Removal of *E. coli* from stormwater by bioretention system: parameter optimization and mechanism

Jianwei Liu, Peng Yue, Yan He and Mengfei Zhao

**ABSTRACT**

Four bioretention simulation columns were used to study the removal effects and influencing factors of *Escherichia coli* (*E. coli*) in stormwater. The mechanism of *E. coli* removal in the bioretention system was also analyzed. The results show that the removal effects of the four new composite filters are better than that of the conventional filter. The specific surface area and porosity of the filter may be the key factors affecting the removal effect; the increase of the filter depth is beneficial to the removal of *E. coli*; the area is conducive to the removal of *E. coli*. Excessive depth of the submerged zone will reduce the *E. coli* removal effect; drying will reduce the *E. coli* removal effect, but it can be restored by rewetting.

**Key words** | bioretention system, *Escherichia coli*, influencing factors, mechanism analysis, new composite filters, stormwater

**HIGHLIGHTS**

- Biochar showed the best *E. coli* removal effect among the fillers used.
- The enhancement of *E. coli* removal decreased with the filter depth.
- Excessive depth of the submerged zone had a negative impact on the removal of *E. coli*.
- Repeated wet–dry cycles may take reduce the removal effects of *E. coli* permanently.
- *E. coli* removal is divided into three steps: interception, migration and inactivation.

**INTRODUCTION**

In recent years, due to the rapid development and disordered expansion of cities in China, the problems of urban hydrological cycle destruction, urban waterlogging and water resource shortage have been caused, making the collection and utilization of runoff come to people’s attention. Urban runoff contains heavy metals, nitrogen, phosphorus, organic matter, pathogenic bacteria and other pollutants, which cause severe pollution to surface water. Therefore, the United States Environmental Protection Agency has listed it as the third largest pollution source of rivers and lakes in the United States.

There may be a variety of pathogenic bacteria with different concentrations in the runoff, because the runoff may wash over the faeces of people and animals. It has potential risks to public health and human health (Dore-vitch et al. 2011). The control of pathogenic bacteria in runoff has become one of the hot issues that people pay close attention to, because when pathogenic bacteria enter into runoff, they may cause a wide range of outbreaks of various intestinal diseases and respiratory diseases.

As a typical source control method in the low impact development technology, bioretention is a runoff pollutant purification system, which is based on the planting of soil and composed of plants, biological filter layer and gravel layer, integrating interception, adsorption, degradation, and filtration. It has been proved to be an effective technology to improve runoff quality (Zuo et al. 2019). Previous studies have shown that a bioretention system can remove N, P and other ordinary pollutants as well as pathogenic bacteria (Chandrasena et al. 2012; Tondera et al. 2013; Mahmoud et al. 2019). However, the current studies on the removal of pathogenic bacteria by bioretention systems are minimal. It is generally believed that pathogenic bacteria are mainly removed in the bioretention system through the joint action...
of filter interception, physical and chemical adsorption, and competitive microbial predation (Zhang et al. 2012). At present, conventional fillers such as sand and soil have been mostly used in the research, but conventional bioretention fillers show considerable fluctuation in the removal of pathogenic bacteria, and the removal effect is easily affected by design parameters and environmental conditions (Li et al. 2012, 2016). New porous composite fillers, such as biochar and zeolite, have been proved to have removal abilities on chemical oxygen demand (COD), N and P, but their unpredictable changes in the application make the study of the removal of pathogenic bacteria microorganisms by new filters limited to theoretical feasibility (Mohanty & Boehm 2015). At present, the research on new fillers mainly focuses on the improvement of traditional filters, that is, mixing the porous composite fillers to improve the removal effect of conventional fillers (Xu et al. 2019). The commonly used new porous composite fillers include fly ash, zeolite, and biochar (Mohanty et al. 2014; Mohanty & Boehm 2015), which have shown significant removal effect improvement. However, there has still been a lack of comprehensive comparison of the removal effects of various new types of fillers, while the simulated evaluation of the factors affecting the removal effect of pathogenic bacteria by bioretention simulated columns modified by various new types of fillers has also been insufficient.

