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How does the loading rate affect the performance of an overland flow system in treating domestic sewage?

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ABSTRACT

Considering the low efficiency of traditional overland flow system denitrification, a 25-cm thick artificial substrate was used instead of clay to fill the surface. In this way, the wastewater can flow through the artificial substrate rather than moving by sheet flow over the surface in expectation to improve the pollutant removal efficiency. In order to evaluate the impact of loading rates, four plots (7.5 m × 10 m for each one) were constructed with a slope of 6%. The hydraulic loading rates (HLRs) of the four plots were 0.007, 0.01, 0.03, and 0.05 $m^3/m^2\cdot d$, respectively. In the second experimental phase, the pollutant loading rates (PLRs) of the four plots were 0.05, 0.15, 0.45, and 0.75 g biological oxygen demand (BOD)/$m^2\cdot d$, respectively. The results indicated that the artificial substrate configuration improved the removal efficiency of pollutants and the ability to resist load shock. Both HLR and PLR were negatively correlated with the removal rate of contaminants. The optimal HLR and PLR were suggested as ranges of 0.01–0.03 $m^3/m^2\cdot d$ and 0.15–0.45 g BOD/ $m^2\cdot d$, respectively. Under the optimal operation conditions, removal rates were 81.5% ± 1.6% for chemical oxygen demand, 82.9% ± 2.7% for NH_4^+–N, 60.1% ± 2.0% for total nitrogen, and 88.8% ± 1.1% for total phosphorus. Nitrifier quantity was reduced by an order of magnitude with an increase in depth from 25 cm to 40, 55, and 70 cm. The activity of nitrate reductase decreased with increasing depth, consistent with the trend of nitrifiers.

Keywords: Overland flow system; Artificial substrate; Loading rate; Removal rate

1. Introduction

Both centralized and on-site treatments have similar efficiency regarding the removal of major contaminants. However, in order to achieve the same quality of treated effluent, the centralized treatment method requires a more complex system compared with a decentralized one, leading to an increased emission of greenhouse gases and higher energy consumption [1]. In this context, land treatments are interesting alternatives for developing countries, especially for isolated rural and urban zones. Thus, land treatments could be employed to treat the wastewater nearby its generation, where traditional treatments cannot be used for a variety of reasons, such as financial unavailability or lack of space [2].

For years, constructed wetlands (CWs) are used as alternatives to centralized treatments. Although horizontal flow CWs tend to have good nitrate (NO_3^-–N) removal, as they provide good conditions for denitrification, they cannot remove ammonium (NH_4^+–N) due to limited ability to nitrify it [3]. Instead, vertical CWs have good NH_4^+–N removal, but their denitrification ability is limited. So, in general, various types of CWs are combined in order to achieve higher nitrogen removal efficiency. But complicated construction accompanied by high operation cost should not be overlooked and to some extent limit the application of CWs [4].

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Overland flow systems (OFSs) are engineered lands that have been designed and constructed to utilize natural processes in treating wastewater. In general, they are used in areas having low soil permeability and a topography that can be shaped to produce a uniform flow distribution. Benefits of OFSs are the results of natural processes occurring simultaneously in a single "ecological reactor", providing physical, chemical, and biological treatment of wastewater as it passes over the soil surface [5–7]. Rhizosphere microbes along with soil interaction significantly reduce pollutant concentrations, especially dissolved ones (in order to minimize the risk of clogging, most suspended solids (SSs) are removed in pretreatments, such as flocculation–sedimentation). Furthermore, they need less energy consumption and maintenance as the influent flows under gravity.

