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Operational effect of green roof systems with a modified substrate adding soda residue soil

Huiteng Wang[a], Hui Luo[a,b,*], Jing Yang[a], Teng Qin[a], Limin Chen[a], Mingyu Yang[a] and Bao-Jie He[c,d,e,f]

[a] School of Civil and Ocean Engineering, Jiangsu Ocean University, Lianyungang 222005, China
[b] Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China
[c] Faculty of Built Environment, University of New South Wales, Sydney, NSW 2052, Australia
[d] Centre for Climate–Resilient and Low–Carbon Cities, School of Architecture and Urban Planning, Chongqing University, Chongqing 400045, China
[e] Key Laboratory of New Technology for Construction of Cities in Mountain Area, Ministry of Education, Chongqing University, Chongqing 400045, China
[f] Network for Education and Research on Peace and Sustainability (NERPS), Hiroshima University, Hiroshima 739-8530, Japan
*Corresponding author. E-mail: water@njfu.edu.cn

HL, 0000-0001-5470-196X

ABSTRACT

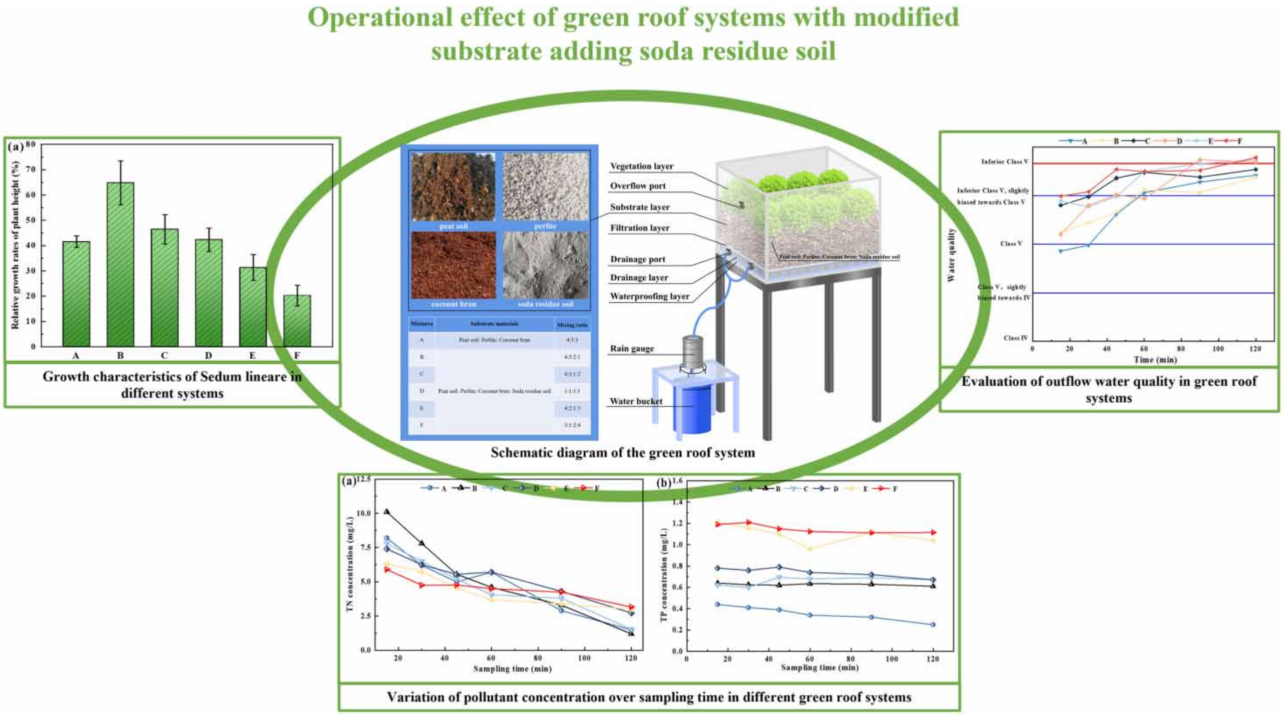
To investigate whether soda residue soil could be used as a green roof substrate, this paper setup six green roof systems with four materials (peat soil, coconut bran, perlite, and soda residue soil) mixed in different volume proportions. The effect of soda residue soil content on *Sedum lineare* growth and pollutant removal from the stormwater runoff was analyzed and the runoff quality index (RQI) was calculated. Results showed that the relative growth rate of *S. lineare* height in system B with 10% soda residue soil was about 21.5–53.2% higher than the other systems. The outflow of system B with 10% soda residue soil had the lowest mass concentration of NH_4^+-N and TN, which were 2.2 and 3.2 mg/L, respectively. The average repetitive rainfall retention rate of system A without soda residue soil was the lowest at 82.6%. System B had the highest RQI at about 0.71. It confirmed that soda residue soil can be a material with practical application value, and when the volume ratio of peat soil, coconut bran, perlite, and soda residue soil was 4:3:2:1, the green roof would have the best performance in regulating and purifying the initial rainwater runoff.

Key words: green roof, runoff quality index (RQI), soda residue soil, stormwater runoff, substrate layer

HIGHLIGHTS

- The pollutant removal effects of six green roof systems with different substrate ratios on stormwater runoff were investigated.
- Soda residue soil was introduced and analyzed for its effect on the operational efficiency of green roofs.
- A runoff quality index (RQI) was calculated to evaluate the comprehensive influences of configurations on the runoff quality.

