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Characterizing stormwater treatment efficiency at the laboratory scale for effective rain garden design

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ABSTRACT

Rain garden is one of the most important low impact development treatment systems of urban stormwater runoff. Unfortunately, the treatment efficiency of rain gardens is not satisfactory due to the ineffective design. This can be attributed to the lack of knowledge on the relationship between the treatment efficiency and influential factors. This research study characterized the stormwater runoff treatment efficiency in laboratory-scale rain garden systems. It was noted that media types and pollutant species are two key influential factors of the treatment efficiency compared to the operating parameters, such as pollutant influent concentration, operating time, and inflow hydraulic loading. Additionally, the research results indicated the difference in treatment efficiency for particulate and dissolved pollutants, and this is independent of media types and operating parameters. This implies that taking into account the targeted pollutant characteristics, such as solubility, should be preferred in the effective rain garden design.

Keywords: Rain gardens; Stormwater runoff; Media types; Pollutant species; Low impact development (LID)

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1. Introduction

Rain garden is among the most important low impact development treatment systems of urban stormwater runoff [1]. However, the treatment efficiency of rain gardens is not satisfactory due to the ineffective design. This can be attributed to the lack of knowledge on the relationship between the treatment efficiency and influential factors since the rain garden treatment performance is multifaceted, such as media type selection, the targeted pollutant species, and the system operating time [2,3]. According to previous research outcomes, even though suspended solids (SS) removal in rain garden systems is very efficient, performances for other pollutant removals, such as nitrogen and phosphorus, appeared to be highly variable. For example, a 97% SS removal through rain garden at the

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University of New Hampshire Stormwater Center was reported [4]. However, Hunt et al. [5] found that ranges of performance of the rain garden in North Carolina for phosphorus were from 65 to 240%. They attributed them to difference in initial levels of phosphorus in the soil selected for the rain garden systems. Additionally, it was noted that total nitrogen mass removal in multi-year field research studies ranged from 33 to 66% [5–7]. This was due to the biogeochemical complexity of the nitrogen species [8,9].

As discussed above, past research studies have investigated the capacity of rain gardens on removing pollutants from stormwater runoff [2,3]. However, most of them focused on examining the treatment efficiency of rain garden systems [7,10]. Few research studies had been undertaken to explore the key influential factors of rain garden treatment performance. An in-depth understanding of the key influential factors of the treatment efficiency is essential for the effective rain garden design, which can lead to paying a particular attention on these key factors based on the treatment requirement rather than focusing on all of parameters. Additionally, particulate and dissolved natures of pollutants could also have an important influence on rain garden performance of stormwater runoff treatment since particulate and dissolved pollutants have different pollutant processes, such as build-up and wash-off [11,12]. This highlights the need to investigate a range of pollutant species including both particulate and dissolved pollutants in analyzing rain gardens' treatment efficiency. Therefore, this gives rise to two important research questions: (1) what are the key influential factors of rain garden treatment efficiency? and (2) how does the treatment performance vary with these influential factors?

To provide answers to these two questions, this paper investigated three types of influential factors of rain garden treatment efficiency, namely media types, pollutant species, and operating parameters (pollutant influent concentration, operating time, and inflow hydraulic loading), which are considered as the primary influential factors in the design of rain gardens [10,13]. The investigation into the relationship between the treatment efficiency and influential factors was carried out by operating laboratory-scale rain garden systems. The research outcomes are expected to contribute to the effective design of rain garden systems.

2. Methods and materials

2.1. Rain garden system set up

This research study was a preliminary study of a field rain garden design project for urban roads in Shenzhen, South China. The outcomes were expected to provide necessary information, such as media type selection and pollutant removal efficiency, to the field rain garden design. For this purpose, a total of five rain garden columns were set up in the laboratory in order to test five media types. These media types were silica sand, gravel, zeolite, activated carbon, and slag. The selection of these media types was due to their wide applications in the stormwater treatment systems [10,14,15]. The 50 × 50 × 50 cm plastic boxes were used as the rain garden columns as shown in Fig. 1(a). Each box was filled with a lateritic red soil (225 mm soil layer), which is a typical soil type in Shenzhen area (soil bulk density is 1.3 g/m^2; total soil porosity is 49.6%; and soil moisture is 14.1%) and was topped with a 12.5-mm layer of mulch (pine bark). This was in order to maintain the soil moisture. The *Hydrocotyle vulgaris* plants with branches 15–20 cm long were installed in each box. Selecting *H. vulgaris* was due to the relatively strong adsorption to pollutants, such as nitrogen and phosphorus [16]. The bottom was the drainage layer (gravel, 50 mm), while the media layer (25 mm) was located between soil and drainage layers. The inner layers in the columns are illustrated in Fig. 1(b).

