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Original Research

Effect of Combinations of Green Roof Substrate with Vegetation Coverage on Rainwater Quality Improvement

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Abstract

The significance of green roofs in stormwater management cannot be overlooked, as they have become an integral component in the creation of sustainable cities. This study not only examined the purifying effects of substrates, but also explored the interplay between substrate and vegetation through a combination planting approach, resulting in an innovative roof greening and planting method that incorporates both substrate and vegetation. In the experiment, 16 planting combinations of green roofs were created by cross-planting four proportioned substrates and four proportioned turfgrass. Subsequently, the outflow water quality indexes including ammonium nitrogen (NH_4^+-N), suspended solids (SS), chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) were analyzed individually. The study findings indicate significant variations in the rainwater quality improvement capacity among the 16 green roof planting combinations, with both exhibiting effective purification of NH_4^+-N and SS. However, all 16 planting combinations were identified as sources of pollution for TP, TN and COD in rainwater. Among the four proportioned substrates, the combination of planting and B substrate (field soil: turfy soil: vermiculite: perlite: zeolite = 5:2:1:1:1) exhibits a superior purification effect with minimal variance. Therefore, it is recommended to promote and apply B substrate in large-scale green roofs. The A2 combination (field soil: turfy soil: perlite: vermiculite = 5:3:1:1 and *Poa pratensis*: *Agrostis matsumurae*: *Lolium perenne* = 5:4:1) exhibited the highest effluent water quality among the 16 combinations tested, while other planting combinations utilizing substrate A did not perform as well. In summary, green roofs have the potential to purify rainwater but also pose a certain risk of pollution.

Keywords: green roof, vegetation cover, rainwater quality improvement, substrate proportioning, planting combination

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Introduction

At present, the world is in the stage of rapid urbanization, and the extent of impervious surface in cities is continuously expanding [1]. The precipitation flows into the urban rainwater pipe network through drainage facilities, leading to rapid accumulation of water. This not only burdens the pipe network but also increases the risk of downstream floods [2]. Urban roof area accounts for about one third of the urban impervious surface area, and making good use of roof for urban rainwater recycling is an effective way to alleviate urban surface runoff and improve urban water cycle [3, 4].

Most urban areas face three interrelated water-related challenges: flooding, scarcity of water resources, and pollution and degradation of the water environment. These issues are becoming increasingly prominent and exacerbate one another [5]. Water scarcity in most urban areas is primarily attributed to water quality issues, while rainwater within cities is regarded as a valuable resource. Calls for its beneficial use are becoming more frequent [6]. One way to solve these problems is to adopt new stormwater management strategies, which vary from country to country. Examples include low-impact development (LID) [7], sustainable urban drainage systems (SUDS) [8], water-sensitive urban design (WSUD) [9]. An important strategy in the WSUD system is to control the source of runoff to improve the quality of stormwater runoff and reduce the amount of water [10, 11]. The installation of green roofs is considered to be the best management measure for reducing peak urban runoff and improving the quality of stormwater runoff [12, 13].

Obviously, one of the most important goals of green roof research is to determine how green roofs affect the quality and quantity of rainwater. This has been studied by a large number of scholars [14-16]. Berndtsson concluded that factors that can effectively improve the water quality and quantity of green roofs include the type of substrate material (soil composition), the depth of the growing substrate, the type of vegetation and the physicochemical properties of pollutants [17]. Different substrate proportions will change the overall physical properties of the substrate [18-20], and the purification effects of different plant species were also different [21, 22]. Furthermore, they have a significant effect on the efficiency of rainwater runoff detention and pollution interception. Some green roof systems have also achieved good purification results by combining with different filters [23]. Therefore, it is imperative to conduct a comprehensive evaluation based on the ratio of nutrient and inorganic adsorption substrates, combined with plant varieties.