GRAPHICAL ABSTRACT



1. INTRODUCTION

With the acceleration of urban modernization, the urban green area is dramatically decreasing, accompanied by other environmental problems such as biodiversity reduction, carbon emissions, and global warming. The improvement of the urban ecological environment is imminent as these situations are becoming more and more serious (Chen *et al.* 2018a; Shafique *et al.* 2018a). According to statistics in 2021, the green space rate of urban built-up areas in China was only 38.7%, and the green space per capita was 14.87 m^2, which was far lower than the standard of 60 m^2 of the best habitat environment proposed by the United Nations (Tan & Wang 2023). Low-Impact Development Measures (LIDMs) is a technical measurement for controlling the quantity of stormwater runoff and pollution problems caused by heavy rainfall, which mainly includes rain gardens, permeable pavements, grass-planted swales, depressed green spaces, and green roofs, etc. (Shafique *et al.* 2018b; Todorov *et al.* 2018; Li & Zhang 2022).

As one of the important measures of Low-Impact Development (LID), green roofs can effectively improve runoff quality through substrate filtration and adsorption, plant absorption and transformation, and microbial degradation compared to traditional roofs (Jamei *et al.* 2021; Leite & Antunes 2023). In practice, it can make full use of the roof space of completed buildings, alleviate the urban heat island effect through roof insulation, and improve the living environment of buildings (Beecham & Razzaghmanesh 2015). Therefore, if impervious roofs can be retrofitted to become 'green roofs', this initiative will significantly affect the management and utilization of urban stormwater resources. A green roof typically consists of several components, including vegetation, substrate, filter layer, drainage material, insulation, root barrier and water proofing membranes. As an important structural layer of a green roof system, the substrate layer provides a growing environment for the vegetation, and the selection of its material and thickness also matters in controlling rainfall (Whittinghill *et al.* 2013; Liu *et al.* 2021).

In recent years, there have been several studies at home and abroad on mixing and proportioning various types of materials as an improved planting substrate and analyzing their purification capacity for rainwater runoff. Common substrate materials include peat soil, perlite, humus, coconut bran, etc. Guo *et al.* (2018) compared the purification ability of 200 mm thick substrate layers of three different ratios of sandy loam, perlite, and coconut bran on rainwater runoff, and the experimental results showed that the ratio combination of sandy loam:perlite:coconut bran = 1:1:2 as the substrate layer of the green roof could effectively reduce NH_4^+-N, Pb and Zn in stormwater runoff. Wang *et al.* (2017) found that the adsorbent matrix layer with the combination of perlite:activated carbon:vermiculite = 1.5:7:1.5 had a higher removal rate of P in the runoff than perlite:activated carbon:vermiculite = 2.5:5:2.5. Therefore, adding more activated carbon in the adsorbent matrix layer could help to increase the pollutant interception capacity of the green roof matrix layer.

However, previous studies have rarely considered recyclable industrial wastes as matrix materials so there has been less research conducted on soda residue (SR) soil. SR soil is created by combining a specific ratio of SR and fly ash. SR is the waste liquid from the evaporation of ammonia during the production of soda ash which contains white solids that precipitate to form calcium carbonate, calcium sulfate, iron, aluminum, silica, and other materials (Ma *et al.* 2020; Zhao *et al.* 2023). The resulting mixture often leads to the formation of SR soil (Pęczkowski *et al.* 2018), and the microstructure of this material boasts several benefits, including a rough surface, large pores, honeycomb shape, high compressibility, and exceptional water retention capabilities (Eksi & Rowe 2016). As a result, it has promising potential for application in green roofs.

In this paper, six green roof systems were set up with different volume proportions of four materials (peat soil, coconut bran, perlite, and SR soil), and simulated rainfall experiments were carried out according to the rainfall characteristics of Nanjing. We analyzed the effects of different substrate ratios on the growth of plants by measuring the growth parameters (plant height and root length) of plants in six systems. The concentration of pollutants (SS, NH_4^+-N, TN, TP, and Pb) and the average load reduction rate were monitored to analyze rainfall quality, and RQI was developed to comprehensively evaluate the water quality of the green roof runoff. The introduction of SR soil as a new substrate material in green roofs provides a reference for the application of recyclable industrial wastes in green roofs.

2. MATERIALS AND METHODS

2.1. Experimental system

In this experiment, six extensive green roof systems with dimensions of 0.5 × 0.5 × 0.3 m were designed, and systems were made of polyethylene with a thickness of 8 mm, called A–F. Each system had one overflow port of 2 cm in diameter and two drainage ports of 2 cm in diameter, respectively, which were placed on a steel frame of 0.4 m in height. A rain gauge was set up underneath the system to monitor the runoff flow rate, and a 10 L water bucket of capacity was used to collect runoff water samples to monitor the runoff water quality.

The green roof consisted of a vegetation layer, a substrate layer, a filtration layer, a drainage layer, and a waterproofing layer in order from top to bottom. The vegetation layer was selected to be *Sedum lineare*, which has high water content, is extremely adaptable and hardy, and has a better runoff reduction capacity than other Sedum plants (Chen *et al.* 2018b). *S. lineare* was first planted in May 2022, excepting for a small amount of irrigation at the beginning of the planting period (all green roofs did not produce runoff), all green roofs were not irrigated or fertilized during the experimental period in the rainy season.

The filtration layer was made of geotextile with a design density of 250 g/m^2, the drainage layer was made of plastic dimpled drainage board with a thickness of 10 mm, and the waterproofing layer was made of 4 mm thick asphalt waterproofing membrane. The other settings and parameters of the system followed the requirements and regulations in Technical Regulations for Planted Roof Engineering (JGJ155-2013) and Specification for Green Roofs (DB11/T281-2015) in China.

