Environ Monit Assess (2019) 191: 304
https://doi.org/10.1007/s10661-019-7466-4

Analysis of the effect of green roof substrate amended with biochar on water quality and quantity of rainfall runoff

Zhang Qianqian · Miao Liping · Wang Huiwei · Wang Long

Received: 10 July 2017 / Accepted: 9 April 2019 / Published online: 25 April 2019

Abstract Green roofs are becoming a popular ecological alternative in urban areas worldwide. In this study, we constructed two modular green roofs (commercial substrate green roof and biochar substrate green roof) and analyzed the effects that the green roof substrate amended with biochar on the runoff retention capacity, water quality, pollutants releasing characteristic, and pollution load by simulating rainfall experiment (rainfall levels 10~80 mm). Results showed that the mean retention ratio was no significant differences between the commercial substrate (72.54%) and the biochar substrate (72.08%). Both the two kinds of substrates showed that the concentrations of total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD), and iron (Fe) decreased gradually with the extension of rainfall time. Electrical conductivity (EC) and pH, as well as mean concentrations of TN, COD, TP, total suspended solids (TSS), and Fe, showed no differences between the green roof runoff of two kind of substrate. However, the neutralizing capacity of biochar substrate for the pH of green roof runoff was stronger than the commercial substrate, and the mean concentration of the TN and COD in the commercial substrate (16.14 mg/L and 171.79 mg/L, respectively) was about two times higher than the biochar substrate (9.85 mg/L and 97.31 mg/L, respectively). Similarly, the pollution load of TN and COD in the commercial substrate was significantly higher than that in the biochar substrate. Therefore, the biochar substrate could effectively reduce the pollution load of TN and COD in the runoff of green roof. Consequently, we suggest that the biochar could be applied to green roof substrates in order to reduce the impact of city non-point pollution on receiving water bodies.

Keywords Green roof · Biochar · Rainfall runoff · Water quality · Water quantity

Introduction

Cities and urban areas in China are expanding at a rapid rate. As a result, the large number of public green spaces has been replaced by impervious surfaces such as concrete pavement for parking lots, roadways, and walkways. The impervious surfaces not only altered the processing of city water cycles, increased the amount of surface runoff, but also brought huge impact on city storm management. On the one hand, urban waterlogging caused by storm was more frequent; on the other hand, urban non-point source pollution, which is the carrier of storm runoff, has become the primary source of urban water environmental pollution (Wang et al. 2001). To combat this ongoing and ever-growing problem, China has proposed the development of

Z. Qianqian (✉) · W. Huiwei · W. Long
Hebei and China Geological Survey Key Laboratory of Groundwater Remediation, Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Science, Shijiazhuang 050061, China
e-mail: z_qqian@163.com

M. Liping
Agriculture Regional Planning Office of Hebei Province, Shijiazhuang 050000, China

"sponge cities" with the hopes of incorporating bio-sustainable and environmentally friendly solutions into urban designs. Therefore, innovative solutions of city non-point source pollution have become an important area of investigation for environmental researchers.

Green roof is one such innovative solution to control city non-point source pollution. Urban designs using green roof technology have been applied and promoted in developed countries such as Germany, the USA, Britain, Singapore, and Sweden (Mentens et al. 2006; Razzaghmanesh et al. 2014; Vijayaraghavan 2016; Vijayaraghavan et al. 2012). However, green roof technology started only recently in China and it is now receiving greater attention in medium and large-sized cities such as Beijing, Shanghai, Tianjin, and Chongqing (Zhang et al. 2015, 2017; Zheng et al. 2013).

The green roof could regulate the hydrologic process of storm runoff. Nawaz et al. (2015) found that application of green roof can effectively reduce runoff volume. Cipolla et al. (2016) found that the runoff retention ratio range of green roof was between 6.4 and 100%, and the annual average runoff retention ratio reached 51.9%. Beecham and Razzaghmanesh (2015) found that the runoff retention capacity was about 51–96% in Adelaide, Australia. In addition, researchers also found that the substrate and plants of green roof can absorb varying amounts of rainwater; thus, green roofs can delay the time of runoff formed and reduce peak flow (Carpenter et al. 2016).

Green roofs not only affect the hydrologic process of storm runoff, but also can affect runoff water quality and the process of pollutant releasing. In recent years, researches on green roofs affecting the storm runoff water quality have become increasingly interest (Carpenter et al. 2016; Ju et al. 2015; Hashemi et al. 2015). Researchers generally believe that green roof can neutralize pH of the rainwater runoff (Chen 2013; Zhang et al. 2015). Conversely, Vijayaraghavan et al. (2012) found that green roof maybe was a potential source of contamination due to its release of a large number of nutrients (such as N and P) and TOC into the runoff. However, Seidl et al. (2013) found the opposite conclusion such that green roofs reduced the concentration of N in runoff and acted as a sink of nutrients. Rowe (2011) found that green roofs that were a source of pollutants tended to be new, whereas those that were older with established vegetation were not a problem. The reasons for the above dispute were likely due to the different green roof substrates used by researchers in different studies. Reduction of the runoff pollutants concentration is accomplished by the green roof substrate through absorption, transformation, and filtering effect. However, there may be a release of pollutants from the substrate into runoff. Therefore, it is necessary to understand the qualities of green roof substrates before an effective construction of urban green roofs for a given city or environment.