However, OFSs are typically designed as surface flow, which is, wastewater moves by sheet flow over the sloped surface rather than infiltrates through the substrate. The removal of pollutants mainly depends on the role of plant rhizosphere microorganisms. As a result, removal rates are limited owing to the minimum soil–water interactions, especially nitrogen. On the other hand, OFSs have always been seen as a "passive" process. Most of the reports focused on the grass type, wastewater type, slope grade, soil constitution, and permeability. Little interest has expressed on its load control. But actually, OFSs are more "positive" elements in both Sponge City construction and decentralized wastewater treatment. To achieve a balance between treatment efficiency and effectiveness, wastewater needs to be introduced into OFSs under the optimal hydraulic and pollutant controls. Given that most of the pollutants are aerobically degraded, their removals can be optimized by balancing the influent load and oxygen transmission. If the influent load exceeds the oxygen transmission rate, the oxidation of the pollutants is limited. And in this case, the sewage flows over the surface in thin layer rather than into the substrate layer, causing environmental degradation, such as odor and bacteria. This balance can be shifted in favor of pollutant removal by decreasing loading rate [8]. But if influent loading is too low, the treatment efficiency and processing scale will be limited.

Therefore, the objectives of the study were (1) to investigate the performance of pilot-scale OFSs with 25-cm effective layer filled with artificial substrate, (2) to suggest optimal ranges of hydraulic loading rate (HLR) and pollutant loading rate (PLR) considering pollutant removal and treatment efficiency, and (3) to explore bacteria distribution and enzyme activity under optimal operating conditions.

2. Materials and methods

2.1. Site description

The site for the pilot study covered 300 m^2 (four sub-sections, 7.5 m × 10 m for each one, dip 6%) with total depth of 0.7 cm. The matrix distribution from top to bottom was artificial substrate (0–25 cm) and clay (25–70 cm) (Fig. 1). The site bottom was laid with 5-mm thick plastic to avoid the wide infiltration of treated wastewater. Collecting tunnel with plastic pipes was equipped at the end of the slope to collect the effluent from each plot.

2.2. Wastewater and materials

Influent was the primary treatment effluent of a combined wastewater. Influent quality was as follows (mean value): dissolved oxygen 3.0 mg/L, pH 6.9, SSs 10 mg/L, biological oxygen demand (BOD$_5$) 15 mg/L, chemical oxygen demand (COD) 56 mg/L, ammonia nitrogen (NH$_4^+$–N) 22 mg/L, total nitrogen (TN) 30 mg/L, and total phosphorus (TP) 0.9 mg/L. Generally, the influent quality can hardly meet the required discharge standards in China, especially NH$_4^+$–N and TN (Landscape Standard of Surface Water

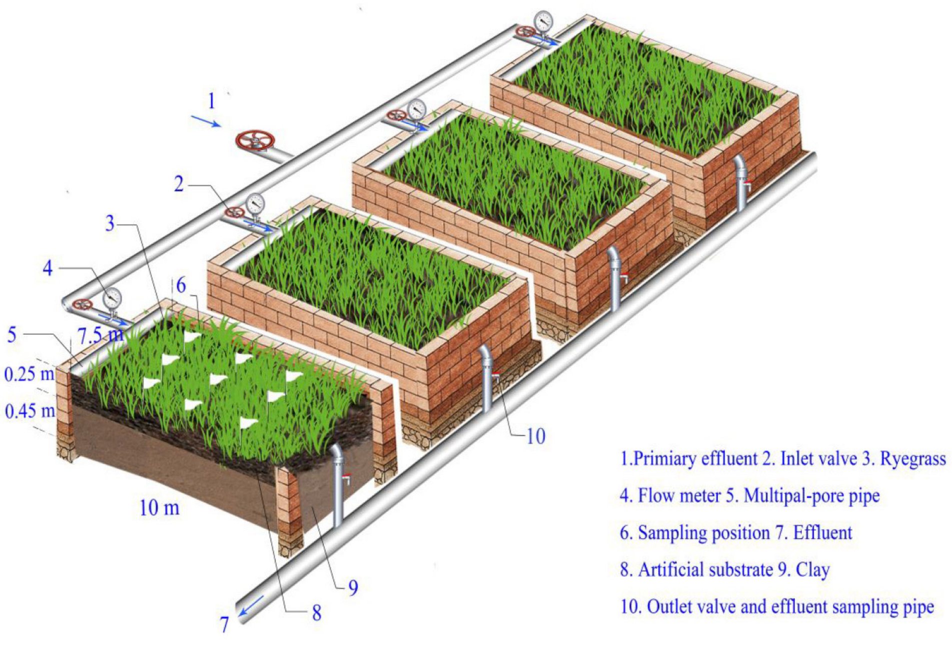

Fig. 1. Sketch showing of the overland flow system.