The rain garden columns were planted and watered prior to starting the experiments as required for two months to allow establishment. The synthetic stormwater, which was made based on pollutant concentrations measured in seven natural runoff events on urban roads in Shenzhen. Use of synthetic stormwater in this research study was to minimize the variation in the pollutant influent concentrations. The detailed information regarding the synthetic stormwater is shown in Table 1.

2.2. Sampling and laboratory testing

SS, total phosphorus (TP), total nitrogen (TN), chemical oxygen demand (COD), and ammonia nitrogen (NH_3-N) were analyzed in this research due to the fact that they are among the most important stormwater pollutants [17–19]. Sample testing was undertaken according to test methods specified in Standard Methods for the Examination of Water and Wastewater [20].

The sampling was undertaken in three batches based on these three important operating parameters of the rain garden system design. Table 1 shows the experimental procedure information.

- Batch 1—pollutant influent concentration (mg/L): there were five groups of experiments undertaken for each rain garden column. Each group of experiment comprises a set of influent concentrations

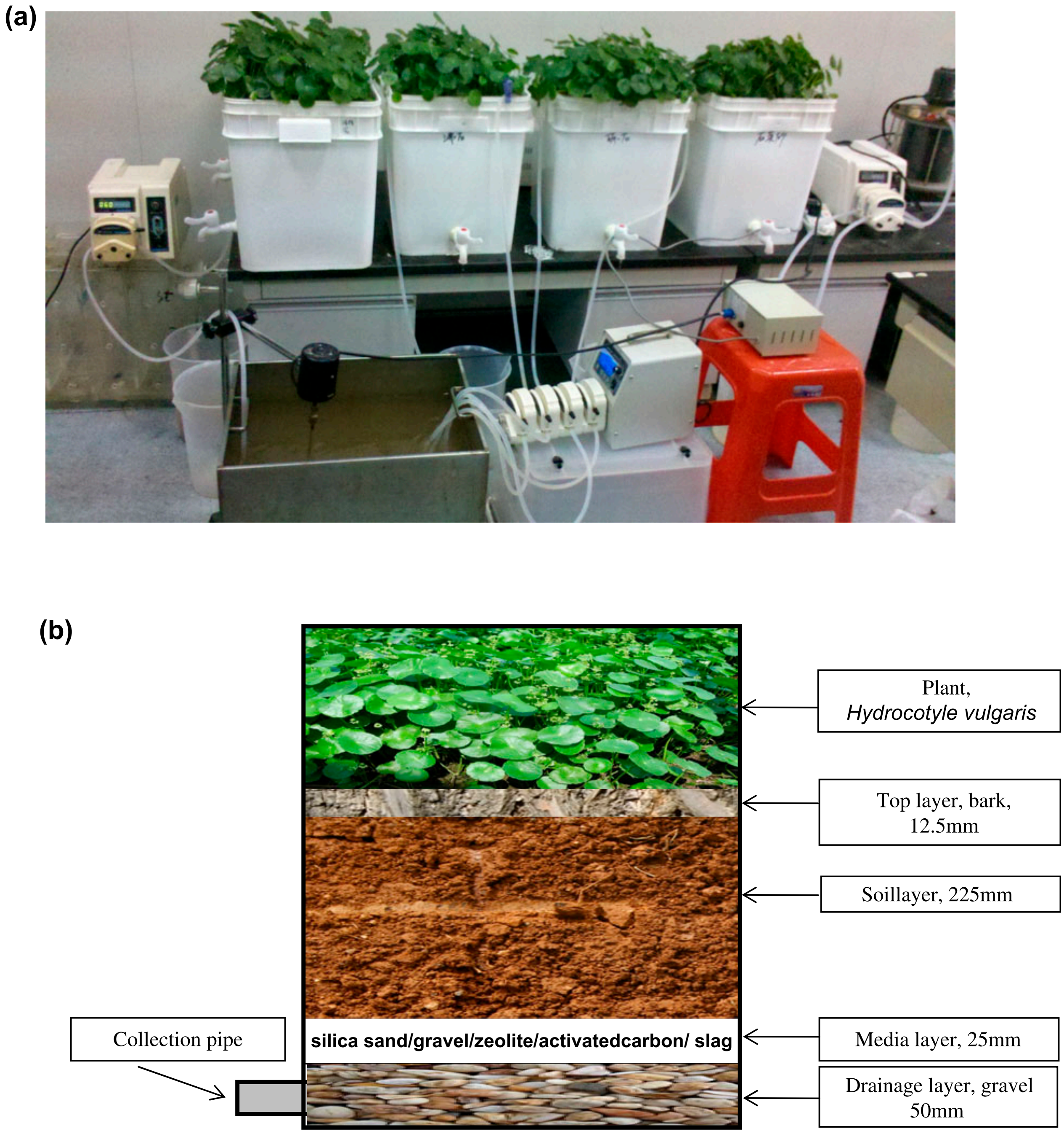

Fig. 1. The laboratory-scale rain garden columns ((a): rain garden column photo; and (b): cross-sectional details of columns).