The substrate materials can be categorized into the nutrient substrate and adsorption substrate according to their function (Kader *et al.* 2022). The substrate materials chosen for this experiment were peat soil, coconut bran, perlite, and SR soil, the four materials were mixed uniformly according to different volume proportions, and the thickness of the substrate was 200 mm. The SR was sampled from Lianyungang Soda Ash Co., Ltd. (Lianyungang, China). The main mineral components of the SR are calcite, gypsum hemihydrate, and calcium sulfate. The chemical compositions of the SR are mainly composed of $CaCO_3$, $CaSO_4$, and $Ca(OH)_2$, which is characterized by large specific surface area, high porosity, and strong adsorption (Zhao *et al.* 2020, 2023). The schematic diagram and substrate materials of the green roof system are shown in Figure 1.

2.2. Experimental design

2.2.1. Simulated rainfall pattern

In this experiment, a typical rainfall was mainly simulated from the beginning to the end of the process, including the whole process of 'rising – peak – falling water'. The commonly used rainfall design rain types at home and abroad include the soil conservation service (SCS) and Chicago rainfall pattern. According to the statistics of typical rainfall characteristics in Nanjing, it was found that the single-peak rainfall pattern was the main way in the short-term rainfall, and the rain peaks were

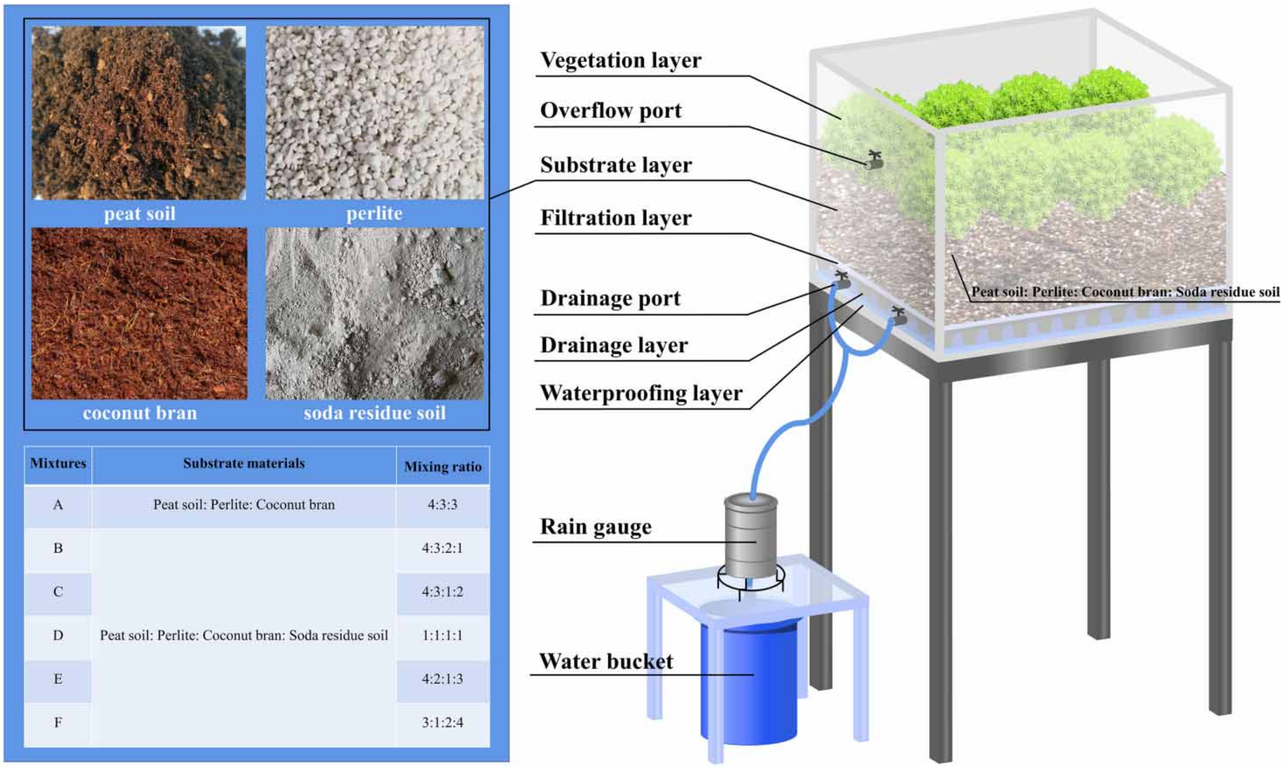


Figure 1 | Schematic diagram of the green roof system.

mostly in the front and middle parts. The Chicago rainfall pattern was more effective when calculating the peak flow rate, rainfall duration, and storage volume. Therefore, the rainfall pattern was adopted from the generalized Chicago rainfall model (Li *et al.* 2018), the rain peak coefficient was selected as 0.5 and the rainfall duration was all 2 h.

2.2.2. Simulated rainfall water quality

The average concentrations of various pollutant indicators were calculated as the actual concentration of pollutants in 10 natural rainfall events. This method ensured that the simulated rainfall in the experiment was more representative of actual rainfall, facilitating the comparison of results. The specific water quality of stormwater runoff and simulated rainfall is shown in Table 1.

2.3. Sample collection, testing, and analytical methods

The water quality indicators of water samples tested in this paper included SS, NH_4^+-N, TN, TP, and Pb. The water samples were collected at 30, 45, 60, 90, and 120 min of the simulated rainfall process, and the sampling records were prepared and labeled. The testing methods for water quality indicators were referred to Zhang *et al.* (2022).

