

Lab-scale Study of the Removal Efficiencies for Nitrogen and Phosphorus from Urban Rainfall Runoff Using Constructed Riparian Infiltration System

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Abstract To strengthen the removal capacity on nitrogen (N) and phosphorus (P) in rainfall runoff and provide scientific basis for the reconstruction of urban riparian zone, a lab-scale layered riparian infiltration system (RIS) was constructed using soil, cinder, zeolite, sawdust, zeolite and medical stone. The removal efficiencies of RIS for nitrogen and phosphorus in simulated urban rainfall runoff were investigated in six repetitive 4-hour experiments. The results showed that the RIS demonstrated removal of ammonia (NH_4^+), total nitrogen (TN) and total phosphorus (TP) but output of nitrate (NO_3^-). The removal efficiencies of NH_4^+ -N and TP were $65.6 \pm 1.2\%$ and $54.9 \pm 19.1\%$ respectively, which were significantly higher than those of TN ($21.1 \pm 13.7\%$), while the average removal efficiency of NO_3^- -N was -1150.0% , which might be due to the oxidization of NH_4^+ and the leaching of NO_3^- in the substrate. The RIS generally had higher and more stable removal efficiencies of NH_4^+ and TP in vertical flow than in horizontal flow. There were significant positive relations between the concentrations in influent and the removal amount for NH_4^+ and TP ($P < 0.01$). Denitrification occurred in the less permeable bottom soil layers, but the removal amount of NO_3^- was far lower than the amount produced by nitrification from the more permeable upper layers. In general, the RIS has demonstrated removal of nutrients in rainfall runoff, but further study and improvement is needed to enhance the denitrification of RIS to reduce the output of nitrate.

Key words lab-scale; nitrogen; phosphorus; removal efficiency; riparian infiltration system (RIS); urban rainfall runoff

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0 Introduction

The rapid conversion of landuse to urban and suburban areas has profoundly altered how water flows during and following storm events, putting higher volumes of water as surface runoff and reducing amounts of infiltration to ground water. Atmospheric deposition, natural nutrient cycling, and other processes contribute nitrogen and phosphorus to stormwater runoff. The inputs of high nutrient loads could lead to eutrophication problems and degrade biodiversity in urban stream system^[1,2]. Due to the critical situation of nutrient pollution, diverse nitrogen transport pathways in the environment and difficulty in managing many nutrient sources, technologies are needed to reduce nutrient inputs to the water environment from a variety of source pathways^[3].

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Storm water infiltration systems are widely used to address the rainfall runoff flow and water quality impacts of urbanization. Although high rates of premature failure due to clogging have been reported^[4], it could be used in excess of 20 years to reduce storm runoff flow and volume, as well as to minimize pollution to receiving water^[5]. Pollutants are primarily trapped within an infiltration system by mechanical and physicochemical filtration, although chemical and biological processes such as sorption and microbial uptake will also contribute to pollutant removal to some extent^[5]. Thus, media used to construct infiltration systems possess strong adsorption capacity or cation exchange capacity, such as soil^[6], zeolite^[7,8], sawdust^[9], sand^[10] and slags^[11]. The layered infiltration systems generally represented high removal efficiencies of $\text{NH}_4^+\text{-N}$, TN and TP but poor removal efficiency for NO_3^- ^[3,12-14]. The addition of organic carbon and the inoculation of denitrification bacteria to the anaerobic layer were proposed to enhance the denitrification in the infiltration systems^[15-19]. In addition, majority of the researches was carried out using the column experiments in lab^[20-21], while the removal efficiencies of pollutants in a lab-scale infiltration system have seldom been reported so far.

Riparian zone, which could remove nutrients from storm runoff, has been widely used to reduce agricultural non-point pollution^[22]. However, due to urban construction, terrain and vegetation in urban riparian zone have been changed. Most commonly, the width of riparian zone narrows and its environmental function weakens. Therefore, it was important and urgent to reconstruct the riparian zone to enhance its environmental functions. Compared with the engineering technologies such as constructed wetlands, grassed swale and bioretention ponds, the vegetation buffer zone and multi-layered infiltration system were more applicable to the narrow urban riparian zone^[1]. In this study, a lab-scale riparian infiltration system (RIS) was constructed with the green vegetation and the combination of soil and other materials. To promote the denitrification at the bottom of the RIS, sawdust mixed with soil as a separate layer was added to supply organic carbon. The removal efficiencies of N and P in RIS and N transformation were investigated in upper layer with high permeability and in less permeable soil during 6 repetitive experiments. The aim of this study was to test if the lab-scale multi-media layered RIS could promote the transformation and purification of nutrients and evaluate the removal efficiencies for the future application of the RIS in the riparian zone.

