IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Annales de Chimie - Science des Matériaux
Vol. 45, No. 2, April, 2021, pp. 161-165
Journal homepage: http://iieta.org/journals/acsm

Experimental Study on the Treatment of Rural Domestic Wastewater Using the Multi-Soil-Layering System Filled with Sludge-Based Biochar

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https://doi.org/10.18280/acsm.450208

Received: 28 November 2020
Accepted: 10 February 2021

Keywords:
sludge-based biochar, rural domestic wastewater, multi-media soil layering system (MSL), hydraulic loading rate (HLRs), zeolite

ABSTRACT

This paper aims to improve the treatment effect of the multi-soil-layering system (MSL) on rural domestic wastewater. For this, sludge-based biochar materials were selected in the experiments to study its impacts on the treatment of rural domestic wastewater using the MSL. The comparative experiments were conducted for the three MSL systems filled with different materials: the sludge-based biochar (a), wood chips (b), and charcoal (c). The results showed that when the sludge-based biochar material was used as a filler, the removal effect of COD, NH_4^+-N, TN, TP is better than that of wood chips and charcoal, and the removal rates were 80%, 90%, 65% and 92%, respectively, meeting the Grade A standard specified in the Hebei Province Rural Domestic wastewater Discharge Standard (DB13/2171-2015); hydraulic loading rates (HLRs) have a great impact on the removal of pollutants, and the pollutant indicators in the system (a)re affected by the HLRs in different degrees, i.e., NH_4^+-N>TP>COD>TN from high to low; considering the treatment efficiency and pollutant removal effect, the HLRs should be selected between 800L/(m^2·d) and 1200L/(m^2·d). It's concluded finally that the sludge-based biochar material can strengthen the removal effect of the MSL system. This study is of theoretical value for the further research on MSL system and resource utilization of the sludge.

1. INTRODUCTION

Rural domestic wastewater is formed in the daily lives of rural residents, mainly including kitchen wastewater, laundry water, and daily cleaning sewage [1]. It has the characteristics of wide dispersion, large seasonal changes, and low pollutant concentration [2]. Due to large differences of the water quality and quantity between rural and urban domestic wastewater, urban sewage treatment technology is not well applicable to the rural area in terms of both technology and economy [3]. The multi-soil-layering [4] system is a kind of soil purification sewage technology [5] emerging in Japan in the 20th century, which can be used as a good decentralized treatment type [6] of domestic sewage, due to its easy clogging, small space requirement, and low hydraulic loading rate. The MSL system is mainly composed of water-permeable layer and soil mixed layers [7], which mainly removes heavy metals in domestic sewage [8], chemical oxygen demand (COD), ammonia nitrogen (NH_4^+-N), total nitrogen (TN), total phosphorus (TP) [9] and other pollutants through physical adsorption, exchange, and biological decomposition. Currently some researches have been conducted on treating rural sewage wastewater, restaurant wastewater, polluted river water, but it still needs further study on how to improve the removal effect of pollutants. For this, the authors analyzed the status quo of water quality, water volume and spatial distribution of rural sewage, and studied the use of MLS system to remove the rural domestic wastewater in Hebei Province, to solve the problems in the process of rural sewage treatment.

Sludge-based biochar is the gas and oil produced through the pyrolysis reaction of sludge under anaerobic conditions [10], as well as the solid residue, namely biochar [11]. Biochar is an environmental functional material with good adsorption [12], rich pore structure, reliable surface properties etc. [13]. It has a certain adsorption effect on heavy metal ions and inorganic pollutants in water [14]. Also, the pore structure of biochar can provide favorable living conditions for aerobic microorganisms in the system to form a biofilm [15], which is beneficial to the removal of pollutants in sewage [16].

The experiments used zeolite as the water-permeable material and sludge-based biochar as the additive material of the soil mixed layer to construct an MSL system. It's aimed to study the removal effect of the system on pollutants and also its stability after changing the hydraulic load.

2. EXPERIMENTS

2.1 Experimental method

The experiments adopted gravity flow with top in and bottom out and fully submerged continuous flow. The effective volume of the experimental column was about 28 L and the column height was 1.3 m. From top to bottom, there was 0.2 m ultra-high and water distribution area, 0.9 m main reaction area, and 0.2 m supporting layer and water outlet area. The test water in the water storage tank was lifted by the water inlet pump and entered the experimental column from the top. When passing through the mixed soil layer and the permeable layer, the suspended particles in the water were intercepted and contacted with the filler to form a biofilm [17]. The raw water was then discharged from the bottom after digestion and decomposition of the biofilm.