for SS, TP, TN, COD, and NH_3-N. The influent concentrations in the five groups of experiments are shown in Table 1. Group 1 was the lowest influent concentrations for each pollutant, while Group 5 represents the highest. The samples were collected in the outflow at every 10 min within a 1-h operation period (the operating time started from the synthetic stormwater flowing into the rain garden columns). Therefore, six samples were collected for each influent concentration group in the five rain garden columns.

- Batch 2—operating time (minute): the five rain garden columns were operated for 3 h and the samples were collected at every 10 min. Therefore, 18 samples were collected for each rain garden column.

Table 1
Experimental procedure information

Parameter	Batch 1						Batch 2	Batch 3
		SS	TP	TN	COD	NH_3-N		
Pollutant influent concentration (mg/L)	Group 1	100	0.07	1.08	52.9	0.5		
	Group 2*	200	0.21	3.52	96.0	1.54	Group 2	Group 2
	Group 3	400	0.54	5.44	219.1	2.89		
	Group 4	800	0.83	9.09	432.9	4.57		
	Group 5	1,000	1.68	11.84	825.3	6.98		
Operating time (h)	1						3	1
Inflow hydraulic loading (m/s)	2.0×10^{-5}**						2.0×10^{-5}	0.5×10^{-5} 1.0×10^{-5} 2.0×10^{-5}

*The concentrations in Group 2 were the mean values of seven natural runoff events on urban roads in Shenzhen.
**2.0×10^{-5} m/s was the maximum filtration coefficient of the soil.

- Batch 3—inflow hydraulic loading (m/s): three inflow hydraulic loadings were tested for each rain garden column. The samples were collected in the outflow on a 10-min basis within a 1-h operation period. Therefore, six samples were collected for each inflow hydraulic loading in the five rain garden columns.

The sampling approach was developed in order to simulate a range of typical rainfall events with different characteristics. For example, in the case of Batch 1, the operating time (1 h) and inflow hydraulic loading (2.0×10^{-5} m/s) were consistent, which represent a certain amount of rainfall. Therefore, the lower pollutant influent concentration (such as Group 1) in Batch 1 was to simulate the rainfall event with relatively shorter antecedent dry days (low pollutant accumulations prior to rainfall occurrence), while the higher (such as Group 5) was to simulate a longer-antecedent-dry-day event (high pollutant accumulations prior to rainfall occurrence), although the rainfall amounts were same. The Batch 2 was expected to simulate rainfall events with same antecedent dry days and rainfall intensity but different rainfall durations, while the Batch 3 was to simulate rainfall events with same antecedent dry days and rainfall duration but different rainfall intensities.

3. Results and discussion

3.1. Comparison of treatment efficiency

The comparison of treatment efficiency was undertaken based on these three operating parameters as shown in Figs. 2–4.

3.1.1. Pollutant influent concentration

The values in Fig. 2 are average pollutant removal percentages of samples collected in each rain garden column. According to Fig. 2, pollutant treatment efficiencies highly varied with media types and pollutant species. It was noted that SS (96.5% at average) and TP (78.9% at average) display higher removal percentages than other three pollutants. Additionally, SS and TP show relatively low variations with media types, particularly SS, while the corresponding values for COD, TN, and NH_3-N strongly fluctuate among these five media types. However, it was also found that the variability of the removal percentages with pollutant influent concentrations was not obvious.

3.1.2. Operating time

The values in Fig. 3 are pollutant removal percentages of each sample collected in the Batch 2 experiment. As shown in Fig. 3, different pollutants have different trends of the removal percentage with the operating time and this is independent of media types. SS shows the highest and relatively consistent percentages (>90%) within the 3-h operation period in all five media types, while TP also displays a relatively high removal percentage although there was an increase in the initial 30 min in all five media types. This could be attributed to the filtration mechanism. It is also noteworthy that other three pollutants (COD, TN, and NH_3-N) have a similar trend with the operating time. Generally, the removal percentages of COD, TN, and NH_3-N decreased initially and then leveled off at a lower value. The decrease in the removal percentages of these three pollutants could be due to the relatively larger surface areas of the media leading to higher adsorption capacity in the early period of the treatment.