1 Materials and methods

1.1 Construction of riparian infiltration system (RIS)

The RIS was constructed in an experiment station located in the riparian zone of Hengdu River, Wenzhou City of China. Summer in Wenzhou City is characterized by hot and humid weather with high rainfall due to the monsoon. The annual average precipitation of the Wenzhou City was 1706 mm, and 70% of the rainfall concentrates between June and August with an average rainfall of 9.5 mm. The RIS was an uncovered cuboid of 300 cm (length) \times 120 cm (width) \times 120 cm (height), which were placed on the concrete bases with eight bottom leachate samplers (Fig. 1). The frame of RIS was built with Plexiglas plates, while the floor of the system was constructed with 2 cm thick polyvinyl chloride plates. There were 8 rows of holes ($\phi = 2$ mm) which allowed the vertical flow infiltrating in the RIS to outflow through them and to be collected by bottom leachate samplers. The concrete bases were 20 cm wide and 30 cm high which were placed at an interval of 20 cm. Additionally, there was also a set of water supply devices including a submersible pump, a flowmeter, a ball valve, water pipes and a water dis-

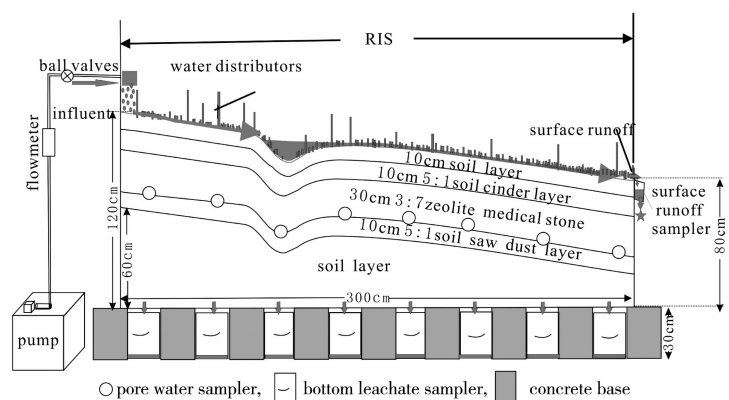


Fig 1 Composition, scale, and structure of the RIS

tributor at one side of the system and a surface water sampler at the other side (Fig. 1).

According to the results of Zhou et al.^[23], the combination of 3:7 volume ratio of zeolite (ϕ 0.5-1.0 mm) and medical stone (ϕ 0.25-0.5 mm) had the best removal efficiencies for nitrogen and phosphorus compared to those of 5:5 or 7:3. Soil, which was mixed with cinder or sawdust, would have higher infiltration rate and adsorption capacity for nitrogen and phosphorus. Moreover, sawdust could supply electron and carbon source to promote nitrogen transformation^[9]. The combination of soil with sawdust or cinder as the volume ratio of 5:1 showed high removal efficiency for pollutants in the urban runoff of Shanghai^[24]. Therefore, soil, cinder, sawdust, zeolite and medical stone were chosen to be the media of RIS. In addition, Ma et al.^[25] found that plant uptake in subsurface wastewater infiltration systems plays an important role in removing nitrogen from sewage, and Chung et al.^[22] found that the pollutant removal efficiency of riparian buffer strips also depended on plant species. Therefore, considering the local climate and the common types of plants used for the city greening, two plant species Manila grass (*Zoysia matrella*) and *Buxus sinica* (Rehd. et Wils.) Cheng were chosen to be planted in RIS.

The slope of the RIS was set at 5°, and a vegetated pool was designed about 100 cm away from the water distributor to promote the infiltration and increase the residence time of surface runoff. The zeolite and medical stones were bought from the Mingyang water purification packing factory, Henan Province, China. Zeolite and medical stones were rinsed with water repeatedly to remove the dissolved nutrients as much as possible. Size fraction and concentration of nitrogen and phosphorus in cinder, zeolite, medical stone and soil were described by Deng et al.^[1]. In order to avoid the holes on the floor being blocked by the soil, 2 cm thick medical stones and 60 mesh screens were laid on the bottom, and then the RIS mesocosm was filled with media in the sequence of soil layer, soil and sawdust ($V:V=5:1$) layer, zeolite and medical stone ($V:V=3:7$) layer, soil and cinder layer ($V:V=5:1$) and soil layer (Fig. 1). Eight pore water samplers were distributed at the surface of the soil and sawdust layer to collect the leachate coming from the zeolite and medical stone layer. Each layer was homogeneously spread and evenly compacted before the next layer was added. After the RIS was finished, according to the greening density of the riparian zone the surface soil of the RIS was planted with Manila grass (*Zoysia matrella*), while the *Buxus sinica* (Rehd. et Wils.) Cheng was planted near the water distributor but not beyond the vegetated pool as the *Buxus sinica* (Rehd. et Wils.) Cheng is only planted on the upper part of the riparian zone.