Green roofs usually need to be modified or trimmed to increase their loading capacity, and in order to reduce the consumption of manpower, material and financial resources, light green roofs with a substrate depth of less than 15 cm are preferred [24]. Scholars have conducted extensive research on substrate selection for light green roofs [25, 26]. At present, most of the plants used for light green roofs are Sedum plants, mainly due to its extreme drought resistance adapted to the harsh environment of lawn green roof [27]. However, the roots of Sedum plants are shallow and sparse, and their ability to reduce rainfall runoff is weak [28]. Nagase and Dunnett monitored the impact of the diversity and structure of 12 plant species used on green roofs on stormwater runoff and found that grass is the most effective at reducing stormwater runoff [29]. It has been found in previous studies that developed plant roots and biofilms attached to their surfaces (containing a large number of protozoa and bacteria) can secrete a large number of enzymes to accelerate the decomposition of pollutants in water and purify water quality [30]. With deeper and more developed roots, turfgrass plants not only have significant advantages in rainwater interception, but also deserve to be studied in terms of rainwater quality improvement ability.

For green roofs, there is significant potential in urban stormwater management. If the roof rainwater can be purified and recycled, it will greatly relieve the pressure of urban water source. The green roof mainly plays the role of rainwater purification through the substrate and plant species. Therefore, the selection and combination of substrate and plant species is very important. However, most of the previous studies focused on the screening and comparison of single substrates or plants, but there were few studies on the combined benefits of plants and substrates. In the early stage, we carried out the application investigation of different proportions of planting substrate and turfgrass combination on the campus roof of Shandong Jianzhu University in China, and we selected some planting combinations suitable for local green roof application. In order to further explore the ecological functions of different combinations, we would like to continue to optimize the relevant combinations and expect to carry out an in-depth investigation on the effect of these combinations in purifying rainwater. On the basis of this idea, the four proportioned substrates without vegetation cover and 16 planting combinations with vegetation cover were explored to understand the influence of different treatment methods on rainwater quality improvement capacity in the green roof. It is anticipated that this study can further promote the development of green buildings and contribute to the sustainability of the city.

Materials and Methods

Green Roof Setup

The experiment began in March 2022 and ended in June 2022. The research site is located on the roof of the Architectural Art Museum (36°40’37”N, 117°11’25”E) of Shandong Jianzhu University, Licheng District, Jinan City, Shandong Province, China. Eight square

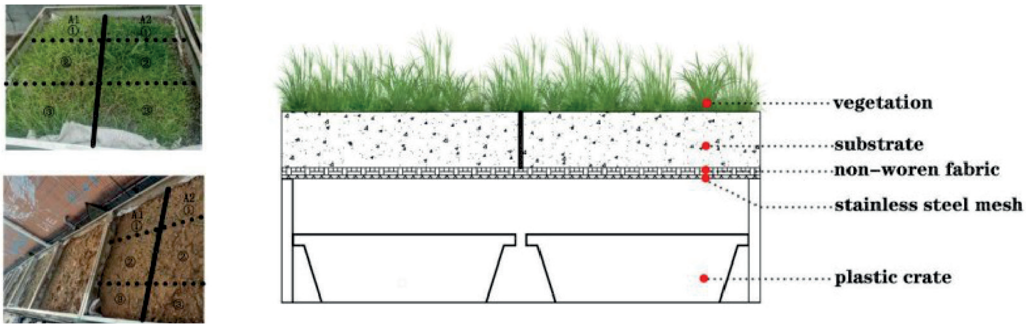

Fig. 1. Design and installation of rainwater quality investigation for green roof. The plot in each stainless-steel planting bed was evenly divided into two treatments. ①, ② and ③ indicated three repetitions of different treatments.

stainless-steel concave planting beds measuring 1 m × 1 m were placed on the roof (Fig. 1). Each square planting bed was divided into two parts from the middle, each part was 0.5 m × 1 m in size. Hollow stainless steel wire mesh was located at the bottom of the concave planting bed, the top of the wire mesh was laid with non-woven fabric, and the top of the non-woven fabric was filled with the corresponding planting substrate. For test measurements, each 0.5 m × 1 m planting bed was again divided into three sections, with each section serving as a test replicate for a total of three replicates. Under the mesh, plastic boxes were placed to collect rainwater outflow. In this study, 16 planting combinations with vegetation cover were set up to investigate the influence of different combinations on rainwater quality improvement in the green roof. The selection of common turfgrass species for both cold and warm seasons aims to enhance the survival elasticity of turfgrass. In order to make the vegetation luxuriant and not cause excessive pollution of runoff, the nutrient substrate and inorganic adsorption substrate were mixed in different proportions.

Experiment Design and Methods

The same experimental design was adopted. Four planting substrates were prepared according to Table 1. Accordingly, four proportioned turfgrass seeds were shown in Table 2.