2.2 Test wastewater quality

Table 1. Test wastewater quality

Test Indicators	Range
pH	6.0-8.0
COD (mg/L)	80-300
NH_4^+-N (mg/L)	10-40
TN (mg/L)	15-50
TP (mg/L)	1.0-5.0

In view of the characteristics of rural domestic wastewater quality, the concentration range of inlet water's COD, NH_4+-N, TN, TP was finally determined, as shown in Table 1.

2.3 Experimental materials

The MSL system is mainly composed of soil mixed layer and permeable layer. Natural soil was used in the mixed layer; sludge-based biochar, wood chips, charcoal and iron chips were also added according to the experimental design. Zeolite was selected for the permeable layer as the filler. The material composition of the three systems is shown in Table 2.

2.4 Sampling and analysis methods

During the system operation, samples were taken regularly every day to analyze the inlet and outlet water quality. Table 3 lists testing indicators and methods.

Table 2. System components

System	Permeable layer	The proportion of the dry mass of each constituent material in the mixed soil layer				
		Natural soil	Iron chips	Sludge-based biochar	Wood chips	Charcoal
a	Zeolite	7	1	2		
b	Zeolite	7	1		2	
c	Zeolite	7	1			2

Table 3. Main testing instruments and analytical methods

Test Items	Test Methods	Instruments
COD	Potassium Dichromate Colorimetry	Reflux device and titration device
NH_4^+-N	Nessler's reagent spectrophotometry	Spectrophotometer/Hash DR5000
TP	Ammonium molybdate spectrophotometry	Spectrophotometer/Hash DR5000
TN	Potassium persulfate oxidation-ultraviolet spectrophotometry	Spectrophotometer/Hash DR5000
DO	Instrument direct reading	Portable dissolved oxygen meter/JPSJ-608
Microbial Morphology	Direct observation	Trinocular Biological Microscope/UB100i

3. RESULTS AND DISCUSSION

3.1 Removal effect on different components

3.1.1 COD removal effect

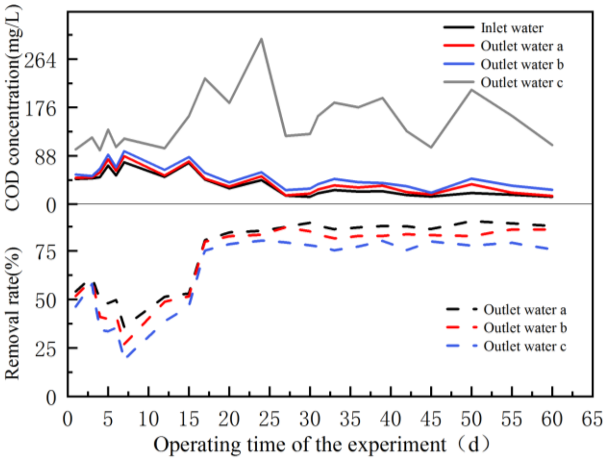

Figure 1. Removal effect of COD

Figure 1 shows that the removal rates of COD by the three systems all first dropped and then rose, and finally stabilized. For the system (a), the COD removal rate basically tended to be stable above 80% after the 17th day, and the COD concentration of outlet water was also below 50 mg/L, which meets the Grade-A standard specified in *Hebei Province Rural Domestic Wastewater Discharge Standard* (DB13/2171-2015). The removal rate of the system (a) is significantly higher than that of (b) and (c) systems. At the initial stage of the test, the COD in the raw water was mainly removed due to the physical barrier and chemical adsorption of the permeable layer and the mixed soil layer; with the formation of the biofilm, it is mainly the adsorption and decomposition of microorganisms [18]. Through comprehensive analysis of the COD removal effect, it's concluded that the removal effect of system (a) is better than the (b) and (c) systems because of its fast biofilm formation and stable operation.

