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Bioswale column experiments and simulation of pollutant removal from urban road stormwater runoff

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ABSTRACT

The concomitant flux of pollutants carried by urban storm water runoff to the surface of water bodies causes a series of environmental issues. Bioswale, which is an effective purification measure of urban surface runoff pollutants, was investigated to determine the relationship between bioswale composition and purification. Results indicate that the pollutant removal rate of bioswales decreases with an increase in influent concentration. Various selected vegetation combinations showed no significant difference in terms of pollutant removal in two months after being planted within a single rainfall. Increasing the thickness of the planting soil and artificial filler layers can improve the contaminant removal rate. Various artificial filler compositions were proven to have different effects on pollutant purification. Planting soil and a mixture of coal ash and sand were the best choice, whereas sand was the worst. The total nitrogen (TN) removal rate increased with submerged zone height, whereas the removal of chemical oxygen demand (COD) and total phosphorus (TP) showed no significant change. The addition of an external carbon source increased TN concentration removal and decreased COD concentration removal without significantly affecting TP. The curve analysis of the pollutant removal rate and various factors was established by processing the statistical results through the SPSS software. The equation of linear regression, which reveals the relationship between the control effect and its influencing factors, was obtained based on the partial least squares model.

Keywords: Road runoff pollution; Bioretention; Multiple linear regression; Partial least squares; Pollutant removal

1. Introduction

Urban areas with impervious surfaces are increasing because of the rapid development of industries and urbanization. Urban stormwater runoff washes out various pollutants from different underlying surfaces, such as nutrient pollutants, heavy metals, suspended solids, and organic pollutants from lawns, roofs, and parking areas [1]. As a result, urban surface runoff carries high levels of various pollutants. Urban surface runoff has been widely identified as a significant source of pollution in many water bodies [2]. Proper control and management methods are required

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to improve the quality of urban surface runoff before its discharge.

Low-impact development (LID) is an environmental initiative that emphasizes managing urban stormwater runoff at the source using natural means. The goal is to establish conditions such that a developed site achieves a hydrology and water quality similar to those of an initially undeveloped site [3–5]. LID reduces runoff and improves water quality through infiltration and transpiration [6].

Bioswale, also known as bioretention, is a widely utilized LID technology that effectively achieves both water quantity and quality goals [7,8]. As they pass through the bioretention unit, pollutants in the runoff can be removed through sedimentation, filtration, sorption on mulch and soil layers, plant uptake, and biodegradation by soil microorganisms [9,10]. The results of water quality performance from laboratory bioretention studies indicate excellent heavy metal retention and very good removal of phosphorus, total Kjeldahl nitrogen (TKN), and ammonium (NH_3-N) [7]. Hunt et al. [11] studied nitrogen removal from several field bioretention facilities in North Carolina. Phosphorus performance was found to be highly dependent on the type of soil used in the bioretention media. Li and Davis [12] monitored two bioretention cells located in College Park and found that bioretention effluents exhibit good water quality for all primary pollutants, except for nitrate, copper, and phosphorus in one cell. Additional media (depth and area), particularly with nitrogen species, may increase water quality performance. Lucas and Greenway [13] showed that vegetation enhances total nitrogen (TN) removal, which suggests that less densely planted bioretention cells may not provide as great nitrogen treatment compared to more densely planted bioretention cells. Vegetation type may also be an important design consideration for fecal microbial removal because root growth characteristics significantly control the movement of water and other pollutants through soils [14,15].

Although many studies have proven that bioswales effectively treat urban surface runoff, particular information on the relationship between the control effect and main influencing factors have not been provided. To address this gap, a total of 30 bioswale columns with different vertical structures were designed and constructed in the outdoor experiment fields of Xi'an University of Technology. Under different conditions of influent concentration, vegetation types, planting soil and artificial filler thickness, artificial filler type, submerged zone height, and addition of external carbon source, the purifying effect of bioswale on urban surface runoff contaminants was analyzed based on the measured data of the column experiments. The statistical relationship between water quality removal and its factors were determined by processing the experimental results through the Statistical Product and Service Solutions (SPSS), a widely utilized statistics software.

2. Materials and methods

2.1. Column setup

A total of 30 bioswale columns were utilized and divided into six groups, each 0.4 m i.d. and containing 0.15 m aquifers, 0.05 m mulch, 0.3 m planting soil, 0.4 m artificial filler, and 0.15 m gravel. Based on the factors mentioned earlier and the actual situation of Xi'an, *Boxwood* (*Buxus sinica*), *Ryegrass* (*Lolium perenne* L), *Border privet* (*Ligustrum obtusifolium*), *Ophiopogon japonicus*, *Glossy privet* (*Ligustrum lucidum Sieb*), *Chlorophytum comosum variegatum* (*Chlorophytum comosum*), *Chinese Iris* (*Iris lacteal var. chinensis*), and other plants were determined to be suitable for bioswales. *Boxwood* and *Ryegrass* (BR), *Border privet* and *Ophiopogon japonicas* (BO), and *Glossy privet* and *Chlorophytum comosum variegatum* (GC) were selected to establish the three vegetation conditions. Five fillers were chosen: sand, planting soil, blast-furnace slag (slag), the mixture of sand and coal ash with volume ratio 5:1 (MSC), and the mixture of sand and slag with volume ratio 1:1 (MSS). Five fillers were chosen: sand, planting soil, blast-furnace slag (slag), the mixture of sand and coal ash with volume ratio 5:1 (MSC), and the mixture of sand and slag with volume ratio 1:1 (MSS). The sand was collected from the Weihe River, and the planting soil was gathered from the topsoil around Xi'an city which was mostly loamy soil. The slag was composed of blast-furnace slag and provided by the Chang'an steel mills, and coal ash was composed of burned residual solids from the Baqiao power plant. The selected particles in the experiment column were sieved before filling. Coarse gravel and slag were sieved in the ranges of 1.5–3 cm and 0.3–1.5 cm, whereas sand was sieved at less than 0.3 cm. The section schematic of a bioswale column is shown in Fig. 1.

Table 1 provides the setup of each of the 30 bioswale group columns. In groups A, B, E, and F, the artificial filler compositions were varied (1–5). Group A was set as the control group without plants. Group B was planted with BR, Group E with BO, and Group F with GC. By comparing the pollutant removal of Groups A, B, E, and F, the effects of different vegetation combinations on treating urban runoff were determined. Five different media compositions were added

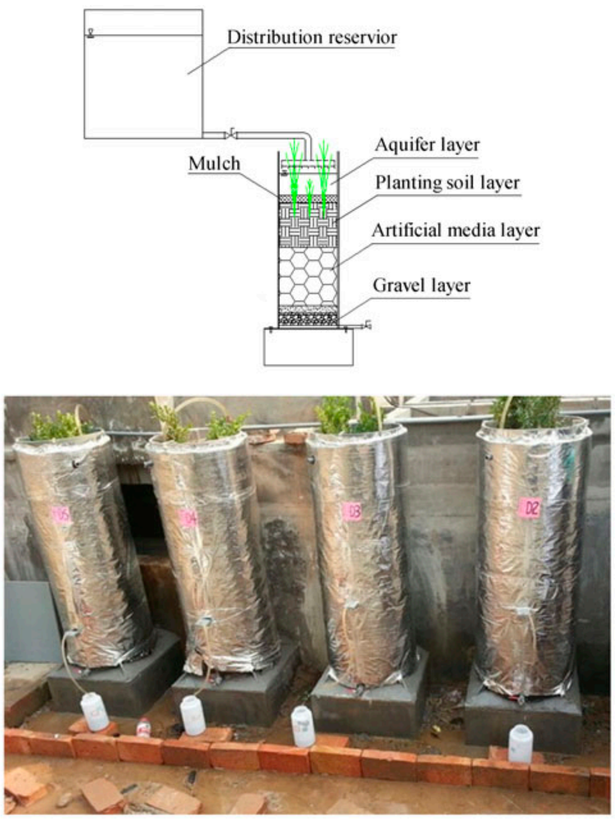

Fig. 1. Sectional schematic and experimental device of the experiment column.

to the five bioswale columns in group B to study the effect of artificial media composition on water quality treatment. In group C, either the planting soil layer thickness or artificial filler thickness were varied. The artificial filler layers of C1, C2, and C3 were adjusted to 300, 500, and 600 mm, respectively, to determine the relationship between filler layer thickness and purifying effect. The planting soil layer of C4 was also adjusted to 200 mm, whereas its artificial filler layer was set to 500 mm. The planting soil layer of C5 was reduced to 100 mm, whereas its artificial filler layer was set to 600 mm. In group D, either the submerged zone height or external carbon source were altered. To study the effects of submerged zone height on pollutant purification, the artificial filler layers of all the columns in group D were set to 400 mm slag, and the submerged zone height of the bioswale columns from D1 to D5 was sequentially set to 0, 500, 500, 400, and 300 mm, respectively. Waste paper, which was laid at the bottom, was also set as a carbon source in group D, except for D2, to compare the pollutant removal with and without an external carbon source.

