Experimental Study on the Retention and Interception Effect of an Extensive Green Roof (GR) with a Substrate Layer Modified with Kaolin

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Abstract: Extensive green roofs (GRs) often appear as pollution sources during actual rainfall events; therefore, it is necessary to study the control of nutrient leaching in the substrate layer. In this study, four extensive GR experimental devices are built: two with artificial granular structure substrate layers improved with kaolin as a binder, one with a commercial substrate layer, and one with a standard roof (SR). Based on the simulated rainfall conditions in different local recurrence periods, the delayed outflow time, rainfall retention rate, event mean concentration (EMC), and cumulative pollutant quality of NH$_4^+$, NO$_3^-$, NO$_2^-$, and PO$_4^{3-}$ in the eflluents were measured and evaluated. The results of the study indicate that under simulated rainfall in all the experimental design recurrence periods, the kaolin-modified substrate layer does not exhibit a more significant retention capacity than the commercial substrate. However, it does show some suppression of the leaching effect of NO$_3^-$ and PO$_4^{3-}$ in the runoff. The reduction rate of cumulative NO$_3^-$ quality is 6.56%, and PO$_4^{3-}$ is 10.54%. In future practical engineering and related research, attention should be paid to the influence of the type and addition amount of the substrate layer modifier on the stability of the granular structure to prevent nutrient loss caused by soil erosion.

Keywords: kaolin; green roof; runoff retention; leaching; nitrate; phosphate

1. Introduction

With the rapid development of global urbanization, the hardening rate of underlying urban areas has increased, leading to frequent cases of urban waterlogging and non-point source pollution. As one of the important low-impact development measures, green roofs (GRs) can effectively address the problem of rainwater management as long as they make full use of the existing roof space, which has generated extensive research by domestic and foreign experts [1–5]. Shafique et al. evaluated the performance of GRs in highly urbanized areas of Seoul, South Korea [6]. The results showed that GRs could reduce runoff by 10% to 60% under different rainfall intensities. Gao et al. used MATLAB to develop the Illinois urban hydrologic model-green roof (IUHM-GR) combination model [7]. The simulation results showed that GRs have a good effect on rainwater retention and could effectively reduce the total amount and peak value of rainwater runoff. Dimitar et al. experimentally showed that PF, TP, NO$_3^-$, and Cl$^-$ in the effluent quality of GRs were better than that of impervious surfaces [8].

The retention and interception ability of GRs on rainwater runoff is affected by several factors, such as the type and material of the substrate layer [9,10], substrate layer thickness [11], GR scale [12], vegetation type [13–15], rainfall time [16], rainfall depth [17], type of drainage layer [18], water storage, whether the layer is set or not, and roof slope. Through a large number of experiments and simulation results, it can be concluded that rainfall depth as well as substrate layer thickness and material type are important parameters affecting the retention and interception capacity of the rainwater runoff of GRs.

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Most research on the substrate layer has been done through mixing materials with good physical properties or by stratifying the nutrient substrate and adsorption substrate, and relying on their high water content and adsorption capacity to improve the overall retention and interception capacity of GRs [19]. In the actual rainfall process, raindrop splashing destroys the surface soil structure of the substrate layer, impacts the thin-layer runoff, increases flow turbulence, enhances the erosion ability of the runoff, and results in nutrient loss [20]. The granular structure is a stable soil structure that has the advantages of good water–air coordination, soil fertility, and erosion resistance [21–23]. By adding adhesive to the GR substrate layer, both the inorganic and nutrient substrates bond to form soil aggregates that can enhance the water-retention capacity of the substrate layer, facilitate the long-term growth of the vegetation layer, and reduce leaching of the substrate layer caused by rainwater runoff [24]. At present, there are few studies on the influence of the artificial granular structure of the substrate layer on the retention and interception capacity of the rainwater runoff of GRs during heavy rainfall, which is of certain research relevance.

In this study, kaolin is used as a binder mixed with peat soil and perlite to construct a GR artificial granular structure substrate layer to study the control ability of the modified substrate layers with different thicknesses on rainfall-runoff retention and nutrient leaching.