3.1.2 NH_4+-N removal effect

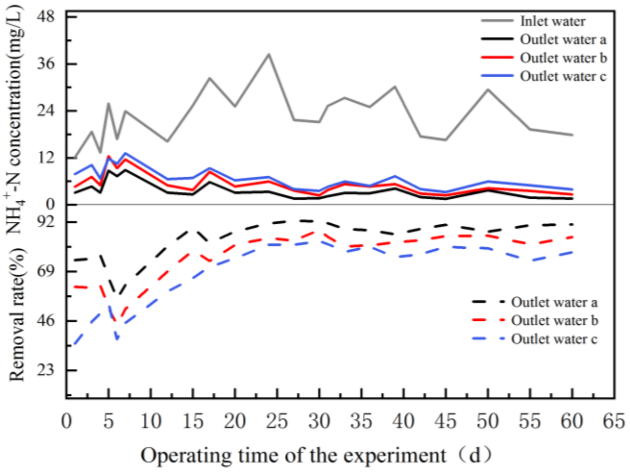

Figure 2. Removal effect of NH_4^+-N

Figure 2 shows that the removal rate of the system (a) is relatively high at the initial stage of operation, mainly due to the adsorption of sludge-based biochar in the mixed soil layer. After reaching saturation, its removal rate was reduced to a minimum. Finally, the removal rate of NH_4^+-N by the system increased through nitrification until it remains stable. After the 27th day, the removal rate of NH_4^+-N by the system (a) basically stabilized, basically up to more than 90%, and the NH_4^+-N of the outlet water was below 5 mg/L, meeting the Grade-A standard of the *Hebei Province Rural Domestic Wastewater Discharge Standard* (DB13/2171-2015). For the systems (b) and (c), the removal efficiency of NH_4^+-N was slightly poor, with a removal rate of about 80%, because of the insufficient oxygen content in the systems and poor nitrification.

3.1.3 TN removal effect

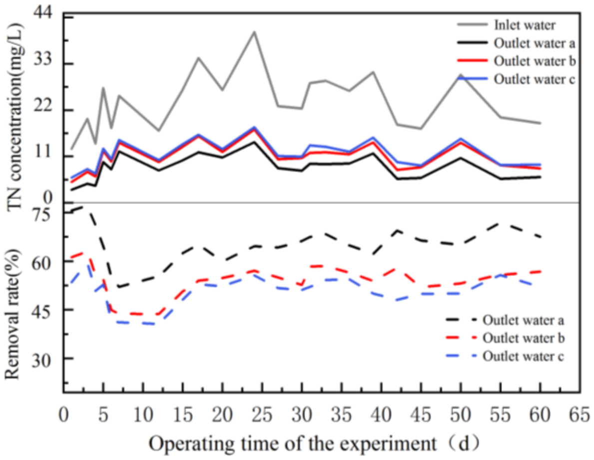

Figure 3. Removal effect of TN

Figure 3 shows that the removal rate of the system (a) was relatively high at the initial stage of operation, mainly due to the adsorption of sludge-based biochar in the mixed soil layer; after reaching saturation, the removal rate was reduced to the minimum. The system finally reduced the TN removal rate through nitrification and denitrification until it remained stable. After the 27th day, the removal rate of TN by the system (a) basically stabilized above 65%, and the TN of the outlet water was basically below 10 mg/L. The three systems all have poor removal effects on TN, with a removal rate below 70. This should be due to the effect of the nitrification and denitrification and the balance of oxygen in the systems, which restricts the removal of nitrogen.

3.1.4 TP removal effect

Figure 4 shows that the removal effect of the three systems on TP is relatively stable. The TP removal rate of the stabilized system (a) was about 92%, and that for the (b) and (c) was 88% and 82%, respectively. The system (a) has a good removal effect on TP, and the TP concentration of the outlet water is stabilized below 1 mg/L, which satisfies the emission requirements. Through comprehensive analysis, it’s found that the removal of TP by the system is mainly due to the physical and chemical effects in the mixed soil layer. The phosphate in the raw water oxidizes the iron in the mixed soil layer to divalent iron, which is further oxidized to iron hydroxide in the permeable layer, and finally removed in the forms of precipitation and complex compound.

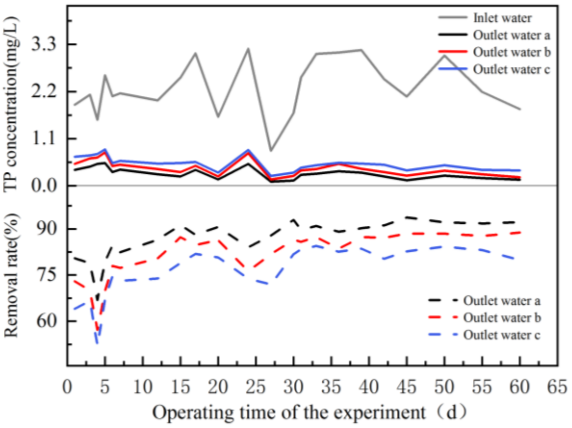

Figure 4. Removal effect of TP

3.2 Impacts of HLRs on removal effect of pollutants

With other parameters unchanged, the tests were conducted under the inlet water’s HLRs of 400L/(m^2·d), 800L/(m^2·d), 1200L/(m^2·d), 1500L/(m^2·d) and 2000L/(m^2·d) respectively, to compare and analyze the removal effect of COD, NH4+-N, TN and TP under different hydraulic loads.