In this study, Escherichia coli was chosen as an indicator, and four bioretention simulation columns, which were respectively filled with four different composite fillers of biochar, quartz sand, anthracite and zeolite, were studied from three aspects.

1. The abilities of the bioretention system filled with four composite fillers to reduce E. coli were compared.
2. The effects of different conditions on the ability of the bioretention system to reduce E. coli were analyzed.
3. The mechanism of E. coli removal by bioretention system was analyzed.

The results will provide a theoretical basis for the total control of pathogenic bacteria in the environment and the design of bioaccumulation engineering.

**METHODS**

**Preparation of four composite fillers**

The sand was passed through a 30 mesh (0.55 mm) sieve to remove surface impurities, treated with 12 M HCl, and then washed in deionized water until the pH of the water became neutral (Mohanty et al. 2014). Four porous fillers of biochar, quartz sand, anthracite and zeolite were selected, which were all purchased from a company in Beijing. The properties of biochar, quartz sand, anthracite and zeolite are shown in Table 1. The sand and the new fillers were dried overnight at 110 °C, autoclaved at 121 °C, 100 kPa for 15 minutes, stored in a sterile container, and then used in a bioretention simulation experiment.

**Synthetic stormwater**

In order to ensure the stability of water quality during the experiment, synthetic stormwater was used for experiments. The water inflow of each bioretention column was 6.7 L to simulate the rainfall of 60 min when the return period of Beijing is 1 year. The concentration of each pollutant in the stormwater was the average concentration in Beijing rainfall as used in previous studies (Yufen et al. 2008; Wu et al. 2015). The target concentrations of COD, total nitrogen (TN), NH3-N and total phosphorus (TP) are 350 mg/L, 6.8 mg/L, 2.4 mg/L and 3.0 mg/L respectively. Glucose, KNO3, NH4Cl, and KH2PO4 were used as the agents for simulating rainwater. All the agents were AR grade. The pH of synthetic stormwater was maintained at 6.8–7.5 by adding either 1 M HCl or 1 M NaOH. The electrical conductivity of synthetic stormwater used was 100–200 μs/cm, which was similar to natural rainfall in Beijing (Wu et al. 2015).

**E. coli preparation**

The E. coli (ATCC25922) used in this experiment was the second generation of subculture after recovery and activation of the lyophilized strains provided by the National Strain Collection Center of China. Under aseptic conditions, a disposable 10 μL sterilization inoculation ring was used to pick a ring of E. coli from the slanted bacteria test tube and spread it evenly on the sterilized LB liquid culture medium, which was then incubated in a constant temperature

| Table 1 | Properties of biochar, quartz sand, anthracite and zeolite |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Particle size (mm) | Specific surface area (m²/g) | Bulk density (g/cm³) | Porosity (%) |
| Biochar | 1–3 | 1,000 | 0.45–0.55 | 60 |
| Quartz sand | 2–6 | – | 1.75 | 45 |
| Anthracite | 1–2 | 300–350 | 1–1.2 | 50 |
| Zeolite | 1–3 | 550–600 | 1.35 | 56 |

All parameters were provided by the merchant. ‘–’ indicates that the merchant did not provide this parameter.
incubator for 18–24 h. After 24 hours, the incubated sample was cooled to room temperature and placed in a refrigerator.

**Bioretention columns**

A total of four PVC (polyvinyl chloride) bioretention simulation columns with an inner diameter of 150 mm were set. The four columns were firstly sandblasted to avoid preferential flow along the column wall and three layers were added in sequence (Figure 1): gravel drainage layer (10 cm), composite filler layer (45 cm) and compound planting soil layer (15 cm). *Iris ensata* Thunb. was chosen as the plant used in the experiment. The four bioretention simulation columns were filled with four composite fillers: 75% sand + 20% biochar + 5% wood chips; 75% sand + 20% quartz sand + 5% wood chips; 75% sand + 20% zeolite + 5% wood chips; 75% sand + 20% anthracite + 5% wood chips. The purpose of adding 5% wood chips was to increase the carbon content. The compound planting soil was composed of pastoral soil, peat soil, and pine needles in a ratio of 3:4:3. Its bulk density is 780–950 kg/m³, and the organic matter content is 34.56%. The runoff reduction rates of the four bioretention simulation columns were 7.02% for biochar column, 6.81% for quartz sand column, 5.03% for anthracite column, and 6.19% for zeolite column respectively, which were calculated through simulated rainfall calculations. The height of the filters was changed through outlets of different heights on the sidewall. The existence of a submerged zone (SZ) was achieved by raising the water outlet of the bioretention device by 15 cm and 30 cm.