Biological carbon (biochar) generally refers naturally occurring solid charcoal formed by pyrolysis in anoxic conditions under relatively low (< 700 °C) temperature. Biochar has an extremely low solubility, and it is generally alkaline, and highly esterified containing a carboxylic acid and aromatic structure. Biochar has a large porosity and specific surface area. These properties give biochar a high adsorption capacity, as well as antioxidant and anti-biodegradation abilities. Biochar has been widely used in the field of agriculture to improve soil quality, maintain soil fertility, and the quality of vegetables (Jha et al. 2010). Previous studies found that when used biochar as a soil amendment, it can increase the soil water retention capacity (Cao et al. 2014) of absorbing inorganic (Cao et al. 2009) and organic pollutants (Beesley et al. 2010; Wang et al. 2010) and reduce soil nutrient (nitrogen and phosphorus) losses. Nowadays, although researchers have begun to focus on that the biochar as the repair materials of green roof substrate for runoff water quality and quantity (Beck et al. 2011; and Kuoppamäki et al. 2016), the results are controversial.

The study mainly focuses on the effect of green roof substrate amended with biochar on water quality and quantity of rainfall runoff. The main aims of this study were to (1) analyze the effects for the substrate of green roof adding biochar on runoff retention capacity; (2) reveal differences between two substrates (biochar substrate green roof and commercial substrate green roof) in pollutants releasing process, runoff water quality, and pollution loads in runoff; and (3) clarify effects of adding biochar to green roof substrate on runoff water quality and quantity. Thus, results from this study will be useful in determining whether used the biochar in green roof technology in urban storm water management.

Materials and methods

Study site

Green roof runoff was monitored from December 2015 to June 2016 in Shijiazhuang City, Hebei Province, China. The experimental site was located on the rooftop of the Institute of Hydrogeology and Environmental

Geology, in the Chinese Academy of Geological Science. The rooftop on all sides was surrounded by roadways and building land. This region was a semi-humid, semi-arid continental monsoonal climate with a mean annual temperature between 13.3 and 15.0 °C (during this study, the monthly average was − 2, − 6, − 1, 5, 13, 17, and 22 °C in December 2015 and January–June 2016, respectively), as well as a mean annual precipitation between 400 and 750 mm. Most precipitation occurred in the period between June and August, with highest temperatures recorded between July and September.

Modular green roof construction

According to the purpose of the experiment, 2 kinds of modular green roof (single modules) were made and placed in indoor when the simulations rainfall experiments were not conducted. The substrate components of green roof 1 (commercial substrate green roof) mainly consist of peat, vermiculite, perlite, and sawdust and the volume ratio of each matrix was 2:3:3:0.5, respectively. The substrate components of green roof 2 (biochar substrate green roof) mainly include peat, vermiculite, perlite, biochar, and sawdust and allocation ratio is 2:3:3:1:0.5, respectively.

Modular green roofs were constructed using a polypropylene box (50 cm long × 33 cm wide × 40 cm high) (Fig. 1) from top to bottom with the structure layer, filtering layer, drainage layer, and the bottom plate (which consisted of the bottom of the plastic box). The thickness of substrate layer is 10 cm, and its physico-chemical properties are outlined in Table 1. We selected coconut shell biochar (the production method of biochar is pyrolysis under high temperature (600 °C)) as the roof substrate modifier and its physico-chemical properties are outlined in Table 2. The second layer was a filter layer in the form of a polyester fiber non-woven fabric and its specification was 100 g/m^2. The third layer was a drainage layer in the form of a large drainage board (length × width × height, 33.3 cm × 33.3 cm × 2 cm). A water outlet was constructed on the bottom of the plastic box.

Simulated rainfall experimental design

The simulated rainfall experiments were carried out by using a self-developed simulated rainfall device (Fig. 2). When simulating rainfall experiment, the frame of simulated rainfall device was placed on top of the modular green roof. In this simulated rainfall device, the flow meter was used to calculate the total rainfall volume. The rotor flowmeter and ball valve switch was used to adjust the flow rate, and control the simulated rainfall intensity and evenness. The six rain pipes were installed at the bottom of the simulated rainfall device and were connected to the water distribution pipeline. Each rain pipe was covered with drip microporous, and the spacing and diameter of each microporous was 1 cm and 0.5 mm, respectively.

The rainfall intensity of the simulated rainfall experiments was set for 10, 20, 30, 40, 50, 60, 70, and 80 mm. In order to ensure the accuracy of the experiment, two green roofs which were simulated rainfall experiments were completed in the same day, and the difference of the simulated rainfall time in two green roofs should be controlled within 10 min. When the green roof began to produce runoff, 1 L samples were taken (sampling interval time is 5~10 min) until the green roof runoff ceased. The experimental water was tap water. Water quality of 8 simulated rainfall experiments is shown in Table 3. Characteristics of simulated rainfall experiments are shown in Table 4.

Physical-chemical analysis

After collection, samples were immediately prepared for analyses. The runoff monitoring parameters included pH, EC, TN, TP, COD, TP, TSS, Pb, Cu, Zn, and Fe. The pH and EC was analyzed by using a portable meter (Hach, USA, HQ40D). The other water quality indicators were measured in accordance with the guidelines set by SEPAC (2002a).

Data analysis

Runoff retention rate

Runoff retention rate from green roof runoff was calculated as:

$$RR = (RV - V)/RV \times 100\% \quad (1)$$

$$RV = R \times A \quad (2)$$

Where RR is the runoff retention rate (%); RV refers to the rainfall volume actually received by green roof

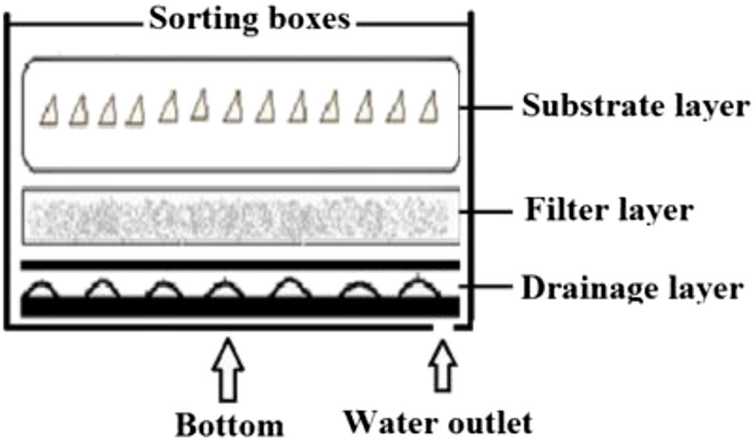

Fig. 1 The sketch of modular green roof

(L); V is the runoff volume of green roof (L); R is the rainfall volume (mm); A is the area of green roof (m^2).