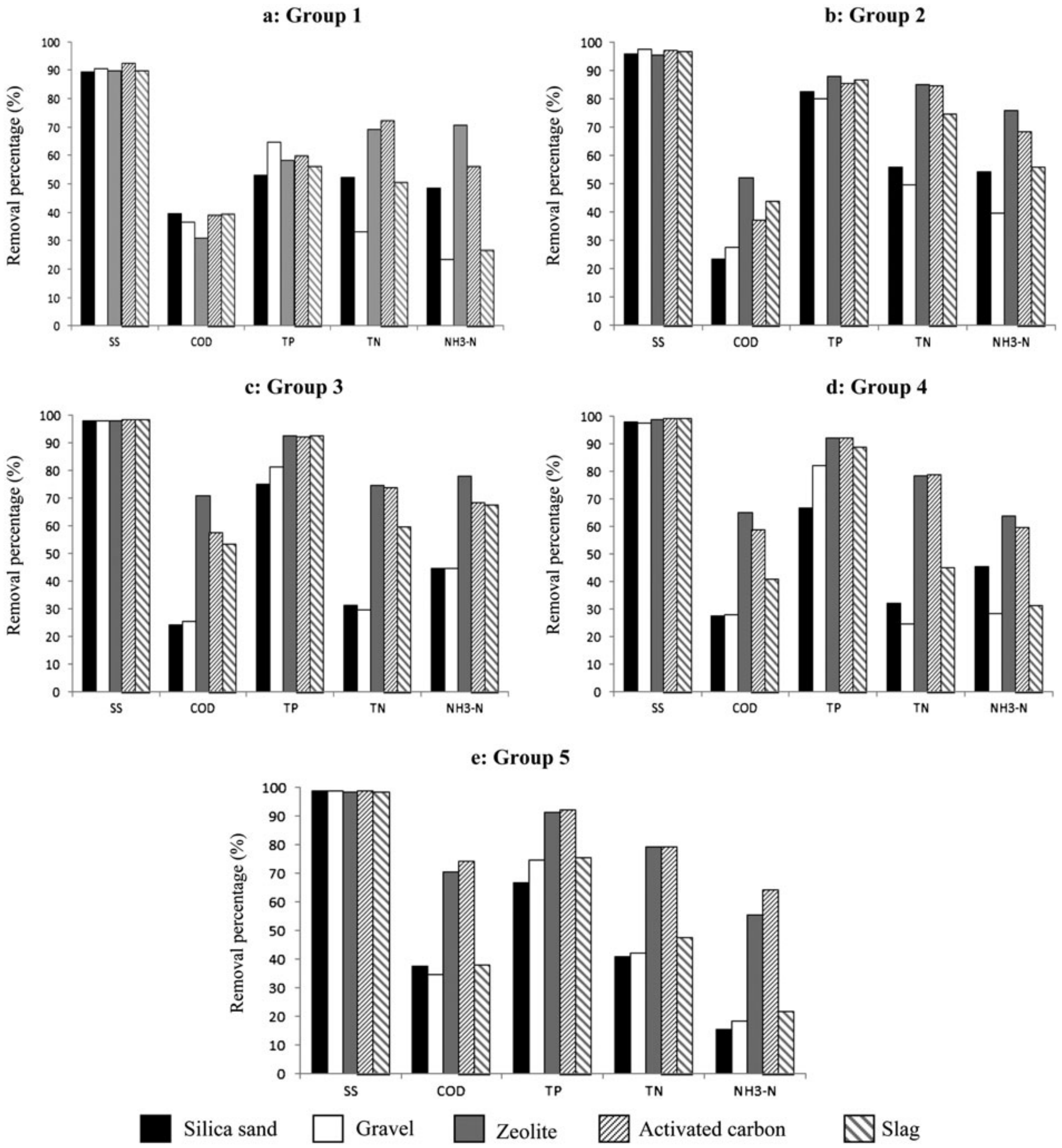

Fig. 2. Comparison of removal percentages among pollutant influent concentrations. (The pollutant influent concentrations increased from Group 1 to Group 5; Group 1 represents the lowest set of influent concentrations, while Group 5 represents the highest.)

3.1.3. Inflow hydraulic loading

The values in Fig. 4 are average pollutant removal percentages of samples collected in each rain garden column. It can be observed from Fig. 4 that SS still shows the highest and relatively consistent removal percentage among these five pollutants, followed by TP, while the corresponding values of TN, NH_3-N, and COD highly vary with media types. However, the variations with inflow hydraulic loadings do not show an obvious trend and this is similar to the outcomes obtained from Fig. 2.