2.2. Test program

The Chicago rainfall pattern was chosen as the design pattern, and the design return period was set to two years. The rainfall duration was 120 min with a time step of 6 min, and the relative position of the rainfall peak was 0.4. The remaining parameters were determined based on the Xi'an storm intensity equation of Lu [16]. The design rainfall was 27.92 mm. Considering the bioswale design method and the need for column experiments to generate an overflow, 8.408 m^2 was selected as the confluence area of each column. Fig. 2 shows the calculated results of the water inflow volume of the design column experiments using the equation:

$$Q = \frac{A_d \times H \times \varphi}{1000} \tag{1}$$

where A_d is the corresponding confluence area, and m^2, φ is the urban road runoff coefficient, which is 0.9.

To simulate the water quality of the urban surface runoff in Xi'an, various pollutants in the experiment were prepared. The concentration of each pollutant was determined through a comprehensive comparison of the monitoring results on the urban surface runoff in Xi'an [17–20]. The runoff pollutant concentration in the initial, middle-term, and latter periods of the rainfall was considered as high, medium, and low influent concentrations, respectively. The influent concentration and monitoring methods of the water quality index—chemical oxygen demand (COD), TN, and total phosphorus (TP)—are presented in Table 2. Two parallel experiments of high, medium, and low influent pollutant concentrations were conducted using a total of six single-factor tests, with each single-factor test covering all the columns. The average value of the two parallel tests was considered in the following experimental analysis and calculation.

The water inflow distribution was controlled by manually regulating the opening of the drainage valve, and the flux of the overflow and outflow was recorded once every 6 min. The overflow samples were taken every 10 min from the beginning of the overflow. The outflow and other samples were taken successively at 30, 60, 90, and 120 min of the experiment operation. To quantitatively analyze the purifying effect of bioswale on urban runoff, the concentration of the removal rate was chosen as the evaluation index:

$$R_C = \frac{C_{in} - C_{out}}{C_{in}} \times 100\% \tag{2}$$

Table 1
Comparison of the setup of each group of 30 columns

Item	A	B	C	D	E	F
Experimental purpose	Blank control	Vegetation conditions and artificial media composition	Media thickness	Submerged zone height and external carbon source	Vegetation conditions	
Vegetation	No	BR	BR	BR	BO	GC
Aquifers layer	15 cm	15 cm	15 cm	15 cm	15 cm	15 cm
Covering layer	5 cm	5 cm	5 cm	5 cm	5 cm	5 cm
Planting soil thickness	300 mm	300 mm	C1, C2, C3: 300 mm C4: 200 mm C5: 100 mm	300 mm	300 mm	300 mm
Artificial filler layer	A1: sand A2: planting soil A3: slag A4: MSC A5: MSS	B1: sand B2: planting soil B3: slag B4: MSC B5: MSS	Slag	Slag	E1: sand E2: planting soil E3: slag E4: MSC E5: MSS	F1: sand F2: planting soil F3: slag F4: MSC F5: MSS
Artificial filler thickness	400 mm	400 mm	C1: 300 mm C2, C4: 500 mm C3, C5: 600 mm	400 mm	400 mm	400 mm
Gravel layer	15 cm	15 cm	15 cm	15 cm	15 cm	15 cm
Submerged zone height	No	No	No	D1: 0 mm D2, D3: 500 mm D4: 400 mm D5: 300 mm	No	No
External carbon source	No	No	No	D2, D3	No	No

Notes: Each group from A to F has five columns. BR was *boxwood* and *ryegrass*; BO was the combination of *Border privet* and *Ophiopogon japonicus*; GC was the combination of *Glossy privet* and *Chlorophytum comosum "Variegatum"*. In groups A, B, E and F, the artificial filler compositions were varied (1–5); MSC was the mixture of sand and coal ash with volume ratio 5:1, and MSS was the mixture of sand and slag with volume ratio 1:1. In group C, either the planting soil layer thickness or artificial filler thickness were varied. In group D, either the submerged zone height or external carbon source were varied.

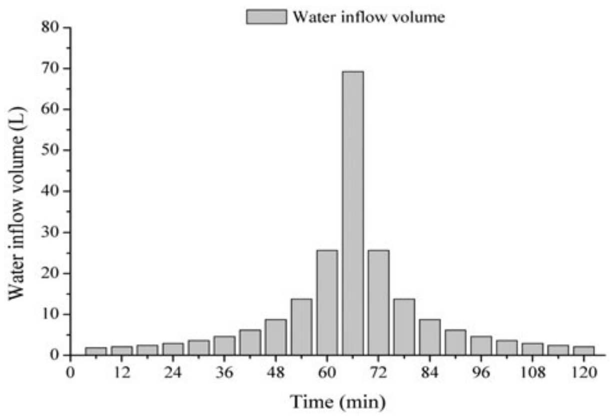

Fig. 2. Water inflow volume of the design column experiments.

where R_C is the concentration removal rate, C_{in} is the influent concentration in mg/L, and C_{out} is the effluent concentration in mg/L.

3. Results and discussion

3.1. Effects of influent concentration

Taking column B4 as an example, where BR was planted and the artificial filler was 400 mm with a mixture of sand and coal ash, the COD removal of B4 was analyzed under different influent flows, as shown in Fig. 3.

The experimental results indicated that B4 approximately had the same variation tendency under different influent COD concentrations. The COD concentration of the overflow remained consistent with that of the inflow and was relatively stable. Thus, the overflow came into contact with the mulch layer and plant surface of the bioswale system only for a brief period, and the inflow was barely treated before the overflow of the upper bioswale. As a result, the water quality of the overflow showed no improvement. The COD effluent concentration increased with rainfall, grew quickly from the initial period, and gradually stabilized. This result occurred because contaminant removal mainly relied on the media sorption, plant uptake, and biodegradation by soil microorganisms in the bioswale system. The pollutant sorption and uptake activities were the highest in the early rainfall period, gradually reached a balance, and remained steady with rainfall. As a result, the COD concentration of the outflow gradually stabilized at a constant level after an initial sudden increase. The above-mentioned COD variation processes of the overflow and outflow were consistent with that of TN and TP. Fig. 3(d) shows that the COD removal rate of B4 is 68.88, 66.72, and 64.85% under low, medium, and high influent concentration conditions, respectively. Thus, the COD concentration removal rate decreased with an increase in the influent concentration of the bioswale system.

Taking C2, E5, and F3 as examples, the TN concentration removal rates under different influent flows are presented in Fig. 4(a). The variation tendency of the TN concentration removal rate of C2, E5, and D3 was substantially similar under different influent concentrations. The TN concentration removal rate was high under low influent concentration, slightly decreased under medium influent concentration, and was the lowest under high influent concentration. The results above indicate that bioswale TN concentration removal rate decreased with an increase in influent concentration. C2 was filled with planting soil, E5 with MSS, and F3 with slag. Overall, the TN removal was as follows: C2 > F3 > E5, which was consistent with the order of media factor for TN removal as follows: planting soil > slag > MSS (Table 4).

Taking A2, B3, and E4 as examples, the TP concentration removal rates under different influent flows were compared (Fig. 4(b)). The variation trend of the TP concentration removal rate under different influent concentrations was consistent with that of COD and TN. Thus, the TP concentration removal rate decreased with an increase in the influent

Table 2
Influent concentration and monitoring methods of the experiment pollutant

Types	COD (mg/L)	TN (mg/L)	TP (mg/L)
High concentration	600	14	2.5
Medium concentration	400	10	1.5
Low concentration	200	6	0.5
Monitoring method	Ultraviolet spectrophotometry	Molybdenum antimony spectrophotometry	Dichromate titration

Notes: COD was chemical oxygen demand, TN was total nitrogen and TP was total phosphorus.

