Enhancing nitrate and phosphorus removal from stormwater in a fold-flow bioretention system with saturated zones

Ran Yang, Fu Zheng-rong*, Ma Man-ying and Liu Xian
School of Civil Engineering, Hunan University of Technology, Zhuzhou 412007, China
*Corresponding author. E-mail: 441680332@qq.com

ABSTRACT

The traditional bioretention systems possess a remarkably low nitrogen and phosphorus removal effect. The removal rate fluctuates greatly, and even appears as negative removal of nitrogen and phosphorus. Four simulated bioretention experimental columns with different bilayer media, packing composition and structure were constructed. Based on the traditional fillers, the modified composite fillers with hydroxy-aluminum and modified vermiculite sludge particle (HAVSP) were added. The traditional filler (C1) and the modified composite filler (C2) were added respectively, moreover saturated zones were set up to enhance the effect of nitrogen and phosphorus removal. Removal of nutrients from experimental columns by simulated runoff efficiency was evaluated and compared. In addition, the effect of media depth on phosphorus retention and denitrifying enzyme activity in bioretention columns was also evaluated. The experimental column #2 filled with C2 had the optimum removal effect on TP (93.70%), however, the removal effect of TP by filling C1 experimental columns was insufficient (57.36%). Designed to remove nitrate (NO3^-/C0-N) and total nitrogen, the experimental column #4 showed the best performance (83.54% and 92.15%, respectively). In this study, we propose a fold-flow bioretention system by filling HAVSP in combination with saturated zones. The runoff water quality can be effectively improved, and a new bioretention cell configuration can be provided for efficient stormwater treatment.

Key words: bioretention, nutrients removal, saturated zones, stormwater runoff

HIGHLIGHTS

• Proposing a novel bioretention system by installing a fold-flow board and combining with saturated zones.
• Filling hydroxy-aluminum vermiculite sludge particle and setting a bilayer filler inside the structure of the bioretention system.
• Evaluating the effect of media depth on phosphorus retention and denitrifying enzyme activity in bioretention columns.
1. INTRODUCTION

With the rise of sponge city construction, the single rapid drainage mode is being gradually replaced (Li et al. 2014). The purpose of sponge city construction is to adopt the characteristics of protecting and re-creating natural landscapes to minimize effective non-permeability, thus creating functional and attractive site drainage (Xu et al. 2017). Due to the development of urbanization and the increase of hardened areas in urban areas, rainwater is discharged directly without treatment after landing on the surface, and the environmental pollution caused by precipitation runoff is increasing. Rainwater surface runoff pollution has become the second largest pollution source after agricultural pollution, and road runoff pollution is the main source of urban surface runoff pollution (Ellis et al. 1987; Ping et al. 2015). The traditional rainwater discharge system of constructing rainwater pipelines expands the impervious area to exclude rainwater runoff, which makes the runoff increase, the peak time advance, and exacerbates urban waterlogging. In addition, during heavy precipitation, rainwater runoff leads to serious surface water pollution, such as stench in natural water bodies, since most of the early drainage systems use a combined flow system. Rainwater diversion systems can reduce the pollution to the water environment, but these should be combined with quick problem solving. The water environment problem can be solved quickly by rebuilding sponge city bioretention facilities, and rainwater can be used through bioretention facilities after treatment. Discharge can alleviate the water environment problems caused by rainwater runoff pollution (Muerdter et al. 2018). The old urban reconstruction includes the whole design and transformation of the sponge district. As part of the construction of the sponge city, bioretention tanks can eliminate the persisting issues of waterlogging and sewage crossflow due to the shortage of drainage facilities, and speed up the solution of urban waterlogging, rainwater collection and utilization and residual water treatment (Kim et al. 2000; Du et al. 2017). Therefore, sponge city-related infrastructure construction is particularly important.

