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Enrichment Evaluation of Heavy Metals from Stormwater Runoff to Soil and Shrubs in Bioretention Facilities

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Abstract: Bioretention facilities with different inflow concentrations, growing media and plants were examined to determine whether the soil in these facilities was polluted with heavy metals and whether runoff had obvious toxic effects on plants. Using Beijing soil background value as the standard, the soils were evaluated by bioaccumulation index and single factor index. The results show that stormwater runoff containing Cu caused slight pollution in soils, and stormwater runoff containing Zn and Pb was not polluted. Nemerow comprehensive index evaluation revealed that the heavy metals content in the facilities containing vermiculite (a yellow or brown mineral found as an alteration product of mica and other minerals, used for insulation or as a moisture-retentive medium for growing plants) and perlite (a form of obsidian characterized by spherulites formed by cracking of the volcanic glass during cooling, used as insulation or in plant growth media) were higher than the standard. High influent concentration caused significantly higher heavy metals content in plants. While Pb accumulation in the two studied plants was the highest, Cu and Zn accumulation, which are essential for plant growth, was relatively low. The contents of the three heavy metals in the studied plants also exceeded their corresponding critical values.

Keywords: bioretention; heavy metals; soil pollution; phytotoxicity; plant growth

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1. Introduction

In recent years, stormwater runoff pollution has become a more serious and important factor, deteriorating the water quality of urban rivers and lakes in most cities in China. To mitigate the problems of urban flood and runoff pollution, China is vigorously promoting the construction of a Sponge City. However, the road stormwater runoff produced during the Sponge City construction process might disturb plant growth. Some researchers believe that heavy metals and other pollutants in road stormwater runoff could cause toxic effects on agricultural soil and plants. Hence, discharge of road stormwater runoff into green space is prohibited in many areas, which undoubtedly hinders the construction of Sponge Cities in corresponding areas. In particular, bioretention facility have become one of the most common and important measures in the source control of Sponge City construction because of the obvious removal effect of substrates and plants on rainwater runoff pollution [1–3], so it is most obviously affected by this regulation.

The bioretention facility in a Sponge City is often established in areas such as parks, both sides of the road, and other places that are often visited. Therefore, it is particularly important to determine whether the soil in the bioretention facility is polluted with heavy metals, and to maintain the growth and beauty of plant life. In addition to their aesthetic effect, plants play an important role in the operation of bioretention facilities. Some studies have shown that the nutrient elements in stormwater runoff can be directly absorbed and degraded by the plant root system. In addition, the secretion generated by the plant root system can provide energy substances for microorganisms, and its large specific surface area can support the growth and attachment of microorganisms [4]. Lange et al. [5], Muthanna et al. [6] and Davis et al. [7] demonstrated that the absorption of heavy metals by plants in bioretention facilities accounted for 0.1–8% of total heavy metal retention. Besides, numerous investigations [8–14] have indicated that plants also play an important role in the infiltration of stormwater, which is mainly reflected in the growth of plant roots, causing the surface layer of the substrate to form tiny vacuoles to some extent, delaying hardening and blocking of soil, and having a positive function in maintaining soil permeability and infiltration. The amount and rate of surface runoff can affect erosion and sediment transport. Thus, soil conservation practices are important in reducing soil erosion. Improving the soil infiltration rate, resulting in less surface runoff, can lead to reduction of soil erosion [15,16]. Plants can also disperse the runoff and slow down the surface flow rate, resulting in effective reduction in the erosion of surface soil by runoff.

The common heavy metals in stormwater runoff include Cu, Zn, and Pb. Although Cu and Zn are essential micronutrients for plant growth, a large number of studies have demonstrated that excessive Cu and Zn have strong phytotoxicity. Excess Cu may alter the membrane permeability, chromatin structure, protein synthesis, enzyme activity, photosynthesis, and respiration in plants [4,17–20], while excess Zn can prevent CO_2 fixation, prevent carbohydrate transport in the phloem, alter membrane permeability, and disrupt plant growth [21]. Pb is a nonessential element for plants, and can inhibit the synthesis of key plant enzymes (such as chlorophyll synthetase), respiration, and photosynthesis. In addition, Pb can also cause growth stagnation by affecting plant cell division and elongation [22].