**Experimental design**

All the plants used were transplanted to the bioretention column after outdoor planting and then were watered with tap water twice a week. The last tap water irrigation was carried out once the plants had been transplanted successfully. Two weeks after the plants were transferred, the experiment was officially carried out.

The four bioretention simulation columns were named after the new fillers added, which were biochar column (BC), quartz sand column (QS), anthracite column (AN), and zeolite column (ZO). The experiments were carried out in the greenhouse, in the rainwater laboratory of Beij ing University of Civil Engineering and Architecture, for 12 weeks. The detailed experimental settings are shown in Table 2. The diluted *E. coli* suspension was added to the synthetic stormwater as the feedwater. Firstly, a control experiment was performed in the first week, and then the effects of filter depth (2–3 weeks), SZ (4–5 weeks), and inflow concentrations (6–7 weeks) were studied on the removal of *E. coli*. The bioretention simulation columns were adjusted for 2 weeks after sampling at week 7 to reduce the experimental error caused by the high inflow concentration. During the period, the four columns were watered twice a week. In order to study the effect of drying on the removal of *E. coli*, a wet–dry–rewet cycle was performed. The main process was as follows: 2 weeks of drying was set after sampling at week 9 (Sampling 8), then watering of the columns was stopped until sampling at week 11 (Sampling 9).

![Figure 1 | Diagram of bioretention column.](image-url)

**Table 2 | Detailed design of experiment and sampling schedule**

<table>
<thead>
<tr>
<th>Experimental conditions</th>
<th>Weeks</th>
<th>Log10 inflow</th>
<th>Depth of filters</th>
<th>SZ</th>
<th>Water frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>6.08</td>
<td>70 cm</td>
<td>None</td>
<td>2/week</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6.23</td>
<td>55 cm</td>
<td>None</td>
<td>2/week</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6.11</td>
<td>40 cm</td>
<td>None</td>
<td>2/week</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>6.36</td>
<td>70 cm</td>
<td>15 cm</td>
<td>2/week</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6.33</td>
<td>70 cm</td>
<td>30 cm</td>
<td>2/week</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>7.07</td>
<td>70 cm</td>
<td>None</td>
<td>2/week</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>8.50</td>
<td>70 cm</td>
<td>None</td>
<td>2/week</td>
</tr>
<tr>
<td></td>
<td>8–9</td>
<td>6.4</td>
<td>70 cm</td>
<td>None</td>
<td>2/week</td>
</tr>
<tr>
<td></td>
<td>10–11</td>
<td>6.13</td>
<td>70 cm</td>
<td>None</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>6.2</td>
<td>70 cm</td>
<td>None</td>
<td>2/week</td>
</tr>
</tbody>
</table>
and then sampling was done again after 1 week of rewetting (Sampling 10).

**Sample collection and measurements**

The detection methods for COD, TN, TP, and NH₃-N were performed in accordance with the methods specified in *Standard Methods for the Examination of Water and Wastewater* (APHA/AWA/WEF 2012). The detection method for *E. coli* was the plate counting method commonly used in previous literature. The unit of measurement for *E. coli* is CFU/100 mL.