The bioretention tank, as a rainwater treatment facility in urban rainwater low impact development technology (LID), can not only store rainwater through the adsorption capacity of internal structure and soil matrix materials, but also effectively attenuate the flood peak flow and runoff of rainwater, and improve rainwater quality through precipitation, filtration, microbial processes and vegetation absorption (Wong & Somes 1995; Liu & Davis 2014; Jiang et al. 2018; Ashoori et al. 2019). Conventional bioretention tanks can effectively remove total suspended solids (TSS), heavy metals/metals, pathogens and oils from rainwater (Wilcock et al. 2012; Halaburka et al. 2017; Osman et al. 2019; Guerra & Kim 2020). More studies
have shown that traditional biological retention tanks can remove 29% to 99% TSS and 98% oil pollution, and can also effectively remove oil pollution with an annual average removal rate of heavy metals such as zinc, copper and lead reaching 98%, 99% and 81%, respectively (Feng et al. 2001; Li & Davis 2009; Li & Davis 2014; Wang et al. 2015; Li et al. 2016; Soleimanifar et al. 2016; Zhang et al. 2019). However, the removal of nitrogen and phosphorus is deficient. Sometimes, leaching of nitrogen and phosphorus will occur in the matrix filler within the biological retention tank, which makes concentrations of total nitrogen (TN) and total phosphorus (TP) increase and leads to their negative removal (Liu & Davis 2014; Liu et al. 2014; Wang et al. 2014; Hsieh et al. 2017; Li et al. 2018; Qiu et al. 2019). In order to overcome the shortcomings of the removal of nitrogen and phosphorus and further remove the rainwater pollution, research on the amended bioretention tank in the rainwater treatment of sponge city was further developed.

The aim of this study was to examine the ecological purification mechanism of stormwater runoff in the bioretention system by employing different coupling systems using plants, media, and saturated areas. This was achieved through the following steps: (a) constructing three different concentrations of storm runoff and evaluating the removal of nitrogen and phosphorus by four systems; (b) the removal effects of NH$_4^+$-N, NO$_3^-$-N, TN, and TP were measured by five systems under different wet-dry cycles, rainfall intensities, and concentrations; and (c) scanning electron microscope (SEM), energy-dispersive spectroscopy (EDS), Fourier transform infrared (FTIR) spectrometry and X-ray diffraction (XRD) were combined to determine the pollutant removal mechanisms of different combinations of the bioretention system. On this basis, an optimization strategy is proposed for the simultaneous removal of nitrogen and phosphorus in the bioretention system. The results provide a reliable and scientific reference for improving the performance of the bioretention system and removing nitrogen and phosphorus from the initial road runoff.

2. MATERIALS AND METHODS

2.1. Equipment of the bioretention columns

This experiment uses the plastic cylindrical structure as the bioretention cell simulation experiment column. The tube diameter is 400 mm, its height is 1,200 mm. Four simulated bioretention experimental columns with different bilayer media, packing composition and structure were constructed. The traditional media (C1) were added to bioretention columns of #1 and the modified composite filler with HAVSP (C2) was added to bioretention columns of #2, #3, #4, respectively, and the saturated zone was set up to enhance the effect of nitrogen and phosphorus removal. The specific experimental column number and structure diagram are shown in Figure 1.

The internal structure of the simulated column consisted of a super-high layer, aquifer, overburden layer, composite packing layer, sand filter layer and gravel drainage layer (Barrett et al. 2013; Palmer et al. 2013; Gilchrist et al. 2014). The devices from top to bottom are listed (Table 1). The height of the super-high layer was 40 mm, and the overflow pipe was set up to

![Figure 1](https://iwaponline.com/wst/article-pdf/84/8/2079/952532/wst084082079.pdf)
prevent the simulated column from flooding and to facilitate the timely discharge of rainwater. The overburden was composed of 70 mm of bark and other organic matter. The composite packing layer (900 mm) contains Planting soil (250 mm), upper media (450 mm) and lower media layer (200 mm); which plays a decisive role in water purification and retention (Lucas & Greenway 2011; Sun et al. 2018). The Planting soil originated from the campus green belt planting soil. The upper layer was filled with Quartz sand that is permeable and can reduce the risk of blockage in the bioretention facilities (Glaister et al. 2014). The upper layer was packed with low permeability material, which can increase the hydraulic retention time and create an anaerobic/anoxic zone (Sun et al. 2018; Qiu et al. 2019; Luo et al. 2020). The height of the aquifer is 100 mm, existing between the overburden and the Planting soil layer, which plays a certain role in regulating the amount of rainwater in order to facilitate the follow-up. The Sand filter layer is composed of coarse sand with a thickness of 90 mm. The gravel layer is the drainage system of the simulated column with a thickness of 100 mm, filled gravel particle size is 12–35 mm, the maximum particle size is no more than 50 mm, and was equipped with 25 mm diameter perforated pipes, which is located at the bottom of the bioretention columns. The sampling ports (25 mm in diameter) were set at three soil depths (300, 600 and 900 mm) at the side wall of the device after water inflow each time, and spiral soil auger was used to collect samples from the sampling ports at the side wall of the device.