Pollutant loading

Pollutant load from green roof runoff was calculated as:

$$PL = V \times EMCs/A \quad (3)$$

Where PL is the pollutant loading ($mg.m^{-2}$); V is the runoff volume from green roof (L); A is the area of green roof (m^2); EMCs are the mean concentrations of the monitoring rainfall events (mg/L).

Statistical analysis

The differences in runoff retention rate, water quality, and pollution load for the green roof of two kinds substrate were evaluated by using the two paired samples Wilcoxon signed-rank test. The two paired samples Wilcoxon signed-rank test were performed using SPSS software (version 21.0; SPSS Inc., Chicago, IL, USA).

Table 1 Several physico-chemical properties of the substrates

Substrate composition	Organic matter (%)	Bulk density ($g·cm^{-3}$)	Available phosphorus ($mg·kg^{-1}$)	Available nitrogen ($mg·kg^{-1}$)
Peat soil	60.31%	0.50	16.40	8.43
Perlite	0.12%	0.16	–	–
Vermiculite	19.31%	0.13	–	–
Sawdust	50.45%	0.19	–	–

Results

Runoff retention characteristics

Based on the runoff retention rate of simulation rainfall experiments with eight kinds of rainfall intensities (Table 5), results showed that the runoff retention rate of green roof 1 (the commercial substrate) ranged from 33.6 to 100%, with an average retention rate of 72.54%. In green roof 2 (the biochar substrate), the runoff retention rate ranged from 33.2 to 100%, with an average retention rate of 72.08%. There were no significant differences in average runoff retention rates ($P = 0.138$) between the two substrates by the two paired samples Wilcoxon signed-rank test. Therefore, there was no significant effect of green roof substrate added biochar on runoff retention.

Quality of green roof runoff water

Due to the 10, 20, and 30 mm simulated rainfall events did not produce runoff, and the concentration of Pb and Cu in green roof runoff to all simulated rainfall event was below the detection limit; thus, they did not participate in the statistical analysis. Based on analyzing simulated rainfall events of the remaining five different intensities (40–80 mm; Table 6), no significant differences in pH and the concentration of EC, TN, COD, TP, TSS, and Fe were found in the runoff of two kind substrates($P > 0.05$). However, pH and the concentration of TP were higher in runoff of biochar substrate than in commercial substrate. The EC, TN, COD, TSS, and Fe were lower in runoff of biochar substrate than in commercial substrate. It is worth noting that the

Table 2 Several physico-chemical properties of the coconut shell biochar

pH	Particle size (mm)	Ash (%)	Moisture (%)	Apparent density (g/mL)	Iodine adsorption value(mg/g)	Methylene blue adsorption rate (mL/g)
6.5	2–4	3.7	3.7	0.47	959	118

concentration of TN and COD in the runoff from the two kinds of substrate exceeded class V of the National Surface Water Environmental Quality Standard (SEPAC 2002b. However, the concentration of TN and COD in runoff of commercial substrate was nearly two times higher than in the runoff of biochar substrate. In addition, after the 40–50 mm simulated rainfall events, the concentration of COD in the runoff of biochar substrate met the class V of the National Surface Water Environmental Quality Standard. Likewise, the concentration of TN was close to class V of the National Surface Water Environmental Quality Standard. Therefore, the biochar substrate effectively reduced the concentration of TN and COD in green roof runoff.

Releasing characteristics of water quality parameters in the green roof runoff

Since simulated rainfall events of 10, 20, and 30 mm did not produce runoff, and the 40 mm rainfall event only yielded one water sample, these events were not analyzed for releasing characteristics of water quality parameters. In this study, pH, TN, TP, COD, and Fe were selected as the representative for the water quality parameters, in order to determine the releasing characteristic of water quality parameters in green roof runoff between the two substrates.

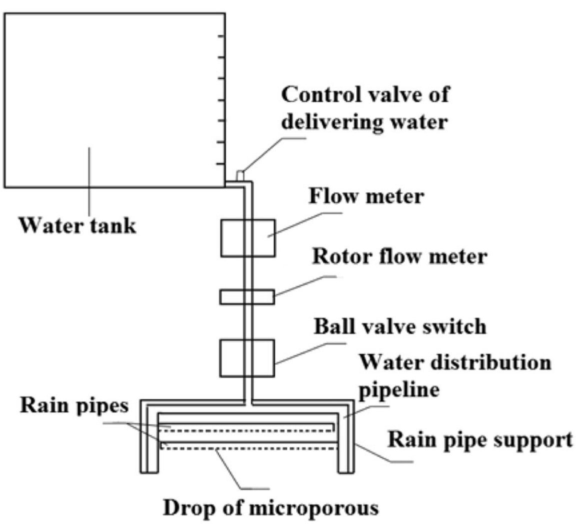

Fig. 2 The sketch of simulated rainfall device

1) Releasing characteristic of pH

As shown in the Fig. 3, with the increase of rainfall time, the pH of green roof runoff of both substrates gradually decreased. In addition, in simulated rainfall events of 40 mm and 50 mm, the pH in the experimental water was 8.05 and 8.21. However, the pH of green roof runoff in both substrates was weakly acidic (the pH of commercial substrate and biochar substrate ranged from 6.02 to 6.18 and from 6.55 to 6.75, respectively), showing that the acidic substances in the green roof substrate were gradually decreased. In simulated rainfall events of 60, 70, and 80 mm, the pH of green roof runoff of commercial substrate and biochar substrate was relatively stable and ranged from 6.8 to 7.3 and from 7.6 to 7.9, respectively. In general, the pH of green roof runoff of the biochar substrate was higher than the commercial substrate because biochar itself was slightly alkaline and the stable nature. Thus, when it is added to the soil, it can maintain long-term stability of soil pH, and can be able to efficiently neutralize runoff pH. In this regard, the neutralization effect of the biochar substrate was stronger than that of the commercial substrate.