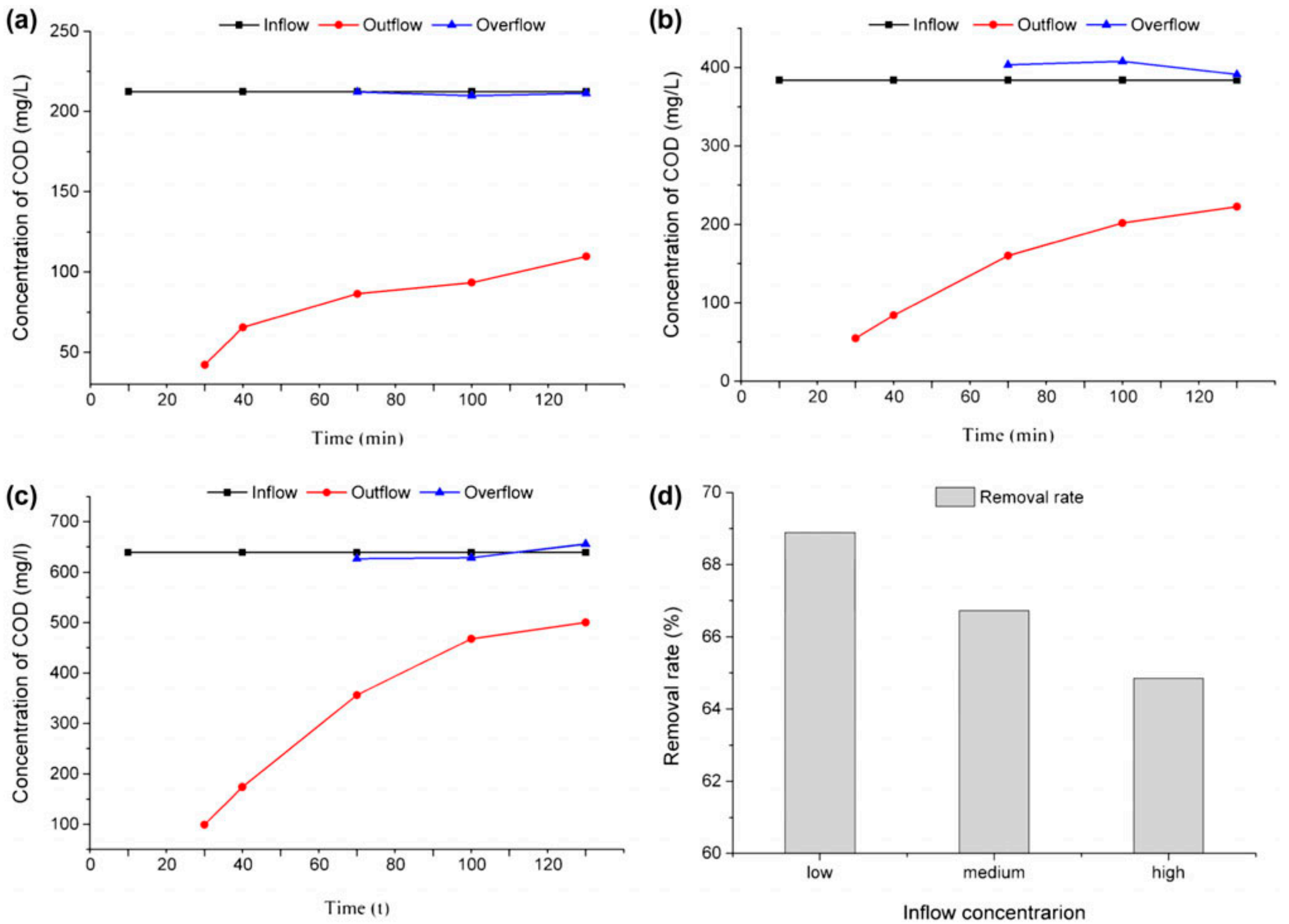

Fig. 3. COD concentrations of column B4 at different inflow concentrations conditions: (a) low concentration, (b) medium concentration, (c) high concentration, and (d) COD removal rate.

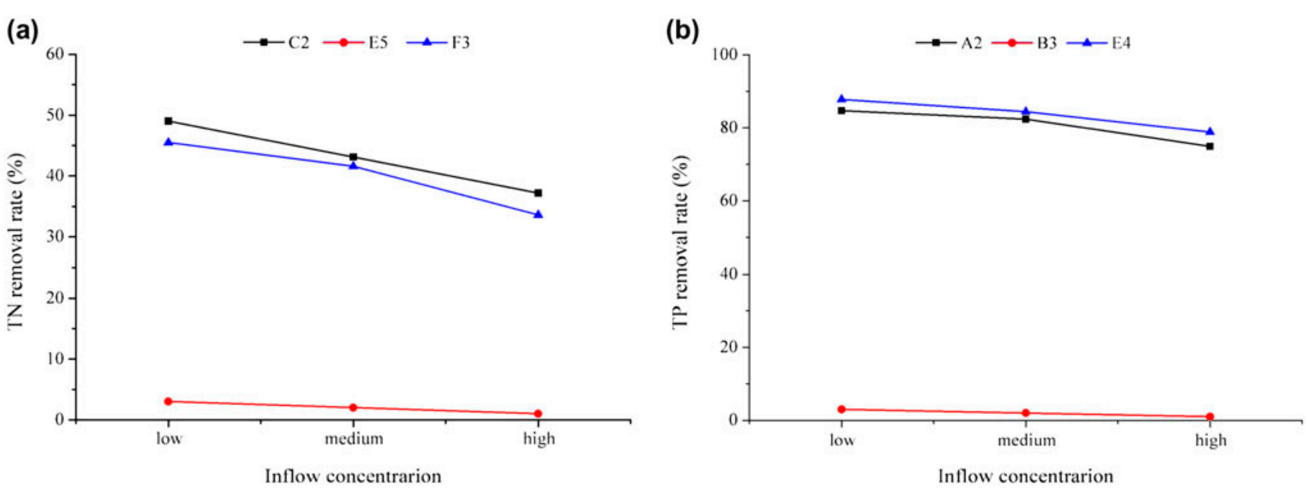

Fig. 4. TN and TP removal under different inflow concentrations: (a) TN removal and (b)TP removal.

concentration of the bioswale column. A2 was filled with planting soil, E4 with MSC, and B3 with slag. Overall, the TP removal was as follows: E4 > A2 > B3, which was consistent with the order of media factor for TP removal as follows: MSC > planting soil > slag (Table 4).

The results above indicate that the removal efficiency of TN, TP, and COD in the bioswale decreases with an increase in the influent pollutant concentration. This is due to the dependence of the removal of pollutants on media sorption, plant uptake, and biodegradation by soil microorganisms with a maximum removal limit. When the influent concentration increases, the removal ability of bioswale contaminants does not vary with influent concentration. Once the bioswale exceeds its capacity during the operation period, its contaminant removal is maintained at a fixed level, or it even loses its normal purifying ability. As a result, an increase in the influent concentration reduces the purifying effect of the bioswale system on urban runoff.

3.2. Effects of vegetation conditions

Plants can decompose pollutants that are adsorbed from their roots. Thus, plants are crucial to the bioswale treatment of urban runoff. Vegetation that exhibits short-term drought resistance and flood tolerance should be considered in the selection of bioswale plants. Local, seasonal, and perennial plants with stronger environment adaptability and lower maintenance pressure should be prioritized. The selected plants should exhibit better response to contamination removal because plants with high nutrient removal can extend the life of the bioswale. Three plant combinations were selected to establish different vegetation conditions: *BR* in Group B, BO in Group E, and GC in Group F . All vegetations above had grown for two months in the columns before the experiments started.

The contaminant removal rate in A2, B2, E2, and F2 with different plant combinations were basically the same(Table 3). Thus, the selected vegetations had approximately the same purification effects in two months after being planted. This finding may be a result of the minor differences in the effects of the selected vegetation conditions on pollutant removal in two months after being planted. It may also be attributed to the contaminant removal of plants that mainly rely on the nutrient uptake, which was through the transpirational pull of water toward the root. Given that the entire test was completed in the winter period, the contaminant removal of vegetation may have been poor because of the non-robust activity of plant roots and lower rates of transpiration.

3.3. Effects of media thickness

To study the effect of the contaminant removal of different media thickness on urban runoff, two scenarios were designed according to varying media thickness and slag as artificial filler in Group C.

In scenario 1, the total media thickness consisted of the planting soil and artificial filler layers. Only the artificial filler layer thickness was varied, whereas the planting soil layer thickness and other vertical structures were kept the same. C1, B3, C2, and C3 were used as examples, with an artificial layer thickness of 300, 400, 500, and 600 mm, respectively.

Fig. 5(a) shows that the concentration removal rates of COD, TN, and TP exhibit the same variation trend, and the removal rate is, C1 < B3 < C2 < C3 (Fig. 4(a)), under the same influent concentration conditions. The results indicate that the COD, TN, and TP concentration removal rates increase with artificial filler thickness, whereas other vertical structures of the bioswale column remain consistent.

In scenario 2, the thickness of the artificial filler layer and that of the planting soil layer were both varied, whereas the total media thickness was held constant. B3, C4, and C5 were used as examples, with a total media thickness of 700 mm, artificial filler (slag) layer thickness of 400, 500, and 600 mm, and planting soil thickness of 300, 200, and 100 mm, respectively.

The pollutant removal capacity of B3, C4, and C5 under different influent concentrations is presented in Fig. 5(b). The results indicate that the concentration removal rates of COD, TN, and TP show the same variation trend as above with removal rates of C5 < C4 < B3, under the same influent contamination concentration. Thus, the concentration removal rates of COD, TN, and TP increased with planting soil thickness under the same conditions of influent contamination concentration.