Sixteen planting combinations were formed by cross-planting four types of proportioned turfgrass seeds (1, 2, 3 and 4) with four different planting substrates (A, B, C and D), as shown in Table 3. It is worth noting that the planting substrate depth was established at 15 cm. A total of 16 planting combinations were shown in Table 3. The turfgrass seed was planted at a standard rate of 60 g·m^{-2}. The corresponding proportion of grass seeds were weighed, evenly dispersed onto the proportioned substrates, and then covered with a thin layer of field soil before being gently compacted. Three biological replicates were set for each planting combinations, and the same maintenance level was adopted. Before the experiment was carried out, all the planting combinations were managed and maintained normally, and the growth was stable for about 60 days. When the coverage reached 85 percent

Table 1. Type and component in four proportioned substrates.

Types	Component and proportion
A	Field soil: turfy soil: perlite: vermiculite = 5:3:1:1
B	Field soil: turfy soil: vermiculite: perlite: zeolite = 5:2:1:1:1
C	Field soil: turfy soil: perlite: vermiculite: wheat straw = 5:2:1:1:1
D	Field soil

Table 2. Species and proportion of four mixed turfgrasses.

Mixed turfgrasses	Species and proportion
1	*Cynodondactylon*: *Zoysia japonica*: *Lolium perenne* = 7:2:1
2	*Poa pratensis*: *Agrostis matsumurae*: *Lolium perenne* = 5:4:1
3	*Poa pratensis*: *Festuca elata*: *Lolium perenne* = 5:3:2
4	*Zoysia japonica*: *Cynodondactylon* = 2:1

Table 3. Sixteen planting combinations of substrate and turfgrass.

Planting combinations	Proportion of substrate and turfgrass
A1	(field soil: turfy soil: perlite: vermiculite = 5:3:1:1 and *Cynodondactylon*: *Zoysia japonica*: *Lolium perenne* = 7:2:1
A2	Field soil: turfy soil: perlite: vermiculite = 5:3:1:1 and *Poa pratensis*: *Agrostis matsumurae*: *Lolium perenne* = 5:4:1
A3	Field soil: turfy soil: perlite: vermiculite = 5:3:1:1 and *Poa pratensis*: *Festuca elata*: *Lolium perenne* = 5:3:2
A4	Field soil: turfy soil: perlite: vermiculite = 5:3:1:1 and *Zoysia japonica*: *Cynodondactylon* = 2:1
B1	Field soil: turfy soil: vermiculite: perlite: zeolite = 5:2:1:1:1 and *Cynodondactylon*: *Zoysia japonica*: *Lolium perenne* = 7:2:1
B2	Field soil: turfy soil: vermiculite: perlite: zeolite = 5:2:1:1:1 and *Poa pratensis*: *Agrostis matsumurae*: *Lolium perenne* = 5:4:1
B3	Field soil: turfy soil: vermiculite: perlite: zeolite = 5:2:1:1:1 and *Poa pratensis*: *Festuca elata*: *Lolium perenne* = 5:3:2
B4	Field soil: turfy soil: vermiculite: perlite: zeolite = 5:2:1:1:1 and *Zoysia japonica*: *Cynodondactylon* = 2:1
C1	Field soil: turfy soil: perlite: vermiculite: wheat straw = 5:2:1:1:1 and *Cynodondactylon*: *Zoysia japonica*: *Lolium perenne* = 7:2:1
C2	Field soil: turfy soil: perlite: vermiculite: wheat straw = 5:2:1:1:1 and *Poa pratensis*: *Agrostis matsumurae*: *Lolium perenne* = 5:4:1
C3	Field soil: turfy soil: perlite: vermiculite: wheat straw = 5:2:1:1:1 and *Poa pratensis*: *Festuca elata*: *Lolium perenne* = 5:3:2
C4	Field soil: turfy soil: perlite: vermiculite: wheat straw = 5:2:1:1:1 and *Zoysia japonica*: *Cynodondactylon* = 2:1
D1	Field soil and *Cynodondactylon*: *Zoysia japonica*: *Lolium perenne* = 7:2:1
D2	Field soil and *Poa pratensis*: *Agrostis matsumurae*: *Lolium perenne* = 5:4:1
D3	Field soil and *Poa pratensis*: *Festuca elata*: *Lolium perenne* = 5:3:2
D4	Field soil and *Zoysia japonica*: *Cynodondactylon* = 2:1

of the square meters, the determination of rainwater quality improvement was performed.