1.2 Sampling and Analysis

As showed in Table 1, the concentrations of N and P in the water of Hengdu River were similar to those of urban rainfall runoff in Wenzhou City^[26,27], therefore the river water was used directly to simulate the rainfall runoff. Six repetitive experiments were conducted in two periods, from July to September of 2011 (rounds 1-4) and from May to June of 2012 (rounds 5 and 6) covering the main rainy seasons. During the experimental periods, the river water was pumped into a reservoir first and then delivered to the RIS once every ten days using a set of water supply devices (Fig. 1) at a rate of $700 \text{ L} \cdot \text{h}^{-1}$ for 4 h, which was equal to a 9.5 mm rainfall in 4 h on 300 m^2 area, and the samples were collected and measured once every twenty days. In each experiment, the samples of influent were collected at each hour, while the surface runoff and bottom leachate samples were collected for the first time once there was water flowing into samplers, and then at an interval of 0.5 h. The pore water samplers were opened for sampling until there was no water leaching out from the bottom of RIS. The volume of horizontal flow was measured. During each experiment, approximately 51 samples were collected in 150 mL polyethylene bottles and then refrigerated for NH_4^+ , NO_3^- , TN and TP analysis. Identical experiments in each period were performed with an interval of 20 days to allow draining and drying, and there was periodical water distribution but no sampling between the two periods in case the RIS tank was too dry to cause the death of microbes.

All the samples were analyzed within 3 days after being collected. The concentrations of NH_4^+ , NO_3^- , TN and TP in water samples were analyzed by using the Nessler's reagent spectrophotometry, the ultravi-

olet spectrophotometry, the alkaline potassium persulfate digestion-UV spectrophotometric method and the ammonium molybdate method after the potassium persulfate digestion, respectively.

1.3 Statistical procedures

Based on the measured concentrations in influent and effluent, the removal efficiencies and removal quantity for NH_4^+ , NO_3^- , TN and TP in each repetitive experiment by RIS were calculated using the following equation (1) and (2):

$$R = \frac{\bar{C}_0 - \bar{C}_i}{\bar{C}_0} \times 100\%, \quad (1)$$

$$RQ = (\bar{C}_0 - \bar{C}_h)Q_h + (\bar{C}_0 - \bar{C}_v)Q_v, \quad (2)$$

$$\bar{C}_i = (\bar{C}_h Q_h + \bar{C}_v Q_v) / (Q_h + Q_v), \quad (3)$$

Where, R is the removal efficiency (%); RQ is the removal quantity in each repetitive experiment (mg); \bar{C}_0 is the average influent concentration (mg/L); \bar{C}_i is the effluent concentration (mg/L); \bar{C}_h is the mean concentration in surface runoff (mg/L); \bar{C}_v is the mean concentration in bottom leachate (mg/L); Q_h is the volume of horizontal flow (L); Q_v is the volume of vertical flow (L), which equals the total influent volume subtracts Q_h .

In order to determine whether the removal efficiencies of RIS for surface water and bottom leachate were statistically different, T-test analysis and one-way ANOVA at a significance level of 0.05 was applied, and correlations between removal quantities and concentrations of N and P in influent were also conducted with SPSS 18.0.

2 Results and discussion

2.1 Concentrations of N and P in influent and effluent

As shown in Table 1, The NH_4^+ , TN and TP concentrations in the simulated rainfall runoff (influent), i.e. the water of Hengdu River were all higher than the type V standard values of the GB 3838-2002 National Environmental Quality Standards for Surface Water. The effluent from RIS, both the surface runoff and bottom leachate had significantly lower concentrations of NH_4^+ and TP than the influent ($P < 0.05$), which was either approaching or lower than their corresponding type V standard values. Furthermore, the concentrations of NH_4^+ and TP in the bottom leachate were significantly lower than those in the surface flow ($P < 0.05$). However, it was just on the opposite for NO_3^- . Concentrations of TN in effluent were also higher than its standard value. The concentrations of NH_4^+ , TN and TP in effluent were lower than those in influent, but it was on the opposite for NO_3^- . NH_4^+ accounted for the most part of TN in the influent, but it was NO_3^- as the major component of TN both in surface runoff and bottom leachate.