Quality, GB/T18921-2002, COD ≤ 50 mg/L, NH_4^+–N ≤ 5 mg/L, TN ≤ 15 mg/L, and TP ≤ 0.5 mg/L).

The artificial substrate consisted of activated sludge and meadow brown soil (volume ratio 1:9). The meadow brown soil was sampled from the top 20 cm of Shenyang Ecological Station. The activated sludge was obtained from the aeration tank of a municipal wastewater treatment plant in Shenyang, China, air dried for 6 h after being centrifuged for 15 min at 1,500 rpm. The substrate contained total organics 35.9 ± 1.2 g/kg, TN 1.8 ± 0.2 g/kg, TP 1.05 ± 0.3 g/kg, and porosity 55% ± 3%. The content of heavy metals in the substrate was lower than the Environmental Quality Standard for Soils of China (GB15618-2018). Gravel was purchased from a local market with average particle size 10–25 mm. Clay was sampled from Shenyang Ecological Station. The permeability, pH, and moisture content of the application clay were 0.04 ± 0.01 cm/h, 6.5 ± 0.6, and 8.2% ± 1.7%, respectively.

2.3. Experimental operation

Primary effluent was pumped from a sedimentation tank to OFS. The wastewater flowed through a horizontal pipe, 7.5 m length and 100 mm diameter with holes (4 mm in diameter) placed in the bottom every 60 mm. The application period was Monday through Thursday each week and 6 h a day. Three days were allocated for drying and soil re-oxygenation. According to the orthogonal test results (not shown here), the experiment was divided into two runs. For the first run (20 January–30 December, 2016), HLRs were 0.007 to 0.01, 0.03, and 0.05 $m^3/m^2{\cdot}d$ for the four plots, respectively, and for the second one (17 January–29 December, 2017), PLRs were 0.05 to 0.15, 0.45, and 0.75 g BOD/ $m^2{\cdot}d$ for the four plots, respectively. For these two experimental stages, the influent water quality was almost the same, as described in Section 2.2.

2.4. Sampling and statistical analysis methods

Water samples were taken twice a week. After applying wastewater for approximately 1 h, influent samples were taken and stored at 4°C and analyzed within 24 h. COD, NH_4^+–N, TN, and TP were analyzed in accordance with American Public Health Association [9].

Soil samples were taken from the depth of 10, 25, 40, 55, and 70 cm per plot twice a month. The number of nitrifiers (NN) and denitrifiers (ND) were counted using the most probable number (MPN) calculation. They were analyzed according to the following process: 1 mL of serial tenfold sterile distilled water dilutions of the soil samples were transferred to 96-cell microtiter plates containing respective medium, then incubated at 28°C for 7 d (for nitrifiers) and 15 d (for denitrifiers), respectively. Meanwhile, 10 g soil samples were oven-dried at 105°C for 12 h to produce a constant weight. Urease, nitrate reductase (NAR) and nitrite reductase (NIR) activities were analyzed according to the method suggested by Lu et al. [2] and Boano et al. [3].

All statistical analyses were carried out by using the computer software package Origin 8.0. With respect to the effluent water quality and pollutant removal rate under different influent loads, a parametric analysis of variance was used to determine any significant ($p < 0.05$) differences.

3. Results

3.1. Effects of HLR on pollutant removal

In the first experimental phase, four OFSs were running simultaneously with PLR fixing at 0.40 g BOD/$m^2{\cdot}d$. Treatment performance became gradually stable during the first 3 weeks for COD, NH_4^+–N, TN, and TP removals. Figs. 2 and 3(a) show the effect of HLR on effluent concentrations and linear correlation between HLR and pollutant removal rates.