2. Materials and Methods

2.1. Device Construction

In this experiment, three GR devices and a standard roof (SR) device were built on the roof of the School of Civil Engineering and Architecture of Nanchang University with an average roof slope of 3%. The experimental devices are shown in Figure 1. The frames of the experimental devices are made of PVC, and each device consists of an exposed cuboid measuring 50 × 50 × 30 cm. Under the plane on the outlet side of the device, there are two outlet holes with a diameter of 2 cm and a distance between them of 20 cm, which are connected with a suitable length of plastic hose to facilitate the collection of the outlet samples.

![Four experimental roof devices in laboratory](image1)
![The schematic diagram of green roof devices](image2)
![The specific measurement of roof devices](image3)

**Figure 1.** Extensive green roof (GR) experimental devices.

The GR devices are composed of a vegetation layer, substrate layer, filter layer, and a drainage layer from top to bottom. The specific structures are shown in Table 1.
### Table 1. Substrate structure of experimental devices.

| Device | Material | Depth | Bulk Density | Character       |
|--------|----------|-------|--------------|----------------|
| GR1    | 66% Perlite + 30% Peat + 4% Kaolin | 10 cm | 0.3345 g/cm³ | Modified substrate |
| GR2    | 35% Perlite + 30% Peat + 35% Ceramsite | 10 cm | 0.3446 g/cm³ | Commercial substrate |
| GR3    | 66% Perlite + 30% Peat + 4% Kaolin | 15 cm | 0.3345 g/cm³ | Modified substrate |
| SR     | -        | -     | -            | -              |

*Sedum lineare* was selected as the vegetation layer, which has the characteristics of short roots, good wind resistance, and strong drought resistance [25]. Moreover, it meets the requirements for vegetation selection in GR construction. Additionally, *sedum lineare* is a local vegetation species with a good long-term growth status and low cost, which conforms to the sustainable development of GRs [26]. Peat, perlite, kaolin, and ceramsite were used in the substrate layer. Peat soil has the characteristics of looseness, good drainage ability and rich organic matter, all of which can provide good growing conditions for the top vegetation layer [6]. Perlite and ceramsite can prevent soil compaction and adjust the soil because of their better water permeability, air permeability, and water absorption [27]. Concurrently, the advantages of both materials with a small bulk density can also better meet the requirements of the built roof load [28,29]. Kaolin has strong plasticity and cohesiveness [30], therefore, it was used as a binder for peat and perlite in GR1 and GR3 to modify the granular structure. At the same time, Jiangxi Province is rich in kaolin resources, making it easy to obtain and low cost. The filter layer was made of permeable non-woven geotextile, to prevent rainfall runoff from passing through the substrate layer and carrying fine particles, which causes an increase in turbidity or other pollutant indicators, resulting in water pollution. The drainage layer was equipped with plastic drainage plates to ensure easy discharge of the rainfall runoff that cannot be retained in the substrate layer to avoid overflow phenomena and negative impact on good vegetation growth.

Considering the monetary cost of each GR substrate, GR1 is CNY 27.99, GR2 is CNY 34.34, and GR3 is CNY 41.98. The four devices performed well during the construction and maintenance period in the summer, from July to September. Moreover, they adapted well to the extremely hot local climate and the vegetation grew abundantly. To facilitate the follow-up rainfall simulation experiment, the experimental devices were moved into the laboratory from October to December. No significant change occurred in the vegetation growth status of the four devices during the experimental period.

#### 2.2. Experimental Design

Following the rainfall formula of Nanchang City, the 2 h rainfall conditions in the recurrence periods of 0.25, 0.5, 1, 5, 20, and 100 years were used as the design rainfall. According to this rainfall formula, the rainfall depths were 32.42, 43.94, 55.46, 82.21, 105.25, and 132.00 mm for the abovementioned conditions, respectively. According to the National Standard of the People’s Republic of China “Grade of Precipitation GB/T 28592-2012”, the design rainfall for the six recurrence periods includes three different rainstorm levels, which are representative. Additionally, the pollutant indexes of six rainfall samples from July to September were measured. According to the experimental results, the simulated rainfall water quality of this experiment was properly selected, as shown in Table 2.