The results of the two scenarios with different media thickness indicate that an increase in the thickness of the planting soil layer and that of the artificial filler layer can improve the contaminant removal capacity. The amount of artificial media in the bioswale column and adsorption ability of pollutant removal increased with artificial media thickness. Slower infiltration extends the exposure time between the media and urban runoff thus the adsorption ability and reaction time are extended because of an increase in planting soil thickness.

3.4. Effects of media composition

Two to four kinds of media are generally utilized in filling a bioswale to achieve the best treatment

Table 3
Pollutant purification of A2, B2, E2, and F2

	Pollutants concentration removal								
	Low influent concentration			Medium influent concentration			High influent concentration		
Vegetation types	COD (%)	TN (%)	TP (%)	COD (%)	TN (%)	TP (%)	COD (%)	TN (%)	TP (%)
A2 (None)	77.25	66.35	74.88	57.35	56.88	82.41	54.84	68.06	84.73
B2 (BR)	76.56	65.74	73.08	59.51	62.57	81.04	57.46	68.54	86.2
E2 (BO)	78.67	65.39	74.94	58.59	57.71	80.42	55.19	66.79	85.79
F2 (GC)	78.78	63.18	72.62	62.04	57.66	81.17	53.52	67.68	85.84

Notes: COD was chemical oxygen demand, TN was total nitrogen and TP was total phosphorus. In columns A2, B2, E2, and F2, vegetation were varied. A2 was black control without plant. B2 was planted with the combination of *boxwood* and *ryegrass* (BR), E2 with the combination of *Border privet* and *Ophiopogon japonicus* (BO), F2 with the combination of *Glossy privet* and *Chlorophytum comosum* "*Variegatum*" (GC).

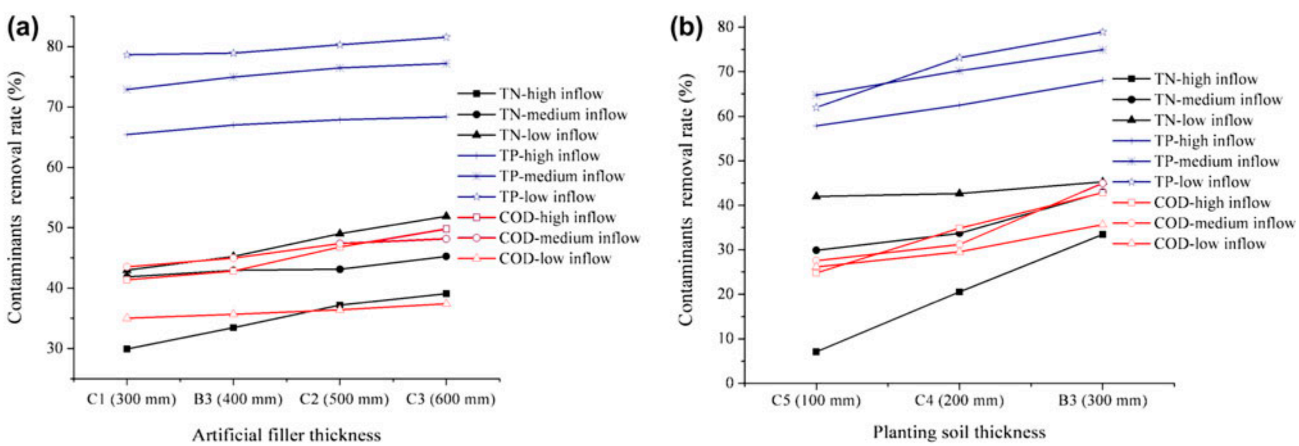

Fig. 5. Pollutant removal of bioswale columns with varying media thicknesses (a) scenario 1 and (b) scenario 2.

effect in consideration of the cost. Given the actual situation of Xi'an, this study selected sand, slag, 5:1 MSC, and 1:1 MSS as the four different artificial filler compositions. These compositions were then compared with planting soil to determine the treatment effects of different artificial fillers on urban runoff pollutants in bioswales. As for a kind of media, the greater the adsorption amount of media on pollutants, the better the pollutant removal effect. Meanwhile, the smaller the infiltration rate of filler, the longer the contact time between filler and rainwater, which also improves pollutant removal effect. Therefore, the media factor was defined to evaluate the purification performance of a media, which was the adsorption amount of media on pollutants divided by the infiltration rate (Table 4). The media with greater media factor has better purification performance. The results showed that the planting soil and the mixture of sand and coal ash with volume ratio 5:1 (MSC) were the preferred media among the study media compositions, which had larger media factors, whereas sand was a weaker media with the smallest media factor.

The pollutant concentration removal under different influent concentrations is shown in Fig. 6.

The removal of COD, TN, and TP removal is as follows: MSC > planting soil > slag > MSS > sand, planting soil > MSC > slag > MSS > sand MSC > planting soil > MSS > slag > sand. Planting soil and the mixture of coal ash and sand were the best choice, whereas sand was the worst. The contaminant removal rates in the bioswale was consistent with its corresponding media factor. Thus, a stronger adsorption property of the media resulted in a better removal by the bioswale. The differences between planting soil and MSC might have been caused by slight changes in media compaction.

3.5. Effects of submerged zone height

Four different submerged zone heights were designed to analyze the effect of bioswale with

Table 4
Pollutant adsorption and media factor of artificial fillers

Artificial filler type	Infiltration rate (m/d)	COD		TN		TP	
		Pollutant adsorption (mg/g)	Media factor (d/km)	Pollutant adsorption (mg/g)	Media factor (d/km)	Pollutant adsorption (mg/g)	Media factor (d/km)
Sand	1.44	142.34	98.85	74.53	51.76	128.44	89.19
Planting soil	0.50	196.24	392.58	132.13	264.22	163.19	326.38
Slag	1.35	232.58	172.28	213.01	157.78	202.79	150.22
MSC	0.45	168.44	374.31	109.72	243.81	159.44	354.30
MSS	1.20	169.80	141.50	166.13	138.44	187.97	156.64

Notes: COD was chemical oxygen demand, TN was total nitrogen and TP was total phosphorus. MSC was the mixture of sand and coal ash with volume ratio 5:1, and MSS was the mixture of sand and slag with volume ratio 1:1. Media factor, which was the adsorption amount of media on pollutants divided by the infiltration rate, was defined to evaluate the performance of a media.

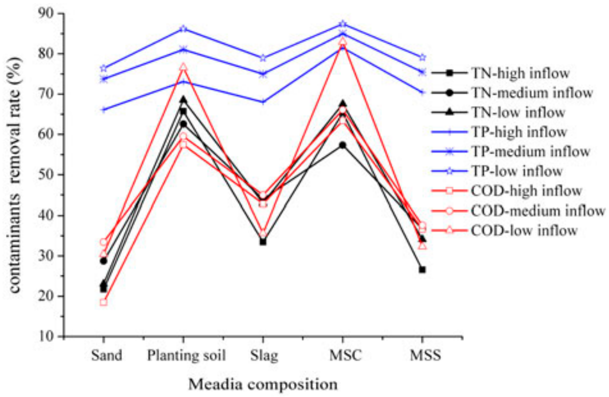

Fig. 6. Pollutant removal of bioswale columns with different artificial media compositions.

different submerged zone heights on urban runoff purification. The submerged zone heights of Group D, except for D2, were 0 (D1), 500 (D3), 400 (D4), and 300 mm (D5), the other vertical structures remained the same. The contaminant concentration removal rates of D1, D3, D4, and D5 under different influent concentrations are presented in Table 5.

Under the same influent concentration, varying submerged zone height had no effect on the removal efficiency of TP and COD. Meanwhile, TN removal capacity increased with submerged zone height. No direct relationship existed between the COD and TP removal mechanism and submerged zone height in the bioswale. However, the submerged zone height facilitates nitrification and denitrification. As a result, increasing the submerged zone height enlarged the

Table 5
Pollutant purification of Group D

	Pollutant concentration removal								
	Low influent concentration			Medium influent concentration			High influent concentration		
Column number	COD (%)	TN (%)	TP (%)	COD (%)	TN (%)	TP (%)	COD (%)	TN (%)	TP (%)
D1	40.58	39.9	66.91	40.58	43.29	66.91	38.89	45.99	80.05
D2	39.48	37.95	68.63	39.48	43.41	68.63	40.22	43.44	79.97
D3	40.13	49.42	67.89	40.13	46.75	67.89	37.61	54.04	79.17
D4	39.37	45.83	68.14	39.37	46.01	68.14	39.59	48.15	80.21
D5	39.02	43.05	68.14	39.02	44.22	68.14	38.31	47.35	79.41

Notes: COD was chemical oxygen demand, TN was total nitrogen and TP was total phosphorus.

