 2005 and was terminated on Dec. 22, 2005 (132th d). The outflow water was collected from each vinyl tube and sampled five times on Aug. 15 (3rd d), Aug. 30 (18th d), Sep. 29 (48th d), Nov. 9 (89th d), and Dec. 7 (117th d) during the experiment of wastewater treatment. Wastewater and outflow water (treated water) were analyzed for the following: BOD, COD, NH_4-N, NO_3-N, NO_2-N, T-N, PO_4-P and T-P.

Results and discussion

Characteristics of water movement inside systems

Figure 2 shows changes in proportion of water flow volume in SML of each system during wastewater treatment. In the system No.I, the proportion sharply decreased to approximately 30% on the 3rd d, and then gradually decreased with time. The decrease probably resulted from proliferation of microorganisms and overgrowth of biofilm in the SML. At the same time, the water which could not flow into SML flowed into PLb. Subsequently, the water probably flowed down into the SML of next layer in MSL systems with more than 2 layers. The facts indicated that the structure of MSL system made possible such high-speed treatment as the conventional soil-based water purification systems could not continue to treat for clogging. As the number of layers increased, it took a longer time before the proportion in SML started to decrease.

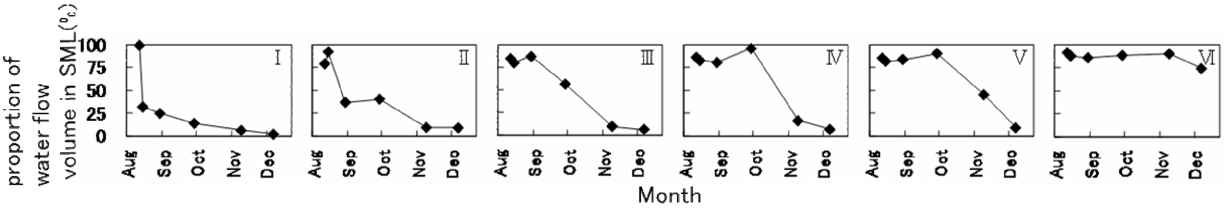


Figure 2. Changes in proportion of water flow volume in soil mixture layer (SML) of each system during wastewater treatment. The first value (0th day) in each graph shows the percentages when well water was flowed into the systems in HLR of 1000 L/m/d.

Processes of organic matter (BOD and COD) removal

In the SML, the concentrations of BOD were extremely low except the system No.I (Figure 3). In contrast, the COD in the SML decreased with the increase in the number of layers. In the both of BOD and COD, their concentrations in SML were lower than those in PLb. Additionally, as the flow rate in SML decreased and the rate in PLb increased, the BOD and COD in the PLb increased in each system (Figure 2, 3). These facts indicated that the efficiency of organic matter removal was higher in SML than in PLb, and the water permeability in SML was important for organic matter removal. COD was higher than BOD in each system. The results suggested the removal of COD needed more number of layers than that of BOD. This was because COD includes easily and slowly decomposable organic matter, whereas BOD represents easily decomposable organic matter.

Processes of phosphorus removal

The PO_4-P and T-P concentrations were lower in the SML and fluctuated less than that in the PLb (Figure 3). Previous studies suggested the phosphorus removal was mainly based on phosphorus adsorption on soil and metal irons added in the SML (Wakatsuki *et al.* 1993). Furthermore, the PO_4-P and T-P in PLb clearly increased with decrease in the flow rate in SML of each system. These results indicated the permeability of SML was also very important on phosphorus removal in MSL system. The concentrations in SML of system No.I-III were showing an upward tendency with time. This was probably because the adsorption of phosphorus on ferric hydroxides decreased and/or the adsorbed phosphorus leached from the SML due to establish an anaerobic condition in those SML.