### Table 2. Simulated rainfall quality.

| Measurement | NH₄⁺ | NO₃⁻ | NO₂⁻ | PO₄³⁻ |
|-------------|------|------|------|-------|
| Concentration | 1 mg/L | 1.2 mg/L | 0.02 mg/L | 0.01 mg/L |

The simulated water used in this study adopts the method of adding the corresponding ion standard solution to the tap water to achieve the quality required for the rainfall simulation. Using the peristaltic pump, the simulated water was pre-mixed through the spray nozzle to uniformly land on the GR receiving surface. Moreover, this was done to ensure that before each experiment, the antecedent
dry period (ADP) and substrate water content of each GR were similar to avoid interference from other factors on the experimental results. Throughout the experiment, the rainwater volumes were measured and recorded in the collection barrel 5, 10, 20, 30, 60, 120 and 180 min after the outflow was generated. Concurrently, samples were taken 5, 10, 20, 30, 60 and 120 min after the outflow was generated and were stored in a designated bottle in a refrigerator at 4 °C. Concentrations of NH$_4^+$, NO$_3^-$, NO$_2^-$, and PO$_4^{3-}$ in all the samples were measured and recorded according to the national standard method within 24 hours after collection. The specific national measurement standard methods are shown in Table 3.

| Measurement | Method |
|-------------|--------|
| NH$_4^+$    | Nessler’s reagent spectrophotometry |
| NO$_3^-$   | Ultraviolet spectrophotometry |
| NO$_2^-$   | Spectrophotometry of naphthalene ethylenediamine hydrochloride |
| PO$_4^{3-}$ | Ammonium molybdate spectrophotometry |

2.3. Evaluation Methods

2.3.1. Evaluation Method of Retention Capacity

Based on the experimental data, this study evaluates the rainwater runoff retention capacity of the four small test devices based on the delayed outflow time and the runoff reduction rate. The difference between the initial outflow time of the green and ordinary roof devices is the delayed outflow time. The runoff reduction rate ($R_r$) can be calculated using the following formula:

$$R_r = \frac{D_i \times S - V_i}{D_i \times S} \times 100\% \quad (1)$$

where $R_r$ is the runoff reduction rate (%), $S$ is the GR area ($m^2$), $i$ is the number of simulated rainfalls, $D$ is the depth of the simulated rainfall (mm), and $V$ is the volume of the GR outflow (L).

2.3.2. Evaluation Method of Interception Capacity

Based on the experimental measurement data, this study evaluates the rainwater runoff interception capacity of the four small test devices through event mean concentration (EMC) and cumulative leaching quality (CLQ). The EMC of each pollutant can be calculated by the following formula:

$$EMC = \frac{\int_0^T C(t)Q(t)dt}{\int_0^T Q(t)dt} \approx \frac{\sum_{i=1}^n C_i V_i}{\sum_{i=1}^n V_i} \quad (2)$$

The CLQ of each pollutant can be calculated by the following formula:

$$CLQ = \int_0^T C(t)Q(t) dt \approx \sum_{i=1}^n C_i V_i \quad (3)$$

where EMC is the event mean concentration (mg/L); CLQ is the cumulative pollutant quality (mg); $C(t)$ is the pollutant concentration distribution in a rainfall outflow with time $t$ (mg/L); $Q(t)$ is the rainfall-outflow volume with time $t$ ($m^3$/s); $T$ is the total -outflow duration (s); $n$ is the number of outflow time segments; $C_i$ is the concentration of a given pollutant in an outflow sample collected during the $i$-th period (mg/L); $V_i$ is the outflow volume in the $i$-th period ($m^3$).
3. Results and Discussion

3.1. Retention Capacity

In this study, based on the design rainfall for the six different recurrence periods, simulated rain experiments were carried out on four GR experimental devices. When no significant differences were observed in the dry period of the devices, the delayed outflow times, outflow volumes, and rainfall retention rates during the experiments were recorded and calculated for all the devices. The specific experimental results are shown in Table 4. SR did not show significant retention capacity in the experimental results, it was omitted from this table.