Chemicals and Method of Artificial Water Distribution

In the experiment, artificial water distribution was used to simulate rainwater runoff. A certain amount of glucose, potassium dihydrogen phosphate, ammonium chloride, ground and screened diatomite and potassium nitrate were added to tap water respectively to simulate the pollutants of chemical oxygen demand (COD), total phosphorus (TP), ammonium nitrogen (NH_4^+-N), suspended solids (SS) and total nitrogen (TN) in runoff. The average concentration of pollutants in rainwater was set by referring to the corresponding roof rainwater pollutant concentration and the actual situation of Jinan city, China [31-36]. The concentrations of SS, COD, TN, NH_4^+-N and TP were 351.5, 85.05, 6.27, 7.33 and 0.17 mg·L^{-1}, respectively.

Sample Collection and Analysis Method

The distributed rainwater was evenly sprinkled with a 5 L sprinkler bucket to the experimental green roof plots, and each plot was irrigated with 15 L. The outflow was collected in plastic boxes. When the outflow was no longer generated, the water samples collected in the plastic boxes were sampled. The effluent samples were transported and stored under dry ice refrigeration, and sent to Nanjing Cavensi Detection Technology Co., Ltd. for SS, COD, TN, NH_4^+-N, and TP analysis. All the parameters were determined according to the national standard method of China. Among them, the gravimetric method (GB 11901-89) was used to detect SS. The measuring principle is based on the retention of suspended solids in water samples passing through a 0.45 µm filter membrane, which are subsequently dried to constant weight at 103-105ºC. The COD was determined using the dichromate method (HJ 828-2017). The principle of determination involves adding a known amount of potassium dichromate solution to the water sample, with silver salt serving as a catalyst in a strong acid medium. After boiling and refluxing, the unreduced potassium dichromate in the water sample is titrated with ferrous sulfate, and the mass concentration of consumed oxygen is calculated from the amount of consumed potassium dichromate. NH_4^+-N was quantified using the spectrophotometric method with Nessler's reagent (HJ 535-2009). The principle behind this method is that free ammonia or ammonium ions react with Nessler's reagent to form a reddish-brown complex, and the absorbance of this complex is directly proportional to the concentration of ammonium nitrogen. The absorbance is measured at a wavelength of 420 nm. TN was determined using the alkaline potassium persulfate digestion spectrophotometric method (HJ 636-2012). The principle behind this method is that at temperatures above 60°C, potassium persulfate decomposes to produce atomic oxygen and potassium bisulfate. In an alkaline medium of sodium hydroxide, the decomposition process can be promoted to completion as potassium bisulfate dissociates in solution to produce hydrogen ions. Under the condition of 120-124ºC, atomic oxygen generated from decomposition can convert nitrogen-containing compounds in water samples into nitrate through oxidation and decomposition of organic matter simultaneously. TP was quantified using the ammonium molybdate spectrophotometric method (GB 11893-89). The analytical principle involves digestion of the sample with potassium persulfate under neutral conditions, resulting in complete oxidation of all phosphorus species to orthophosphate. In an acidic medium, orthophosphate reacts with ammonium molybdate and antimony salt to form a phosphomolybdate heteropoly acid that is subsequently reduced by ascorbic acid to yield a blue-colored complex.

The formula Rc of pollution concentration reduction rate is as follows (1):

$$Rc = [(C_{in} - C_{out}) \div (C_{in})] \times 100\% \quad (1)$$

Where C_{in} is the concentration of a pollutant in the inflow ($mg \cdot L^{-1}$), C_{out} is the concentration of a pollutant in the outflow ($mg \cdot L^{-1}$), and the reduction rate of a pollutant by a certain proportioned substrate or planting combination can be obtained through the above equation.