For COD, HLR had negative effect on its removal. Mean effluent concentration increased from 33.5 ± 3.2 mg/L under HLR 0.007 $m^3/m^2{\cdot}d$ to 51.0 ± 2.8 mg/L under HLR 0.05 $m^3/m^2{\cdot}d$ ($p < 0.05$). High HLR impaired NH_4^+–N removal rate significantly, which decreased from 83.9% ± 2.3% to 55.3% ± 1.6% when HLR increased from 0.007 to 0.05 $m^3/m^2{\cdot}d$ ($p < 0.05$). When HLR was less than 0.03 $m^3/m^2{\cdot}d$, average TN removal rate higher than 60.7% was observed, suggesting that under low hydraulic conditions, ecological structure of the microbial system remained at dynamic balance [10]. However, TN removal rate decreased to 33.3% ± 4.0% with an increase in hydraulic load to 0.05 $m^3/m^2{\cdot}d$. The effluent concentration of TP in all treatments was lower than that of influent. The lowest effluent concentration of 0.3 ± 0.2 mg/L was observed when the HLR was 0.007 $m^3/m^2{\cdot}d$. Considering the removal rate of pollutants and treatment efficiency, it was recommended that HLR to be no higher than 0.03 $m^3/m^2{\cdot}d$.

3.2. Effects of PLR on pollutant removal

In the second experimental phase, the fixed HLR was 0.03 $m^3/m^2{\cdot}d$. A negative correlation between PLR and pollutant removal rate was found (Figs. 3(b) and 4). Especially when PLR was improved from 0.45 to 0.75 g BOD/$m^2{\cdot}d$, COD removal rate decreased from 81.5% ± 1.6% to 60.3% ± 4.4%, NH_4^+–N removal rate decreased from 82.9% ± 2.7% to 51.2% ± 2.1%, TN removal rate decreased from 60.1% ± 2.0% to 50.7% ± 2.9%, and TP removal rate decreased from 88.8% ± 1.1% to 52.5% ± 4.2% ($p < 0.05$). When PLR varied between 0.15 and 0.45 g BOD/$m^2{\cdot}d$, effluent quality met the standard. In order to achieve high-quality effluent and reduce land usage, the recommended PLR was 0.45 g BOD/ $m^2{\cdot}d$. Under this condition, pollutant removal rates were 81.5% ± 1.6% for COD, 82.9% ± 2.7% for NH_4^+–N, 60.1% ± 2.0% for TN, and 88.8% ± 1.1% for TP.

3.3. Microbial distribution involving in nitrogen removal process

Under the recommended operation conditions (HLR 0.03 $m^3/m^2{\cdot}d$ and PLR 0.45 g BOD/$m^2{\cdot}d$), the performance of OFSs came to stable within 2 weeks. Soil samples at different depths were sampled for evaluating NN, ND, and enzyme activity of urease, NAR, and NIR. The results are presented in Table 1.

Because most nitrifiers are aerobic bacteria, reports show that in wastewater soil treatment systems (e.g., CWs), NN decreased with an increase in depth [11,12]. In this study, from 25 cm to 40, 55, and 70 cm, there was a significant decrease in NN (one order of magnitude, $p < 0.05$), indicating that the low permeability of clay limited the downward transmission of oxygen. In comparison, ND increased with