Table 1 Concentrations of N and P in influent, effluent and urban runoff of Wenzhou City/mg · L⁻¹

	Urban rainfall runoff of Wenzhou City ¹	Influent ²	effluent		Type V standard values ³
			Surface runoff	Bottom leachate	
NH_4^+ -N	0.32-5.55	5.97 ± 1.74 a	2.42 ± 1.02 b	0.54 ± 0.35 c	2.0
NO_3^- -N	0.01-4.70	0.57 ± 0.27 a	3.20 ± 1.88 b	6.47 ± 4.06 c	/
TN	/	8.00 ± 1.99 a	6.02 ± 2.58 b	7.73 ± 3.11 ac	2.0
TP	0.02-2.24	0.68 ± 0.29 a	0.34 ± 0.12 b	0.02 ± 0.02 c	0.4

TN: total nitrogen; TP: total phosphorus. The different small letters in the same line indicate the significant difference ($P < 0.05$), and the same small letters indicate no significant difference ($P > 0.05$); 1: Results according to Qi et al^[26] and Zhou et al^[27]; 2: The influent is the water of Hengdu River in Wenzhou City; 3: The type V standard values are requirements for the agriculture water and common landscape water body in GB3838-2002.

2.2 The removal efficiency of N and P in surface runoff and bottom leachate

Infiltration rates were controlled by the original media and subsequent captured suspended solids on the media surface^[3]. In this study, the media filled in the RIS including cinder, zeolite and medical stone had

high infiltration rates, and the concentrations of suspended solids in the influent were relatively low with a range of $10.6 \text{ mg} \cdot \text{L}^{-1}$ – $25.8 \text{ mg} \cdot \text{L}^{-1}$. Therefore, the infiltration rate in each 4-hour experiment was supposed to be constant, which was also verified by the steady flow rate of the bottom leachate.

The overall NH_4^+ , NO_3^- , TN and TP removals in the RIS were summarized from Fig. 2 to Fig. 5. The left data (a) in each figure showed the mean removal efficiency in each 4-hour experiment, and the right (b) showed the mean removal efficiency, taken at half an hour intervals over the six repetitive experiments. Error bars indicated one standard deviation.

As shown in Fig. 2(a), the removal efficiencies for NH_4^+ in bottom leachate were higher than that in surface runoff in each experiment. The average NH_4^+ removal efficiency of RIS was $89.6 \pm 7.7\%$ for bottom leachate and $58.6 \pm 12.3\%$ for surface runoff. The standard deviations of NH_4^+ removal efficiencies for surface runoff with a range of 5.3% – 13.6% were obviously greater than those for bottom leachate (0.7% – 3.3%). The NH_4^+ removal efficiencies for bottom leachate rose from about 76% to 90% with the increase of the repetitive times of the experiments, while the NH_4^+ removal efficiencies for surface runoff dropped from approximately 60% to 55% . Fig. 2b shows the average NH_4^+ removals efficiencies on a half-hour basis during the six repetitive experiments. Similar to Fig. 2(a), the NH_4^+ removal efficiency for surface water was lower than that for bottom leachate throughout the 4-hour experiments, and it gradually decreased from 80.4% initially to 49.8% in the end of the experiment. However, a steady and high efficient treatment rate ($85.3 \pm 9.3\%$) was demonstrated for NH_4^+ in bottom leachate.

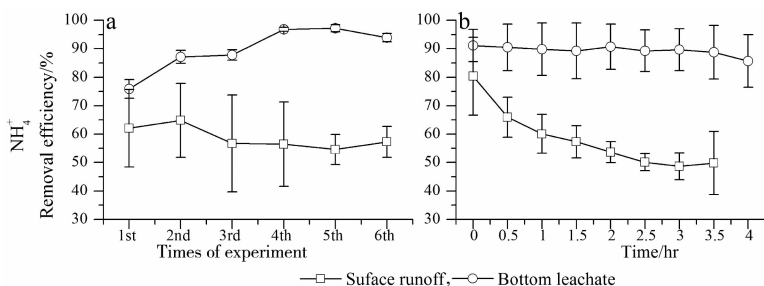


Fig 2 NH_4^+ removal efficiency and its change with time in the six repetitive experiments