Because heavy metals are common pollutants causing oxidative stress, how can plants protect themselves from its dangerous effects? In the present study, the impact of stormwater runoff containing three heavy metals, Cu, Zn, and Pb, on the soil and plants in bioretention facilities was analyzed. The experiments were conducted using different runoff concentrations and bioretention facilities constructed with different types of media. The purpose of this study is to explore whether these three heavy metals in stormwater runoff pollute the soil of bioretention facilities and pose a threat to plant growth.

2. Materials and Methods

2.1. Experimental Device and Design Scheme

Experimental devices made of PVC material were set up in the Stormwater Laboratory of Beijing University of Architecture (N 39045′1.47′′, E 116016′56.85′′), with height, length, and width of 0.6, 0.8, and 0.8 m, respectively (Figure 1). The depth of the water storage layer of the device was 10 cm; vegetation layer was a mixture of plants; thickness of the media layer was 40 cm; the filter layer of the device was composed of geotextile with a density of 250 g/m^2; and the bottom of the device comprised a drainage layer composed of gravel with a thickness of 10 cm and diameter of about 1 cm and a drainage pipe made up of a 5-cm-diameter through-hole blind pipe.

A total of four devices, with three different types of media (SS-L (garden soil (40%) + sand (60%)), SSH-L (garden soil (30%) + sand (60%) + humus (10%)), and SSVP-L (garden soil (20%) + sand (60%) + vermiculite (10%; a yellow or brown mineral found as an alteration product of mica and other minerals, used for insulation or as a moisture-retentive medium for growing plants) + perlite (10%; a form of obsidian characterized by spherulites formed by cracking of the volcanic glass during cooling, used as insulation or in plant growth media))) and two different influent concentrations were employed in this study. Road runoff was simulated by adding an analytically pure chemical to tap water, and pollutant concentration was obtained according to volumetric analysis. The low concentration (C) inflow (device SS-L) was based on the actual water quality of the road stormwater runoff in Beijing [23], and the concentration of Cu, Zn and Pb were 0.5 mg/L, 2.0 mg/L and 100 µg/L, respectively. The high concentration (2C) inflow (device SS-H) was twofold higher than that of the low concentration inflow. However, some differences between the test concentration and design value were noted. After investigating the typical plants on the main road of the Beijing "Sponge City" pilot area, two species of shrubs (*Rosa xanthina* Lindl and *Berberis thunbergii* DC.) were chosen to be included in this study. Each experimental device comprised both plant species, with 6–8 plants of each species. The rationale and method for the specific setting of influent concentration and other specific experimental configurations can be found in the study of Gong et al. [24].

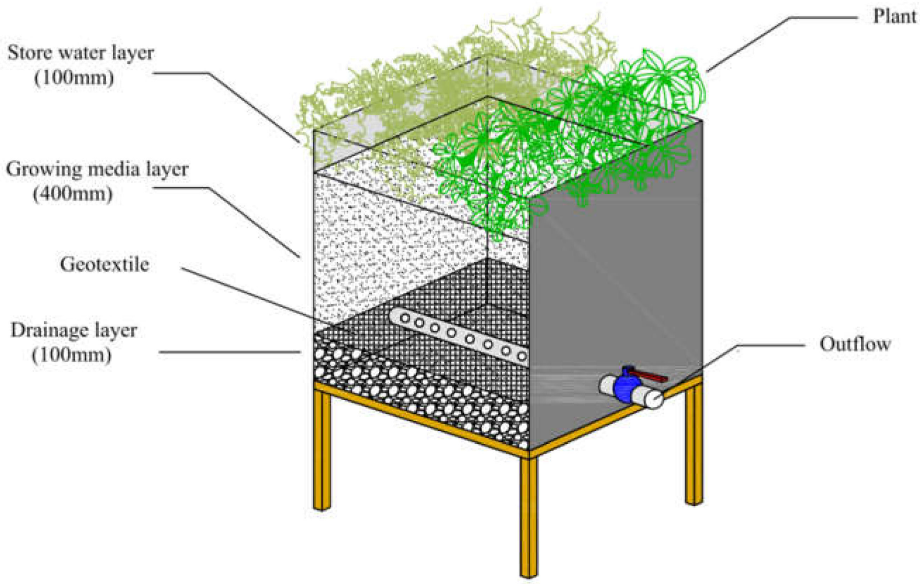

Figure 1. Schematic diagram of the experimental device.