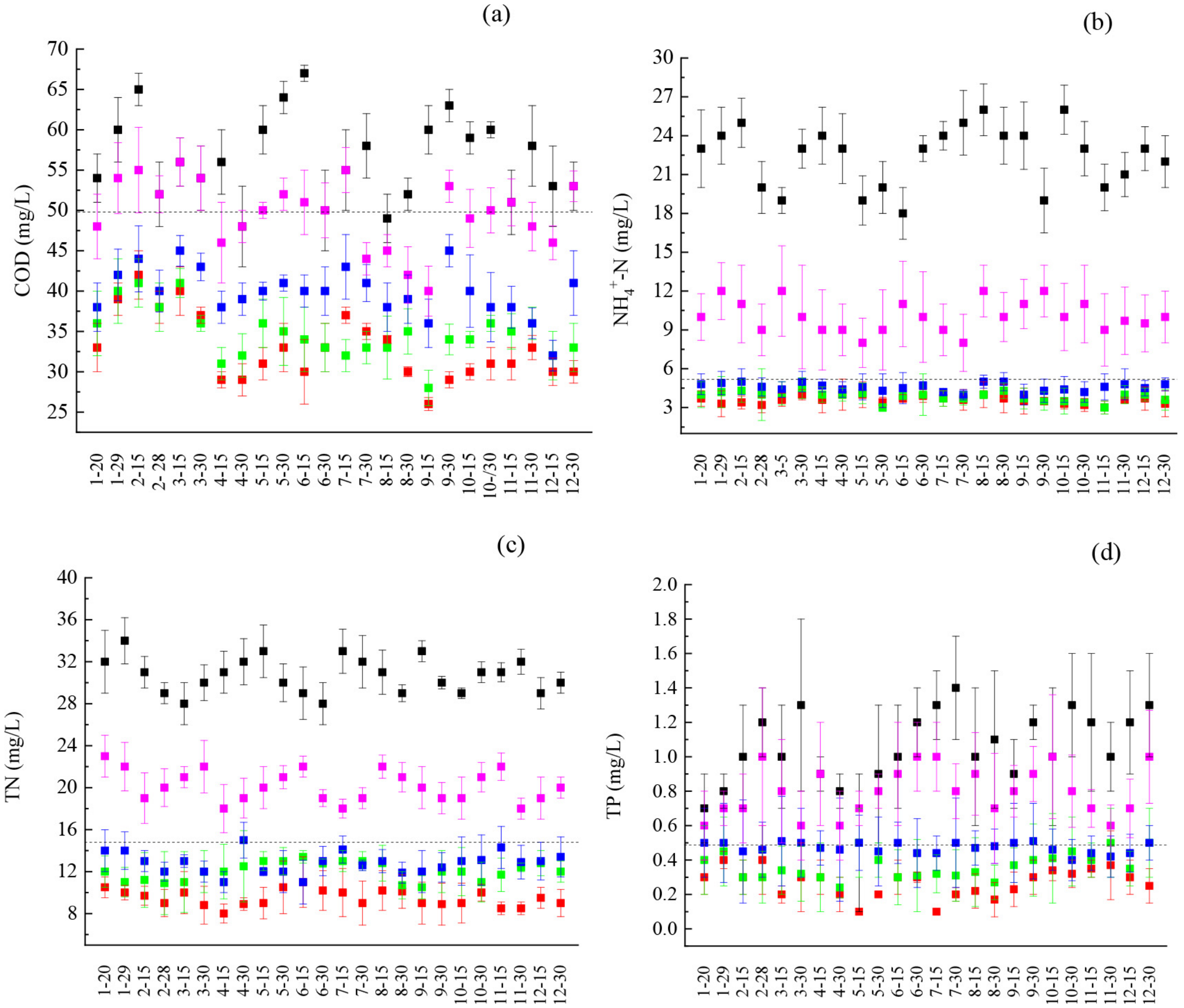

Fig. 2. Effect of HLR on effluent concentrations of (a) COD, (b) NH_4^+–N, (c) TN, and (d) TP (🟥 0.007 m³/m²·d, 🟩 0.01 m³/m²·d, 🟦 0.03 m³/m²·d, and 🟪 0.05 m³/m²·d; ■ influent concentration)—effluent quality requirement (Water Quality Standard for Scenic Environment Use in China, GB/T18921-2002: COD ≤ 50 mg/L, NH_4^+–N ≤ 5 mg/L, TN ≤ 15 mg/L, and TP ≤ 0.5 mg/L).