Higher NH_4^+ removal efficiencies for bottom leachate than for surface runoff in the RIS may be related to the ammonia adsorption, i. e. be absorbed through a cation exchange reaction with the substrate^[28]. Soil, zeolite, medical stone, sawdust and cinders all had great cation exchange capacity to promote NH_4^+ adsorption. As the vertical runoff infiltrated through the RIS and the horizontal runoff only infiltrated in upper media, the hydraulic retention time was longer for the vertical runoff than for the horizontal runoff. Therefore the NH_4^+ in the vertical flow was prone to be absorbed compared to the horizontal runoff. With the inflow time increasing and the adsorptive sites on the media decreasing, NH_4^+ removal efficiencies for surface runoff decreased Fig. 2(b).

As showed in Fig. 3, the RIS overall demonstrated an output of NO_3^- both in surface runoff and bottom leachate with the negative removal efficiencies ranging from -85.1% to -8199.7% . The mean NO_3^- removal efficiency for surface runoff is -894.3% , higher than that (-2039.8%) for bottom leachate, indicating greater output of NO_3^- in vertical flow than in horizontal flow. The NO_3^- removal efficiencies remained relatively stable in the first five experiments, and the average removal efficiency was -488.4% – -99.2% for surface runoff and -1427.9% – -364.3% for bottom leachate but it dropped significantly to -3804.2% and -8199.7% in the sixth experiment respectively. Examining the NO_3^- removal efficiencies based on the half-hour sampling (Fig. 3(b)), a stable continuous output of NO_3^- was observed for bottom leachate, and a gradual decreasing output of NO_3^- for surface runoff. In contrast to NH_4^+ removal efficiencies in Fig. 2(b), the variations of NO_3^- removal efficiency for surface runoff were smaller than those for bottom leachate. In the RIS, on the one hand, most of NH_4^+ absorbed on the media might be oxidized into NO_2^- by ammonia-oxidizing bacteria and then into NO_3^- by nitrite-oxidizing bacteria^[29], especially during the periodic draining

between the repetitive experiments^[3,28,30], and on the other hand, soils and other materials including the cinder, zeolite and medical stone used to fill the RIS mesocosm still contained a certain amount of nitrate^[1], which could dissolved in the flow. Moreover, NO_3^- , as an anion was not easily adsorbed by the substrate^[30]. Therefore higher NO_3^- concentrations were observed in the effluent than in the influent, resulting in a significant output of NO_3^- through the RIS.

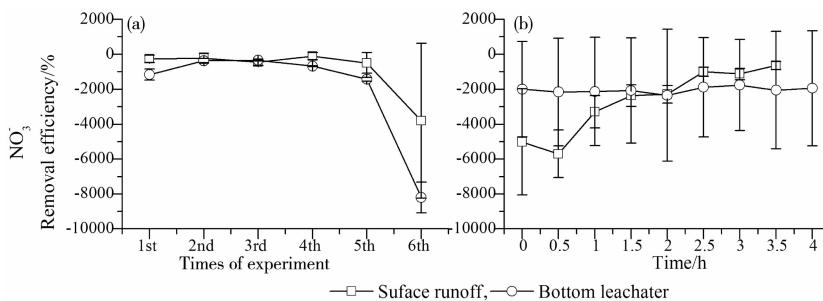
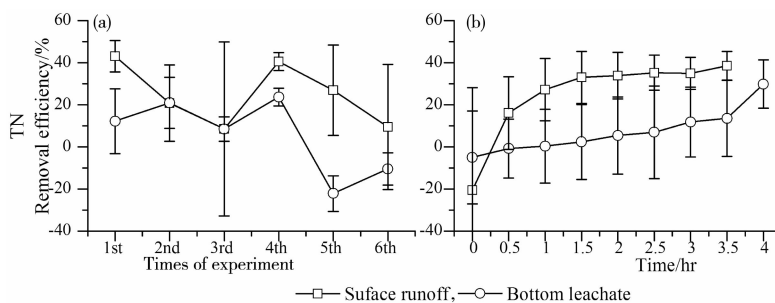


Fig 3 NO_3^- removal efficiency and its change with time in the six repetitive experiments