A total of 10 samples were taken during the 12-week experiment. The detailed schedule of sampling is shown in Table 2. In order to ensure the accuracy of the experiment, 500 mL PVC sampling bottles were used to take feedwater for testing before each experiment. During the 60-minute rainfall process, samples were taken at the first minute and 10 minutes, 30 minutes, and 60 minutes after the feedwater was injected. PVC sampling bottles, each 200 mL, were used and stored at 4 °C in the refrigerator for each sampling, and testing was completed within 24 hours after being removed from the refrigerator. Previous studies had found that the oufflow concentration of *E. coli* during different periods of rainfall process showed a large difference (Soberg et al. 2019). In order to make the experimental results as close to reality as possible, in this study, the first outflow concentration of a water intake process and the outflow concentrations of *E. coli* at 10 min, 30 min, and 60 min after the outflow started were tested respectively and the mean concentration was obtained as the event mean concentration (EMC).

**Data analysis**

The normality of the data was assessed by the Shapiro–Wilk test. The inflow or outflow concentration (C) of *E. coli* and the removal effect of the bioretention systems on *E. coli* were expressed as log₁₀ reduction value (LRV), and the calculation methods are shown in Formula (1).

\[
E.\text{coli} \text{ LRV} = \log C_{\text{inflow}} - \log EMC
\]

\[
EMC = \frac{C_{\text{first outflow}} + C_{\text{10min outflow}} + C_{\text{30min outflow}} + C_{\text{60min outflow}}}{4}
\]

Additionally, the nonparametric analysis of the data obtained was tested. The Spearman correlation analysis was used to determine the correlation between inflow concentration and outflow concentration. The univariate analysis of variance was used to determine whether LRVs had a significant difference as factors changed. The above data processing was performed using IBM SPSS 25 and all the tables and figures in this study were drawn using Origin 9.0.

**RESULTS AND DISCUSSION**

**General removal capacities of *E. coli* via four amended bioretention simulation columns**

In 10 samples, the LRVs of *E. coli* by four bioretention simulation columns are shown in Figure 2. It was found that the four bioretention simulation columns could maintain an effective *E. coli* LRV under various experimental conditions. The study of Mahmoud et al. (2019) showed that 0.31 average LRV of *E. coli* was obtained by a bioretention system filled with conventional soil filler. Compared to the conventional bioretention systems, the four bioretention systems filled with four new types of composite fillers in this study were more suitable for the removal of *E. coli*. This is mainly because the composite porous fillers selected in this study have a high specific surface area and porosity. High specific surface area can provide more adsorption sites for *E. coli* while larger pore size increases the filler to the adsorption area of *E. coli*. Mohanty et al. (2014) found that the average specific surface area of the biochar was about 4–5 orders of magnitude higher than that of sand with the same volume, leading to the higher LRVs for *E. coli*. Xu et al. (2019) studied the removal of *E. coli* by the bioretention simulation columns filled with water treatment residual (WTR) modified by Fe₂O₃, resulting in significant porosity increase of the modified WTR, causing the better LRV of *E. coli* (from 0.11 to 0.73).

Additionally, the highest LRV of *E. coli* was observed in the BC (Figure 2). A possible reason is that the biochar has the largest specific surface area of the four porous fillers selected. Lau et al. (2017) found that *E. coli* removal effect of biochar was 60% higher than that of modified sand filter, as the specific surface area of biochar was two to three times higher. Moreover, the organic carbon content of the filler is also a key factor affecting the LRVs of *E. coli*. Biochar has relatively high organic carbon content, leading to an increased non-DLVO (Derjaguin–Landauer–Verwey–Overbeek) force from the filler to *E. coli* (Abel et al. 2013). Non-DLVO force explained hydrophobic and spatial interaction forces (Mohanty et al. 2014), and has
been proved as an important influence on the attachment of *E. coli* to the filler (Chen & Walker 2012).

Meanwhile, the removal ability for COD, TP and NH$_3$-N of the four composite filters were monitored in this study. The removal rate of COD was in the order of BC > AN > ZO > QS. The highest removal efficiency (RE) of COD was 39%, which was found in the BC. Similar results were reflected in the RE of NH$_3$-N by the bioretention systems, which were 53% for BC, 57% for QS, 48% for AN and 45% for ZO. Moreover, the best removal ability for TP (82%) was shown in the BC, which was 16%, 8% and 3% higher than QS, AN and ZO, respectively. The results showed that the simultaneous, stable and efficient removal of *E. coli* and ordinary pollutants was achieved in the composite biochar filler.