**Table 1** | The structure design of improved bioretention columns

| Structure       | Thickness | #1               | #2               | #3               | #4               |
|-----------------|-----------|------------------|------------------|------------------|------------------|
| Overburden      | 70 mm     | Bark and organic matter |                   |                   |                   |
| Planting soil   | 250 mm    | Green belt soil on campus |                   |                   |                   |
| Upper media     | 450 mm    | Sand Quartz sand |                   |                   |                   |
| Lower media     | 200 mm    | Sand 90% sand + 5% sawdust + 5% HAVSP | 90% sand + 5% sawdust + 5% HAVSP | 90% sand + 5% sawdust + 5% HAVSP |
| Sand filter     | 90 mm     | Coarse sand (diameter 1–2 cm) |                   |                   |                   |
| Drainage layer  | 100 mm    | Gravel (diameter 12–35 mm) + DN25 perforated pipes |                   |                   |                   |

2.2. Media preparation and modification

The raw material of water treatment residual (WTR) originated from the Zhuzhou tap water treatment plant in Hunan Province. The water plant used aluminum salt as a water treatment coagulant. Because of its high humidity, the WTR needed to be weathered naturally to make its free water content zero, then the air-dried WTR was screened with a 2 mm sieve and crushed to powder for reserve.

The expansion vermiculite was purchased from the Zhuzhou local building materials market. The particle size of the expanded vermiculite was 1–3 mm, granular, soft but with a large internal void ratio, which could be used as a good adsorption material. On the basis of expanded vermiculite, the impurity in the inter-layer pore of the expanded vermiculite was dissolved, the internal pore size became larger, the adsorption property of expanded vermiculite was improved, and then the adsorption effect of phosphorus in water was improved by aluminum modification:

1. Hydrochloric acid modification. Here, 1 mol/L of hydrochloric acid solution was prepared, expanded vermiculite was added to the hydrochloric acid solution, oscillated at 25 °C in a constant temperature oscillator for 3 h, and then washed with deionized water for 24 h until the pH value was about 7.0, then dried for 2 h in a 110 °C constant temperature box.

2. Hydroxy-aluminum modification. Based on 1 mol/L hydrochloric acid-modified vermiculite, the acid-modified vermiculite was first soaked in 0.03 mol/L aluminum sulfate solution for 24 h, according to the solid:liquid ratio of 1:5. Then the pH value was adjusted to neutral with 0.01 sodium hydroxide solution, the aluminum-modified vermiculite (HAV) was...
obtained by soaking for 12 h, and washing the vermiculite with deionized water, the thermostat was set at 110 °C and the vermiculite dried and set aside. After grinding, the 200 mesh modified vermiculite powder was prepared.

(3) The water treatment residual (WTR) and aluminum modified vermiculite (HAV) were mixed evenly, stirred fully with water, and prepared by mixing the solid particles in a pressure ball molding machine, then dried in an automatic programmed oven, and finally baked in an oven furnace, cooled to room temperature, to make the hydroxy-aluminum vermiculite sludge particles (HAVSP).

2.3. Determination of physicochemical characteristics of media

The pH of WTR, HAV, soil, sand were measured by adding 25 g of the corresponding samples into a beaker and adding 25 mL of deionized water. The corresponding liquids were vibrated for 15 min. The ash content of the measured media was tested by weighing a 1 g sample into a crucible and firing in a muffle furnace at 800 °C for 4 h, then cooling to room temperature and calculating the ash content. The cation exchange capacity (CEC) was measured by the ammonium acetate method. The appearance and water-releasing characteristics were described by Brunauer–Emmett–Teller (BET) surface area measurement, and SEM. In addition, the morphology and structure of the samples were analyzed by SEM. The elemental analysis of HAVSP was characterized by EDS. The ζ-potential of the media was determined using a solid surface Zeta potentiometer.