Influenced by the output of NO_3^- , TN removal efficiencies were not very high and even negative as illustrated in Fig. 4a. The gross removal efficiency of the RIS was $21.1 \pm 13.7\%$. Yang et al^[12] also found low removal efficiency of TN ($4.9\% - 16.8\%$) in a subsurface infiltration system. The removal efficiency for TN in horizontal flow ($24.5 \pm 26.6\%$) was higher than that ($6.3 \pm 18.9\%$) in vertical flow, both of which showed great variability during the experiments. In general, the mean removal efficiencies for TN were positive indicating removal of nitrogen except those in the 5th and 6th experiments. As illustrated in Fig. 4(b), there were output of TN both in surface runoff and bottom leachate at 0 hr due to the negative removal efficiencies, which were $-20.5 \pm 48.7\%$ and $-5.0 \pm 22.1\%$ respectively, which might be related with the dissolution of nitrate in horizontal flow and the reduction of nitrate by denitrification in the bottom media^[28,31]. And then the removal efficiencies for TN in bottom leachate increased gradually to 29.8% , while the removal efficiency for TN in surface runoff rose significantly to 16.2% at 0.5 hr and then increased gradually to 38.5% at the end of the experiments.



The error bars represent the standard deviations.

Fig 4 TN removal efficiency and its change with time in the six repetitive experiments

As illustrated in Fig. 5(a), higher removal efficiencies for TP in bottom leachate ($97.2 \pm 2.8\%$) were observed than in surface runoff ($42.6 \pm 29.9\%$) in the repetitive experiments. And the variations of TP removal efficiencies for bottom leachate with a range of $1.0\% - 4.4\%$ were smaller than those ($3.4\% - 47.4\%$) for surface runoff. Compared with the stable removal efficiencies for TP in vertical flow, the average treatment rates of the RIS for TP in surface runoff decreased from 79.1% in the first experiment to 5.1% in the 3rd experiment, and then increased to 45.1% and remained relatively stable till the 6th experiment. Considering the removal efficiencies in the 4-hour experiments, which were shown in Fig. 5(b), the removal efficiencies for TP in vertical flow with the average ranging from 94.9% to 98.3% were significantly higher than those ($34.8\% - 55.3\%$) in horizontal flow. Greater variations of removal efficiencies were observed for the surface runoff which was from 24.1% to 45.7% than for the bottom leachate ($1.2\% - 5.8\%$). The average removal efficiencies for surface runoff initially decreased from 55.3% at 0 h to 44.8% at 0.5 h, and

then they remained relatively stable till the end of the experiment (3.5 h). The substrate of the RIS, including the soil, zeolite, sawdust and slags all had high phosphorus adsorption capacity^[11], and phosphorus in the simulated rainfall runoff was absorbed onto the solid phase of the substrate at first, and then it might undergo biological transformations into organic forms, which might enhance the immobilization of phosphorus^[9]. Therefore, high removal efficiencies for TP were demonstrated in the RIS.

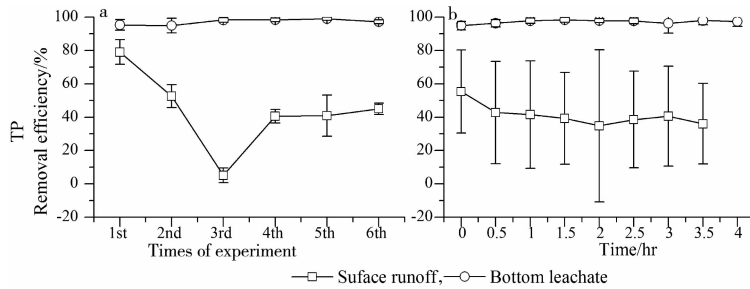


Fig 5 TP removal efficiency and its change with time in the six repetitive experiments

2.3 Removal amount of N and P and its relationship with the concentrations of influent

The average amount of input and output of N and P in the six repetitive experiments were calculated using the formula adopted by Hsieh et al.^[3], and then the net removal amount as well as the removal efficiencies of the RIS could be acquired. The results were presented in Table 2. In general, the RIS demonstrated significant net removal of NH_4^+ -N and TP but a net increase of NO_3^- -N, which might come from the oxidation of NH_4^+ and the leachate of the substrate. This led to the low removal efficiencies for mineral nitrogen (8.99%) and TN (21.1%). These results supported the hypothesis that there should be nitrification in the RIS, as the high removal efficiency of NH_4^+ both in the surface runoff and bottom leachate (Fig. 2).