The difference of treatment efficiency among SS, TP, TN, COD, and NH_3-N identified from Figs. 2 to 4

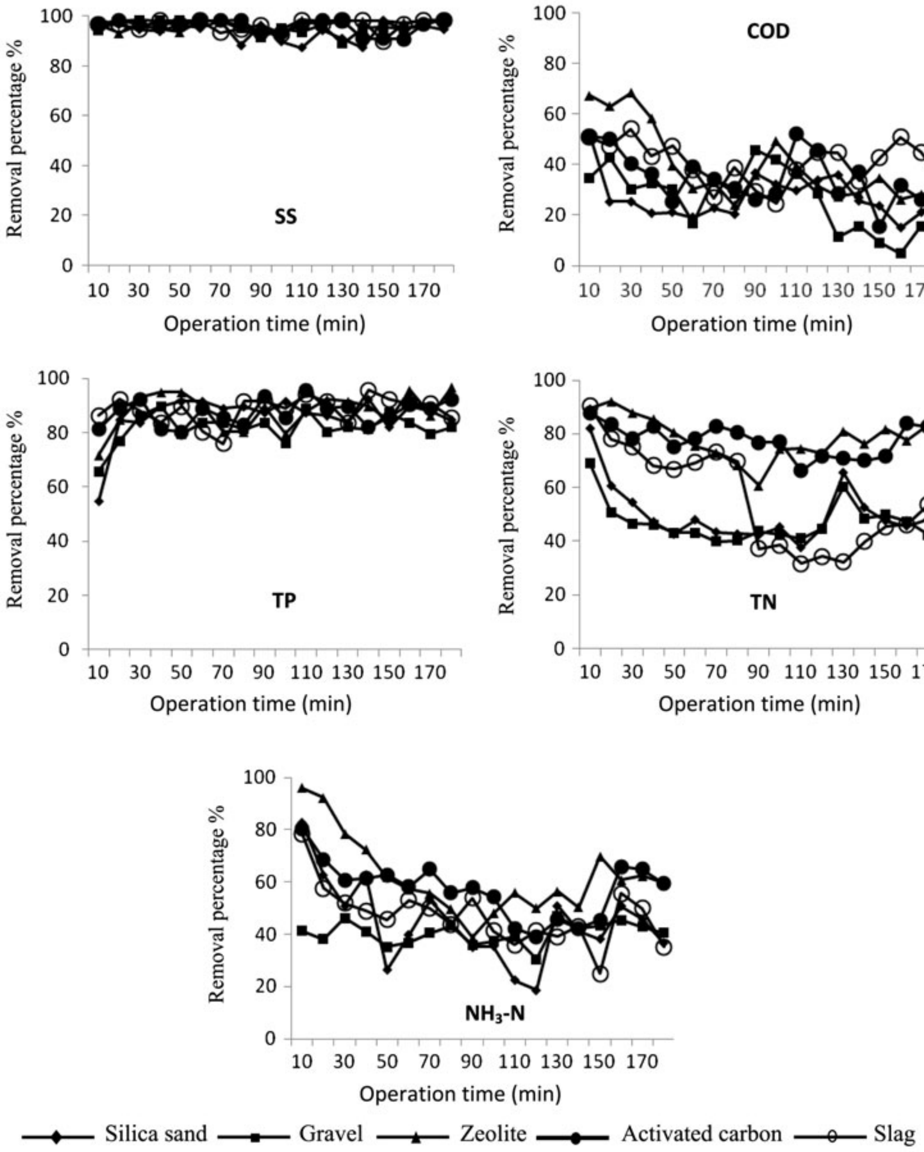

Fig. 3. Comparison of removal percentages within a 3-h operation time.

analysis means that the treatment performance of rain gardens could strongly depend on the pollutant species. The higher removal percentages of SS and TP can be attributed to their particulate natures since Miguntanna et al. [11] has pointed out that phosphorus is primarily attached to particles. This could be due to the fact that the removal of these particulate pollutants in rain gardens could be primarily by the media filtration [2]. Instead, nitrogen (TN and NH_3-N) and organic matter (COD) could be primarily in dissolved form, and hence the adsorption could be the primary removal mechanism [3].

The analysis outcomes of Figs. 2–4 also confirm that the treatment efficiency of rain gardens is multi-faceted, such as media types, pollutant species, and operating parameters. However, it is also noted that the degrees of these factors in influencing the treatment efficiency are different. This means that not all of these influential factors play a significant role in affecting the treatment performance. Therefore, this highlights the need to identify the key influential factors and further investigate how these influential factors affect the pollutant removal performance of the rain gardens.