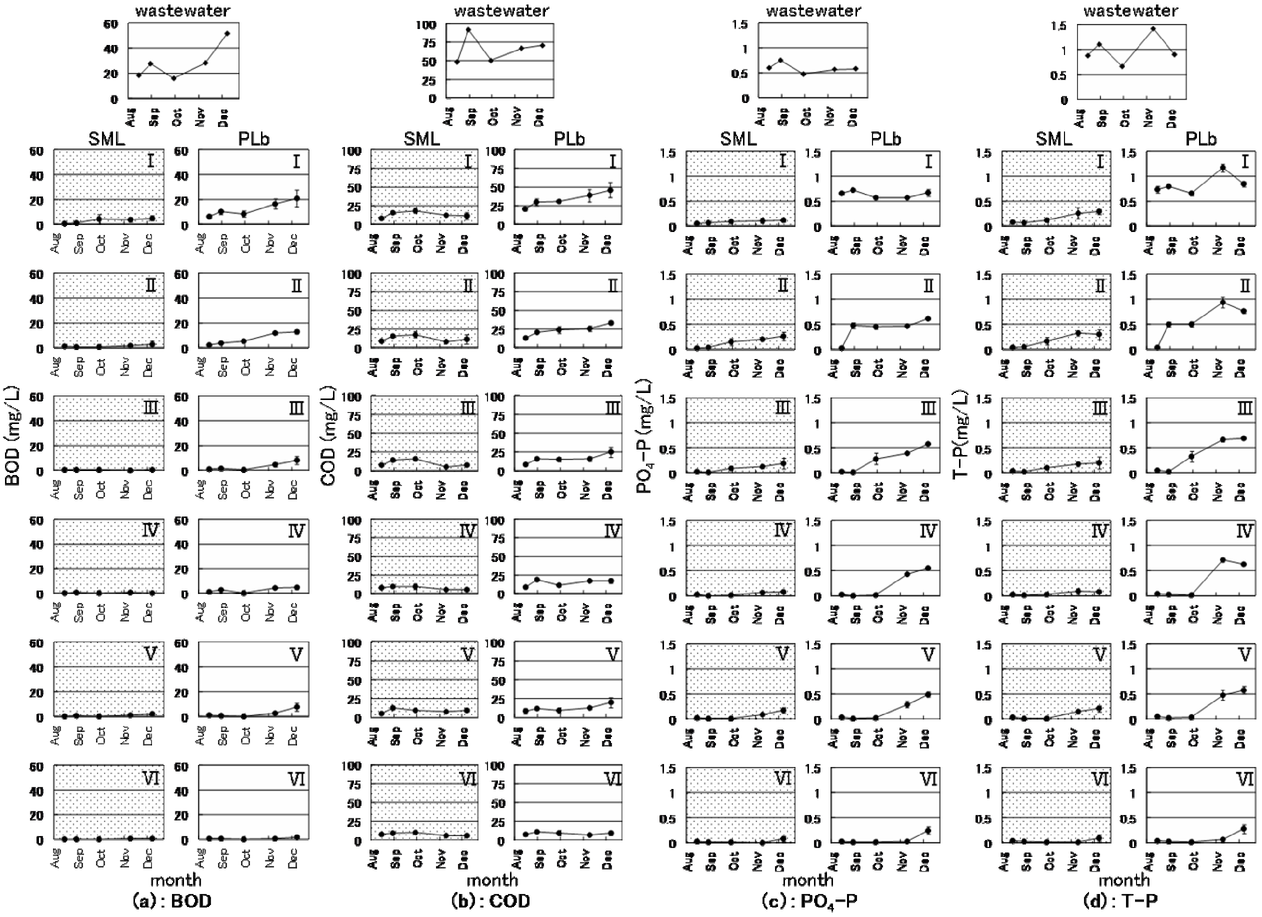


Figure 3. Changes in mean concentrations of (a)BOD, (b)COD, (c)PO_4-P and (d)T-P of the wastewater and treated water in each system. The error bars show the standard deviations. SML: Soil Mixture Layer, PLb: Permeable Layer between SML.