**Effect of inflow concentration**

The effect of four bioretention simulation columns on the removal of *E. coli* at different inflow concentrations is shown in Figure 5(a). It was shown that the outflow concentration of *E. coli* increased with the increase of the inflow concentration of *E. coli*, whereas the average LRVs of *E. coli* by the four bioretention simulation columns fluctuated stably within a certain range (1.77–2.24) with the increase in inflow concentration of *E. coli*. Similar results have been shown in the studies of Soberg et al. (2019), which found a relatively stable removal rate and increased outflow concentration with the increase in inflow *E. coli* concentration. The removal of *E. coli* is mainly achieved by adsorption in the bioretention system. The limited surface
area of the filler means the above bacteria cannot be absorbed indefinitely via the bioretention system. When the adsorption site cannot accommodate more bacterial individuals, the un-adsorbed $E. coli$ will flow out, resulting in the increasing inflow concentration of $E. coli$.

The results of linear regression fitting of the log10 inflow concentration and log10 outflow concentration are shown in Figure 3(b). The $R^2$ of the four bioretention systems were 0.98056 for BC, 0.98023 for QS, 0.98313 for ZO, and 0.96254 for AN respectively. The results suggested that there is a significant linear correlation between the outflow concentration and the inflow concentration of $E. coli$ for all bioretention systems. The adsorption sites for $E. coli$ are limited. When the inflow concentration increased, the bacteria that cannot be adsorbed will flow out of the system, causing an increase in the concentration of the outflow, whereas with the increasing outflow concentration, the LRV of $E. coli$ decreases with the increasing inflow concentration. In practice, the $E. coli$ concentration of the bioretention system can be predicted according to the linear regression equation to evaluate the outflow quality.

**Effect of filter depth**

The effect of filter depth on the ability of the four enhanced composite bioretention simulation columns to remove $E. coli$ is shown in Figure 4(a). The filter depth in the bioretention system can significantly affect the LRVs of $E. coli$.
(p < 0.05). Lowest LRVs of *E. coli* were found at the upper outlet of the bioretention simulation columns, which were 1.48 for BC, 1.19 for QS, 1.51 for AN and 1.47 for ZO respectively. As the filter height increased, the LRVs of *E. coli* at the lower outlet were gradually increased. The LRVs of the four bioretention systems were 1.80 for BC, 1.60 for QS, 1.74 for ZO and 1.70 for AN respectively at the filter height of 55 cm. Referring to the control experiment (2.10 for BC, 2.01 for QS, 1.91 for AN and 1.90 for ZO), it can be found that the LRVs of *E. coli* increased with the filter height. Similar conclusions were revealed by Hathaway & Hunt (2011), who found that bioretention devices with a filter depth of 60 cm had an LRV of 0.55 for *E. coli* while a negative LRV of *E. coli* was observed on the bioretention devices with the filter depth of 20 cm. The removal of *E. coli* by bioretention system is mainly achieved by adsorption, which is positively affected by the hydraulic retention time (HRT) (Kim et al. 2012). The increasing of filter depth improved the adsorption of *E. coli* to the bioretention systems by increasing the HRT, leading to a longer adsorption time. It can be explained by two reasons. On the one hand, the sufficient contact between *E. coli* and filters could increase the solid/liquid interface (Wang et al. 2019). On the other hand, it will increase the probability of the re-adsorption of *E. coli*, which are separated from the middle or bottom of the filters due to flow shear, at the top of the bioretention system.

Additionally, all bioretention simulation columns (BC, QS, ZO, and AN) showed a decrease in the growth rate of LRVs with the increasing depth of filters. For example, the LRV of *E. coli* in BC increased by 0.32 from 40 cm to 55 cm of the filter depth but by only 0.25 from 55 cm to 70 cm. The distribution of *E. coli* in biochar bioretention system was studied (Figure 4(b)), suggesting that the quantity of *E. coli* decreased with the filter depth. The quantity of *E. coli* in the surface layer was much higher than the background (2.85 x 10^6 CFU/g dry filter) while the quantity of *E. coli* in the bottom layer was slightly higher than the background, concluding that *E. coli* mainly existed on the top of the bioretention system. Surface interception is considered to be one of the main ways to remove *E. coli* from the bioretention system (Mohanty et al. 2013), and mainly occurs on the top of the filter. These findings suggested that the slower growth rate of the LRVs of *E. coli* with the filter depth is due to the lack of bacteria for absorption by new filters because most of the bacteria have been intercepted at the top.