Based on the existing research foundation (Varol 2020) and the test method proposed by Zhang *et al.* (2022), a runoff quality index (RQI) was constructed to comprehensively evaluate the runoff water quality of different configurations of green roofs, and the calculation method of RQI was divided into the following three steps:

Table 1 | Natural and simulated rainfall water quality

Water quality indicators	SS	NH_4^+-N	NO_3^--N	TP	TN	Pb
Stormwater runoff (mg/L)	7.43–1,058	1.74–7.74	1.23–5.45	0.26–3.73	1.32–21.66	0.08–1.91
Simulated rainfall (mg/L)	220 ± 15	5 ± 1.0	2 ± 0.5	1.2 ± 0.2	7 ± 1.5	0.3 ± 0.1

(1) The load of pollutant j in runoff from green roof i (L_{ij}) was calculated by Equation (1):

$$L_{ij} = c_{ij} \times R_i \quad (1)$$

where c_{ij} is the concentration of pollutant j in the runoff from green roof i for field rainfall (mg·L^{-1} or μg·L^{-1}); R_i is the runoff volume (L) from green roof i for field rainfall.

(2) Lower pollutant loads indicate better water quality in green roof runoff, and Equation (2) was used to standardize the pollutant loads in runoff from each green roof:

$$S_{ij} = \frac{1}{1 + (L_{ij}/L_{mj})^{2.5}} \quad (2)$$

where S_{ij} is the score of pollutant j in runoff from green roof i after standardization, with a score between 0 and 1, with higher scores representing better water quality; and L_{mj} is the average of pollutant j loads in runoff from the 12 experimental green roofs.

(3) Based on S_{ij}, Equation (3) was used to calculate the RQI for green roof i:

$$RQI_i = \sum_{i=1}^{n} W_j S_{ij} \quad (3)$$

where n is the total number of pollutant indicators; W_j is the weight of pollutant j. In this study, principal component analysis was used to extract the common factor variance of each pollutant indicator, and W_j is the ratio of the common factor variance of each indicator to the sum of the common factor variances.

3. RESULTS AND DISCUSSION

3.1. Growth characteristics of plants with different substrates

During the operation period, the height and number of leaves of *S. lineare* in the six groups of green roof systems increased significantly with time. The growth condition of *S. lineare* in the substrates mixed with different proportions of SR soil varied, and the height of *S. lineare* after 30 d was as follows: C (12.3 ± 2.9 cm) > B (11.7 ± 1.5 cm) > D (11.1 ± 1.4 cm) > A (10.9 ± 2.7 cm) > E (10.9 ± 2.2 cm) > F (9.5 ± 1.9 cm).

As shown in Figure 2, the overall relative growth rates of *S. lineare* height and root length in all units were in the following order: B > C > D > A > E > F. The relative growth rates of height and root of *S. lineare* in system B (64.8 and 63.4%) were

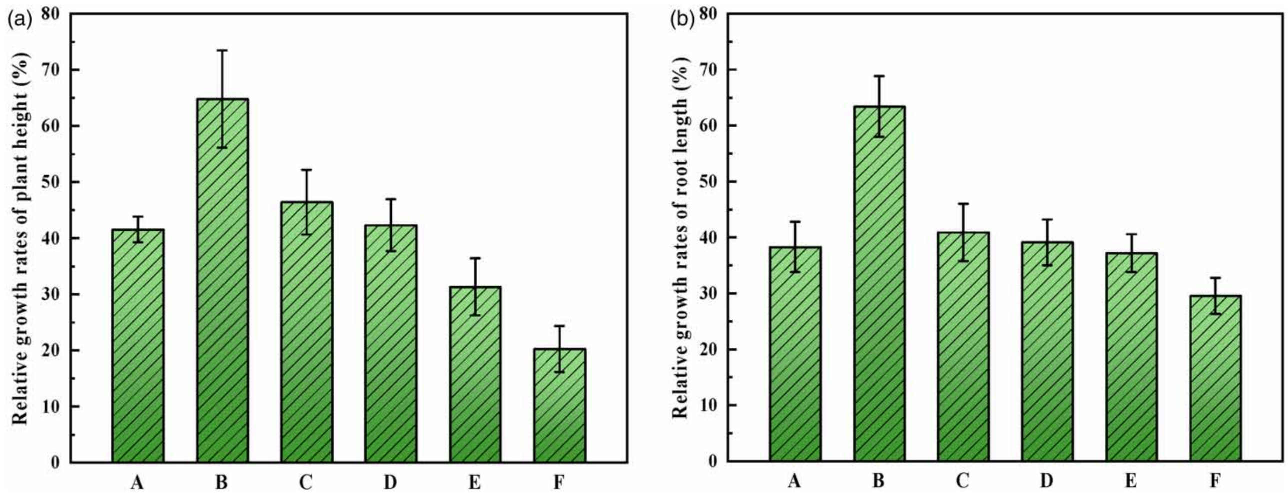


Figure 2 | Growth characteristics of plants in different systems.

higher than those in other systems, and the relative growth rate of height of *S. lineare* was higher than those in other systems by about 21.5–53.2%. Moreover, the relative growth rates of *S. lineare* height and root length in system B were increased by about 23.2 and 25.1%, respectively, compared with system A without SR soil. System C and D also had higher relative growth rates of *S. lineare* height and root length compared with device A, which increased by about 4.9, 0.8, and 2.6%, respectively. Compared with system B, *S. lineare* height, root length and relative growth rate of system E, F were sharply reduced, of which the *S. lineare* height relative growth rate was reduced by about 33.5 and 44.5%. It may be due to the proportion of SR soil in the substrate increases, the overall pH value of the substrate rises, soda soil inhibits the root growth of *S. lineare* to a certain extent. In addition, it was found that (Eksi & Rowe 2016; Cheng *et al.* 2020; Liu *et al.* 2020) the growth condition of *S. lineare* is better in acidic or slightly acidic soil and the suitable pH value of the substrate is 5.5–6.5.