Table 4. Rainfall runoff retention capacity of the three green roof (GR) devices.

| Recurrence Period (a) | Rainfall Depth (mm) | Rainfall (mL) | ADP (h) | Delayed Outflow Time (s) | Outflow Volume (mL) | Retention Rate (%) |
|-----------------------|---------------------|---------------|---------|-------------------------|---------------------|-------------------|
|                       |                     |               |         | GR1 | GR2 | GR3 | GR1 | GR2 | GR3 | GR1 | GR2 | GR3 |
| 0.25                  | 32.42               | 810.10        | 70.5    | 1015 | 1995| 1315| 6342| 5689| 5865| 21.75%| 29.80%| 27.62%|
| 0.5                   | 45.94               | 10,985        | 74      | 960  | 1465| 1285| 8689| 8029| 8305| 20.90%| 26.90%| 25.30%|
| 1                     | 55.46               | 13,864.75     | 65.5    | 730  | 1280| 995 | 11,176| 10,371| 10,536| 19.40%| 25.20%| 24.00%|
| 5                     | 82.21               | 20,551.75     | 70      | 500  | 915 | 805 | 16,959| 16,008| 15,836| 17.48%| 22.11%| 22.95%|
| 20                    | 105.25              | 26,311.5      | 71      | 422  | 645 | 570 | 23,614| 22,206| 22,772| 10.25%| 15.60%| 13.45%|
| 100                   | 131.99              | 32,998.5      | 68      | 340  | 570 | 435 | 31,449| 30,332| 31,213| 4.70% | 8.69% | 5.41% |

Table 4 shows that as the recurrence period increases, the rainfall depth increases, and the delayed outflow time of each device gradually decreases. This is because, during the simulated rainfall experiment, the increase in rainfall depth and intensity increased the runoff seepage velocity. Additionally, the substrate layer thickness was constant and the outflow time shortened. Notably, the effect of GR2 on the delayed outflow time across the six different rainfall depth experiments is significantly better than that of GR1 and GR3. Ceramsite probably has a stronger ability to delay outflow time than perlite, owing to its porous physical properties. It is also possible that the granular structures of GR1 and GR3 with kaolin as a binder can increase the macropore ratio and water conductivity of the substrate layer, resulting in a faster outflow of GR1 and GR3, this compares to previous research results [31,32]. Compared to GR1, GR3 has a greater ability to delay outflow time owing to the greater thickness of its substrate layer. Therefore, substrate layer thickness is an important factor affecting the outflow time of GR runoff.

It can be seen from Table 4 that as the recurrence period increases, the rainfall depth, as well as the outflow of each device, increases, and the rainfall retention rate decreases. As the retention capacity of GRs is mainly determined by the physical properties of the materials and the thickness of the substrate, the total retention capacity of GRs is limited and does not change significantly at different rainfall depths [33,34]. With the runoff volume increasing, the rainfall retention rate decreases. Similar to the delayed outflow time, GR3 has a thicker substrate layer compared to GR1; therefore, it has a greater rainfall retention capacity and retention rate under the same rainfall depth. However, GR2 has a greater rainfall retention capacity and retention rate compared to GR3, with a thinner substrate layer because the porous nature of ceramsite provides good water retention. Moreover, owing to the unique granular structure substrate layer of GR1 and GR3, with many small pores and high water-retention capacity, the device cannot recover its full rainfall retention capacity in a short dry period [35]. Notably, the storage capacity of GR1 and GR3 at 20a and 100a is much lower than that of the previous four simulated rainfalls. The reason may be that the artificial granular structure is easy to destroy under the condition of a raindrop hitting the substrate layer surface at a high rainfall intensity, leading to the decrease of the retention capacity of the device; similar results were reported in Simon’s research [36]. The retention capacity of GR2 remains relatively stable during the heavy rainfall events of the recurrence periods 20a and below. This is probably because ceramsite is hard enough to resist damage to the substrate structure by raindrop splashing, and the retention capacity of GR2 weakens significantly under the 100a rainfall event.
3.2. Interception Capacity

In this study, the concentrations of NH$_4^+$, NO$_3^-$, NO$_2^-$, and PO$_4^{3-}$ in the effluent from four devices were measured at 5, 10, 20, 30, 60, and 120 min after the start of outflow generation under different rainfall intensity return periods. Using the previous formula, the EMC, average EMC, and cumulative pollutant quality of each pollutant were calculated to show the interception ability of the four experimental devices under different rainfall return periods. The specific experimental results are shown in Figures 2–5. Except for NH$_4^+$, all four devices have different degrees of leaching effect under simulated rainfalls in different return periods.