**Effects of SZ**

SZ is always set at the bottom of the system by raising the drainage opening for enhancing the capacity of the bioretention system for treating runoff, which increases the HRT. An anaerobic environment at the bottom of the system has also been created, which improves the nitrogen removal capacity of the bioretention system (Palmer et al. 2013). Currently, there are few studies on the effect of SZ and its depth in bioretention systems on the *E. coli* removal.

The four bioretention simulation columns were operated with different depth of SZ (15 cm, 30 cm) to reveal the effect of the depth of SZ on the LRVs of *E. coli*, which are shown in Figure 5.

It can be seen from Figure 5 that the depth of the SZ had a significant effect on the LRVs of *E. coli* (p < 0.05). Compared with the control experiment for the LRVs of *E. coli*, the setting of the SZ significantly improved the ability of the bioretention simulation column to remove *E. coli*. The LRVs of *E. coli* by the four bioretention simulation columns were 2.56 for BC, 3.11 for QS, 2.30 for AN and 2.07 for ZO respectively at the SZ depth of 15 cm. However, as the depth of the SZ increased, the *E. coli* removal effect decreased. When the depth of the SZ was 30 cm, the LRVs of the four composite filters were 2.28 for BC, 2.37 for QS, 2.00 for AN and 1.75 for ZO respectively. Similar results have been shown by Batrieres et al. (2008), who found that the average LRV of *E. coli* increased to 1.1 after setting the SZ while the bioretention system without the SZ under the same conditions had an LRV of *E. coli* of 0.23. The preliminary analysis of the SZ was to change the hydraulic gradient, resulting in a lower
E. coli LRV variation during a wet–dry–rewet cycle

Due to different rainfall frequencies, different lengths of dry periods existed in the bioretention systems. During the drying period, the soil structure will be affected and fissures will be formed in soil or filter due to the decrease of water content, which will increase soil infiltration rate, leading to the decrease of adsorption of the system. In practice, there is often a wet–dry–rewet cycle, which was rarely considered in the previous studies. A wet–dry–rewet cycle was designed to study its effect on the removal of E. coli. The results are shown in Figure 6.

It can be observed that the LRVs of E. coli by the four bioretention simulation columns were reduced after 2 weeks of drying (Figure 6). Before the drying period, the LRVs of E. coli by BC, QS, AN, and ZO were 2.12, 2.04, 1.85, and 1.97 respectively. After the drying period, the LRVs of E. coli were reduced, which were 1.98 for BC, 1.88 for QS, 1.50 for AN, and 1.69 for ZO respectively. The 2-weeks drying reduced the average LRVs of E. coli by the BC, QS, AN, and ZO, which were 0.34, 0.79, 0.47, and 0.47 respectively. This phenomenon fully illustrated that drying would adversely affect the removal of E. coli by the bioretention system. Similar results have been shown by Chandrasena et al. (2014), who found that after 2 weeks of pre-drying, the E. coli removal effects were significantly decreased as the outflow concentration in the bioretention was seven times higher than before. This is related to the reduction of moisture content in bioretention systems. Soils or fillers in the bioretention system can form voids or fissures due to reduced water content, and the death and decay of the plant roots in the system will also be accelerated by insufficient water (Li et al. 2016), causing short flows in the system, which will affect the interception effect for E. coli.