2.2. Sample Collection and Processing

After every simulated rainfall event (frequency, light rain: moderate rain: heavy rain plus storm rain = 2:1:1), three soil samples were collected from each device at different depths between 0 and 20 cm of the surface layer, and plant roots, stones, and other impurities were removed. Then, the three samples collected from each device were mixed, transported to the laboratory, air-dried, ground, screened (200 mesh), and stored. Subsequently, three stems and leaves from different plants of the two shrub species in each device were extracted, washed with deionized water f3–4 times, dried in an oven for 48 h, and stored in self-sealed bags.

2.3. Sample Analysis

Three soil samples (0.50 g) were collected from the same device and treated with the Tessier five step extraction method respectively. The samples were filtered with filter paper with a 0.45 µm pore size before being tested on the machine [25]. Concentrations of Cu, Zn and Pb were determined by ICP-MS (Agilent 7900 ICP-MS, Agilent Technologies, Santa Clara, CA, USA). Three 1.00-g plant samples were collected from the same plant and digested with mixed acid (HNO_3:$HClO_4$ = 4:1), respectively. The apparatus and method for determination of the three heavy metals in plants were the same as those employed for detection in soil. Potassium dichromate–sulfuric acid solution was used to oxidize soil organic carbon, and the excess potassium dichromate was titrated with ferrous sulfate standard solution [26]. The pH of the soil was tested by potential method, and the soil:water ratio was 1:1 [26].

2.4. Evaluation Method

2.4.1. Mull Pollution Index

The cumulative index method (Mull pollution index) was used to evaluate the accumulated level of heavy metals in the soil as follows:

$$I_{geo} = log_2[C_n/(k \times B_n)] \quad (1)$$

where C_n is the concentration of the element n in the sample; B_n is the background concentration; and k = 1.5 is the correction index, which is usually used to characterize sedimentary characteristics, rock geology, and other effects. The degree of heavy metals pollution was classified according to Foerstner and Mueller [27] as follows: level 0, no pollution ($I_{geo} < 0$); level 1, no pollution–moderate pollution ($0 \leq I_{geo} <1$); level 2, moderate pollution ($1 \leq I_{geo} <2$); level 3, moderate pollution–strong pollution ($2 \leq I_{geo} <3$); level 4, strong pollution ($3 \leq I_{geo} <4$); level 5, strong pollution–very strong pollution ($4 \leq I_{geo} <5$); and level 6, extremely strong pollution ($I_{geo} \geq 5$).

2.4.2. Single Factor Index

Single factor index can be calculated as follows:

$$P_i = C_i/S_i \quad (2)$$

where P_i denotes pollution index of the heavy metal element i in soil, C_i refers to the measured value of the heavy metal element i in soil (mg/kg), and S_i indicates the evaluation standard of the heavy metal element i in soil (mg/kg).

2.4.3. Composite Index

Composite index can be calculated as follows:

$$N = \sqrt{\frac{P_{ijmax}^2 + P_{ijave}^2}{2}} \quad (3)$$

where N denotes comprehensives pollution index of heavy metals in surface soil of sample J; P_{ijmax} indicates the maximum value of all single factor pollution indices of the heavy metal element I in surface soil of sample J; and P_{ijave} represents the average value of all single factor pollution indices of the heavy metal element I in surface soil of sample J.

Tables 1 and 2 show the evaluation of Chinese soil using single factor index and Nemerow comprehensive index evaluation methods, respectively [28].

Table 1. Pollution evaluation using single factor pollution index.

Contamination Degree	P_i [a]	Pollution Condition
1	$P_i < 1$	Non-polluting
2	$1 \leq P_i < 2$	Mild pollution
3	$2 \leq P_i < 5$	Moderate pollution
4	$P_i > 5$	Heavy pollutio

[a] The pollution index of the heavy metal element i in soil.

Table 2. Grading standard for Nemerow comprehensive index evaluation of heavy metals pollution.

Pollution Level	N [a]	Degree of Contamination
1	$N \leq 0.7$	Safety level
2	$0.7 < N \leq 1$	Alert level
3	$1 < N \leq 2$	Mild pollution
4	$2 < N \leq 3$	Moderate pollution
5	$N > 3$	Heavy pollution

[a] The comprehensives pollution index.