Figure 2. Event mean concentration (EMC) and cumulative pollutant quality of NH$_4^+$.

Figure 3. EMC and cumulative pollutant quality of NO$_3^-$.

Figure 2 shows that regarding NH$_4^+$, the average EMC values of all the roof devices are lower than those of the simulated rainwater. Additionally, GR2 and GR3 have a more significant reduction effect than SR because the GR vegetation layer and substrate layer material have certain adsorption effects on NH$_4^+$; a similar result was reported by Guo [37]. The reduction rate of GR2 to NH$_4^+$ is close to 25%, which is the best performance among the four roof devices. This is because ceramsite has a higher adsorption capacity than perlite owing to its porous characteristics and the better runoff retention capacity of GR2. The small outflow volume results in the lowest NH$_4^+$ cumulative pollutant quality of GR2. The average EMC of GR1 is higher than that of SR because peat soil in GR1 has a certain risk of NH$_4^+$ leaching, while perlite does not have a higher NH$_4^+$ adsorption capacity. GR1 and GR3 have the same type and proportion of substrate materials, but GR1 shows a greater NH$_4^+$ leaching effect compared to GR3 because GR1 has a thinner substrate layer, a shorter rainfall seepage time, and a lower adsorption efficiency of substrate layer materials compared to GR3. For these
reasons, the leaching effect of NH$_4^+$ in the GR1 substrate layer is greater than the adsorption effect of the substrate layer material, resulting in an increased NH$_4^+$ concentration. This also explains why the NH$_4^+$ concentration in the GR1 effluent is significantly high during the 0.25a rainfall recurrence period. GR1 has a good interception effect under the 0.5, 1, and 5a rainfall intensities, but appears as a source of NH$_4^+$ pollution at 0.25, 20, and 100a. This is because the special artificial granular structure of GR1 is easily destroyed under heavy rain events, soil erosion occurs, and nutrients are leached out, eventually resulting in an increased NH$_4^+$ concentration in the effluent.

![Figure 4. EMC and cumulative pollutant quality of NO$_2^-$](image)

Figure 4 shows that although the average EMC values of all roof devices are greater than those of the simulated rainwater, which appears as a source of pollution, indicating that rainfall runoff scouring through the roof and infiltration through the GR cause an increase in NO$_3^-$ concentration. The average EMC and cumulative pollutant quality values of the SR are lower than that of the other GR devices because the three GR devices have peat soil in their substrate materials and the substrate layer leaches during the rainwater seepage process [38]. Concurrently, some of the NH$_4^+$ is nitrated and converted into NO$_3^-$, increasing the NO$_3^-$ concentration. GR1 and GR2 have the same substrate layer thickness and peat soil content. However, GR2 shows a stronger NO$_3^-$ leaching effect than GR1. Additionally, it can be seen that the NO$_3^-$ EMC and cumulative pollutant quality values of GR2 and GR3 are almost the same. However, GR3 has a higher peat soil content, a more significant risk of NO$_3^-$ leaching, and more outflow than GR2. Nevertheless, GR3 shows a stronger ability to intercept NO$_3^-$ This shows that the artificial granular structure made with kaolin has some ability to control nutrient leaching from the GR substrate layer; this agrees with the results reported by Zhang [39]. According to the conclusions

![Figure 5. EMC and cumulative pollutant quality of PO$_4^{3-}$](image)

Figure 5. EMC and cumulative pollutant quality of PO$_4^{3-}$.
of Morteza's previous research, kaolin can adsorb and intercept NO$_3^-$ . This explains why the EMC values of GR1 and GR3 are lower than those of the other roof devices [40]. Finally, the NO$_3^-$ EMC values of GR1 at 1a and GR3 at 5a increased significantly. This was probably because the artificial granular structures of GR1 and GR3 were damaged by the rainfall intensity of these two recurrence periods, which led to an increased leaching effect, ultimately resulting in abnormal NO$_3^-$ changes in the effluent.