3.2.1 The impact of the HLRs on COD removal rate

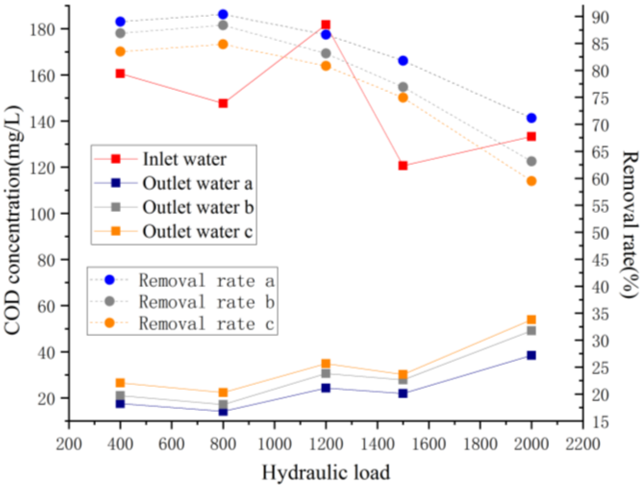

Figure 5. Impact of the HLRs on COD removal rate

It can be seen from Figure 5 that for the three systems, the COD removal rates all decreased with the increase of HLRs. When HLRs were between 400L/(m^2·d) and 1200L/(m^2·d), the average removal rate of COD by system (a) was above 85%, and the COD concentration of outlet water was less than 50 mg/L. When HLRs increased from 1200L/(m2·d) to 2000L/(m2·d), the removal rate of COD in system (a) decreased by 15.49%, and the COD concentration of outlet water increased. Considering system water volume, treatment efficiency, and operating cost, HLRs between 800L/(m^2·d) and 1200L/(m^2·d) should be selected.

3.2.2 The impact of the HLRs on the removal rate of NH_4^+-N

Figure 6 shows that when the HLRs was 800L/(m^2·d), the removal rates of NH_4^+-N by the three systems were 90.01%, 84.01%, and 79.81%, respectively, and the ammonia nitrogen concentration in the outlet water was 1.95mg/L, 3.12mg/L and 3.94mg/L. When HLRs increased from 1200L/(m^2·d) to

2000L/(m^2·d), the removal rate of NH_4^+-N by the three systems decreased by 33.71%, 34.73% and 34.13%, respectively. This is because the changes with the hydraulic load of the system have affected the reoxygenation and changed the conditions of nitrification and denitrification.