Processes of nitrogen removal

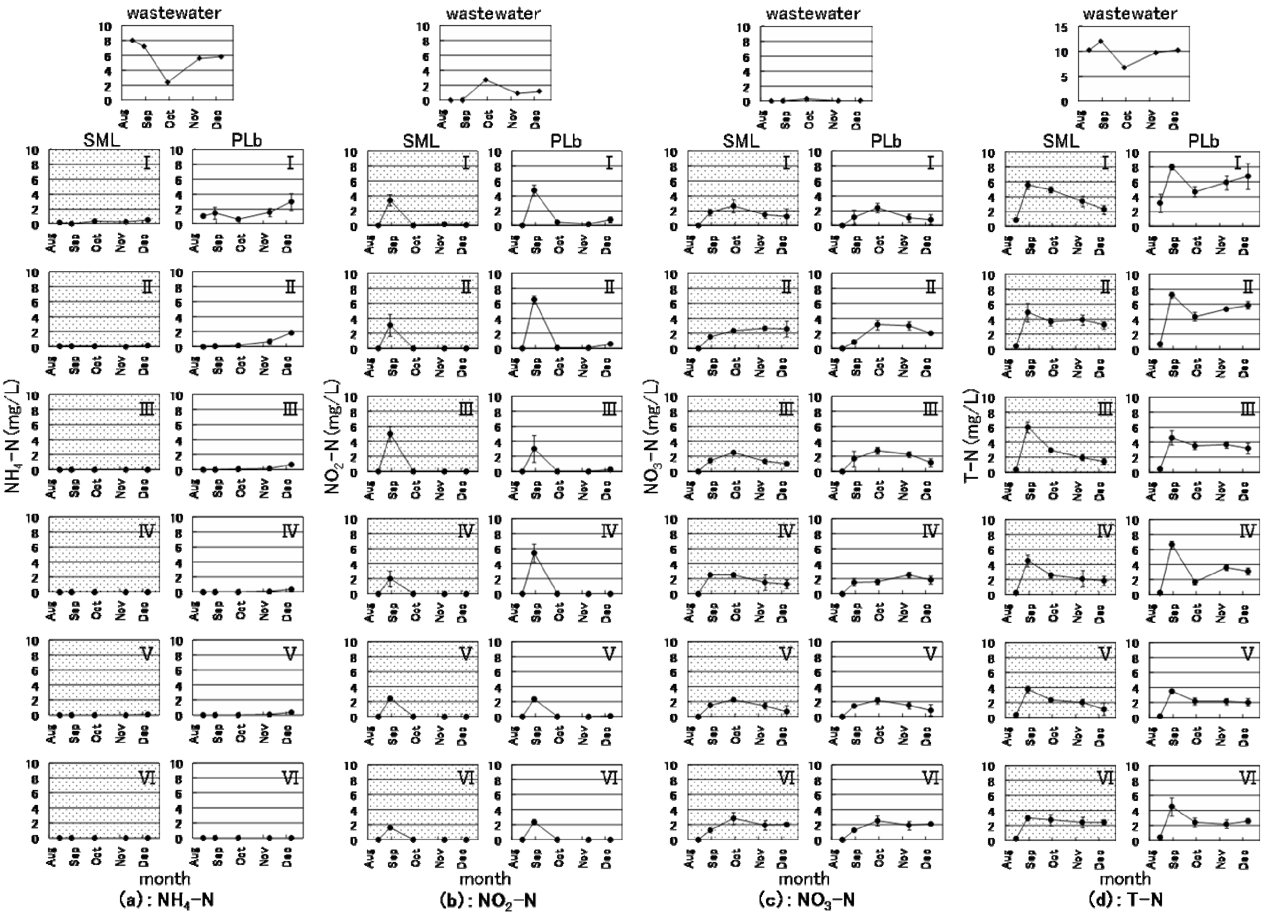
NH_4-N was significantly low in every SML and PLb of the systems with more than 3 layers (Figure 4), probably because NH_4-N adsorption on soil materials and zeolite took place and nitrification proceeded with time. The concentration showed an increasing trend with time in PLb of system No.I and II. It was because the contact efficiency of wastewater with the soil and zeolite decreased due to the increase in flow rate in PLb with time. The peaks of NO_2-N were observed in each part on 18th d (Figure 4). NO_3-N increased to 48th d from start of this experiment, followed by the trend of decreasing was observed except system No.II. This was because nitrification proceeded from the start and denitrification occurred later. In system No.I, reducing of nitrification probably also contributed to the decrease in NO_3-N after 48th d because NH_4-N also increased with time in the system. In system No.II, the decreasing of NO_3-N was not observed in SML. This was probably because NH_4-N which was not removed in first layer transformed to NO_3-N by nitrification in SML of second layer. Although the decreasing of NO_3-N by denitrification was observed in system No.III after 48th d, the difference of NO_3-N concentration among system No.IV-VI was small. Although decreasing of Eh with decrease in the water flow rate was observed in the SML of 1st - 3rd layer, Eh in SML of 4th - 6th layer and PLb of each part showed relatively high value (data not shown). In addition to that, BOD almost removed up to 3rd layer (Figure 3), and it was suggested that denitrification mainly occurred in SML of 1st to 3rd layer. The trend of T-N shows such behaviour as sum of concentrations of NH_4-N, NO_2-N and NO_3-N.

(a): NH_4-N
(b): NO_2-N
(c): NO_3-N
(d): T-N

Figure 4. Changes in mean concentrations of (a) NH_4-N , (b) NO_2-N , (c) NO_3-N and (d)T-N of the wastewater and treated water in each system. The error bars show the standard deviations. SML: Soil Mixture Layer, PLb: Permeable Layer between SML.

Conclusion

In this study, the water flow rate in SML was an essential factor for removal of organic matter, phosphorus and ammonia. This result and previous studies suggested that selection of soil with proper particle size, mixing of high permeable materials with SML and setting of aeration regime were important to keep the proper flow rate in SML (Sato *et al*. 2002, 2005). Proper aeration has shown effective in the prevention of clogging. Additionally, the ammonia adsorption and nitrification were almost completed up to 3rd layer, and denitrification did not so much proceed after 4th layer. These results suggested that the aeration in upper parts of the system for nitrification and the extra addition of organic matter (especially high CN ratio materials) to SML in the lower parts for denitrification were effective for simultaneous removal of organic matter, phosphorus and nitrogen.

References

Masunaga T, Sato K, Zennami T, Fujii S, Wakatsuki T (2003) Direct Treatment of Polluted River Water by the Multi-Soil-Layering Method. *Journal of Water and Environment Technology* **1**, 97-104.

Sato K, Masunaga T, Inada K, Tanaka T, Arai Y, Unno S, Wakatsuki T (2005) The Development of High Speed Treatment of Polluted River Water by the Multi-Soil-Layering Method : Examination of Various Materials and Structures. *Japanese journal of soil science and plant nutrition* **76**, 449-458. [in Japanese with English abstract]

Sato K, Masunaga T, Wakatsuki T (2002) Treatment of Bio-genic Wastewater by Multi-Soil-Layering Method : Effect of Various Positions of Aeration Using Small Model Systems. *Journal of Japan Society on Water Environment* **25**, 234-241. (in Japanese with English abstract)

Wakatsuki T, Esumi H, Omura S (1993) High-Performance and N-Removable and P-Removable on-Site Domestic Waste-Water Treatment System by Multi-Soil-Layering Method. *Water Science and Technology* **27**, 31-40.