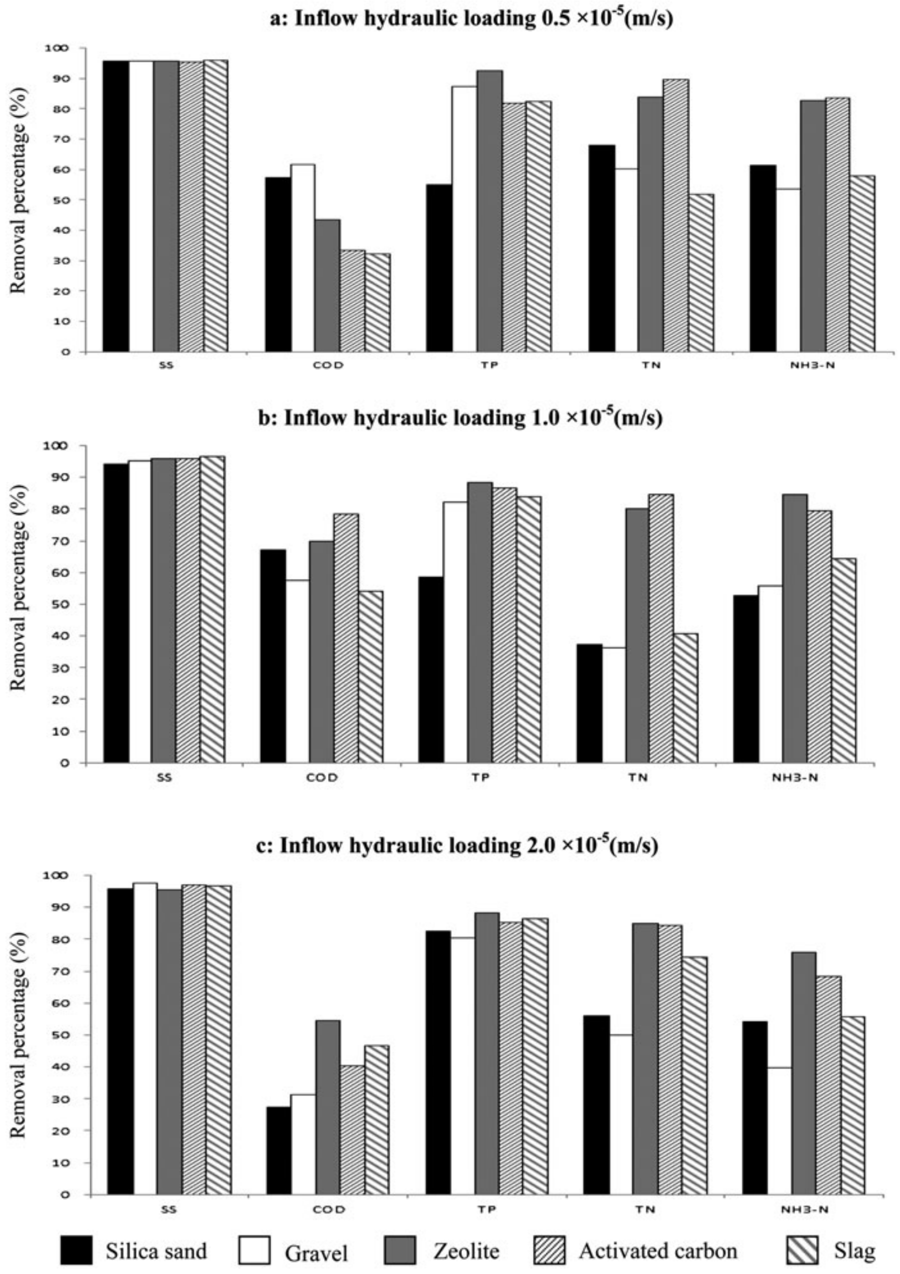

Fig. 4. Comparison of removal percentages among three inflow hydraulic loadings.

3.2. Relationships between influential factors and pollutant removal

The relationships between influential factors and pollutant removal were conducted by principal component analysis (PCA), which is an effective technique to explore correlation among variables and objects [21]. The number of significant principal components was selected using the Scree plot method [22]. Statisti-XL software [23] was used for PCA. The PCA was performed based on these three operating parameters.

3.2.1. Pollutant influent concentration

The data matrix of 25 × 30 was submitted to PCA. For PCA, these five media types in the five groups of pollutant influent concentrations were seen as objects, while the removal percentages of SS, TP, COD, TN, and NH_3-N at every 10 min over the 1-h operation period were considered as variables. Fig. 5(a) shows the resulting PCA biplot.

As shown in Fig. 5(a), all the objects are categorized based on media types rather than the pollutant influent concentrations. This implies that the pollutant influent concentration could not have an important influence on the rain garden treatment efficiency compared to media types. According to Fig. 5(a), most of zeolite and activated carbon objects are projected on the positive PC1 axis, which all of removal percentage vectors are also projected on, while all of silica sand and gravel and most of slag objects are projected on the negative PC1 axis. This means that the zeolite and activated carbon have a higher capacity to remove pollutants than other three media types, regardless of pollutant species. Additionally, pollutant removal percentage vectors are divided into two groups along the PC2 axis. All of SS and TP vectors are projected on the negative PC2 axis, while most of TN, COD, and NH_3-N vectors are on the positive PC2 axis. These observations suggest that SS and TP could experience different treatment mechanisms from other three pollutants due to their particulate natures. This means that the effective design of rain gardens should take into account the targeted pollutant species and their characteristics, such as the solubility.