2.4. Synthetic stormwater runoff

For the purpose of studying the removal effect of phosphorus in rainwater runoff from the modified composite packing bioretention tank under different inundation height conditions, the effluent inundation heights of 200, 400, 600 mm of the experimental column were set up respectively. Stormwater occurs from December to February every year due to abundant and relatively concentrated rainwater in Zhuzhou City. April–August is the period of heavy rain, with an annual average rainfall of 1,400–1,700 mm. The annual rainfall volume is calculated according to The Technical Regulations of Planning and Management in Zhuzhou City, Hunan Province (2018 revised edition), the local stormwater intensity formula is:

\[
q = \frac{1839.712 (1 + 0.724 \log P)}{(t + 6.986)^{0.703}}
\]

where q is design stormwater intensity [L/(s·h·hm²)]; t is rainfall duration (min); P is design recurrence period (a). General area is 3–5 years, important area is 5–10 years.

The ratio of bioretention facility area to sink surface area is 5%, and runoff coefficient is 0.8. Five different recurrence intervals (P) in years (2a, 5a, 10a, 20a, 30a) were used in semi-synthetic runoff. The semi-synthetic runoff continuously influent 6 h, influenced flow 60.59 ml/min. The average concentrations of semi-synthetic runoff pollutants on local roads and roofs were TN (8 mg/L), NH₄⁺-N (2 mg/L), NO₃⁻-N (2 mg/L), PO₄³⁻-P (2 mg/L). In order to determine performance evaluation of amended bioretention systems in the case of excessive nutrients contaminated in stormwater runoff, three different concentrations of synthetic stormwater runoff were used, as presented in Table 2.

### Table 2 | The concentrations and components of semi-synthetic runoff

| Parameters | Component     | Low concentration | Typical concentration | High concentration | Adding reagents     |
|------------|---------------|-------------------|-----------------------|-------------------|--------------------|
| TN         | Organic and inorganic N | 4 mg/L as N       | 8 mg/L as N           | 16 mg/L as N      | C₂H₅NO₂, NH₄Cl, KNO₃ |
| NH₄⁺-N     | NH₄⁺          | 1 mg/L as N       | 2 mg/L as N           | 4 mg/L as N       | NH₄Cl              |
| NO₃⁻-N     | NO₃⁻          | 1 mg/L as N       | 2 mg/L as N           | 4 mg/L as N       | KNO₃               |
| TP         | Orthophosphate| 1 mg/L as P       | 2 mg/L as P           | 4 mg/L as P       | KH₂PO₄             |
| pH         | –             | 7.0               | 7.0                   | 7.0               | HCl/NaOH            |
2.5. P retention and denitrification potential

The core soil samples were taken out along the depth of the column after synthetic stormwater runoff to investigate P retention and denitrifying enzyme activity (DEA) in the bioretention tanks. In total, 24 samples were collected at the depths of 300, 600, and 900 mm from bottom to top. Here, 1 g of each soil sample was placed in a crucible, dried at 105 °C for 24 h to measure the water content. The remaining samples were tested by air drying. Denitrification potential of the media was determined by measuring the DEA (Guo et al. 2014). The DEA was estimated using the following formula:

\[ A = \frac{1000}{V \times T} \left[ S_1 - \frac{(S_2 - S_3) \times V}{1000} \right] \]

where \( S_1 \) is the quality of \( \text{KNO}_3 \) used (mg), \( S_2 \) is the concentrations of \( \text{NO}_3^-\text{N} \) in the samples (mg/L), \( S_3 \) is the concentrations of \( \text{NO}_3^-\text{N} \) in the control group (mg/L), \( V \) is the total volume of the extracting solution (mL), \( W \) is the amount of soil sample used (g), \( T \) is incubation time of soil samples in the solution (h), and \( A \) is the DEA of the samples (\( \mu g/g.h \)).