2) Releasing characteristics of TN, TP, and COD

With the increase of rainfall time, except for the 50 mm simulated rainfall event (in this case, the runoff volume was less; therefore, the concentration of TN and TP was high), the concentration of TN, TP, and COD in runoff from both substrates showed a fluctuating yet decreasing trend (Fig. 4a, b, and c). Accompanied by an increase of simulated rainfall numbers, the concentration of TN and COD in runoff from both substrates was decreased gradually, primarily due to the nutrients and organic pollutants being released. It is worth noting that

Table 3 Water quality of experiment water

Date	8 simulated rainfall experiments	Parameters of experiment water					
		pH (μS·cm-1)	EC ($mg·L^{-1}$)	TN ($mg·L^{-1}$)	COD ($mg·L^{-1}$)	TP ($mg·L^{-1}$)	TSS ($mg·L^{-1}$)
2015.12.12	1	7.87	655	2.26	3.06	0.02	5
2016.1.8	2	8.06	757	1.87	5.26	0.00	1
2016.2.2	3	7.99	648	2.04	0.00	0.01	2
2016.2.29	4	8.05	611	2.36	2.68	0.00	0
2016.3.24	5	8.21	729	2.31	8.92	0.00	3
2016.4.15	6	8.09	601	2.83	0.00	0.00	5
2016.5.10	7	8.13	563	2.16	6.50	0.00	4
2016.6.1	8	8.11	584	2.04	0.00	0.00	0

the concentration of TN and COD was lower in the biochar substrate runoff than in the commercial substrate runoff. In addition, after 40 mm and 50 mm simulated rainfall events, the concentrations of TN and COD in the biochar substrate runoff were close to meeting V class of the National Surface Water Quality Standard. Therefore, green roof with the biochar substrate could significantly reduce the concentrations of TN and COD in runoff. With the increase of simulated rainfall numbers, the concentration of TP in the commercial substrate runoff was decreased gradually; however, the concentration of TP in the biochar substrate runoff was higher than the commercial substrate. Similarly, the fluctuation of the TP concentration in the biochar substrate runoff was greater than that in the commercial substrate. Thus, the biochar substrate released part of P into the runoff and may even be a potential source of TP.

Table 4 Rainfall characteristics for the simulated rainfall events

Rain event		ADWP (day)	Rainfall (mm)	Time of producing runoff (Min)	Delay time of producing runoff (Min)	Runoff volume (mm)	Rainfall duration (Min)
2015.12.12	Roof 1	–	10	–	–	–	20
	Roof 2	–	10	–	–	–	22
2016.1.8	Roof 1	28	20	–	–	–	29
	Roof 2	28	20	–	–	–	30
2016.2.2	Roof 1	26	30	–	–	–	41
	Roof 2	26	30	–	–	–	44
2016.2.29	Roof 1	28	40	9	50	4.4	56
	Roof 2	28	40	8	45	4.7	50
2016.3.24	Roof 1	25	50	17	47	11.0	61
	Roof 2	25	50	15	44	11.7	56
2016.4.15	Roof 1	23	60	35	26	34.2	59
	Roof 2	23	60	33	23	35.1	54
2016.5.10	Roof 1	26	70	41	18	44.4	56
	Roof 2	26	70	44	20	44.0	60
2016.6.1	Roof 1	23	80	49	21	53.1	68
	Roof 2	23	80	48	19	53.5	62

ADWP, antecedent dry weather period

Table 5 Comparison of runoff retention ratio for two kind green roof

8 simulated rainfall experiments	Rain intensity (mm)	Runoff retention ratio (%)	
		Green roof of commercial substrate	Green roof of biochar substrate
1	10	100.00	100.00
2	20	100.00	100.00
3	30	100.00	100.00
4	40	89.10	88.18
5	50	78.06	76.60
6	60	42.93	41.52
7	70	36.62	37.13
8	80	33.60	33.20
	Mean value	72.54[a]	72.08 [a]

The two paired samples Wilcoxon signed-rank test was to determine if there was a difference between two groups of data

3) Releasing characteristic of Fe

As shown in Fig. 5, there were no significant differences for the releasing characteristic of Fe in the runoff of the two substrates. These data showed that the concentration of Fe decreased gradually with rainfall duration. In addition, there were no significant differences between the concentration of Fe in the commercial substrate and the biochar substrate runoff, indicating that the biochar substrate failed to reduce the concentration of Fe in runoff.

Runoff pollution load

By comparing the pollution load of TN, COD, TP, TSS, and Fe in runoff from both substrates (Table 7), it was found that the pollution load of TP, TSS, and Fe showed no significant differences between the commercial substrate and the biochar substrate runoff. However, the pollution load of TN and COD in the commercial substrate runoff was significantly higher than that in the biochar substrate runoff ($P < 0.05$), indicating that the biochar substrate significantly reduced the pollution load of TN and COD in runoff.