3.2. Analysis of the removal effect of runoff pollutants from green roof systems

3.2.1. SS and Pb

Simulated rainfall tests were conducted for six groups of green roof systems, and Figure 3 shows the mass concentration and the average load reduction rate of pollutants in each system. As shown in Figure 3(a), the mass concentrations of SS in the runoff from the green roof systems were in the following order: A (41.20 $\pm$ 2.90 mg/L) > B (27.60 $\pm$ 1.90 mg/L) > C (24.50 $\pm$ 1.70 mg/L) > E (23.60 $\pm$ 1.61 mg/L) > D (20.40 $\pm$ 1.40 mg/L) > F (17.30 $\pm$ 1.20 mg/L). The average load reduction rate of SS in system A was 81.3%, and the average load reduction rates of SS in systems B–F were 87.5–92.1%, indicating that the green roofs play a better role in removing SS from runoff, and the overall reduction effect of the green roof systems mixed with a certain amount of SR soil was better than that of the systems without SR soil. The average mass concentration of SS in the runoff from system F was the lowest, about 17.3 mg/L, and the average load reduction rate was the highest, which

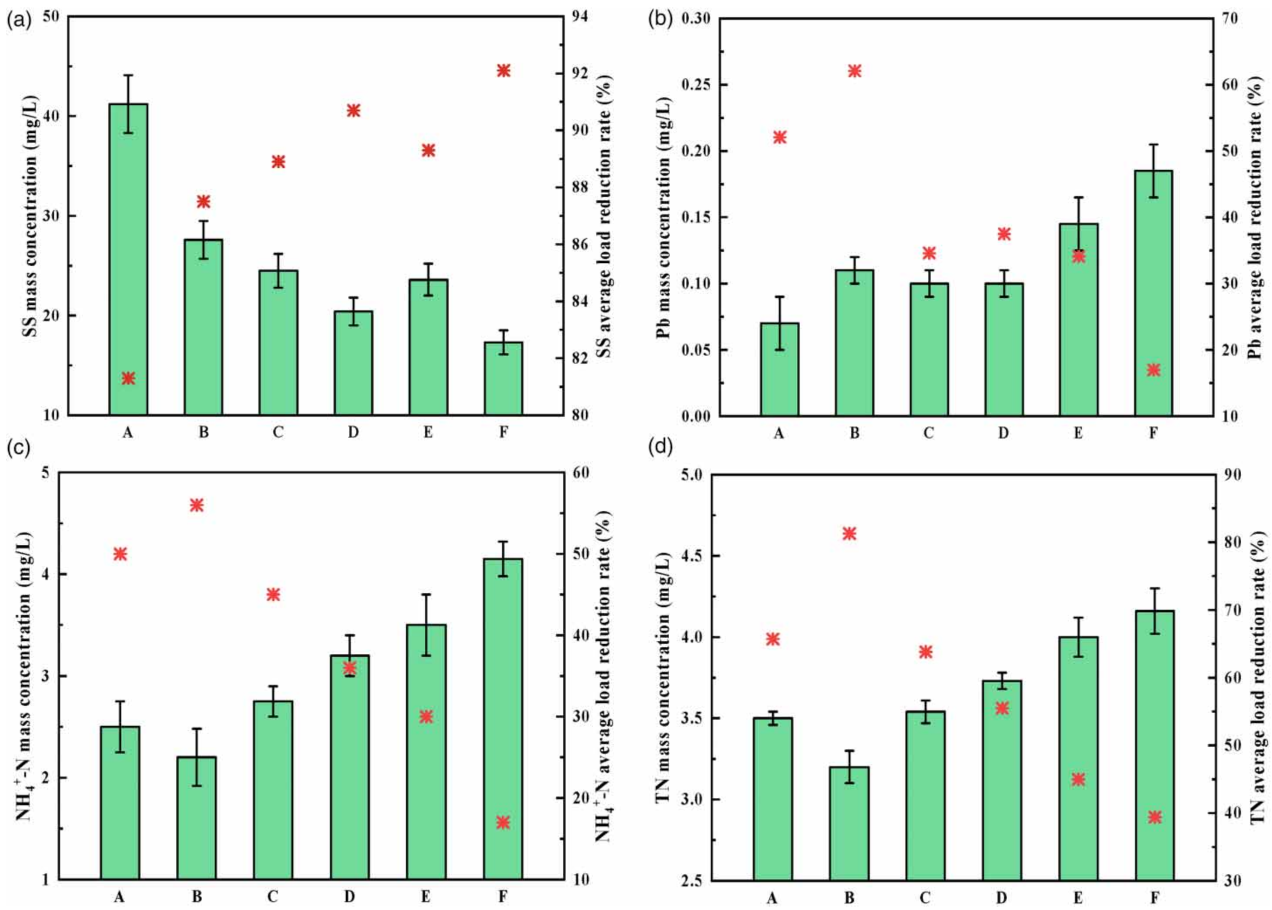


Figure 3 | Mass concentration and average load reduction rate of pollutants in different green roof systems.

increased by 10.8% compared with that of system A. The difference in the planting substrate's resistance to scouring would lead to the difference in runoff SS loads from different green roof systems (Sims *et al.* 2016; Fleck *et al.* 2022).