2.5. Enrichment Factor Method

Bioaccumulation factor (BCF) refers to the ratio of heavy metals concentration in a certain part of a plant to the heavy metals content in the soil where the plant is located, which reflects, to a certain extent, the difficulty of heavy metals migration from soil to plant [29]. The BCF can be calculated as follows:

$$BCF = C_{plant}/C_{soil} \tag{4}$$

where C_{plant} denotes the heavy metal content in plant (mg/kg) and C_{soil} represents the heavy metal content in soil (mg/kg).

To analyze the heavy metals in soil and plants, IBM SPSS statistics 25 was employed, the data were calculated using Excel 2016, and images were constructed with Origin 2018 software.

3. Results and Discussion

3.1. Change in Heavy Metals Content in Soil and Plants in Each Device

3.1.1. Cu

Comparison of the Cu content in soil from the four devices (Figure 2) revealed certain differences in the Cu content at the beginning of the experiment. However, with the progress of the experiment, the Cu content in the soil of SS-L and SSH-L gradually increased. The final Cu content in the soil of SS-L and SSH-L was 264% and 388% higher than the background value before the experiment, respectively. In contrast, while the change in the Cu content in the soil of SSVP-L was not significant in the early stage, the increase in the Cu content between 20 August 2018 and 14 September 2018 was obvious; nevertheless, a slight decrease in the Cu content was noted between 14 September 2018 and 15 October 2018, and the final Cu content in the soil was 158% higher than the background value. The following trend was observed with regard to Cu enrichment capacity: device SSH-L > device SS-L > device SSVP-L. However, analysis of the effect of different road stormwater runoff concentrations revealed that, although the Cu content in the soil of SS-H with high influent concentration showed an overall increasing trend, the final increase in the Cu content in the soil was only 147% higher than the background value recorded before the start of the experiment and was significantly lower that noted in SS-L with low influent concentration.

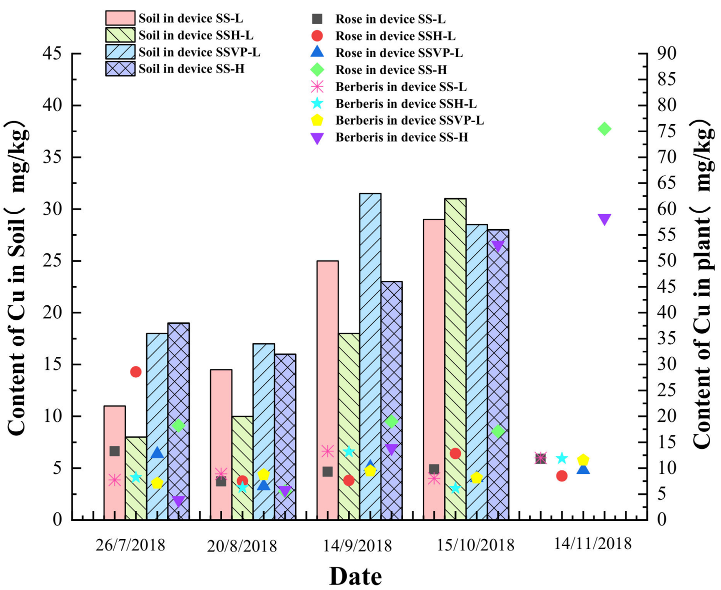

Figure 2. Relationship between Cu content in soil and plants in the four devices.

Furthermore, when compared with the background Cu content determined before the start of the experiment, the final Cu content in *R. xanthina* in SS-L, SSH-L, SSVP-L, and SS-H was 105.3%, 103.3%, 91.4%, and 414.1%, respectively, while that in *B. thunbergii* in SS-L, SSH-L, SSVP-L, and SS-H was 140.5%, 113.7%, 165.7%, and 1513.2%, respectively. Under the condition of high influent concentration, the final increase in the Cu content in *R. xanthina* and *B. thunbergii* was 4- and 10-fold higher than that noted at low influent concentration.