3.2.2. Operating time

The data matrix of 90 × 5 was submitted to PCA. The objects included pollutant removal percentages for SS, TP, TN, COD, and NH_3-N at every 10 min over the 3-h operation period, while variables consisted of the five media types. Fig. 5(b) shows the resulting PCA biplot.

It was noted that all of objects are categorized into two groups based on pollutant species. SS and TP removal percentage objects are projected on the positive PC1 axis, which the five media type vectors are also projected on while nearly all of TN, COD, and NH_3-N are on the negative PC1 axis. These observations mean that the rain gardens have relatively higher treatment efficiency of SS and TP than TN, COD, and NH_3-N, and this is regardless of media types. This outcome is in agreement with the analysis outcomes obtained in Section 3.1. This implies that effectively designing rain gardens for stormwater runoff treatment should give more attention on dissolved pollutants, such as nitrogen and organic matters, since how to effectively remove these dissolved pollutants could be crucial to the treatment capacity enhancement of rain garden systems. Additionally, this suggests that the conventional approach, where the other stormwater pollutants are treated by removing SS, proves to be inappropriate.

It is also noteworthy that the operating time does not have a significant influence on pollutant removal percentage since nearly all of removal percentage objects within the same pollutant species are clustered although these percentages were measured on a 10-min basis over a 3-h operation period. This means that the operating time is secondary to media types and pollutant species in influencing rain gardens' treatment efficiency.

3.2.3. Inflow hydraulic loading

The data matrix of 9 × 30 was submitted to PCA. These five media types in these three hydraulic loadings were seen as objects, while the removal percentages of SS, TP, COD, TN, and NH_3-N at every 10 min over the 1-h operation period were considered as variables. Fig. 5(c) shows the resulting PCA biplot.

It can be observed that the media type objects are divided into two groups and this is not based on inflow hydraulic loadings. This means that inflow hydraulic loading is not an important influential factor of the rain garden treatment efficiency compared to media types. The zeolite and activated carbon objects are on the negative PC1 axis, which most of pollutant removal percentage vectors are projected on while all of gravel and silica sand and most of slag objects are on the positive PC1 axis. Furthermore, the pollutant species are divided along the PC2 axis, where all of SS and TP removal percentage vectors are on the positive PC2 axis, while the most vectors of TN, COD, and NH_3-N are projected on the negative PC2 axis. These outcomes further confirm that zeolite and activated carbon have a relatively higher capacity of removing pollutants from stormwater runoff compared to other three media types. Additionally, these observations also confirm that particulate pollutants, such as SS and TP, and dissolved pollutants, such as nitrogen and organic matter, could experience different treatment mechanisms as discussed in Section 3.1. Therefore, taking into consideration the targeted pollutants' natures of solubility should be preferred in the effective rain garden design.

3.3. Implications for effective rain garden design

The research outcomes show compared to operating parameters, such as pollutant influent concentration, operating time and inflow hydraulic loading, media types, and pollutant species, play a more important role in affecting the treatment efficiency of rain garden systems. This implies that in the design process, more efforts should be made on selecting appropriate media types and understanding the targeted pollutant characteristics, such as solubility.