Figure 3(b) shows the mass concentration and the average load reduction rate of Pb in six systems. Among the six groups of devices, the average load reduction rate of Pb was ranked from high to low as follows: B (62.1%) > A (52.1%) > D (37.5%) > C (34.6%) > E (34.1%) > F (17%). The substrate ratio of system B was peat soil:perlite:coconut bran:SR soil = 4:3:2:1, and the highest average load reduction rate of Pb was about 62.1%, which was 3.7 times higher than that of system F. The effluent mass concentration of Pb in system F was the highest, which amounted to about 0.19 mg/L, and the effluent concentration of system A was the lowest, which was about 62.2% less than that of system F.

3.2.2. NH_4^+-N and TN

As seen in Figure 3(c), the average concentrations of NH_4^+-N in the effluent from the six systems were lower than the simulated rainfall stormwater quality. There was a certain NH_4^+-N pollution effect of the peat soil on the stormwater runoff, but as the simulated rainfall continued, the risk of the pollution of NH_4^+-N within the substrate layer reduced so that the mass concentrations of NH_4^+-N in the outflow from the systems all decreased. The lowest mass concentration of NH_4^+-N in the effluent of system B was about 2.2 mg/L, and the mass concentration of NH_4^+-N in the effluent of system F increased by about 1.9 mg/L compared with that of system B. The average load reductions of NH_4^+-N in systems A–F were 50, 56, 45, 36, 30, and 17%, respectively, and the average load reduction of system B was the highest, which was about 39% higher compared with that of system F. The average load reductions in system A–F were about 2.3, 2.4, 2.4, and 2.4%, respectively.

In Figure 3(d), the effect of different substrate ratios on TN effluent concentration was differential. The TN mass concentrations of 3.5, 3.2, 3.54, 3.73, 4.0, and 4.16 mg/L for systems A–F, respectively, with system B having the lowest mass concentration, which was reduced by about 0.3 and 0.96 mg/L compared to systems A and F, respectively. The average load reduction rate was 81.3% in system B, followed by systems A and C, with average TN load reduction rates of 65.7 and 63.8%, respectively, and then systems D and E, with 55.5 and 45%, respectively, and system F, which had the lowest average load reduction rate of about 39.4%. System B had the highest average TN load reduction rate, with an increase in the average load reduction rate compared with the other installations of about 15.6–41.9%. Fly ash and SR has a good adsorption performance and ion exchange capacity (Gollakota *et al.* 2019; Zong *et al.* 2023), and the main components of SR soil are SR and fly ash so SR soil can effectively adsorb part of the nitrogen, phosphorus, and nutrients.

Figure 4(a) shows the variation of TN concentration in the outflow with sampling time during the whole experiment, it can be seen that the mass concentration of TN in the outflow of the system with different substrate ratios decreased with the simulated rainfall experiment, which mainly relied on the adsorption capacity of perlite in the substrate layer for NH_4^+-N and NO_3^--N of stormwater runoff and the reduction of the leaching risk of peat soil. The average concentration of TN in the outflow did not increase with the increase of peat soil ratio throughout the experiment but showed an irregular trend. This was attributed to the fact that the substrate layers constructed with different ratios of peat soil, perlite, coconut bran, and SR soil possessed different TN leaching risks and the ability to inhibit the leaching of TN.

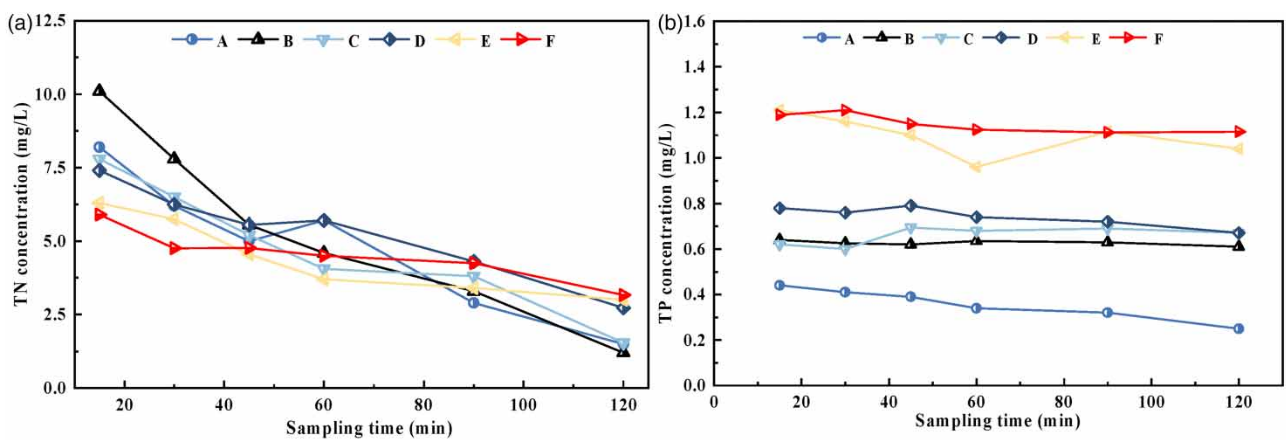


Figure 4 | Variation of pollutant concentration over sampling time in different green roof systems.