Table 2 Removal amount of N and P by RIS and its Pearson correlations with the concentrations of influent in the six repetitive experiments

Parameter	NH_4^+	NO_3^-	$\text{NH}_4^+ + \text{NO}_3^-$	TN	TP
Input from influent (g N/P)	16.7 ± 4.88 A	1.60 ± 0.74 A	18.3 ± 4.38 A	22.4 ± 5.68 A	1.97 ± 0.77 A
Out from effluent (g N/P)	5.73 ± 1.57 B	11.01 ± 5.97 B	16.74 ± 6.92 A	17.76 ± 6.16 B	0.78 ± 0.25 B
Removal amount (g N/P)	10.99 ± 3.38	-9.41 ± 6.23	1.58 ± 5.02	4.63 ± 3.03	1.19 ± 0.74
Removal efficiency (%)	65.6	-1150.0	8.99	21.1	54.9
Correlation coefficients ¹	0.993 ^a	0.405	-0.08	0.100	0.947 ^a

The different capital letters in the same column indicate the significant difference ($P < 0.05$), and the same capital letters indicate no significant difference ($P > 0.05$). ¹The correlation coefficients between the removal amount and the concentrations of N and P in influent. a: $P < 0.01$.

There were generally positive relationships between the nutrient concentrations in inflow and the removal efficiencies for N and P found in the free-water surface wetland system and multilayer infiltration system^[32,33]. In this study, there were significantly positive correlations between the concentrations in influent and the removal amount for NH_4^+ and TP, but no significant correlations for NO_3^- and TN (Table 2). It was probably because NH_4^+ and TP were mainly removed by adsorption, while NO_3^- as an anion was not adsorbed by the substrates and most of TN in effluent was NO_3^- , which was produced by nitrification in RIS.

2.4 Nitrification and denitrification in RIS

The nitrification in the RIS had been verified by the higher NO_3^- concentrations in the outflow than the inflow, which results in the negative removal efficiencies as discussed in 2.2. However, as showed in Table 2, there was a positive removal efficiency for mineral nitrogen ($\text{NH}_4^+ + \text{NO}_3^-$). NO_3^- can be removed by denitrification or absorbed by plants. In the RIS, the absorbance of NO_3^- by the plants in the surface layer was limited and could be negligible in the 4-hr experiment, therefore, denitrification was the only way to remove the nitrogen. According to Hsieh et al.^[3], overall denitrification occurred at the bottom soil layer in layered bioretention columns. The study of Kong et al.^[31] found that the aerobic respiration and nitrification mainly took place in the upper aerobic stage and autotrophic denitrification occurred in the bottom anaerobic stage in a soil infiltration system incorporated with sulfur-utilizing autotrophic denitrification. So in

the RIS, the nitrification and denitrification process was probably separated at the interface of the layer of zeolite and medical stones and the layer of soil and sawdust. The leachate at the interface was sampled using the pore water samplers (Fig. 1) and analyzed with the same methods as those of the inflow and outflow. The NO_3^- concentrations ($9.64 \pm 6.38 \text{ mg} \cdot \text{L}^{-1}$) in the influent seepage from the upper layer were much higher than those in influent and effluent (Table 1). Through mass-balance analysis^[20], the amount of NO_3^- which was produced by nitrification and removed by denitrification was calculated. The amount of NO_3^- produced by nitrification was $5.90 \pm 4.30 \text{ g N}$ for surface runoff and $5.28 \pm 3.67 \text{ g N}$ for bottom leachate respectively. Although the NO_3^- concentrations in the bottom leachate were much higher than those in surface runoff (Table 1), the amount of NO_3^- produced by nitrification in the bottom leachate were lower than that in surface runoff because the volume of bottom leachate only accounted for about 20% of the total volume of the outflow in the repetitive experiments. The total amount of NO_3^- produced by nitrification was $11.18 \pm 7.46 \text{ g N}$, which was about 6.3 times of that removed by denitrification ($1.77 \pm 1.66 \text{ g N}$).

Other studies also demonstrated poor removal efficiencies of NO_3^- and TN for both in bioretention and infiltration systems due to the lack of anoxic conditions to promote denitrification^[3,12-14]. However, when different mixture of media was adopted in the systems, the removal rates for NO_3^- increased and could even reach to 49%^[3,34]. In this study, the RIS had the least permeable soil layer at the surface and the bottom, and between the two soil layers, there were mixture of media with higher permeability. Moreover, the sawdust in the soil and sawdust (V:V=5:1) layer was to supply electron and carbon source to promote the denitrification. The draining during the intervals of experiments improved the removal capacity of the RIS and the water distribution promoted the formation of reduction conditions which was favor of denitrification. However, being affected by the strong nitrification, the RIS only demonstrated an overall very low reduction (8.99%) of mineral nitrogen ($\text{NH}_4^+ + \text{NO}_3^-$).