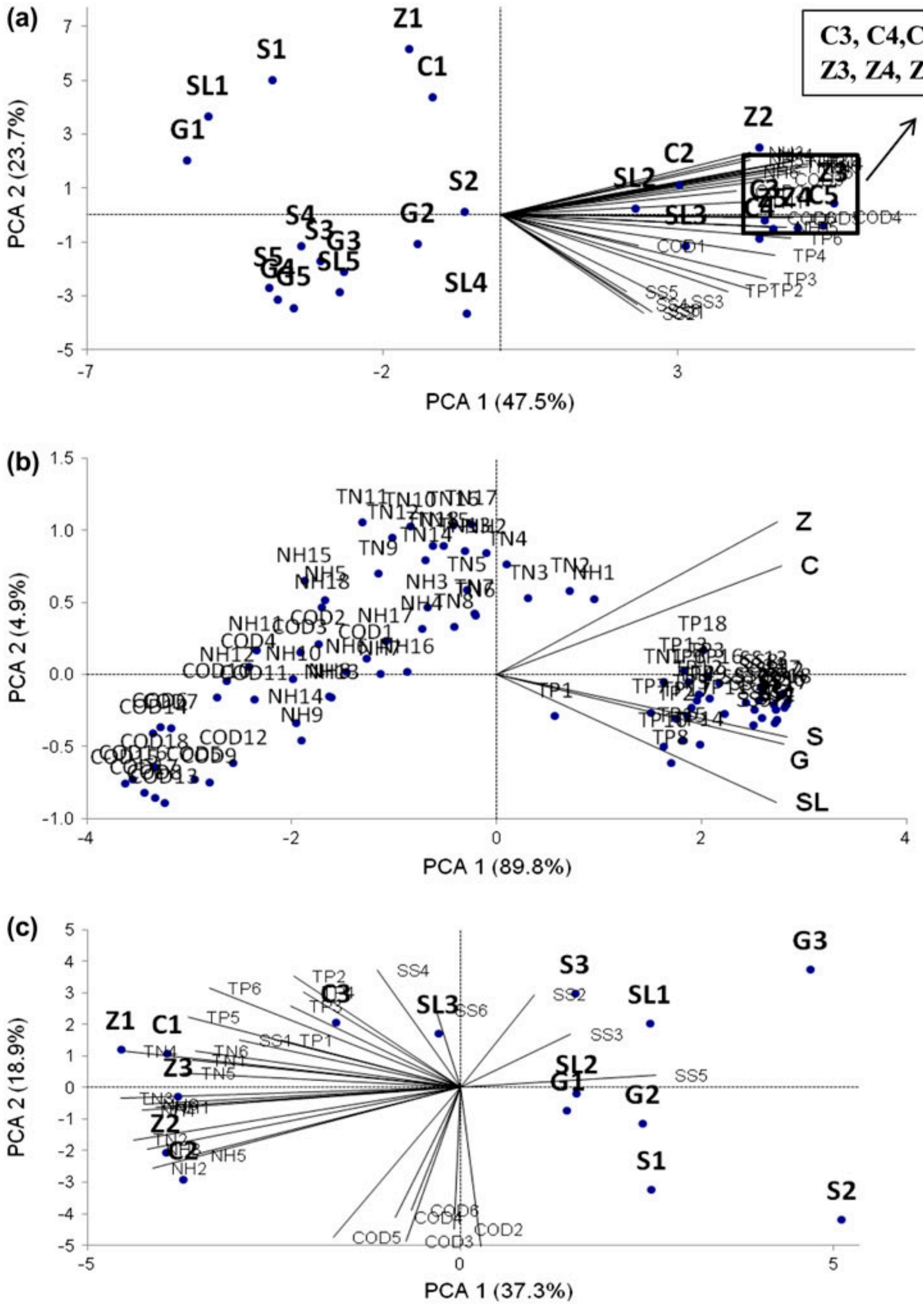

Fig. 5. PCA biplots ((a): Objects, the first letter represents the media type; the digital represents the group of influent concentrations. For example, S3 represents the Group 3 of influent concentration in silica sand rain garden column. Variables, the capital letters represent the pollutant species; the digitals represent the sampling time. For example, TP4 represents the TP removal percentage at the 40th min of operating time. (b): Labels refer to Fig. 5(a). (c): Objects, the first letter represents the media type; the digital represents the inflow hydraulic loading, 1 = 0.5×10^{-5} m/s; 2 = 1.0×10^{-5} m/s; and 3 = 2.0×10^{-5} m/s. For example, S3 represents the 2.0×10^{-5} m/s of inflow hydraulic loading in silica sand rain garden column. Variables: labels refer to Fig. 5(a)).

Additionally, the research results indicate the difference in treatment efficiency for particulate and dissolved pollutants and this could be attributed to the different treatment mechanisms, such as filtration and adsorption mechanisms. This could lead to different design strategies. For example, the rain gardens targeting phosphorus could enhance the treatment efficiency by removing solids (such as selecting appropriate media types with the strong filtration capacity), while targeting nitrogen and organic matters could focus on improving the adsorption capacity of media. Furthermore, the research outcomes also suggest that the conventional approach, where the other stormwater pollutants are treated by removing SS, proves to be inappropriate.

4. Conclusions

This research study characterized the stormwater runoff treatment efficiency in laboratory-scale rain garden systems. It was noted that media types and pollutant species are two key influential factors of the treatment efficiency compared to the operating parameters, such as pollutant influent concentration, operating time, and inflow hydraulic loading. Zeolite and activated carbon have a relatively higher capacity of treating stormwater runoff than gavel, silica sand, and slag, regardless of pollutant species. Additionally, the rain garden systems showed a higher treatment efficiency of particulate pollutants than dissolved ones and this is independent of media types and operating parameters. This implies that taking into account the targeted pollutant characteristics, such as solubility, should be preferred in the effective rain garden design.

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