3.2.3. TP

The average concentration of TP in the outflow of the six systems was lower than that of the simulated rainwater, which demonstrated the purification effect of TP in the stormwater runoff (Figure 4(b)). The average TP concentration of outflow in system A was 0.25 mg/L and lower than that of other systems throughout the experimental process, and the average TP concentration of outflow from systems E and F was 1.04 and 1.12 mg/L, respectively, which was higher than that of system A. Perlite can play a role in chemical phosphorus removal due to the presence of a certain amount of Al_2O_3 (Wang *et al.* 2017), thus the substrate layer constructed by combining peat soil and perlite can effectively reduce TP in stormwater runoff, and the reduction effect of TP decreases with the increase of SR soil. Various substrate ratios can affect TP concentration in green roofs due to different substrate phosphate retention capacities and soil characteristics (Susca *et al.* 2011). The substrate ratios of the two green roofs with lower effluent TP concentrations in this paper were A (peat soil:perlite:coconut bran = 4:3:3) and B (peat soil:perlite:coconut bran:SR soil = 4:3:2:1).

3.3. Analysis of water retention capacity in green roof systems with different substrate ratios

The average retention rate of the six green roof systems for repetitive rainfall is shown in Figure 5(a). For the retention rates, the six groups of systems had good water retention effects for light and medium rainfalls (0–15 mm), with the average retention rates of A (82.6%), B (84.1%), C (86.7%), D (89.4%), E (91.3%), and F (88.3%), respectively. Systems B–F with SR soil were more effective than A in retaining runoff, with average repetitive rainfall retention rates ranging from 84.1 to 91.3%, with system E having the highest average retention rate. This may be because the SR soil has large pores and good water absorption, and the substrate mixed with SR soil can effectively absorb stormwater runoff and slow down its flow rate in the substrate, which in turn improves the substrate retention capacity.

The variation of rainfall retention rate for repetitive rainfall in six green roof systems is shown in Figure 5(b). With the increase in rainfall, the retention rates of all systems showed a decreasing trend, and the decreasing trend of system A was the most obvious, which decreased by about 34.8%. The average retention rates of the six systems in two heavy rainfalls (15–30 mm) in the field of rainfall decreased by 3.1–14.3% compared with the two light and medium rainfalls. The decreasing trend in two heavy rainfalls (>30 mm) was even more obvious, with a decrease of the average retention rate by 15.7–34.8%, among which the average retention rate of system A decreased the most, about 18.3% more than that of system B. Therefore, the substrate with the appropriate amount of SR was more effective in slowing down the decrease of runoff retention rate in heavy, light, and medium rainfall than the ordinary substrate without SR soil.

3.4. Comprehensive evaluation of runoff water quality in green roofs

The RQI of different configurations of green roof runoff was calculated based on loads and weight of pollutants, and outflow concentrations of pollutant indicators are shown in Table 2. The weight of pollutants (SS, NH_4^+-N, TN, TP, and Pb) was 0.193, 0.158, 0.174, 0.138, and 0.150, respectively. According to Equation (3), the average values of the RQI of system B and system

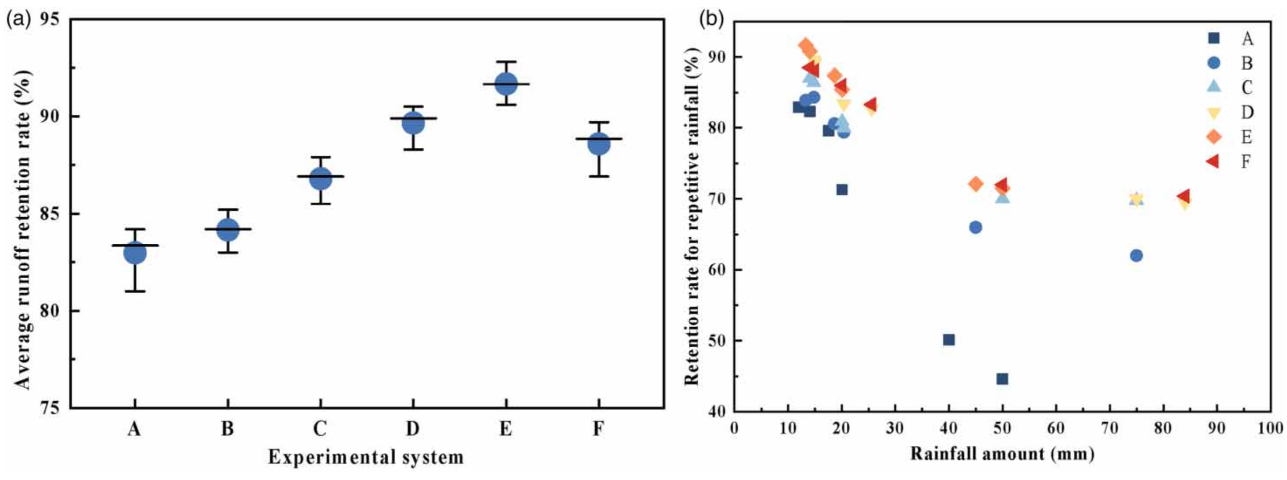


Figure 5 | Repetitive rainfall retention rates for different green roof systems.

Table 2 | Pollutant concentrations of runoff in green roofs with different substrate ratios

Indicator/(mg·L^{-1})	A	B	C	D	E	F
SS	41.20 $\pm$ 2.90	27.60 $\pm$ 1.90	24.50 $\pm$ 1.70	20.40 $\pm$ 1.40	23.60 $\pm$ 1.61	17.30 $\pm$ 1.20
NH_4^+-N	2.50 $\pm$ 0.25	2.20 $\pm$ 0.28	2.75 $\pm$ 0.15	3.20 $\pm$ 0.21	3.50 $\pm$ 0.30	4.15 $\pm$ 0.17
TN	3.50 $\pm$ 0.04	3.20 $\pm$ 0.11	3.54 $\pm$ 0.07	3.73 $\pm$ 0.15	4.01 $\pm$ 0.12	4.16 $\pm$ 0.24
TP	0.25 $\pm$ 0.13	0.61 $\pm$ 0.03	0.67 $\pm$ 0.05	0.67 $\pm$ 0.11	1.04 $\pm$ 0.17	1.12 $\pm$ 0.07
Pb	0.07 $\pm$ 0.03	0.11 $\pm$ 0.04	0.10 $\pm$ 0.02	0.10 $\pm$ 0.01	0.15 $\pm$ 0.03	0.19 $\pm$ 0.02

C were similar, respectively, 0.71 and 0.69, which were higher than system A (0.67). System F had the lowest mean value of RQI of about 0.59, which was about 0.12 lower compared to system B.