In order to promote the denitrification and improve the removal efficiency of NO_3^- -N, there are two ways proposed. One is to add organic carbon such as peat or biochar to the anaerobic part of the infiltration system to promote denitrification^[15-17]. The other is to implement bioaugmentation of anaerobic denitrification bacteria to enhance nitrogen removal in the infiltration systems. Kong et al.^[19] found that the removal efficiency of NO_3^- -N has reached 95% when anoxic part of the soil infiltration system was inoculated with sulfur autotrophic denitrifying bacteria. Liu et al.^[18] added seven psychrophilic strains (heterotrophic nitrifying bacteria and aerobic denitrifying bacteria) to the subsurface wastewater infiltration systems (SWISs) with different bioaugmentation strategies and the SWISs with the embedding strategy exhibited satisfactory NO_3^- -N and TN removal efficiencies. Therefore, in the future, the RIS should be further improved from the selection of organic carbon source and the implementation of bioargmentation.

3 Conclusions

The RIS demonstrated removal of NH_4^+ , TN and TP but output of NO_3^- . The average removal efficiencies of nutrients decreased in the order of NH_4^+ (65.6%) > TP (54.9%) > TN (21.1%) > NO_3^- (-1150.0%). The RIS generally had higher and more stable removal efficiencies of NH_4^+ and TP in vertical flow than for horizontal flow due to the adsorption of substrate. The output of NO_3^- might come from the oxidation of NH_4^+ and dissolution of nitrate in substrate. The average removal amount of RIS during the six repetitive 4-h experiments was 10.99 g for NH_4^+ , 4.63 g for TN and 1.19 g for TP respectively, and the output for NO_3^- was 9.41 g. There were significant positive relations between the concentrations in influent and the removal amount for NH_4^+ and TP, but not for NO_3^- and TN. The NO_3^- concentrations in leachate from upper permeable layers were much higher than the influent and effluent due to the nitrification and dissolution of nitrate in substrate. Denitrification occurred under the less permeable soil layers. According

to the mass balance, the removal amount of NO_3^- by denitrification was 1.77 ± 1.66 g N, which was far lower than the amount (11.18 ± 7.46 g N) produced by nitrification. The removal efficiencies of nutrients and denitrification in the RIS based on the lab-scale experiments generally seemed not as strong as those in the other infiltration systems based on the results of column experiments, indicating that the scale of the experiment might have an influence on the results. Further study and improvement is needed to enhance the denitrification of RIS to reduce the output of nitrate.

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河岸渗滤系统对城市降雨径流中氮磷去除效率的中试研究

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摘要 为加强城市河岸带对降雨径流中氮磷的去除能力,为城市河岸带的改造提供科学依据,采用土壤、煤渣、沸石、锯末、沸石和麦饭石构建了一个中试规模的河岸渗滤系统(riparian infiltration system, RIS),并通过6次试验研究了RIS对模拟城市降雨径流中氮磷的去除效率。结果表明,RIS能去除径流中的氨态氮(NH_4^+)、总氮(TN)和总磷(TP),但会输出硝态氮(NO_3^-)。该系统对 NH_4^+ 和TP的去除效率分别为 $65.6 \pm 1.2\%$ 和 $54.9 \pm 19.1\%$,显著高于对TN的去除效率($21.1 \pm 13.7\%$);而 NO_3^- 的平均去除效率为 -1150.0% ,这可能是由于系统中 NH_4^+ 的氧化及 NO_3^- 在介质中的浸出。RIS对垂向流中 NH_4^+ 和TP的去除效率较水平流更高且更稳定;且系统对 NH_4^+ 和TP的去除量与其入水浓度均具有显著的正相关关系($P < 0.01$)。反硝化作用发生在渗透性较差的底部土壤层中,但其对 NO_3^- 的去除量远低于渗透性较好的上层土壤介质层中硝化作用产生的量。RIS总体上对降雨径流中营养物质具有一定的去除作用,但还需要进一步的研究和改进,以加强RIS的反硝化作用从而减少硝酸盐的输出。

关键词 中试;氮;磷;去除效率;河岸渗滤系统;城市降雨径流