Table 6
Correlation analysis of influent concentration and COD concentration removal

Column number	Curve analysis	Column number	Curve analysis
A1	$y = -0.025x + 38.100$ ($R^2 = 0.392$)	D1	$y = -0.005x + 43.401$ ($R^2 = 0.654$)
A2	$y = -0.051x + 84.266$ ($R^2 = 0.761$)	D2	–
A3	$y = -0.012x + 34.836$ ($R^2 = 0.421$)	D3	$y = -0.007x + 44.119$ ($R^2 = 0.723$)
A4	$y = -0.022x + 82.054$ ($R^2 = 0.351$)	D4	–
A5	–	D5	$y = -0.003x + 41.755$ ($R^2 = 0.526$)
B1	$y = -0.030x + 39.990$ ($R^2 = 0.684$)	E1	$y = -0.028x + 39.170$ ($R^2 = 0.486$)
B2	$y = -0.042x + 81.700$ ($R^2 = 0.733$)	E2	$y = -0.054x + 86.519$ ($R^2 = 0.816$)
B3	$y = -0.015x + 35.028$ ($R^2 = 0.426$)	E3	$y = -0.016x + 33.754$ ($R^2 = 0.397$)
B4	$y = -0.043x + 88.486$ ($R^2 = 0.760$)	E4	$y = -0.039x + 87.383$ ($R^2 = 0.662$)
B5	$y = -0.009x + 31.836$ ($R^2 = 0.684$)	E5	$y = -0.012x + 30.271$ ($R^2 = 0.509$)
C1	$y = -0.014x + 34.136$ ($R^2 = 0.437$)	F1	$y = -0.017x + 36.151$ ($R^2 = 0.322$)
C2	$y = -0.023x + 37.757$ ($R^2 = 0.633$)	F2	$y = -0.059x + 89.225$ ($R^2 = 0.951$)
C3	$y = -0.028x + 33.234$ ($R^2 = 0.784$)	F3	$y = -0.017x + 32.344$ ($R^2 = 0.793$)
C4	$y = -0.012x + 37.018$ ($R^2 = 0.914$)	F4	$y = -0.044x + 89.565$ ($R^2 = 0.829$)
C5	$y = -0.004x + 27.672$ ($R^2 = 0.311$)	F5	–

Table 7
Correlation analysis of media thickness, media composition, and COD concentration removal

Influencing factor	Column number	Curve analysis		
		Low influent concentration	Medium influent concentration	High influent concentration
Planting soil thickness	B3/C4/C5	$y = 0.474x + 20.957$ ($R^2 = 0.973$)	$y = 103.531x + 52.291$ ($R^2 = 0.974$)	$y = 0.902x + 16.133$ ($R^2 = 0.996$)
Artificial filler thickness	B3/C1/C2/C3	$y = 0.292x + 32.054$ ($R^2 = 0.973$)	$y = 0.163x + 38.652$ ($R^2 = 0.960$)	$y = 0.163x + 38.652$ ($R^2 = 0.967$)
Media composition	A	$y = 0.188x + 6.519$ ($R^2 = 0.980$)	$y = 0.091x + 26.701$ ($R^2 = 0.919$)	$y = 0.133x + 12.631$ ($R^2 = 0.842$)
	B	$y = 0.185x + 7.865$ ($R^2 = 0.967$)	$y = 0.099x + 24.932$ ($R^2 = 0.940$)	$y = 0.120x + 15.444$ ($R^2 = 0.821$)
	E	$y = 0.194x + 5.592$ ($R^2 = 0.974$)	$y = 0.091x + 26.912$ ($R^2 = 0.940$)	$y = 0.121x + 15.052$ ($R^2 = 0.836$)
	F	$y = 0.193x + 5.945$ ($R^2 = 0.976$)	$y = 0.103x + 24.287$ ($R^2 = 0.974$)	$y = 0.111x + 16.736$ ($R^2 = 0.865$)

denitrification area, which increases the TN removal rate.

3.6. Effects of external carbon source

To study the effect of external carbon source on urban runoff purification, the vertical structures of D2 and D3 were kept the same, while D3 had an external carbon source, the waste paper was supplied at the bottom. The purification effect of D2 and D3 on the pollutants were analyzed under the same conditions of influent contamination concentrations (Table 5).

The addition of an external carbon increased TN removal but had no effect on TP removal. The COD removal with an external carbon source was slightly worse than that without the external carbon source under the same influent pollutant concentration. This is due to the carbon supplied for denitrification and for enhancing denitrification intensity, which improve TN removal. The COD pollution load increased because of the addition of external carbon source, which eventually decreased the corresponding COD removal capacity.

3.7. Statistical analysis

Bioswales have shown to exhibit various pollutant removal capacities under different conditions, such as influent concentration, artificial filler composition and thickness, planting soil thickness, and submerged zone height. A significant number of studies on bioswale columns indicate better pollutant removal capacity, with artificial fillers showing a higher adsorption performance and those whose planting soil thickness and setting of submerged zone height are greater, especially at a lower influent concentration.

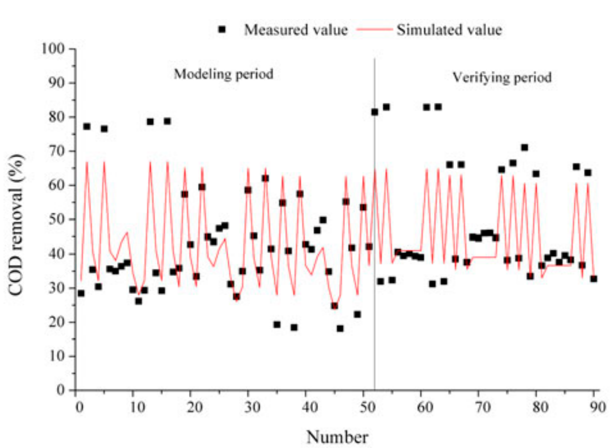

Fig. 7a. Comparison of measured value and simulated value for COD with PLS model.

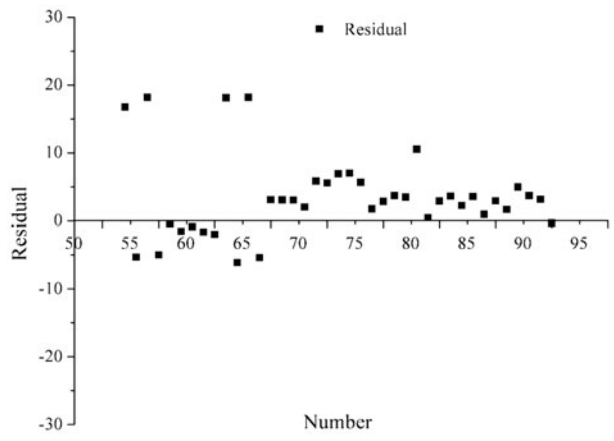

Fig. 7b. Residual of COD concentration removal.

3.7.1. COD removal and its factors

The results of previous studies on bioswale columns indicate better COD removal with high adsorption media and relatively high soil thickness and artificial filler thickness under lower influent concentration. The corresponding correlation analysis was conducted, using SPSS software, to determine the relationship between the COD removal and factors, respectively, such as influent concentration, artificial filler thickness, planting soil thickness, and artificial filler compositions.

Table 6 presents the calculated COD removal rate curves of each of the bioswale columns configurations at different influent concentrations. The correlation coefficients of all the columns are higher than 0.3, and most of the correlation coefficients are more than 0.5. As a result, a strong linear and inverse relationship is identified between the COD removal rate and influent concentration.

Taking B3, C4, and C5 as examples, the curve analysis between the planting soil thickness and COD removal rate was conducted. The high correlation coefficients indicate a linear and direct relationship between planting soil thickness and COD removal rate (Table 7).

Taking B3, C1, C2, and C3 as examples, the COD removal rate increased linearly with artificial filler thickness (Table 7).

Taking Groups A, B, E, and F as examples with different influent concentrations, the correlation coefficients indicate a strong linear and direct relationship between COD removal rate and media composition.