Discussion

Urban non-point source pollution caused by storm runoff has become the primary source of urban environmental pollution (Wang et al. 2001). To combat this problem in China, green roof designs have become an innovative solution. Researchers have

Table 6 Comparison of runoff water quality for two kind green roof

Rainfall (mm)		pH	EC (μS·cm^{-1})	TN (mg·L^{-1})	COD (mg·L^{-1})	TP (mg·L^{-1})	TSS (mg·L^{-1})	Zn (mg·L^{-1})	Fe (mg·L^{-1})
40	Roof 1	6.18	925.00	32.62	453.61	0.26	6.00	0.03	0.29
	Roof 2	6.75	901.00	29.38	359.26	0.41	7.00	0.02	0.21
50	Roof 1	6.03	901.27	24.86	219.53	0.19	3.04	0.03	0.26
	Roof 2	6.57	736.74	12.10	85.95	0.28	2.37	0.02	0.23
60	Roof 1	6.88	714.13	12.55	94.00	0.08	5.19	–	0.03
	Roof 2	7.62	553.72	3.24	23.74	0.08	6.33	–	0.03
70	Roof 1	7.07	500.70	5.40	54.55	0.09	11.66	–	0.02
	Roof 2	7.85	413.34	2.23	1.50	0.13	7.15	–	0.02
80	Roof 1	7.22	511.25	5.28	37.29	0.12	11.08	–	0.04
	Roof 2	7.83	500.09	2.31	16.12	0.14	9.42	–	0.03
Mean value	Roof 1	6.68[a]	710.47[a]	16.14[a]	171.79[a]	0.15[a]	7.39[a]	–	0.13[a]
	Roof 2	7.32[a]	620.98[a]	9.85[a]	97.31[a]	0.21[a]	6.45[a]	–	0.10[a]
Standards		6~9	–	≤2.0	≤40	≤0.4	–	≤2.0	–

(1) Roof 1 = green roof of commercial substrate; Roof 2 = green roof of biochar substrate; (2) The value followed by different letters between roof 1 and roof 2 designates significantly different at $P < 0.05$ level by the two paired samples Wilcoxon signed-rank test; (3) The standards are the grade V of surface water standard of China (GB3838-2002)

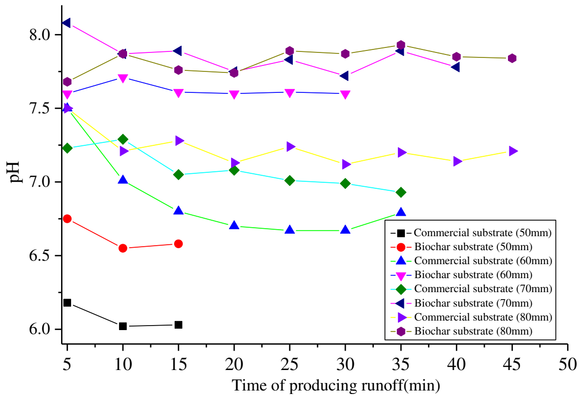

Fig. 3 Pollutographs for the pH with the roof runoff time

demonstrated that the green roof can regulate and control the hydrologic process of storm runoff. For example, green roofs can reduce runoff volume by acting as a "sponge," delaying runoff time and reducing peak flow. Therefore, green roofs may significantly reduce the risk of floods (Mentens et al. 2006; Stovin et al. 2012). In addition, green roofs can impact the water quality of storm runoff. For example, previous studies found that green roofs could release nutrients (N and P) and organic pollutants (TOC and COD) into the runoff, as a potential source of pollution (Vijayaraghavan et al. 2012; Zhang et al. 2014). Recently, the green roof substrate materials have been innovated and improved to enhance the runoff water quality and increase the retention runoff ability (Cao et al. 2014; Kuoppamäki et al. 2016).

Biochar, a soil remediation material, has been widely used in the field of agriculture (Jha et al. 2010). Previous researchers found that biochar applied to the soil can increase soil water holding capacity (Cao et al. 2014), adsorb organic and inorganic pollutants in the soil (Beesley et al. 2010; Cao et al. 2009; Wang et al. 2010), reduce nutrients (N and P) leaching from the soil (Sohi et al. 2009), and increase the ion exchange capacity (Cheng et al. 2008). However, when it was used as a repair material in green roof substrates, the effects of biochar on runoff water quality and retention runoff capacity have rarely been reported in the literature.