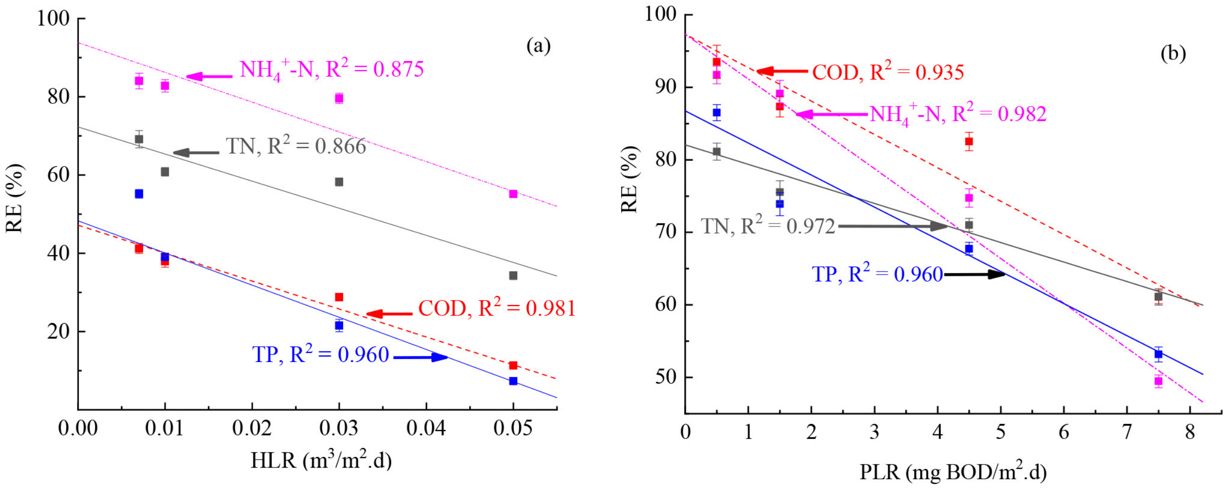

Fig. 3. Linear relationship between (a) HLR, (b) PLR, and pollutant removal rate (🟥 COD, 🟪 NH_4^+–N, ■ TN, and 🟦 TP).