3.1.2. Zn

As shown in Figure 3, a certain difference was noted in the Zn content in the soil of the four devices before the start of the experiment. During the study period, SS-L and SSH-L presented a relatively similar change in the soil Zn content, when compared with the background Zn value, and both the devices exhibited a gradual decline in the soil Zn content from 26 July 2018 to 14 September 2018, and a subsequent increase from 14 September 2018 to 18 October 2018, exceeding their respective background Zn values, with final Zn content in the soil of SS-L and SSH-L being 140.5% and 113.7% higher than the background values, respectively. Before the start of the experiment, the background Zn content in the soil of SSVP-L was lower than that in the soils of SS-L and SSH-L, and presented a different variation trend. The Zn content in the SSVP-L soil increased from 26 July 2018 to 20 August 2018, decreased from 20 August 2018 to 14 September 2018, and increased again from 14 September 2018 to 18 October 2018, finally becoming 165.7% higher than the background value.

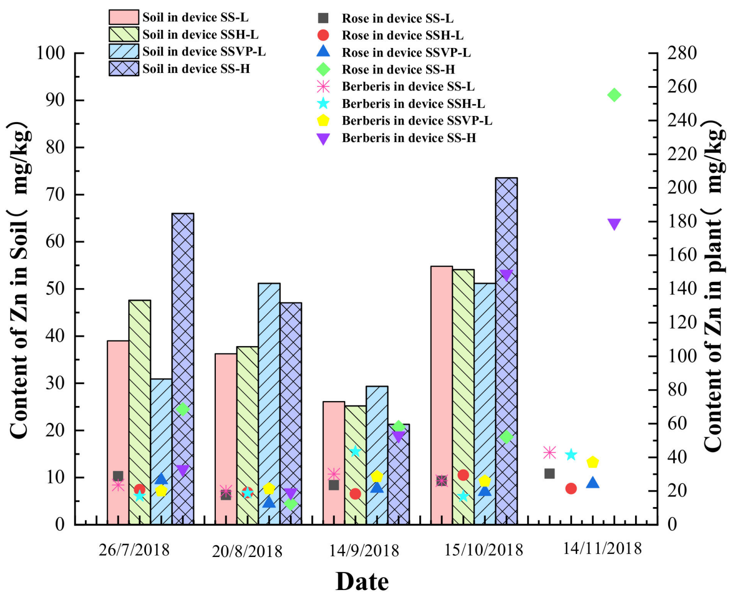

Figure 3. Relationship between Zn content in soil and plants in the four devices.

It has been reported that heavy metals in soil mainly exist in four forms: dissolved, exchangeable organic and inorganic forms, minerals, and precipitates formed with other soil components [30,31]. However, plants can only absorb dissolved heavy metals and exchangeable heavy metals in organic and inorganic forms from the soil. Most of the heavy metals in the soil are combined with mineral and organic matter, which cannot be utilized by plants. Therefore, organic matter plays an important role in determining the availability and mobility of heavy metals in soil [32]. Organic matter can participate in the supply of organic chemicals to the soil solution, which may act as chelates to increase the supply of heavy metals to plants [33]. In addition, when compared with passive absorption of Cu by plant roots, Zn can be actively absorbed by plant roots in the form of ions and, to a certain extent, in the form of organic chelate [21]. This can also explain the reason for decrease in the Zn content in the soil of the devices examined in the present study, with decrease in

Zn content decline in SSH-L with higher organic matter content being greater than that of SS-L. Comparison of the Zn enrichment ability of soil in the three devices with different media layers revealed the following trend: SSVP-L > SS-L > SSH-L. The final Zn content in *R. xanthina* in SS-L, SSH-L, SSVP-L, and SS-H was 105.3%, 103.3%, 91.4%, and 372.3% higher than the corresponding background Zn content determined in *R. xanthina* before the start of the experiment, respectively. The final increase in the Zn content in *B. thunbergii* in SS-L, SSH-L, SSVP-L, and SS-H was 181.5%, 244.9%, 184.2%, and 544.4%, respectively. Under the condition of high concentration of influent, the final increase in the Zn content in *R. xanthina* and *B. thunbergii* was four- and three-fold higher than that noted under low influent concentration, respectively.

3.1.3. Pb

The Pb content in the soil of the four devices (Figure 4) examined showed an overall upward trend. In particular, a significant positive correlation was observed between the Pb content and Cu content in the soil of SS-L and SSVP-L ($p < 0.05$); however, after the increase in the Pb content to a certain extent in the SSVP-L, a downward trend was observed, which may be owing to self-purification promoted by microorganisms and various acids in the soil, as well as soil Pb absorption by plants.