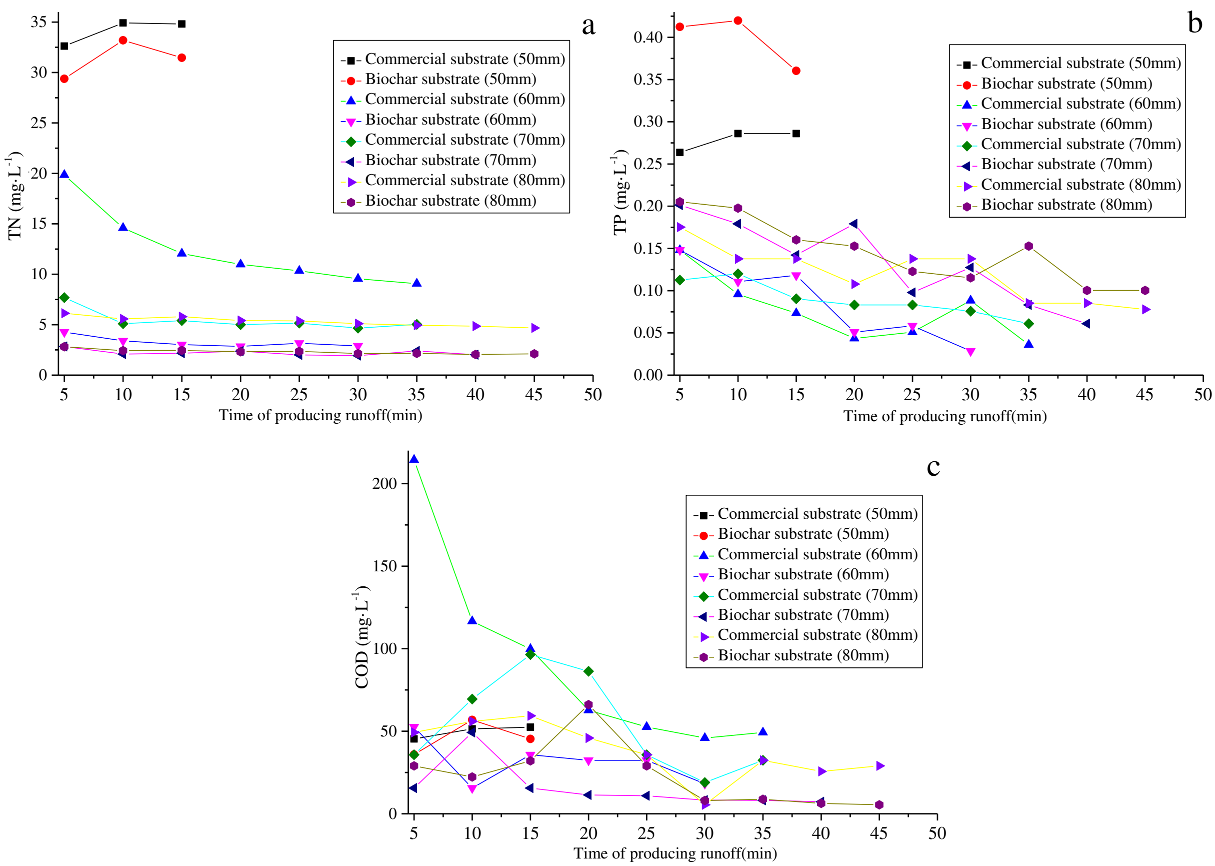

Fig. 4 Pollutographs for the TN (**a**), TP (**b**), and COD (**c**) with the roof runoff time

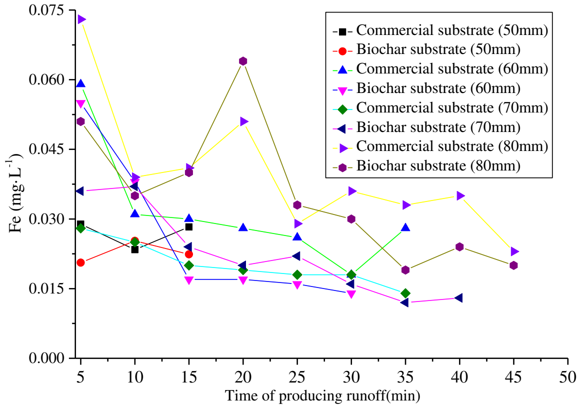

Fig. 5 Pollutographs for the Fe with the roof runoff time

Effects of biochar as a green roof substrate on retention runoff capacity

In the present study, two substrate materials for the construction of green roofs were used: commercial substrate (a commercially available product) and biochar substrate (commercial substrate adding the biochar). The mean retention rates of the commercial substrate and biochar substrate green roofs were 72.54% and 72.08%, respectively, showing no significant differences. Thus, the green roof substrate with biochar has no significant effect on runoff retention rate. These results were inconsistent with previous studies. Beck et al. (2011) found that the green roof substrate adding 7% biochar (consisting of 70% agricultural carbon (including coconut shells, walnut shells, and rice husks) and 30% processing waste carbon (car tire carbon obtained by pyrolysis)) could increase runoff retention volume by 4%. Cao et al. (2014) found that biochar (city green waste) significantly increased the water retention capacity of the green roof substrate, and the water retention capacity increased gradually with increasing biochar volume. However, this relationship was not found in this study, which mainly due to that the environmental temperature was low during simulated rainfall experiments (the monthly average was −3, 9, and 19 °C in December to February, March to April, and May to June, respectively). In addition, the modular green roof was placed in the shade; therefore, evaporation loss of soil moisture was less (Berndtsson 2010). Furthermore, the modular green roof constructed in this study was without the inclusion plants. Thus, the retention water by biochar was unused or evaporated due to the lack of plant consumption and plant transpiration (Kuoppamäki et al. 2016). Kuoppamäki et al. (2016) also found that, in a simulated indoor experiment, the use of green roof biochar was different from the outdoor experiment. These researchers found that biochar did not increase the retention runoff capacity of the green roof. In addition, Novak and Busscher (2013) found that the retention runoff capacity of biochar made from large wood materials was stronger than biochar made from smaller materials (such as, rice shells) because it have large porosity and surface area. In this study, the biochar was made from coconut shells (litter materials); hence, it did not show obvious runoff retention ability.

Effects of biochar as a green roof substrate on runoff water quality

The concentration of nutrients found in green roof runoff is 5–10 times that of rain. Thus, green roof is often considered as a pollution source of nutrients (such as N, P, and DOC (dissolved organic carbon)) (Harper et al. 2015; Buffam and Mitchell 2015). However, since plants grown in green roofs need nutrients, designers of green roof often add some nutrients into the substrate for plants to thrive. During heavy rains, the added nutrients will leached from the green roof substrate and it will lead to the pollution in runoff water. Therefore, researchers began to pay attention to the repair materials used in green roof substrates, attempting to improve the runoff water quality. Previous studies found that biochar could reduce the leaching of nutrients in the soil by its adsorptive properties (Sohi et al 2009; Lehmann et al. 2003). However, the effect of adding biochar into green roof substrate on runoff water quality has rarely been reported.