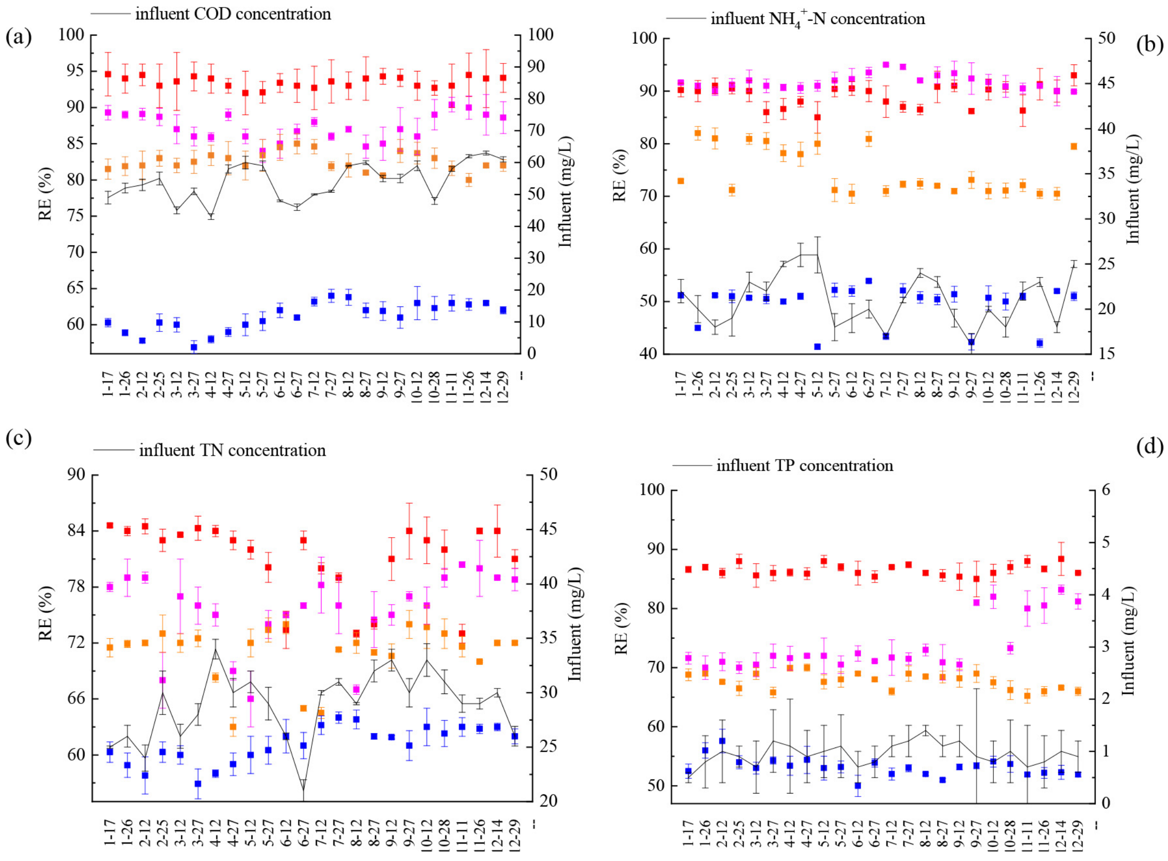

Fig. 4. Influence of PLR on the removal rate of (a) COD, (b) NH$_4^+$–N, (c) TN, and (d) TP (🟥 0.05 mg BOD/m^2·d, 🟪 0.15 mg BOD/m^2·d, 🟧 0.45 mg BOD/m^2·d, and 🟦 0.75 mg BOD/m^2·d).

Table 1
Distribution of nitrogen removal bacteria and enzyme activity

Index	Depth (cm)				
	10	25	40	55	70
NN (MPN/g)	$(3.6 \pm 1.0) \times 10^4$	$(2.6 \pm 1.1) \times 10^4$	$(4.4 \pm 0.9) \times 10^{3a}$	$(3.8 \pm 0.6) \times 10^{3a}$	$(2.1 \pm 0.1) \times 10^{3a}$
ND (MPN/g)	$(7.2 \pm 1.5) \times 10^6$	$(8.8 \pm 1.4) \times 10^6$	$(6.3 \pm 0.4) \times 10^{7a}$	$(2.4 \pm 1.0) \times 10^{8b}$	$(1.0 \pm 0.4) \times 10^{8b}$
Urease (mg/g·d)	16.12 ± 1.28	15.45 ± 0.24	16.92 ± 1.25	15.89 ± 2.07	14.32 ± 2.44
NAR (mg/g·d)	0.94 ± 0.11	0.75 ± 0.08	0.51 ± 0.04^a	0.47 ± 0.15^a	0.42 ± 0.14^a
NIR (mg/g·d)	0.35 ± 0.03	0.29 ± 0.02	0.20 ± 0.01	0.20 ± 0.02	0.19 ± 0.02

Note: Compared with the results at 10 cm and 25 cm, ^{a}represents a difference and ^{b}represents a significant difference.

depth increasing. Depth and sampling point had an effect on the activity of urease and NAR. Due to the high concentration of organic matter in the influent, the urease activity near the inlet was higher ($p < 0.05$). In addition, there was no significant change in urease activity at different sampling depths ($p > 0.05$). For NAR, the strong activity in top soil was consistent with the higher NN at these points.

4. Discussion

4.1. Paths for phosphorus removal

Phosphorus removal is accomplished mainly through adsorption, chemical precipitation, and nutrient assimilation. In the OFS, its removal rate ranged from 20% to 89% [13]. Even so, Elodie et al. [14] reported that hydraulic loads had significant effect on phosphorus removal. HLR 0.01 m^3/m^2·d was suggested to be the optimum value. Sparling et al. [7] found that low loadings and extended application periods resulted in 66% removal of phosphorus. Similarly, the research by Yang and Chu [15] indicated that HLR had adverse effect on the phosphorus removal efficiency.

However, the study by Sundberg et al. [16] presented that only 20%–23% phosphorus removal was obtained even if loading rate was as low as 0.001 m^3/m^2·d. They came to a conclusion that loading rate and detention time had less impact on the removal of phosphorus. The reason for the controversy lies in that the substrate used in the study was different, exerting different physicochemical properties.