After rewetting, the E. coli LRVs in the bioretention system were recovered; the LRVs increased by 0.2, 0.63, 0.12, and 0.19 for BC, QS, AN, and ZO respectively. It showed that the bioretention system had a certain anti-drying ability, and the negative effect of drying on the removal effect of E. coli in the bioretention system is reversible. However, the average E. coli LRVs after rewetting were less than the first test (except for the biochar) (Figure 6). It can be explained by two aspects. One is that long-term drying has caused damage to the roots, which cannot recover in a short time, which will weaken the interception effect of plant roots on E. coli. The other is the loss of surface soil. Drying reduces the moisture content of the soil layer and accelerates the weathering of the surface soil layer, which may result in the formation of permanent short-flow channels.

Generally speaking, long-term drying will reduce the water content of the bioretention system and reduce the ability of the bioretention system to remove E. coli. Moreover, the negative effect will lead to the permanent reduction in the removal of E. coli. Therefore, in practical applications, the bioretention system should be watered regularly to maintain the proper moisture content in it. In future studies, mathematical models could be established to study the optimal watering frequency of bioretention systems.

Preliminary analysis of the removal mechanism of E. coli

The removal of E. coli in the bioretention system is divided into three processes: initial interception of the medium, dynamic migration and inactivation in the aqueous phase (Figure 7). All three processes are affected by the properties...
of the medium and the environmental conditions of the system.

Firstly, E. coli is intercepted by the filler of the system under the combined action of physical filtration, electrostatic attraction, van der Waals force, hydrophilicity, surface tension, and rough surface adsorption. The physical and physicochemical properties of the filler, such as moisture content, specific surface area, pore size, and organic matter content, can significantly affect the interception of E. coli in the medium. The results described in the ‘Effect of filter depth’ section showed that the quantity of E. coli in the top of the filters was higher, which indicated that most of the E. coli is intercepted at the top of the system at the height of 1–10 cm. Moisture content in filters is an important factor affecting the adsorption performance of E. coli, as it affects the interception in the system.

The second is the movement and migration of E. coli in the medium system. E. coli that is not intercepted by the filler migrates with the inflow while the surface of the filler which is not adsorbed or firmly intercepted will move out of the filter gradually under the shear force of the flow. As one of the main factors affecting the migration of E. coli, the decrease of seepage rate lowered the shear force of E. coli, leading to the low probability of migration and detachment from the surface of the filler. It also increased the contact time between E. coli and filler, enhancing the adsorption and interception of E. coli in the systems. As described in the ‘Effects of SZ’ section, the migration characteristics of E. coli in the system changed with the increase of HRT due to the setting of SZ. Another explanation is that more internal voids in the filter make E. coli less affected by flow shear, which reduces the probability of movement and migration.

The final removal process is the inactivation of E. coli in the bioretention system. The distribution of E. coli in bioretention systems, which has been revealed in the ‘Effect of filter depth’ section, showed that after 2 weeks, E. coli in the filters had completely died or been irreversibly intercepted. Biological factors are one of the important factors that affect the inactivation of E. coli in the bioretention system (Søberg et al. 2019), which is affected by plant roots, protozoa predation and competition among microorganisms in the filters.

**CONCLUSION**

The E. coli removal effects of four bioretention systems filled with four different composite filters under different conditions were systematically discussed and the removal mechanism of E. coli in the bioretention system was preliminarily explained. Four main conclusions were drawn as follows.

1. The four bioretention systems all showed good removal effect on E. coli. BC, especially, efficiently removed E. coli and COD, N, and P at the same time.
2. Inflow concentration, filter depth, SZ and its depth, as well as dry–wet cycles all showed a significant effect on bioretention simulation columns for the removal of E. coli. High inflow concentration was not conducive to the removal of E. coli. The rate of increase in E. coli LRVs decreased with the increase of filter depth. The setting of SZ was beneficial to the removal of E. coli, but the excessive depth of SZ had a negative impact on the removal of E. coli. Drying could reduce the removal rate of E. coli, but after wetting again, the LRVs were restored.
3. The E. coli removal in the bioretention system is divided into three processes: initial interception by the medium, dynamic migration, and inactivation in the aqueous phase.
ACKNOWLEDGEMENTS

The authors would like to thank China’s ‘13th Five-Year Plan’ under the Water Pollution Control and Governance Major Science and Technology Projects (2017ZX07102004-005) for financially supporting this research.

REFERENCES