Table 7 Comparison of the pollution load of runoff water quality for two kinds green roof (mg/m^2)

Substrate	TN	COD	TP	TSS	Fe
Green roof of commercial substrate	0.205 ± 0.089^a	1.854 ± 0.632^a	0.002 ± 0.001^a	0.159 ± 0.136^a	0.001 ± 0.001^a
Green roof of biochar substrate	0.096 ± 0.042^b	0.757 ± 0.637^b	0.003 ± 0.001^a	0.131 ± 0.098^a	0.001 ± 0.001^a

The value followed by different letters between roof 1 and roof 2 designates significantly different at $P < 0.05$ level by the two paired samples Wilcoxon signed-rank test

In this study, five simulated rainfall events producing runoff were conducted. Data from these experiments showed that measurements of the pH and EC of runoff water, as well as the mean concentrations of TN, COD, TP, TSS, and Fe, exhibited no significant difference between the biochar substrate and the commercial substrate. However, the average concentrations of TN and COD in the commercial substrate were close to two times higher than in the biochar substrate. This is primarily due to several factors. First, the green roofs were newly formed containing more initial nutrients in the substrate. Second, the runoff volume in the simulation rainfall events of 40 and 50 mm was less and showed high pollutant concentration, affecting the overall statistical analysis. Third, after the simulated rainfall events of 30 and 40 mm, the concentration of COD in runoff from the biochar substrate met V class of the National Surface Water Environmental Quality Standard (SEPAC 2002b), and the concentration of TN was close to the V class standard. In these studies, the pollution load of TN and COD in runoff from the commercial substrate was significantly higher than in the biochar substrate. Thus, the biochar substrate can effectively reduce the concentration of TN and COD in runoff. The results of this study were similar to those of Beck et al. (2011), who found that biochar reduced TN and NO_3^--N emissions in green roof runoff by 79–97%, and reduced the TOC emission by 67–72%. However, Beck et al. (2011) also found that biochar reduced TP emission in green roof runoff by 20–52%, in contrast to the results of our study. In this study, the concentration and pollution load of TP in runoff has on significant differences between the biochar substrate and the commercial substrate. One possible explanation is that the concentration of TP used by Beck et al. in their green roof substrate was very high (10.3–22.1 mg/L), in contrast to this study, where the concentration of TP (0.26–0.41 mg/L) in the substrate was lower. This may have resulted in a lower adsorption effect of biochar for TP.

In summary, previous studies found that the use of biochar in green roof substrates could improve the water holding capacity and purify the water quality of runoff. In this respect, as a green roof substrate alternative, biochar holds a very broad application in controlling city storm water runoff. However, the application of biochar in green roof technology is still in the initial research stage. Research of different categories and adding methods of biochar is still needed, which maybe affect the growth of green roof plants, roof micro-ecological environment, runoff water quality, and hydrological process. In addition, the adsorption effect of biochar on heavy metals and organic pollutants (such as polycyclic aromatic hydrocarbons) in green roof runoff needs to be evaluated.

Conclusions

The present study investigated the efficiency of two green roof substrates, namely the commercial substrate and the biochar substrate. These substrates were used in the constructed green roofs to assay water quality and quantity of simulated rainfall runoff by using eight different rainfall intensities. The water quality parameters of pH, EC, TN, TP, COD, TP, TSS, Pb, Cu, Zn, and Fe were measured for both substrates and the following conclusions were drawn. There were no significant differences in average runoff retention rates between the commercial substrate and the biochar substrate. The ability to neutralize pH in the biochar substrate was stronger than that observed in the commercial substrate and the concentration and pollution load of TN and COD in runoff of the biochar substrate was significantly lower than the commercial substrate. However, the biochar substrate failed to reduce the concentration of TP, Fe, and TSS in green roof runoff. In summary, biochar, as a repaired material of green roof substrate, can purify water quality in runoff, and it has a broad application for controlling city storm water runoff. Future studies are still needed to verify the prospects of biochar used in green roof technology.

Funding information The study was supported by Open Foundation of the State Key Laboratory of Urban and Regional Ecology of China (No. SKLURE2019-2-3) and National Natural Science Foundation of China (No. 41401593), National Key R&D Program of China (2017YFF0207303), and the Fundamental Research Funds of the Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences (No. SK201707).

References

Beck, D. A., Johnson, G. R., & Spolek, G. A. (2011). Amending greenroof soil with biochar to affect runoff water quantity and quality. *Environmental Pollution, 159*(8–9), 2111–2118.

Beecham, S., & Razzaghmanesh, M. (2015). Water quality and quantity investigation of green roofs in a dry climate. *Water Research, 70*(C), 370–384.

Beesley, L., Morenojiménez, E., & Gomezeyles, J. L. (2010). Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil. *Environmental Pollution, 158*(6), 2282–2287.

Berndtsson, J. C. (2010). Green roof performance towards management of runoff water quantity and quality: a review. *Ecological Engineering, 36*(4), 351–360.

Buffam, I., & Mitchell, M. E. (2015). Nutrient cycling in green roof ecosystems. Chapter 5. In R. Sutton (Ed.), *Green Roof Ecosystems* (pp. 107–137). New York: Springer.

Cao, X. D., Ma, L., Gao, B., & Harris, W. (2009). Dairy-manure derived biochar effectively sorbs lead and atrazine. *Environmental Science & Technology, 43*(9), 3285–3291.

Cao, C. T. N., Farrell, C., Kristiansen, P. E., & Rayner, J. P. (2014). Biochar makes green roof substrates lighter and improves water supply to plants. *Ecological Engineering, 71*, 368–374.

Carpenter, C. M., Todorov, D., Driscoll, C. T., & Montesdeoca, M. (2016). Water quantity and quality response of a green roof to storm events: experimental and monitoring observations. *Environmental Pollution, 218*, 664–672.