Table 2
Comparison of influent loading and pollutant removal rate between reports

PLR (g BOD/m²·d)	HLR (m³/m²·d)	Removal rate (%)				References
		COD	NH_4^+–N	TN	TP	
0.10	0.01	52.0[c]	48.0[c]	33.0[c]	67.2[b]	[2]
–[a]	0.01	65.6[c]	60.2[c]	67.4	69.8[b]	[5]
0.02	0.002	84.7	80.0	67.7	98.0[b]	[13]
0.20	0.006	–	44.0[c]	30.6[c]	66.7[b]	[14]
0.12	0.005	80.4	–	62.3	–	[18]
0.15	0.02	–	62.7[b]	34.8[c]	67.3[b]	[20]
0.45	0.03	81.5 ± 1.6	82.9 ± 2.7	60.1 ± 2.0	88.8 ± 1.1	This study

[a]Not mentioned.
Note: Comparing the results of this study, [b]represents a difference and [c]represents a significant difference.

More importantly, OFSs were filled with low-permeability substrate at the top active layer. Wastewater moved by sheet flow over the surface rather than infiltrating through the substrate. As a result, phosphorus removal is limited owing to the minimum soil–water interactions [6].

Consistent with the findings of Elodie et al. [14] and Yang and Chu [15], the results of this study indicated that HLR had significant effect on the removal rate of phosphorus. There may be two reasons for this phenomenon. First, the active layer (0–25 cm) was filled with better permeability substrate, allowing the influent penetrate into the substrate layer instead of flowing over the surface. Consequently, the phosphorus has more soil interactions. Second, activated sludge encouraged the adsorption of phosphates. Hydraulic application at a rate of 0.007 m³/m²·d provided the highest phosphorus removal. At HLR 0.05 m³/m²·d, a shorter detention time reduced the opportunities for phosphorus to come in contact with the activated sludge, which resulted in the lower TP removal rate.

4.2. Impact of artificial substrate on pollutant removal

According to Davidson et al [17], soil type has the most significant influence on infiltration rate and removal of contaminants. Works on the performance of 15 soil infiltration treatments in the United States showed that artificial substrate with excellent adsorption capacity and high organic carbon content could improve N and P removal by 5%–10% [18,19]. In this study, activated sludge was an important component of artificial substrate, which had high adsorption and immobilization ability of NH_4^+–N and TP as reported before [12]. Experimental results also suggested that substrate seeding with activated sludge had higher biomass content. As a consequence, more rapid biofilm establishment was achieved, as well as there was an increase in COD and NH_4^+–N removal rates under high loads [12]. The third advantage of activated sludge was that its organic carbon content was as high as 57.5 mg/kg [20]. Seeding with activated sludge can stimulate denitrification process and TN removal efficiency by providing sufficient carbon source.

Reports have noted that when using OFS to treat domestic wastewater, the optimal HLR and PLR ranges were 0.002–0.02 m³/m²·d and 0.02–0.15 g BOD/m²·d, respectively. Owing to the usage of artificial substrate amended with 10% activated sludge, there was a significant improvement in the efficiency of pollutant removal and the ability to resist load shock, as shown in Table 2.

5. Conclusion

This study investigated the effect of influent load on the efficiency of pilot-scale OFS treatment with artificial substrate. The results indicated that the addition of activated sludge to the substrate helped to improve the removal of contaminants. Loading rates (i.e., HLR and PLR) were inversely proportional to the pollutant removal rates. Taking the treatment efficiency and application feasibility into consideration, the optimal HLR and PLR were suggested ranging from 0.01 to 0.03 m³/m²·d and from 0.15 to 0.45 g BOD/m²·d, respectively. Under these conditions, the effluent quality (COD, NH_4^+–N, TN, and TP) met the requirement for reuse (Water Quality Standard for Scenic Environment Use in China, GB/T18921-2002). Microbial experiments showed that NN decreased by one order of magnitude from 25 cm to 40, 55, and 70 cm ($p < 0.05$). In comparison, ND increased as soil depth increased.

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