Data Analysis

Data analysis was conducted using SPSS Statistics 26.0 and Microsoft Excel 2010, with a significance level set at $P \leq 0.05$. Graphs were drawn using GraphPad Prism 9.0. Each combination of turfgrass and substrate was considered as a whole. Therefore, one-way variance was also used for data analysis of 16 planting combinations. The data were subjected to the Shapiro-Wilk normality test, and the ANOVA test was performed on the data with a normal distribution and the Kruskal-Wallis test on the data without a normal distribution. When the ANOVA was significant, the minimum significance difference (LSD) was used to distinguish the differences between treatments, where different lowercase letters represented significant differences between treatments. According to the method of Li et al. [37], fuzzy mathematics subordinate function value method (SFV) or anti-subordinate function value method (ASFV) was used for comprehensive evaluation. The subordinate function value was calculated as follows:

① If the index is positively correlated with the rainwater quality improvement effect, it can be calculated according to Equation (2):

$$X(\mu) = \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$
$$\Delta = \sum X(\mu)/n \quad (2)$$

② If the index is negatively correlated with the rainwater quality improvement effect, it can be calculated according to Equation (3):

$$X(\mu) = 1 - \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$
$$\Delta = \sum X(\mu)/n \quad (3)$$

Where $X(\mu)$ is the subordinate function value, X is the measured average value of an indicator, X_{min} and X_{max} are the minimum and maximum value of an indicator, and n is the number of indicators.

Results and Discussion

Effect of 16 Planting Combinations on COD

There were significant differences ($P \leq 0.05$) in COD concentration in the outflow of 16 planting combinations (as shown in Fig. 2). The COD concentration in the outflow runoff of the 16 plant combinations was higher than that of the prepared rainwater, which showed that it was a pollution source. The COD concentration in the outflow ranged from 87.67 $mg \cdot L^{-1}$ to 236.33 $mg \cdot L^{-1}$. The top three planting combinations with the highest

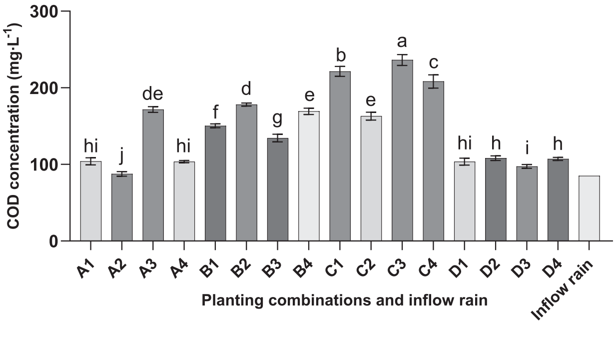

Fig. 2. Effect of 16 plant combinations covered by vegetation on COD. Different lowercase letters represent the significant difference, $P \leq 0.05$.

COD concentration in the outflow were C3, C1, and C4, which were 236.33 mg·L^{-1}, 221.33 mg·L^{-1}, and 208.33 mg·L^{-1}, respectively. C3 demonstrated the highest COD concentration and there were significant differences among these three combinations. Besides, the planting combinations using substrate C as the growth substrate had poor performance. In view of this, substrate C as a growing substrate for green roof would increase the risk of COD pollution in runoff. On the contrary, A2 had the lowest COD concentration at 87.67 mg·L^{-1}. Additionally, the COD concentration in the outflow of A1, A4 and D1 was only higher than that of A2, and there was no significant difference between the three groups. Green roofs usually become the source of COD pollution because of the nutrients contained in the substrate [38]. Previous studies have found that in the substrate containing more nutrients, COD elements in runoff increase significantly [39]. This is consistent with our results.

Effect of 16 Planting Combinations on TP

According to Fig. 3, there were significant differences ($P \leq 0.05$) in the outflow concentration of the established plant combination, and the concentration of TP in the outflow of the established plant combination was higher than that of the prepared rainwater, which was identified as the source of pollution. C1 and C2 had the highest outflow concentration of TP, 2.8 mg·L^{-1} and 2.74 mg·L^{-1}, respectively, and there was no significant difference between them. It revealed that both combinations contained the strongest pollution. Conversely, the lowest TP concentration was 1.17 mg·L^{-1} in the outflow of D2, followed by A4 and B1, and the TP concentrations were 1.25 mg·L^{-1} and 1.26 mg·L^{-1}, respectively. And more importantly, there was no significant difference among D2, A4 and B1. Some scholars have found that phosphorus is leached from the green roof substrate and the aggregate used in its composition, which may be the reason for the increase of phosphorus in roof greening runoff [40]. Akther et al. found that the higher the proportion of nutrient elements in the substrate, the higher the concentration of pollutants in the runoff of roof greening, which may be due to leaching to release water-soluble pollutants (such as PO_4^{3-}) from the substrate [41].