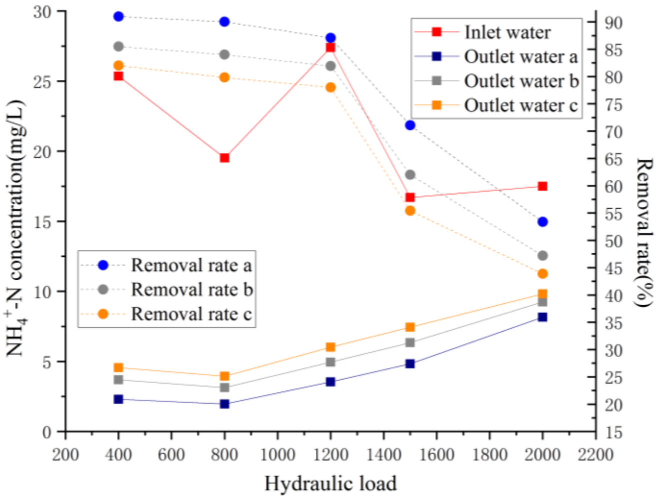

Figure 6. Impact of the HLRs on NH_4^+-N removal rate

3.2.3 The impact of the HLRs on TN removal rate

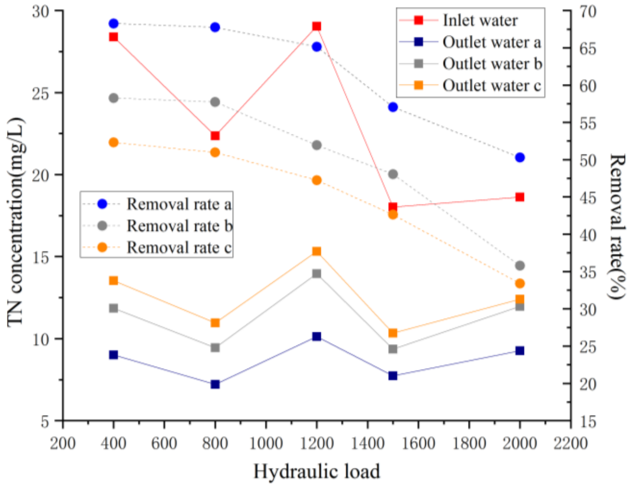

Figure 7. Impact of the HLRs on TN removal rate

It can be seen from Figure 7 that when the HLRs was 800L/(m^2·d), the removal rates of TN by the three systems were 67.75%, 57.74%, and 50.98%, respectively, and the TN concentrations of the effluent were 7.21mg/L, 9.45mg/L and 10.96mg/L. When HLRs increased from 1200L/(m^2·d) to 2000L/(m^2·d), the removal rate of TN by them decreased by 14.85%, 16.13% and 13.86% respectively. The reason should be the changes of oxygen balance in the system which have changed the conditions of nitrification and denitrification, and made it difficult to remove nitrogen.

3.2.4 The impact of the HLRs on TP removal rate

Figure 8 shows that the removal rate of TP by the three systems decreases with the increase of HLRs. When the HLRs were 800L/(m^2·d), the average removal rates of TP by the three systems were 90.98%, 87.45%, and 83.14%, respectively, and the TP concentration of the effluent was less than 0.5 mg/L. When HLRs increased from 1200L/(m^2·d) to 2000L/(m^2·d), the removal rate of the TP by the systems a, b, and c decreased rapidly by 15.9%, 19.27%, and 22.42%, respectively. Overall, the system (a) has a better removal effect on TP, but when the hydraulic load is increased, the oxygen content in the system decreases, which affects the formation of strong adsorbents (complexes of iron, aluminum, calcium, etc.), and mitigates the removal effect of phosphorus.

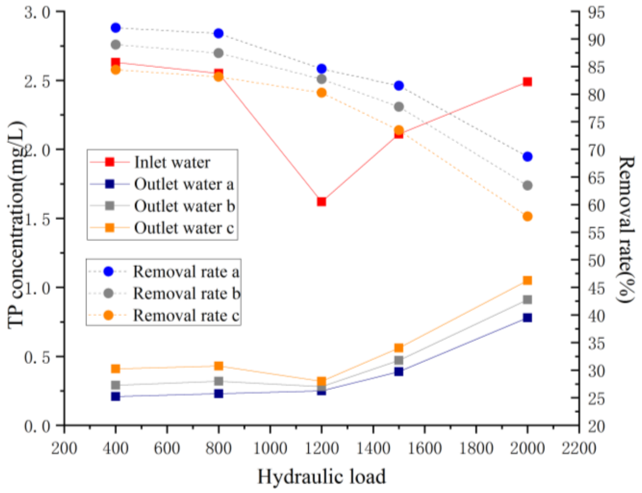

Figure 8. Impact of the HLRs on TP removal rate

4. CONCLUSIONS

(1) The experiments indicate that the system (a) has the best removal effect on pollutants in rural domestic wastewater, enjoys better effluent quality, and operates more stably due to its fast biofilm culturing. After stable operation of the system (a), the average removal rates of COD, NH4+-N, TN and TP were 88.35%, 89.74%, 68.12% and 92.16%, respectively.

(2) Hydraulic loading rates (HLRs) have great impacts on the removal effect of pollutants. The removal effect of each pollutant decreases with the increase of HLRs, especially NH4+-N and TP. In the experiments, the impact degree of HLRs on different components was ranked as NH4+-N>TP>COD>TN from high to low. Considering the treatment efficiency and water volume, the inlet water HLRs of the system between 800L/(m^2·d) and 1200L/(m^2·d) should be selected.

ACKNOWLEDGEMENTS

This paper was supported by Hebei Province Talents Training Project (Grant No.: A201901047) and Science and Technology Foundation of Agricultural University of Hebei (Grant No.: LG201631).

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