The correlation analyses generally indicate that the COD removal rate has a linear relationship with influent concentration, planting soil thickness, artificial filler composition, and artificial filler thickness. The

Table 8
Curves analysis of influent concentration and TN concentration removal

Column number	Curve analysis	Column number	Curve analysis
A1	$y = -0.464x + 29.811$ ($R^2 = 0.316$)	D1	$y = -0.838x + 50.383$ ($R^2 = 0.998$)
A2	$y = -0.158x + 65.134$ ($R^2 = 0.409$)	D2	$y = -0.796x + 48.558$ ($R^2 = 0.840$)
A3	$y = -1.292x + 53.574$ ($R^2 = 0.574$)	D3	$y = -0.546x + 54.848$ ($R^2 = 0.291$)
A4	$y = -0.114x + 62.614$ ($R^2 = 0.508$)	D4	$y = -0.300x + 49.288$ ($R^2 = 0.717$)
A5	$y = -1.386x + 46.802$ ($R^2 = 0.724$)	D5	$y = -0.571x + 49.862$ ($R^2 = 0.793$)
B1	$y = -0.200x + 26.251$ ($R^2 = 0.639$)	E1	$y = -1.269x + 40.115$ ($R^2 = 0.858$)
B2	$y = -0.373x + 68.833$ ($R^2 = 0.208$)	E2	$y = -0.106x + 64.230$ ($R^2 = 0.406$)
B3	$y = -1.319x + 51.478$ ($R^2 = 0.689$)	E3	$y = -0.646x + 48.473$ ($R^2 = 0.516$)
B4	$y = -0.276x + 69.798$ ($R^2 = 0.735$)	E4	–
B5	$y = -1.050x + 41.510$ ($R^2 = 0.531$)	E5	$y = -1.038x + 43.816$ ($R^2 = 0.899$)
C1	$y = -1.986x + 56.269$ ($R^2 = 0.947$)	F1	$y = -0.440x + 26.544$ ($R^2 = 0.589$)
C2	$y = -1.494x + 56.093$ ($R^2 = 0.994$)	F2	$y = -0.455x + 66.821$ ($R^2 = 0.725$)
C3	$y = -1.618x + 59.478$ ($R^2 = 0.990$)	F3	$y = -1.545x + 53.765$ ($R^2 = 0.992$)
C4	$y = -2.818x + 56.797$ ($R^2 = 0.999$)	F4	$y = -0.106x + 62.303$ ($R^2 = 0.647$)
C5	$y = -4.473x + 65.200$ ($R^2 = 0.991$)	F5	$y = -1.876x + 54.418$ ($R^2 = 0.674$)

partial least squares (PLS) method was employed to fit the linear equations between the contaminant removal rates and various factors using SPSS.

By substituting the above-mentioned influencing factors into the PLS model, the original variable equation was determined as $y = d_1x_1 + d_2x_2 + d_3x_3 + d_4x_4 + d_0$, where y is the COD concentration removal rate in %, x_1 is influent concentration in mg/L, x_2 is planting soil thickness in cm, x_3 is artificial filler adsorption capacity factor in d/km, which equals to filler adsorption capacity divided by filler infiltration rate, and x_4 is artificial filler thickness in cm.

A1, A2, A3, B1, B2, B3, C1, C2, C3, C4, C5, E1, E2, E3, F1, F2, and F3 were considered the modeling samples for the PLS analysis. The corresponding COD concentration removal rate and the parameter values in each of the bioswale columns above, were generated in the software for calculation. The calculated original variable regression equation was $y = -0.010x_1 + 0.915x_2 + 0.118x_3 + 0.270x_4 - 15.525$.

A4, A5, B4, B5, D1, D2, D3, D4, D5, E4, E5, F4, and F5 were considered as the test samples for PLS analysis. The corresponding COD concentration removal rate and parameter values in each of the bioswale columns above, were substituted into the software for calculation.

The deterministic coefficient (Nash–Suttcliffe simulation efficiency coefficient) was adopted to test the simulation results. The Nash–Suttcliffe simulation efficiency coefficient (Ens) was calculated as:

$$\text{Ens} = \frac{\sum_{i=1}^{n}(Q_0 - Q_p)^2}{\sum_{i=1}^{n}(Q_0 - Q_{avg})^2} \quad (3)$$

where Q_0 is the measured value, Q_p is the simulated value, Q_{avg} is the average value of the measured data, and n is the total number of measured data.

The simulated and tested results were substituted into the equation presented above. The calculated results were obtained as follows: the Ens of the simulation was 0.8199 and that of the verification test was 0.8181. The comparison of the simulated and measured values of the COD removal rate in PLS analysis is shown in Fig. 7a. The residual analysis of the COD removal rate is presented in Fig. 7b.

Based on Fig. 7a, the differences between the predicted and measured values of the model are minimal. Combined with the deterministic coefficient, the Ens of the simulation and test results are relatively close to 0.82, indicating that the simulated equation is an appropriate and reasonable choice.

The residual values substantially fluctuate around ±20, and the data are comparatively concentrated near 0, demonstrating that the simulated value is close to the measured value (Fig. 7b). Error analysis was conducted by tracking the points with larger residuals:

(1) The simulated values of Group D are generally higher than the measured values under the condition of high and medium influent concentrations because of the embedded shredded newspaper in Group D, which may have increased the COD concentration load and resulted in a poor removal effect.
(2) The deviation of the simulated and measured values is larger in the bioswale columns with planting soil as the media filler, and the residual values are even higher than 10. This may

Table 9
Estimation of media thickness, media composition, submerged zone height, and TN concentration removal

Influencing factor	Column number	Curve analysis		
		Low influent concentration	Medium influent concentration	High influent concentration
Planting soil thickness	B3/C4/C5	$y = 0.050x + 41.547$ ($R^2 = 0.956$)	$y = 0.702x + 21.797$ ($R^2 = 0.934$)	$y = 1.319\text{x} - 6.023$ ($R^2 = 1.000$)
Artificial filler thickness	B3/C1/C2/C3	$y = 0.306x + 33.517$ ($R^2 = 0.992$)	$y = 0.094x + 39.323$ ($R^2 = 0.721$)	$y = 0.312x + 20.845$ ($R^2 = 0.982$)
Media composition	A	$y = 0.208x + 12.555$ ($R^2 = 0.982$)	$y = 0.137x + 22.201$ ($R^2 = 0.957$)	$y = 0.228x + 4.158$ ($R^2 = 0.910$)
	B	$y = 0.232x + 7.570$ ($R^2 = 0.966$)	$y = 0.162x + 18.179$ ($R^2 = 0.982$)	$y = 0.236x + 2.206$ ($R^2 = 0.895$)
	E	$y = 0.164x + 19.662$ ($R^2 = 0.931$)	$y = 0.133x + 22.775$ ($R^2 = 0.943$)	$y = 0.208x + 8.010$ ($R^2 = 0.945$)
	F	$y = 0.200x + 14.343$ ($R^2 = 0.999$)	$y = 0.182x + 14.406$ ($R^2 = 0.929$)	$y = 0.223x + 3.785$ ($R^2 = 0.865$)
Submerged zone height	D1/D3/D4/D5	$y = 0.069x + 43.002$ ($R^2 = 0.874$)	$y = 0.069x + 43.002$ ($R^2 = 0.874$)	$y = 0.178x + 39.199$ ($R^2 = 0.905$)

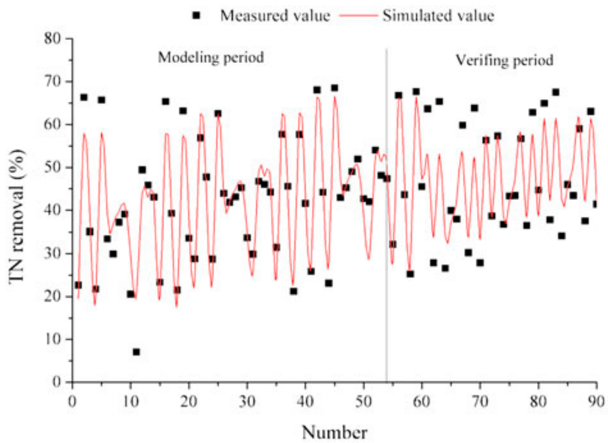

Fig. 8a. Comparison of measured value and simulated value for TN with PLS model.

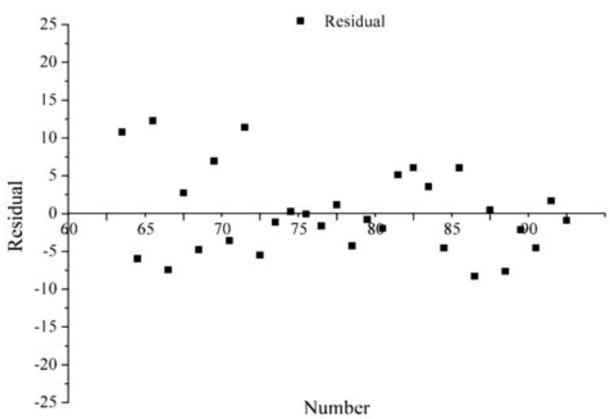

Fig. 8b. Residual of TN concentration removal.

be due to the planting soil, which easily exhibited compaction and perforation(channeling) after the experiment operation. Thus, the infiltration rate and actual media layer thickness of the bioswale column were altered, and the actual contact time between the soil and contaminants was probably shortened.

(3) Part of the residual is attributable to the system operator error, which is mostly observed in the experiments with low influent concentration. These experiments were conducted at the beginning of the experiment, and the requirements at the initial operation period may not have been met because of system instability. Thus, some residual errors were caused by the system errors at the initial period.