Effect of 16 Planting Combinations on TN

The concentration of TN in the outflow of the 16 plant combinations was higher than that of the prepared rainwater, and these results indicated that the combinations acted as pollution sources (as shown in Fig. 4). There were significant differences in the concentration of TN in the outflow of different planting combinations ($P \leq 0.05$). The concentration of TN in the outflow of A3 was the highest (31.31 mg·L^{-1}), which showed the highest pollution. However, the concentration of TN in the outflow of B1 was the lowest (20.4 mg·L^{-1}). Pęczkowski et al. found that the total nitrogen concentration of green roof outflow increased in two systems with vegetation layer based on lightweight expansive clay aggregate and perlite, similar to this study [42]. Gong et al. found that green roofs had higher total nitrogen (TN), ammonia nitrogen (NH_4^+-N) concentrations than traditional concrete roofs, their findings are consistent with this study [43].

Effect of 16 Planting Combinations on NH_4^+-N

There were significant differences in the reduction rate of NH_4^+-N concentration among different planting combinations ($P \leq 0.05$). The concentration of NH_4^+-N in runoff of 16 planting combinations was lower than that of rainwater, and these combinations showed a better effect on NH_4^+-N (as shown in Fig. 5). In other words, NH_4^+-N on green roofs can be effectively reduced [44]. The NH_4^+-N reduction rates of B3 and D2 were the highest, which were 91.84% and 91.76% respectively, and there was no significant difference between them. Instead, the NH_4^+-N reduction rates of A3 and C2 were the lowest, which were 85.12% and 85.33% respectively, but equally, there was also no significant difference between them. In this study, it was observed that adding zeolite to the substrate reduced the outflow of NH_4^+-N and improved the water quality of roof greening.

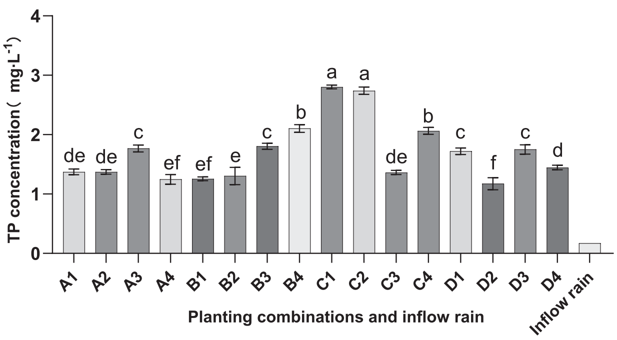

Fig. 3. Effect of 16 plant combinations covered by vegetation on TP. Different lowercase letters represent the significant difference, $P \leq 0.05$.

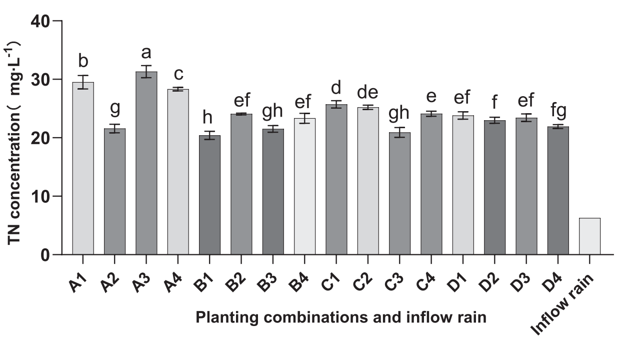

Fig. 4. Effect of 16 plant combinations covered by vegetation on TN. Different lowercase letters represent the significant difference, $P \leq 0.05$.

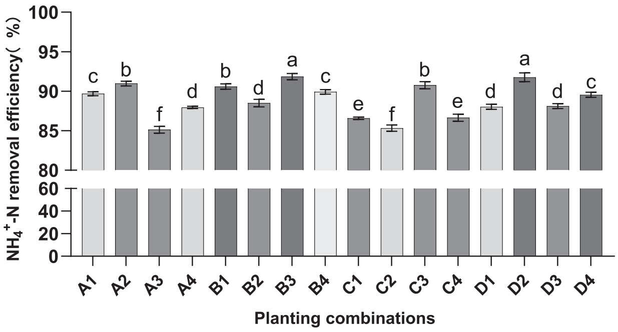

Fig. 5. Effect of 16 plant combinations covered by vegetation on the removal rate of NH_4^+-N. Different lowercase letters represent the significant difference, *P*≤0.05.