The results of the water quality evaluation are shown in Figure 6, with the extension of rainfall time, the overall water quality of different green roof systems became worse. In the early stage of rainfall, although the water quality of the six systems was inferior to Class V, its fuzzy comprehensive index range was 4.93–5.43, slightly biased toward Class V. In the late stage of the rainfall test, the outflow water quality of six green roof systems was inferior to Class V, green roof system F was the worst and its fuzzy comprehensive index was 5.89, the outflow water quality of different systems ranked as B > A > C > D > E > F. Compared to the initial infiltration runoff, system B had a certain control effect on pollutants such as nitrogen, phosphorus and heavy metals in the stormwater runoff, but the effluent water quality was still difficult to reach the threshold of surface water.

4. CONCLUSIONS

(1) The relative growth rates of *S. lineare* height and root length in the six systems were in the following order: B > C > D > A > E > F. The best growth condition was observed in the peat soil:perlite:coconut bran:SR soil = 4:3:2:1, and the relative growth rate of *S. lineare* height was higher than that of the other systems by about 21.5–53.2%.

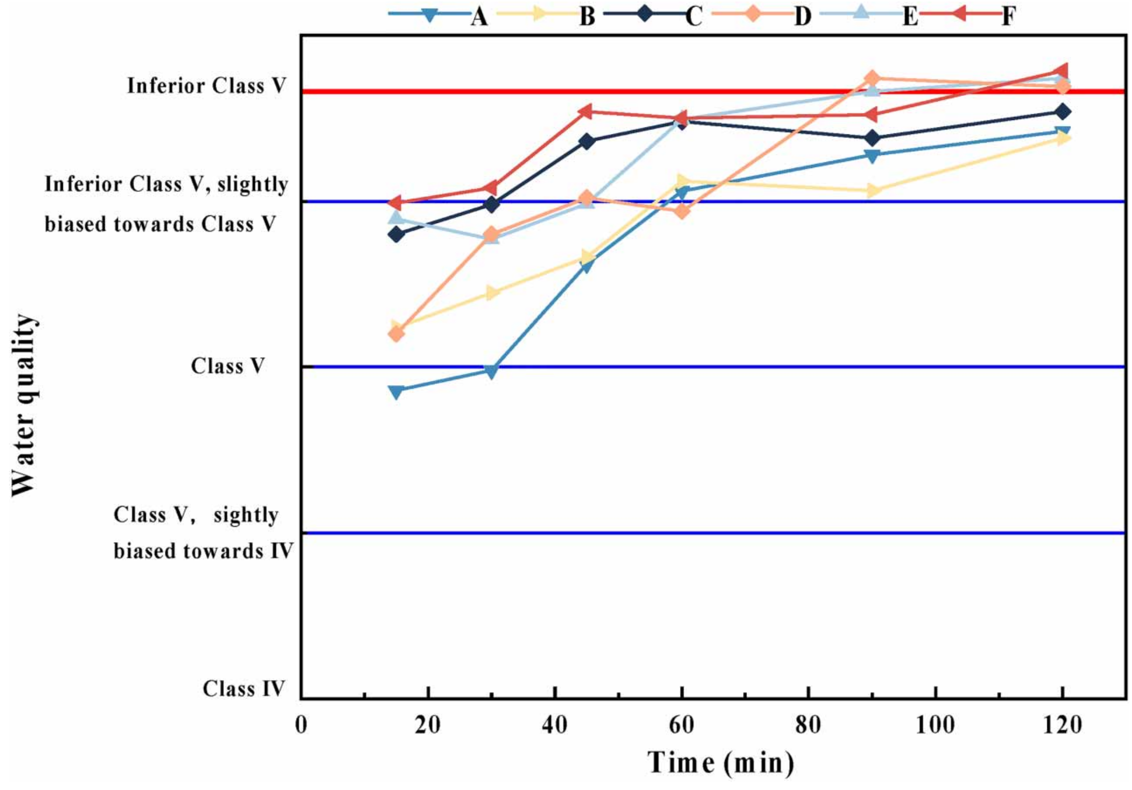


Figure 6 | Evaluation of outflow water quality in green roof systems.

(2) Under simulated rainfall conditions, the lowest mass concentrations of NH_4^+-N and TN were found in device B (peat soil: perlite:coconut bran:SR soil = 4:3:2:1), which had the highest average load reduction rates at this time, 56.0 and 81.3%, respectively.
(3) All six groups of systems had good water retention at light to medium rainfall (0–15 mm) with average retention rates of A (82.6%), B (84.1%) C (86.7%), D (89.4%), E (91.3%) and F (88.3%), respectively.
(4) The appropriate addition of SR soil to the substrate could help green roofs to regulate and purify the initial rainwater runoff, and the ROI was 0.71 when peat soil:perlite soil:coir soil:SR soil = 4:3:2:1, which was the best combined effect. The results of this study not only help to alleviate the social and environmental problems caused by SR waste, but also provide a reference for the application of SR soil as a green roof substrate.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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