3.7.2. TN removal and its factors

The results of studies on bioswale columns indicate better TN removal when columns were filled with high adsorption artificial filler and relatively high soil thickness and artificial filler thickness under lower influent concentration. The TN removal rates of bioswale columns under three kinds of different influent concentrations (i.e. high, medium, and low) were analyzed, and the curve analyses of different influent concentrations was conducted (Table 8). The results indicate a strong linear and inverse relationship between the TN removal rate and influent concentration. Table 9 presents the results of the curve analysis of TN removal rate and its factors, such as planting soil thickness, artificial filler thickness, artificial filler

Table 10
Curve analysis of influent concentration and TP concentration removal

Column number	Curve analysis	Column number	Curve analysis
A1	$y = -5.424x + 80.530$ ($R^2 = 0.993$)	D1	$y = -6.947x + 85.301$ ($R^2 = 0.942$)
A2	$y = -5.305x + 89.029$ ($R^2 = 0.886$)	D2	$y = -6.002x + 84.392$ ($R^2 = 0.957$)
A3	$y = -4.775x + 81.280$ ($R^2 = 0.941$)	D3	$y = -5.982x + 83.355$ ($R^2 = 0.981$)
A4	$y = -5.363x + 92.610$ ($R^2 = 0.955$)	D4	$y = -6.390x + 84.883$ ($R^2 = 0.961$)
A5	$y = -3.373x + 81.860$ ($R^2 = 0.910$)	D5	$y = -5.981x + 83.517$ ($R^2 = 0.987$)
B1	$y = -5.467x + 80.759$ ($R^2 = 0.915$)	E1	$y = -4.987x + 79.793$ ($R^2 = 0.896$)
B2	$y = -6.998x + 61.215$ ($R^2 = 0.978$)	E2	$y = -5.988x + 89.717$ ($R^2 = 0.998$)
B3	$y = -5.820x + 83.221$ ($R^2 = 0.968$)	E3	$y = -4.839x + 81.982$ ($R^2 = 0.956$)
B4	$y = -3.153x + 89.639$ ($R^2 = 0.982$)	E4	$y = -4.916x + 91.339$ ($R^2 = 0.966$)
B5	$y = -4.633x + 82.355$ ($R^2 = 0.987$)	E5	$y = -4.837x + 83.720$ ($R^2 = 0.980$)
C1	$y = -6.935x + 83.370$ ($R^2 = 0.991$)	F1	$y = -5.326x + 79.760$ ($R^2 = 0.963$)
C2	$y = -6.499x + 85.243$ ($R^2 = 0.943$)	F2	$y = -7.124x + 91.050$ ($R^2 = 0.960$)
C3	$y = -6.906x + 89.720$ ($R^2 = 0.954$)	F3	$y = -5.991x + 83.372$ ($R^2 = 0.907$)
C4	$y = -5.580x + 77.513$ ($R^2 = 0.927$)	F4	$y = -5.313x + 92.329$ ($R^2 = 0.946$)
C5	$y = -2.110x + 64.874$ ($R^2 = 0.335$)	F5	$y = -4.917x + 83.742$ ($R^2 = 0.976$)

Table 11
Curve analysis of media thickness, media composition, and TP concentration removal

Influencing factor	Column number	Curve analysis		
		Low influent concentration	Medium influent concentration	High influent concentration
Planting soil thickness	B3/C4/C5	$y = 0.848x + 54.400$ ($R^2 = 0.967$)	$y = 0.848x + 54.400$ ($R^2 = 0.967$)	$y = 0.509 + 52.600$ ($R^2 = 0.998$)
Artificial filler thickness	B1/C1/C2/C3	$y = 0.101x + 75.319$ ($R^2 = 0.944$)	$y = 0.145x + 68.868$ ($R^2 = 0.959$)	$y = 0.178x + 72.318$ ($R^2 = 0.713$)
Media composition	A	$y = 0.042x + 72.365$ ($R^2 = 0.948$)	$y = 0.044x + 68.848$ ($R^2 = 0.957$)	$y = 0.037x + 64.478$ ($R^2 = 0.849$)
	B	$y = 0.041x + 72.679$ ($R^2 = 1.000$)	$y = 0.040x + 69.478$ ($R^2 = 0.947$)	$y = 0.046x + 61.956$ ($R^2 = 0.806$)
	E	$y = 0.042x + 72.523$ ($R^2 = 0.978$)	$y = 0.036x + 70.394$ ($R^2 = 0.931$)	$y = 0.039x + 63.999$ ($R^2 = 0.922$)
	F	$y = 0.042x + 72.438$ ($R^2 = 0.978$)	$y = 0.041x + 69.326$ ($R^2 = 0.945$)	$y = 0.037x + 63.081$ ($R^2 = 0.803$)

composition, and submerged zone height. The correlation coefficients are higher than 0.8 and close to 1.0, which indicate a strong linear and direct relationship between the TN removal rate and the factors mentioned above. The TN concentration removal rate of a bioswale column exhibits a linear relationship with influent concentration, planting soil thickness, artificial filler factor, artificial filler thickness, and submerged zone height. The PLS method was used to fit the linear equations between the TN removal rate and its various factors. The calculated original variable regression equation is $y = -0.010x_1 + 0.915x_2 + 0.118x_3 + 0.270x_4 - 15.525$, where y is the TN concentration removal rate in %, x_1 is the influent concentration in mg/L, x_2 is the planting soil thickness in cm, x_3 is the artificial filler adsorption capacity factor in d/km, x_4 is the artificial filler thickness in cm, and x_5 is the submerged zone height in cm.

The simulation and validation results were substituted into the Ens calculated equation. The calculated results are as follows: the Ens of the simulation is 0.8991, and that of the verification test is 0.8153. The simulations and measured values of the TN concentration removal rate in the PLS analysis are compared in Fig. 8a. The residual analysis of the TN concentration removal rate is presented in Fig. 8b.

Based on Fig. 8a, the differences between the predicted and measured values of the model are minimal. Combined with the deterministic coefficient, the Ens of the simulation and that of the test results are relatively close, and their values are more than 0.81, indicating that the simulated equation is a reasonable choice.

Fig. 8b shows that the residual values fluctuate around ±10. Only a few points are beyond ±10, and the data are comparatively concentrated near 0, which indicates that the simulated values are close to the measured values. The data with relatively higher residuals were mostly found in the high influent concentration experiments, and the simulated values were generally higher than the measured values. These observations are attributable to the temperature decrease in the experiments with low and medium influent concentrations compared to the high influent concentration period. Microbial activity also decreases with a decrease in temperature and microbial metabolism. As a result, the nitrogen reaction effect of nitrifying and denitrifying bacteria, which is closely related to TN removal, is reduced, thereby affecting TN removal.

3.7.3. TP removal and its factors

The TP removal rate was higher in bioswale columns with lower influent concentration and when filled with high-adsorption artificial filler and had relatively high soil thickness and artificial filler thickness. The curves between different influent concentrations and TP removal were calculated under three different conditions of influent concentration (Table 10). The results indicate a strong linear and inverse relationship between the TP removal rate and influent concentration. Table 11 presents the curve analyses between the TP removal rate and influent concentration, planting soil thickness, artificial filler thickness, and artificial filler composition. The correlation coefficients were higher than 0.7 and close to 1.0, which indicated a strong linear and direct relationship between the TP removal rate and its factors. The PLS method was adopted to fit the linear equations between the TP removal rate and influent concentration, planting soil thickness, artificial filler factor, and artificial filler thickness. The calculated original variable

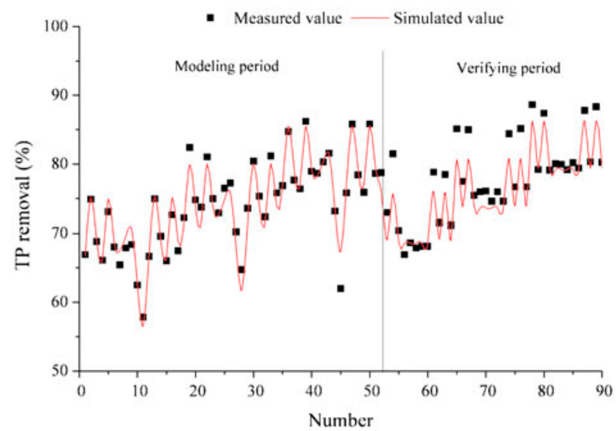

Fig. 9a. Comparison of measured value and simulated value for TP with PLS model.