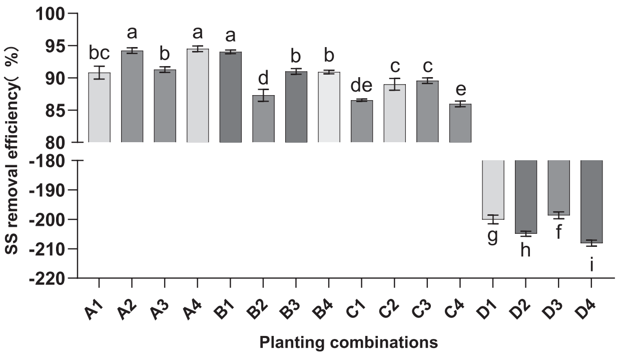

Fig. 6. Effect of 16 plant combinations covered by vegetation on the removal rate of SS. Different lowercase letters represent the significant difference, *P*≤0.05.

Leyva-Ramos obtained similar results through outdoor experimental research [45].

Effect of 16 Planting Combinations on SS

According to Fig. 6, there were significant differences (*P*≤0.05) in the reduction rate of SS concentration among different planting combinations. Among the 16 planting combinations, the SS concentration in runoff of the other 12 groups was lower than that of the prepared rainwater. Furthermore, the reduction rate of SS concentration of 12 groups was about 90%, except the one based on substrate D. Similarly, all the 12 combinations showed a good rainwater quality improvement effect. Surprisingly, A2, A4 and B1 showed the highest SS reduction rate, which were 94.22%, 94.5% and 94.03, respectively. In addition, there was no significant difference between the three combinations. However, the concentration of SS in the outflow of the combination containing substrate D was increased significantly. Among them, D4 had the lowest SS reduction rate of -208.11%.

Previous study has shown that adding biochar to roof greening substrate can reduce the total suspended solids (TSS) content in leachate [46]. Some scholars' research results show that the average concentration of SS in roof greening runoff has decreased by 37.85% [47]. The results of this survey are consistent with those in previous reports.

Comprehensive Analysis of Rainwater Quality Improvement of 16 Planting Combinations

The lower the concentration of COD, TP, TN, NH_4^+-N and SS in runoff, the better the rainwater quality improvement effect of the planting combination was. The rainwater quality improvement of 16 vegetation-based planting combinations evaluated comprehensively using ASFV method is presented in Table 4. A2 planting combination showed the best improvement effect on rainwater runoff, whereas A3 ranked at the bottom of the 16 combinations. It manifested that the planting combination based on substrate A possessed great difference in rainwater quality improvement. That is to say, in practical application, if the vegetation covered was not properly matched, its improving effect would be greatly reduced. The rainwater quality improvement effect of B1 and B3 was second only to that of A2. It was worth noting that the rainwater quality improvement effect of B2 and B4 was also in the top ten, indicating that the effect of substrate B combined with different turfgrass was stable, with higher fault tolerance rate and wider application range. Group C1 displayed the worst effect, moreover, all the planting combinations based on substrate C performed poor rainwater quality improvement except C3. Therefore, substrate C could only play a better effect when combined with mixed grass species 3. However, the comprehensive evaluation showed that all the four planting combinations based on substrate D performed poorly. The order of comprehensive evaluation effect was as follows: A2>B1>B3>C3>D2>A1>A4>B2>B4>D4>D3>D1>C4>C2>A3>C1. According to the results, A2 was considered as the best planting combination for rainwater quality improvement capacity, but the planting combination based on substrate A exhibited unstable effect. While B1 and B3 were second only to A2, and the planting combination based on substrate B revealed a stable rainwater quality improvement effect. Additionally, the application range of the matching mixed grass species was wider. Therefore, from this point of view, substrate B might be more suitable as a planting substrate for green roofs.

The concentrations of TN and TP in the outflow increased, it means that N, P elements from green roof are released [48, 49]. The main reason may be that the growth substrate contains a large proportion of nutrient-rich substrates, and a large number of nutrient elements are leached out during rainfall, while the plants themselves are not enough to purify these pollutants. It is also possible that the artificially prepared rainwater did not keep in the green roof system for a long time during the experiment, and the substrate and plants did not have enough time to play the role of purification. There is a large amount of humus in the turfy soil. Under the action of leaching, organic nutrients

Table 4. Comprehensive evaluation of rainwater quality improvement effect of 16 plant combinations based on fuzzy mathematics subordinate function value method.