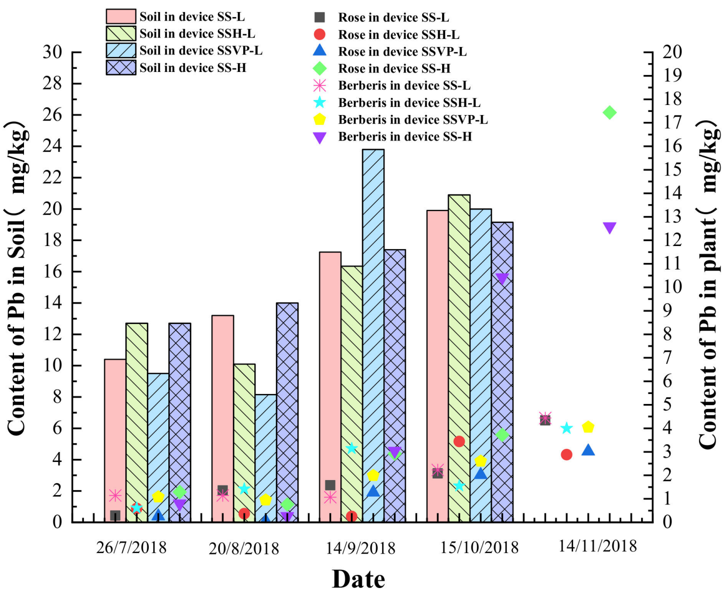

Figure 4. Relationship between Pb content in soil and plants in the four devices.

With the change in soil content, owing to the unique chemical properties of Pb (such as high negative charge, weak Lewis acid, and ability to easily form a covalent bond with Fe, Al, Mn oxides, organic matter, and carbonate), the soil Pb is not easily absorbed by plants. Although Pb can enter the plant root system, it is only transferred to a few plant parts above the ground. Therefore, in the present study, the Pb content in *R. xanthina* and *B. thunbergii* was not high.

The final Pb content in *R. xanthina* in SS-L, SSH-L, SSVP-L, and SS-H was 1496.6%, 488.1%, 1161.5%, and 1351.9%, respectively. *B. thunbergii* showed a similar overall increase in Pb content as that noted in *R. xanthine*; however, the increase was much less. The final Pb content in *B. thunbergii* in SS-L, SSH-L, SSVP-L, and SS-H was 398.5%, 655.7%, 375.0%, and 1573.8%, respectively. It must be noted that the final Pb content in *Berberis* under the condition of high influent concentration was four-fold higher than that under low influent concentration.

In this study, the final increase in the Cu, Zn and Pb content in *B. thunbergii* of the four devices were higher than that of *R. xanthina* in the same device, which indicated that

B. thunbergii had stronger enrichment capacity for Cu, Zn and Pb than *R. xanthina* no matter which conditions of runoff concentration or media type.

3.2. Heavy Metals Accumulation Index

The geo-accumulation index method is employed to evaluate the impact of human factors on the accumulation of heavy metals in the soil environment considering the geographical background, and is commonly used in China for the assessment of heavy metals in soil [33–35] (Han et al., 2018; Zhou et al., 2018; Tian et al., 2017). As shown in Table 3, the pollution degree of heavy metals in the rhizosphere soil of plants in each device was evaluated based on the geo-accumulation index. Under the same heavy metal condition, the mull pollution index for the four devices was not different, and the pollution levels of Cu, Zn, and Pb in the four devices were all 0. This finding revealed that heavy metals in stormwater runoff had no obvious impact on the soils of the devices. The background concentration employed in this study is the background value of soil in Beijing (Cu: 18.7 mg/kg; Zn: 57.5 mg/kg; Pb: 24.6 mg/kg) [36], and is lower than the secondary standard requirements of soil environmental quality standard in China (GB156818-1995), with relatively strict pollution assessment.

Table 3. Heavy metals contamination in the rhizosphere soil of plants evaluated by geo-accumulation index method.

Device Code	Cu		Zn		Pb	
	Mull Pollution Index [a]	**Class of Pollution**	**Mull Pollution Index**	**Class of Pollution**	**Mull Pollution Index**	**Class of Pollution**
SS-L	−0.5	0	−1.14	0	−1.28	0
SSH-L	−0.74	0	−1.07	0	−1.3	0
SSVP-L	−0.24	0	−1.08	0	−1.26	0
SS-H	−0.38	0	−0.73	0	−1.22	0

[a] The index was calculated based on the average value of a heavy metal element in the experimental stage of each device.