Moreover, the P interception efficiency at different heights in the media was calculated using the following equation:

\[ B = \frac{(m_e - m_0)}{m} \]

where \( B \) is the DEA (mg/g); \( m_0 \) and \( m_e \) are the TP concentrations of the media at the beginning and end of the experiment, respectively; \( m \) is the mass of the media (g). TP concentrations of the media were determined by the alkali fusion-Mo-Sb antisorphotometric method.

2.6. Water samples analytical methods

The outflow water samples were analyzed for COD, TN, \( \text{NH}_4^+\text{N} \), \( \text{NO}_3^-\text{N} \) and TP, respectively. The water samples were filtered through a 0.45-\( \mu \)m filter paper to test the concentrations of \( \text{NH}_4^+\text{N} \), \( \text{NO}_3^-\text{N} \) and TP. The testing method is based on the standard for Monitoring and Analysis Method of Water and Wastewater (fourth edition).

3. RESULTS AND DISCUSSION

3.1. Physicochemical characteristics of media

Table 3 shows the physical and chemical characteristics of WTR, HAV, Quartz sand, Planting soil and Sand. As is shown, the pH of HAV is the lowest, while that of WTR, Quartz sand, Planting soil and Sand is approximately equivalent. The increase in acid pH of HAV may be attributed to the preparation and modification of amended vermiculite to some extent. Furthermore, the ash contents of WTR or HAV were conspicuously lower than those of Planting soil and Sand, and the ash of HAV was slightly higher than that of WTR. This indicated that HAV possesses more organic components and provided favorable conditions for the demand of denitrifying carbon sources. Furthermore, the CEC of WTR and HAV are relatively similar, which may be due to the loading of aluminum ions on the face of HAV. At pH 7, the high and low permeabilities of all media demonstrated that the \( \zeta \)-potential is negative, and the \( \zeta \)-potentials of WTR and HAV are lower than those of Quartz sand, Planting soil and Sand. The surface area of HAV was approximately 11.2% more than that of WTR.

SEM was performed to further explore the micro-morphology of the media. As is shown in Figure 2, WTR and HAV had a rough surface and a compact microporous structure, which can provide an ideal environment for the growth of the biofilm and
improve the adsorption performance for nitrogen and phosphorous (Hsieh et al. 2017; Qiu et al. 2017; Zhang et al. 2019). In addition, Table 4 shows the content of nitrogen and phosphorous for WTR and HAV. The content of nitrogen and phosphorous of WTR are higher than that of HAV, which may lead to the release of nitrogen and phosphorous and increase the effluent concentration. In addition, the surface of WTR contains more metal ion compounds such as iron and aluminum, indicating that WTR could have a better adsorption performance for phosphorous removal (Li et al. 2018). WTR is mainly composed of Fe, Si, Al and other elements, and Fe, Al plasma metal ions, Al content is 8.21%, Fe content is 6.12%, aluminum in WTR exists in a stereotypic form, which can effectively increase the adsorption ion exchange capacity and chemical precipitation in phosphorus. Aluminum ions as a flocculent can produce adsorption complex cooperation for phosphorus in a water body, and effectively remove N, P pollutants in water. The highest surface areas of HAV could be conductive to ammonia nitrogen removal and create favorable conditions for the attachment and reproduction of denitrifying bacteria (Guo et al. 2014).

FTIR spectrometer analysis of the HAVSP results are shown in Figure 3. HAVSP has rich overactive groups, its infrared spectrograph consisted of multiple peaks of different intensities: the absorption peaks at 3,351.747 and 1,643.546 cm\(^{-1}\) refers to the expansion and bending vibration of hydroxy, the absorption peaks at 1,049.086 cm\(^{-1}\) refers to the expansion vibration of Si-O, the absorption peak at 950.252 cm\(^{-1}\) refers to the expansion vibration of C-O, the absorption peak at 729.043 cm\(^{-1}\) refers to the telescopic vibration of the Fe-O. The XRD analysis of HAVSP results are shown in Figure 4. HAVSP is mainly composed of mineral substances such as SiO\(_2\), KAl\(_2\)(AlSi\(_3\)O\(_{10}\))(OH)\(_2\), Al\(_2\)(Si\(_2\)O\(_3\))(OH)\(_4\), and Ca\(_3\)Al\(_2\)Si\(_3\)O\(_{12}\) with contents of 71%, 15.7%, 11% and 2.3%, respectively.