Groups	NH_4^+-N	SS	COD	TP	TN	Mean	Rank
A1	0.678	0.988	0.890	0.877	0.165	0.720	6
A2	0.870	0.999	1.000	0.877	0.892	0.928	1
A3	0.000	0.989	0.435	0.636	0.000	0.412	15
A4	0.421	1.000	0.892	0.955	0.274	0.708	7
B1	0.815	0.998	0.579	0.949	1.000	0.868	2
B2	0.502	0.976	0.392	0.920	0.664	0.691	8
B3	1.000	0.988	0.686	0.614	0.897	0.837	3
B4	0.714	0.988	0.451	0.429	0.731	0.663	9
C1	0.216	0.974	0.101	0.000	0.512	0.361	16
C2	0.030	0.982	0.493	0.039	0.560	0.421	14
C3	0.840	0.984	0.001	0.883	0.953	0.732	4
C4	0.227	0.972	0.188	0.454	0.659	0.500	13
D1	0.433	0.027	0.892	0.665	0.687	0.541	12
D2	0.988	0.011	0.863	1.000	0.763	0.725	5
D3	0.448	0.031	0.935	0.646	0.722	0.556	11
D4	0.658	0.000	0.870	0.832	0.862	0.644	10

in the matrix enter the runoff, which may lead to the increase of pollution concentration in the effluent of roof greening and planting combination [50].

Zeolite added in substrate B can remove pollutants through physical adsorption and ion exchange, thus improving the outflow quality of roof greening. The outflow water quality of green roof is improved by adding perlite, zeolite and other inorganic fillers to the substrate, indicating that increasing the proportion of inorganic fillers with adsorption and purification contributes to improve the outflow water quality [51, 52]. However, this should be done on the basis of meeting the minimum nutritional growth needs of plants. Otherwise, it is not helpful to the appearance, nor is it conducive to the purification of the plant itself. Long-term monitoring of green roof was found that elements such as organic carbon, phosphorus and nitrogen in the outflow changed dynamically with time [53]. The comparison of two substrates of different ages shows that, with the passage of time, the growth substrate of green roof will undergo various chemical and physical changes, such as soil particles may be lost, soluble substances will be washed away by water, organic content may increase, soil porosity will change and so on. High concentrations of Cu, Pb and Zn have been found in runoff from aging green roofs, suggesting that aging green roofs may be a source of legacy metal pollution [54]. In future, it is suggested to monitor the roof greening for a long time and analyze the changes of its matrix and plants according to the seasons, so as to quantify the benefits of improving runoff water quality.

Conclusions

The aim of this study is to identify substrates and planting combinations that exhibit superior rainwater purification effects, thereby providing a reference for the future combined application of substrates and plants in green roofs. Although the optimal substrate-plant combination was selected during experimentation, they only demonstrated a purifying effect on two pollution indices. The effluent quality of different combinations of roof greening is significantly different, and all of them have good effects on improving the rainwater quality of NH_4^+-N and SS. The concentrations of COD, TP and TN in the effluent increased obviously, showing pollution sources. Among 16 planting combinations, A2 planting combination has the best purification effect on rainwater runoff. However, the purification effect of A3 is at the bottom, which shows that the purification effect of the combination of planting and planting based on A is quite different, and the purification effect will be greatly reduced if the vegetation covered is not properly matched in practical application. The purification effect of the combinations using B substrate is good and the difference is small, so it can be considered to popularize and apply B substrate in large-area green roofs. In addition, the higher the concentration of pollutants released by leaching in the runoff of the planting combination with a higher proportion of nutrient substrates, the use of zeolite-added substrates is beneficial to improve the effluent quality of the planting combination Therefore, it is better to further increase the proportion of inorganic adsorption matrix in the proportion matrix. The ultimate goal is to balance the benefits of plant nutrition and pollutant purification. At the same time, it is necessary to study the effluent quality of roof greening for a long time, so as to increase the understanding of its purification potential and promote the sustainable development of the city.

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Conflict of Interest

The authors declare no conflict of interest.

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