Chen, C. F. (2013). Performance evaluation and development strategies for green roofs in Taiwan: a review. *Ecological Engineering, 52*(2), 51–58.

Cheng, C. H., Lehmann, J., & Engelhard, M. H. (2008). Natural oxidation of black carbon in soils: changes in molecular form and surface charge along a climosequence. *Geochimica et Cosmochimica Acta, 72*(6), 1598–1610.

Cipolla, S. S., Maglionico, M., & Stojkov, I. (2016). A long-term hydrological modelling of an extensive green roof by means of SWMM. *Ecological Engineering, 95*, 876–887.

Harper, G. E., Limmer, M. A., Showalter, W. E., & Burken, J. G. (2015). Nine-month evaluation of runoff quality and quantity from an experiential green roof in Missouri, USA. *Ecological Engineering, 78*, 127–133.

Hashemi, S. S. G., Mahmud, H. B., & Ashraf, M. A. (2015). Performance of green roofs with respect to water quality and reduction of energy consumption in tropics: A review. *Renewable & Sustainable Energy Reviews, 52*, 669–679.

Jha, P., Biswas, A. K., Lakaria, B. L., & Rao, A. S. (2010). Biochar in agriculture—prospects and related implications. *Current Science, 99*(9), 1218–1225.

Ju, Y. L., Min, J. L., & Han, M. (2015). A pilot study to evaluate runoff quantity from green roofs. *Journal of Environmental Management, 152*, 171–176.

Kuoppamäki, K., Hagner, M., Lehvävirta, S., & Setälä, H. (2016). Biochar amendment in the green roof substrate affects runoff quality and quantity. *Ecological Engineering, 88*, 1–9.

Lehmann, J., Jr, J. P. D. S., Steiner, C., Nehls, T., Zech, W., & Glaser, B. (2003). Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments[J]. *Plant and Soil, 249*(2), 343–357.

Mentens, J., Raes, D., & Hermy, M. (2006). Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape & Urban Planning, 77*(3), 217–226.

Novak, J.M., Busscher, W.J. (2013). Selection and Use of Designer Biochars to Improve Characteristics of Southeastern USA Coastal Plain Degraded Soils. Advanced Biofuels and Bioproducts. Springer New York, 69–96.

Nawaz, R., Mcdonald, A., & Postoyko, S. (2015). Hydrological performance of a full-scale extensive green roof located in a temperate climate. *Ecological Engineering, 82*, 66–80.

Razzaghmanesh, M., Beecham, S., & Kazemi, F. (2014). Impact of green roofs on stormwater quality in a South Australian urban environment. *Science of the Total Environment, 471*(2), 651–659.

Rowe, B. (2011). Green roofs as a means of pollution abatement. *Environmental Pollution, 159*(8–9), 2100–2110.

Seidl, M., Gromaire, M. C., Saad, M., & De, G. B. (2013). Effect of substrate depth and rain-event history on the pollutant abatement of green roofs. *Environmental Pollution, 183*(2), 195–203.

Sohi, S., Lopez-Capel, E., Krull, E., & Bo, R. (2009). Biochar, climate change and soil: A review to guide future research. In: *CSIRO Land and Water Science Report* 05/09 (pp. 64).

State Environment Protection Agency of China (SEPAC). (2002a). *Methods of monitoring and analysis for water and wastewater* (4th ed.). Beijing: China Environmental Science Press (in Chinese).

State Environment Protection Agency of China (SEPAC). (2002b). *Environmental quality standards for surface water (GB3838–2002)*. Beijing: China Environmental Science Press (in Chinese).

Stovin, V., Vesuviano, G., & Kasmin, H. (2012). The hydrological performance of a green roof test bed under UK climatic conditions. *Journal of Hydrology, 414*(2), 148–161.

Vijayaraghavan, K. (2016). Green roofs: a critical review on the role of components, benefits, limitations and trends. *Renewable & Sustainable Energy Reviews, 57*, 740–752.

Vijayaraghavan, K., Joshi, U. M., & Balasubramanian, R. (2012). A field study to evaluate runoff quality from green roofs. *Water Research, 46*(4), 1337–1345.

Wang, L., Lyons, J., Kanehl, P., & Bannerman, R. (2001). Impacts of urbanization on stream habitat and fish across multiple spatial scales. *Environmental Management, 28*(2), 255–266.

Wang, H., Lin, K., Hou, Z., Richardson, B., & Gan, J. (2010). Sorption of the herbicide terbuthylazine in two New Zealand forest soils amended with biosolids and biochars. *Journal of Soils and Sediments, 10*(2), 283–289.

Zhang, Q. Q., Wang, X. K., Hou, P. Q., Wan, W. X., Li, R. D., Ren, Y. F., et al. (2014). Quality and seasonal variation of rainwater harvested from concrete, asphalt, ceramic tile and green roofs in Chongqing, China. *Journal of Environmental Management, 132*(1), 178–187.

Zhang, Q. Q., Miao, L. P., Wang, X. K., Liu, D. D., Zhu, L., Zhou, B., et al. (2015). The capacity of greening roof to reduce stormwater runoff and pollution. *Landscape & Urban Planning, 144*(1), 142–150.

Zhang, Q. Q., Miao, L. P., Wang, L., Liu, B., & Geng, Y. D. (2017). Effect of different substrate components of green roof on water quality and quantity of rainfall runoff. *Acta Scientiae Circumstantiae, 37*(4), 1341–1348 (in Chinese).

Zheng, M. F., Deng, Y., Liu, R. F., Mi, J. S., & Luo, X. M. (2013). Influence of two greenroofs on runoff quantity and quality. *Journal of Zhejiang University (Engineering Science), 47*(10), 1846–1851 (in Chinese).