3.2. Effect of concentrations on nutrients removal

Based on the above preliminary analysis of physicochemical characteristics of media. HAVSP were suggested as the filler media applied in bioretention systems. In order to determinate the effect of different concentrations for nutrient removal in the
bioretention systems, three different concentrations of synthetic stormwater runoff were used. Figure 5 shows the TP and NH₄⁺ removal efficiency of different concentrations at different bioretention columns. For TP, the columns of #2, #3, #4 could exhibit high TP removal efficiency (>86.34%), while the column for #1 presented the lowest TP removal efficiency. The #2 experimental column, where TP removal efficiency exceeded 90% in three different concentrations of synthetic stormwater runoff, even the highest TP removal efficiency climbed to 96.68%. It was observed that high influent concentrations was associated with high effluent concentration, which was agreed with the inflow rainwater with higher nutrient concentrations and would result in higher concentrations in the bioretention outflow (Qiu et al. 2017). All columns expressed a certain concentrations of influent that could improve the surface adsorption activity and adsorption performance. At the same time, excessive concentrations resulted in lower removal efficiency than at low concentrations. The phosphorus removal rate of #3, #4 was lower than that of #2, and the results were consistent with expectations, which shows that changing the runoff flow pattern can affect the nitrogen and phosphorus removal effects. It is worth noting that the #2 column is better in phosphorus removal. However, the #2 and #3 columns simultaneously showed a stable and efficient phosphorus removal effect, indicating that the bioretention system has a strong ability to intercept phosphorus and needs to devote more energy to the regulation and control of runoff nitrogen. For NH₄⁺, the removal efficiency of #2, #3, #4 columns had the similar removal effect, indicating that the removal of NH₄⁺ in the experimental columns mainly occurs in the upper media, and possibly the NH₄⁺ adsorbed by the upper media is eventually
Figure 5 | TP removal efficiency of (a) 1#, (b) 2#, (c) 3# and (d) 4# at different concentration. NH₄⁺ removal efficiency of (e) 1#, (f) 2#, (g) 3# and (h) 4# at different concentration.
Figure 6 | NO$_3^-$ removal efficiency of (a) 1#, (b) 2#, (c) 3# and (d) 4# columns at different concentrations. TN removal efficiency of (e) 1#, (f) 2#, (g) 3# and (h) 4# at different concentrations.
converted to NO$_3^-$ through nitrification (Xiong et al. 2019). The 1# experimental column presented that the lower NH$_4^+$ removal efficiency might be attributed to lack of HAVSP and the bilayer media structure.

Figure 6 shows the NO$_3^-$ and TN removal efficiency of different concentrations at different bioretention columns. For NO$_3^-$, the #3, #4 columns demonstrated superior NO$_3^-$ removal effect, while the 1# experimental column even had the negative removal phenomenon of nitrite nitrogen. The disparity may be accountable in four aspects: (1) the difference in constituents of the upper and lower layers of media, (2) the sawdust served as denitrifying carbon sources, (3) saturated zones formed for enhancement of outflow level, which may create an environment that promotes the denitrification process (You et al. 2019), (4) the fold-flow bioretention system created several submerged areas, which formed several continuous aerobic and anaerobic blocks in the soil layer and submerged area. The 4# experimental column, where the NO$_3^-$ removal rate reached 83.54%, was the most stable and efficient. The NO$_3^-$ removal of the 3# experimental column was the second highest, with an average removal rate of over 75%.

The columns with HAVSP showed better removal effect of NO$_3^-$ than traditional media, implicating that the surface of HAVSP created favorable conditions for the attachment and reproduction of denitrifying bacteria. In addition, all columns showed that the higher the nutrient load, the higher was the removal rate of NO$_3^-$ (Qiu et al. 2019). TN, TN and NO$_3^-$-N showed the same trend, the TN removal efficiency in case of high nutrient concentrations could maintain a high and stable removal rate, especially the two columns with saturated zones (>76.34%). Generally, the TN in the #3, #4 columns was effectively removed, and volatility was low, which indicated that the removal efficiency of TN by the saturated zones and the fold-flow was stable.