The single factor index and Nemerow comprehensive index evaluation methods were used to assess the soil of the four devices. The single factor index results showed mild Cu pollution in the soil of SS-L, SSVP-L, and SS-H, but no Cu pollution in the soil of SSH-L, whereas no Zn and Pb pollution was detected in the soil of the four devices. As shown in Table 4, under the complete influence of Cu, Zn, and Pb, the pollution level of SS-L and SS-L was "Alert level" and "still clean," respectively, while the pollution level of both SSVP-L and SS-H was "Mild pollution," i.e., the soil pollutants exceeded the background value of soil in Beijing. Thus, under the same influent concentration, addition of vermiculite and perlite in soil may strengthen the adsorption of heavy metals in runoff by media in the bioretention facility, resulting in heavy metals content in the soil of the devices exceeding the background value of soil in Beijing. However, although the pollution level of SSVP-L surpassed the background value of soil in Beijing, it did not exceed the specified range, when compared with the secondary standard requirements of the soil environmental quality standard in China (GB156818-1995). In addition, under the same conditions of other factors such as packing composition of bioretention facilities, the influence of influent with high pollutants concentration on soil pollution was more obvious than that of influent with low pollutants concentration.

Table 4. Pollution level determined based on single factor index and Nemerow comprehensive index.

Device Code	Single Factor Index Method [a]			Nemerow Composite Index N	Degree of Pollution	Pollution Level
	P_{Cu}	P_{Zn}	P_{Pb}			
SS-L	1.06 ± 0.39 [a]	0.68 ± 0.18	0.62 ± 0.15	0.93	Warning line	Still clean
SSH-L	0.9 ± 0.48	0.72 ± 0.19	0.61 ± 0.17	0.82	Warning line	Still clean
SSVP-L	1.27 ± 0.34	0.71 ± 0.18	0.62 ± 0.27	1.09	Light pollution	Soil pollutant exceeds background value
SS-H	1.15 ± 0.24	0.9 ± 0.35	0.64 ± 0.10	1.03	Light pollution	Soil pollutant exceeds background value

[a] Single factor index data are mean ± SD.

3.3. Heavy Metals Enrichment Coefficient

Under the condition of same influent concentration, but different media types, the enrichment coefficients of Cu, Zn, and Pb in the soils of the three devices, namely, SS-L, SSH-L, and SSVP-L, were all <1, whereas those in the two plant species grown in different media types were not obviously different (Table 5). Comparing the device SS-L and device SS-H of the same media type, it can be found that the enrichment coefficients of the three heavy metals in the yellow thorn rose and barberry have increased under the condition of high concentration of water. This shows that the increase in the concentration of heavy metals in the influent in this study has a promoting effect on the increase in the enrichment coefficient of this heavy metal in plants. The enrichment coefficients for Cu and Zn in *B. thunbergii* in SS-H under high influent concentration were both > 1, indicating that the contents of Cu and Zn in *B. thunbergii* stem and leaves were greater than those in the soil; in other words, *B. thunbergii* has a strong ability to absorb Cu and Zn, and high concentration of heavy metals in the runoff has an impact on *B. thunbergii*.

Table 5. Heavy metals enrichment coefficient for the two studied plants.

Device Code	Cu		Zn		Pb	
	Rosa Xanthina Lindl	*Berberis Thunbergii* DC.	*Rosa Xanthina* Lindl	*Berberis Thunbergii* DC.	*Rosa Xanthina* Lindl	*Berberis Thunbergii* DC.
SS-L	0.34	0.28	0.48	0.48	0.1	0.11
SSH-L	0.41	0.2	0.54	0.31	0.16	0.07
SSVP-L	0.28	0.28	0.38	0.51	0.1	0.13
SS-H	0.61	1.9	0.71	2.03	0.19	0.54

It has been reported that the Cu content in plants normally ranges from 5 to 20 mg/kg, and that most plants become Cu intolerant when the content of Cu in organs is >60 mg/kg. The normal Zn content in plants ranges from 1 to 160 mg/kg, the average content of Zn in the plant leaves is about 80 mg/kg, and the standard Pb content in the organs of plants is about 10 mg/kg [21]. In the present study, the Cu, Zn, and Pb contents in the two plant species grown in SS-L, SSH-L, and SSVP-L were within the normal ranges noted in plants (threshold of 20, 80, and 10 mg/kg, respectively). However, under the condition of high influent concentration (SS-H), the Cu, Zn, and Pb contents in the two plant species were higher than the corresponding normal limits in plants. The Cu content in majority of the organs of *B. thunbergii* was 58.26 mg/kg, which was noted to be within Cu threshold limit.