Figure 4 shows that although the average EMCs of the roof devices have a leaching ratio between 35.5 and 140.5%, the leaching concentrations of NO$_2^-$ for each device are approximately 0.0071–0.0281 mg/L because of the low NO$_2^-$ concentration in natural rainwater. The reasons for the increased EMC of NO$_2^-$ may be the leaching of peat soil in the substrate layer. Alternatively, as the composite substrate layer has a high porosity and good aeration, NH$_4^+$ likely generated a certain amount of NO$_2^-$ through nitrification in that aerobic environment, leading to an increase in the concentration of NO$_2^-$ in the effluent. Compared to GR1 and GR3, GR2 and SR have smaller EMC and cumulative pollutant quality values. Therefore, the artificial granular structure made with kaolin cannot intercept NO$_2^-$ in rainfall runoff, nor can it effectively inhibit NO$_2^-$ leaching. However, according to Figure 4, the substrate layer structure of GR3 contains more peat soil than GR1, which has a higher risk of leaching, but shows a lower EMC and cumulative pollutant quality of NO$_2^-$ . It may be that the thicker substrate layer of GR3 has certain anaerobic zones, conducive to denitrification, resulting in the conversion of some of the NO$_3^-$ into nitrogen, leading to a decrease in the NO$_3^-$ concentration in the effluent. Additionally, it can be seen that GR1 shows a sharp increase in the NO$_2^-$ EMC in the three heavy rainfall intensities of 5, 20, and 100a. However, GR3 does not show a significant change because its thicker substrate layer is relatively strong and resistant to raindrops under heavy rain. Its granular structure is not easily damaged and the leaching effect of NO$_3^-$ is weakened.

Figure 5 shows that for PO$_4^{3-}$, the effluents from the three GR devices show a significant leaching effect relative to the simulated rainwater. The effluent of SR remains largely unchanged, indicating that roof scouring is not the cause of the increase in PO$_4^{3-}$ . Additionally, GR1 has a greater ability to inhibit leaching of PO$_4^{3-}$ than GR2 and GR3. During the experiment, the average EMC of PO$_4^{3-}$ was 0.1237 mg/L, presenting only 75% and 66% of the GR2 and GR3 values, respectively. This is because the unique artificial granular structure of GR1 has a greater ability to inhibit leaching of PO$_4^{3-}$ compared to the commercial substrate. This confirms the findings reported by Helena [41], who suggested that granular structures help to reduce the phosphorus load in soils. GR3 shows more PO$_4^{3-}$ leaching because of its thicker substrate layer. The EMC of PO$_4^{3-}$ in GR3 shows the same abnormal trend as that of NO$_3^-$ in 5a, which may be caused by the same reason.

4. Conclusions

This paper draws the following conclusions based on the comparison of the rainfall runoff retention and pollutant interception capacity of an artificial granular structure substrate layer modified to different thicknesses using kaolin as a binder, a commercial substrate layer, and a standard roof under different rainfall recurrence periods.

1. The commercial substrate layer containing 30% peat, 35% perlite, 35% ceramsite is superior to the kaolin artificial granular structure substrate layer in delaying the outflow time and runoff retention rate, even if the former is thinner than the latter.

2. The kaolin artificial granular structure substrate layer has some leaching control effect on NO$_3^-$ and PO$_4^{3-}$ in rainfall runoff and has no significant adsorption effect on NH$_4^+$. The reduction rate of cumulative NO$_3^-$ quality is 6.56%, and PO$_4^{3-}$ is 10.54%. In actual engineering applications and subsequent experimental studies, attention should be paid to soil erosion caused by the destruction of the granular structure of the substrate layer by intense rainfall.

3. Future relevant research should focus on the effect of the type and amount of addition of the substrate layer modifier on the stability of the granular structure on the interception effect of rainfall runoff. Additionally, we should also consider the contribution of the initial rainfall runoff pollution to
the total amount of pollutants in the entire rainfall process and carry out the transformation of the extensive GR substrate layer structure according to the initial rainfall interception effect.

**Author Contributions:** C.X. and Z.L. performed the experiments, collected rainfall-runoff data, result analysis and prepared the manuscript draft. J.Z. supervised data analysis and revised the manuscript. G.C. supervised the writing and data analysis. All authors made contributions to the study and the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

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