3.3. Effect of drought period on nutrients removal

Figure 7 shows TP, NO$_3^-$, NH$_4^+$ and TN removal efficiency of (a) 1#, (b) 2#, (c) 3# and (d) 4# in different drought periods. It was observed that the increase in drought period was beneficial to the removal of TP and nitrite nitrogen, but hindered the

![Figure 7](image-url)
removal of ammonia nitrogen. The experimental columns filled with C2 had the best removal effect on TP (96.8%) in the increasing drought period, however the removal effect of ammonia nitrogen, nitrite nitrogen, TN by filling C2 experimental columns performed best (94.6%, 98.3% and 93.70%, respectively). The drought period could promote a favorable anaerobic environment for the formation of phosphorous in accumulating bacteria and denitrifying bacteria (Yan et al. 2016). The #2, #3, #4 columns showed that removal effect is superior to the 1# experimental column, indicating that the HAVSP can be applied to the changes of wet and dry, and have a strong resistance to the change of environment.

3.4. Performance analysis on nutrients removal

Figure 8(a) shows the DEA of media at different heights. The removal of NO$_3$ is attributed to the assimilation and dissimilation of microorganisms using NO$_3$ (Tian et al. 2019). The above result for NO$_3$ removal effect was consistent with DEA. The DEA at the bottom of media in the #3, #4 columns was significantly higher than that that in the #1, #2 columns, which demonstrated superior NO$_3$ removal effect. In addition, the DEA of #4 column was also higher than that of #3 column. The construction of fold-flow baffles formed several continuous aerobic and anaerobic blocks in the soil layer and submerged area, so that denitrifying microorganisms were no longer distributed solely in the system, but dependent on the alternating aerobic and large area anoxic environment, which made the nitrification and denitrification processes more multi-stage, to improve the denitrification effect of the bioretention system. Figure 8(b) shows the water content of media at different heights. At the media height of 300, 600, and 900 mm, the four columns had the highest water content compared to the other three columns. The #4 column showed the highest water content of 25.45%, and the #1 column showed the worst water content. It was proved that filling HAVSP and constructing fold-flow baffles was more conducive to water absorption and retention. Figure 8(c) shows the TP content of media at different heights. After increasing media height, the adsorption and removal of phosphorous were easily available. Moreover, the TP content in lower layer media was over 13.65 mg/g at the #2 column. It is proved that HAVSP was more conducive to the removal of phosphorous, and bilayer media, saturated zones, fold-flow were subtly hindered in the removal of phosphorous.

4. CONCLUSION

Four bioretention columns were constructed to enhance the effect of nitrogen and phosphorus removal. The main findings were as follows:

(1) The #2 column only filled with HAVSP, compared that of #3, and #4 columns, had the best removal effect on TP (93.70%), which showed that changing the runoff flow pattern by setting fold-flow baffles, and combining with saturated zones could not enhance the removal effect of TP.

(2) The removal of NH$_4^+$ in the experimental columns mainly occurs in the upper media, and it could be that the NH$_4^+$ adsorbed by the upper media is eventually converted to NO$_3$ through nitrification.

(3) The #4 experimental column, where the NO$_3$ removal rate reached 83.54%, was the most stable and efficient. TN and NO$_3$-N showed the same trend. The fold-flow bioretention system created several submerged areas, which formed several continuous aerobic and anaerobic blocks in the soil layer and submerged area.
(4) The increase in the drought period was beneficial to the removal of TP and nitrite nitrogen, but hindered the removal of ammonia nitrogen.

Compared with traditional bioretention systems, the amended bioretention systems had very significant advantages, and its removal efficiency of pollutants was relatively stable. In addition to the good removal effects of TSS, heavy metals, oils and pathogenic bacteria in rainwater runoff, it could also effectively remove nitrogen and phosphorus. The amended bioretention systems are mainly used for initial rainwater treatment and the transformation of rainwater and sewage confluence pipelines in old urban construction communities. At the same time, this should be fully integrated into the concept of sponge city construction, to strengthen the natural biological characteristics and vegetation attributes of the biological detention pool, further cooperate with the landscape design, and unify effective water storage and effective water purification.

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**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

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