3.4. Correlation among Heavy Metals in Plants

A significant positive correlation was observed between Cu and Zn contents in the two plant species grown in the four devices (Table 6). Besides, the Zn and Pb contents in *B. thunbergii* in SSVP-L and SSH-L were positively correlated. In addition, a significant positive correlation was observed among Cu, Zn, and Pb in the two plant species in SS-H, and the contents of the three heavy metals in the plants in SS-H were much higher than those in the plants in SS-L. These findings indicated that the synergistic correlation among the heavy metals became more obvious with the increasing content of heavy metals in *R. xanthina* and *B. thunbergii*.

Table 6. Correlation among different heavy metals in plants.

Device Code	Plant Species	$Cu_{plant.i}$-$Zn_{plant.i}$	$Cu_{plant.i}$-$Pb_{plant.i}$	$Zn_{plant.i}$-$Pb_{plant.i}$
SS-L	*Rosa xanthina* Lindl	0.910 *	0.046	0.384
	Berberis thunbergii DC.	0.668	0.294	0.875
SSH-L	*Rosa xanthina* Lindl	0.112	−0.142	0.836
	Berberis thunbergii DC.	0.956 *	0.804	0.931 *
SSVP-L	*Rosa xanthina* Lindl	0.916 *	−0.035	0.353
	Berberis thunbergii DC.	0.925 *	0.792	0.946 *
SS-H	*Rosa xanthina* Lindl	0.998 **	0.987 **	0.978 **
	Berberis thunbergii DC.	0.992 **	0.995 **	0.999 **

* indicates significant correlation at the 0.01 level (two sides); ** indicates significant correlation at the 0.05 level (two sides).

4. Conclusions

In this study, a bioretention system was set up to perform experiments designed with different media types and influent concentrations to determine the impact of stormwater runoff containing three heavy metals, Cu, Zn, and Pb, on the soil and plants in the bioretention facility. Through artificial water inflow, a simulation of the actual rainfall and practical application scenario was established. The following conclusions were drawn from the experiments:

(1) Among the three examined heavy metals, Zn and Pb did not pollute the soil in the bioretention facilities, while Cu caused slight pollution in SS-L, SSVP-L, and SS-H. The Nemerow comprehensive index evaluation revealed that the heavy metals contents in the facilities containing only vermiculite and perlite were higher than the standard. Furthermore, addition of media with large particle size increased soil porosity, which increased the adsorption of heavy metals. The pollution level of SS-H with high-concentration runoff inflow exceeded the background value, indicating that widespread pollution of heavy metals in soil was more obvious with the increasing concentration of heavy metals in the influent.

(2) The evaluation standard for the three heavy metals in four devices examined was higher than the Beijing soil background values, but lower than the secondary standard requirements of soil environment quality standard in China (GB156818-1995), suggesting that the pollutants in the runoff will have a certain impact on the accumulation of heavy metals in the soil in the bioretention device, but this impact is within a certain range and will not cause the soil in the device to reach the pollution standard.

(3) The concentrations of heavy metals in plants and the correlation among heavy metals contents in plants increased with the increasing runoff concentration. The accumulation of Pb was the highest in *R. xanthina* and *B. thunbergii*, while that of Cu and Zn, which are essential for plant growth, was relatively low.

(4) At the end of the study period, the contents of the three heavy metals in both the studied plants in SS-H with high influent concentration exceeded the critical values of heavy metals contents in plants, which was owing to the high concentration of stormwater runoff. However, the two plant species in SS-H did not show apparent differences in growth when compared with those in the other devices.

In conclusion, various heavy metals accumulated in the matrix at different degrees after the flow of road stormwater runoff into the green space; however, neither the soil nor plants were significantly contaminated or poisoned. Thus, heavy metals in road stormwater runoff can have a certain effect, which is not significant, on soil and plants in the bioretention facility.

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