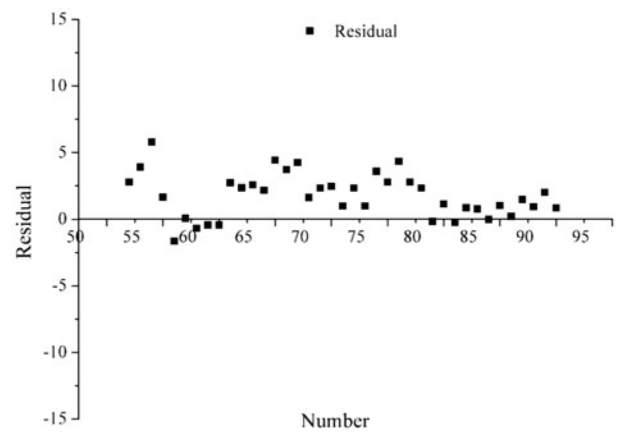

Fig. 9b. Residual of TP concentration removal.

regression equation is $y = -5.657x_1 + 0.704x_2 + 0.035x_3 + 0.104x_4 + 52.207$, where y is the TP concentration removal rate in %, x_1 is the influent concentration in mg/L, x_2 is the planting soil thickness in cm, x_3 is the artificial filler adsorption capacity factor in d/km, and x_4 is the artificial filler thickness in cm.

The simulation and validation results were substituted into the Ens calculated equation. The calculated results were obtained as follows: the Ens of the simulation is 0.9476, and that of the verification test is 0.8203. The simulations and measured values of the TP concentration removal rate in the PLS analysis are compared in Fig. 9a. The residual analysis of the TP concentration removal rate is shown in Fig. 9b. Fig. 9a indicates that the differences between the prediction value and measured value of the model were minimal. Combined with the deterministic coefficient, the Ens of simulation results and test results were higher than 0.82, which indicates that the simulated equation was a more reasonable choice. Fig. 9b shows that the residual values fluctuate around ±4. Only a few points fluctuate from ±4 to ±6. The data are highly concentrated near zero, indicating that the simulated and measured values are basically the same. No point with larger residuals is observed, which indicates that the data statistical regulation on simulating the TP removal experiment is positive and accurate. Thus, the constructed model can provide support to similar problems.

4. Conclusion

The COD, TN, and TP removal rates in bioswales increased with a decrease in inflow contamination concentration. Various selected vegetations had approximately the same effect on pollutant concentration removal in two months after being planted within a single rainfall. An increase in planting soil layer and artificial filler layer thickness significantly improved pollutant concentration removal. Various artificial media compositions were shown to exhibit different pollutant purification effects. The preferential order of artificial media on COD removal was as follows: mixture of coal ash and sand > planting soil > slag > mixture of slag and sand > sand. The preferential order of artificial filler on TN removal was as follows: planting soil > mixture of coal ash and sand > slag > mixture of slag and sand > sand. The preferential order of artificial media on TP removal was as follows: mixture of coal ash and sand > planting soil > mixture of slag and sand > slag > sand. The pollutant purification of planting soil and the mixture of coal ash and sand were the best, and that of sand was the worst. The removal of contaminations by bioswale column is consistent with the adsorption capacity of artificial media. The TN removal rate increased with submerged zone height, whereas the removal rate of COD and TP show no significant change. Adding an external carbon source increased the TN concentration removal and reduced COD concentration removal without an evident effect on TP. In summary, bioswales exhibited better pollutant removal in columns filled with high-adsorption artificial fillers and higher artificial filler and planting soil layer thickness under lower influent concentration. The adsorption performance of artificial fillers refers to the ratio of artificial filler adsorption and permeability. The setting of the bottom of the submerged zone height improves TN removal.

The curve analyses of the relationship between the pollutant removal rate influent concentration, planting soil thickness, artificial filler thickness, artificial filler compositions, submerged zone height, and external carbon source, was conducted using SPSS. The result indicated a linear relationship between the various factors and the pollutant removal rate of the bioswale column. The COD concentration removal rate increased linearly with planting soil thickness, media factor of artificial media, planting soil thickness, and artificial filler thickness. The removal rate decreased linearly with influent concentration. Planting soil thickness, the media factor of artificial media, planting soil thickness, artificial media thickness, and submerged zone height linearly increased with the removal rate of TN concentration, whereas influent concentration decreased linearly with TN concentration. The TP concentration removal rate exhibits a linear and direct relationship with planting soil thickness, media factor of artificial media, and media thickness, whereas TP concentration removal rate decreased linearly with influent concentration.

The statistical relationship between the factors and pollutant removal rate was analyzed with the experimental results using the SPSS software based on PLS model. The differences between the predicted and measured values of the COD, TN, and TP model were minimal. Combined with the deterministic coefficient, the Ens of the simulation and validation results was relatively high, which indicates that the selection of the simulated equation above is reasonable. The residual error of the regression equation is relatively smaller, indicating that the monitoring values are highly reliable.

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References

[1] S.P. Walters, A.L. Thebo, A.B. Boehm, Impact of urbanization and agriculture on the occurrence of bacterial pathogens and stx genes in coastal waterbodies of central California, Water Res. 45(4) (2011) 1752–1762.

[2] A.P. Davis, M. Shokouhian, H. Sharma, C. Minami, Laboratory study of biological retention for urban stormwater management, Water Environ. Res. 73(1) (2001) 5–14.

[3] C.H. Hsieh, A.P. Davis, Evaluation and optimization of bioretention media for treatment of urban storm water runoff, J. Environ. Eng. 131(11) (2005) 1521–1531.

[4] A.P. Davis, Field performance of bioretention: Water quality, Environ. Eng. Sci. 24(8) (2007) 1048–1064.

[5] A.P. Davis, Field performance of bioretention: Hydrology impacts, J. Hydrol. Eng. 13(2) (2008) 90–95.

[6] G.E. Palhegyi, Modeling and sizing bioretention using flow duration control, J. Hydrol. Eng. 15(6) (2010) 417–425.

[7] A.P. Davis, M. Shokouhian, H. Sharma, C. Minami, D. Winogradoff, Water quality improvement through bioretention: Lead, copper, and zinc removal, Water Environ. Res. 75(1) (2003) 73–82.

[8] W.F. Hunt, J.T. Smith, S.J. Jadlocki, J.M. Hathaway, P.R. Eubanks, Pollutant removal and peak flow mitigation by a bioretention cell in urban Charlotte, NC, J. Environ. Eng. 134(5) (2008) 403–408.

[9] H. Yang, E.L. McCoy, P.S. Grewal, W.A. Dick, Dissolved nutrients and atrazine removal by column-scale monophasic and biphasic rain garden model systems, Chemosphere 80(8) (2010) 929–934.

[10] M.H. Kim, C.Y. Sung, M.H. Li, K.H. Chu, Bioretention for stormwater quality improvement in Texas: Removal effectiveness of *Escherichia coli*, Sep. Purif. Technol. 84 (2012) 120–124.

[11] W.F. Hunt, A.R. Jarrett, J.T. Smith, L.J. Sharkey, Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina, J. Irrig. Drain. Eng. 132(6) (2006) 600–608.

[12] H. Li, A. Davis, Water quality improvement through reductions of pollutant loads using bioretention, J. Environ. Eng. 135(8) (2009) 567–576.

[13] W.C. Lucas, M. Greenway, Nutrient retention in vegetated and nonvegetated bioretention mesocosms, J. Irrig. Drain. Eng. 134 (2008) 613–623.

[14] S. Le Coustumer, T.D. Fletcher, A. Deletic, S. Barraud, P. Poelsma, The influence of design parameters on clogging of stormwater biofilters: A large-scale column study, Water Res. 46(20) (2012) 6743–6752.

[15] J. Read, T.D. Fletcher, T. Wevill, A. Deletic, Plant traits that enhance pollutant removal from stormwater in biofiltration systems, Int. J. Phytorem. 12(1) (2009) 34–53.

[16] J.S. Lu, Y. Chen, Q. Zheng, S.P. Wang, J.P. Wang, Derivation of rainstorm intensity formula in Xi'an City, China Water Waste Water 26(17) (2010) 82–84 (in Chinese).

[17] J.K. Li, G.F. Du, H.E. Li, B. Shen, Y.J. Li, Purification effects of biological filter on urban road runoff, J. Soil Water Conserv. 26(4) (2012) 1–6, 11 (in Chinese).

[18] H.L. Yuan, H.Q. Chen, Y. Lin, Y.J. Gao, L. Gong, Analysis of quality variation of rainwater in Xi'an, J. Xi'an Univ. Archit. Technol. 43(3) (2011) 391–395 (in Chinese).

[19] B.S. Wang, Study on urban stormwater pollutants transportation processes. Xi'an University of Architecture & Tecnology, PhD Thesis, Xi'an, China (2011) (in Chinese).

[20] Y. Chen, J.Q. Zhao, B. Hu, Pollution characteristics of urban trunk road runoff in Xi'an City, China Environ. Sci. 31(5) (2011) 781–788 (in Chinese).