Experimental study on the selection of common adsorption substrates for extensive green roofs (EGRs)

Chen Xu, Zaohong Liu, Guanjun Cai and Jian Zhan

ABSTRACT

Adsorption substrate in the substrate layer of an extensive green roof (EGR) is one of the most important factors affecting rainwater retention and pollution interception capacity. However, the contact time between runoff and adsorption substrate is extremely short in actual rainfall, and adsorption substrate cannot show fully rainwater retention and pollution interception capacity. So, selection of adsorption substrate based on its physical properties and theoretical adsorption capacity is unreliable. In this study, eight commonly-used adsorption substrate experimental devices are constructed with the same configuration. The delayed outflow time and runoff reduction rate of each device, along with event measurement concentration (EMC), average EMC, and cumulative pollutant quantity of SS, ammonium (NH₄⁺), nitrate (NO₃⁻), total nitrogen (TN), and total phosphorus (TP) in each device outflow under nine simulated rainfall events are measured and evaluated. The results indicate that vermiculite has a significant interception effect on NH₄⁺ and TP with the advantages of low bulk density, high porosity, low cost, and a good rainfall runoff retention capacity under torrential rain and downpour events. In future practical engineering and related studies of EGR, attention should be paid to ameliorating the deficiencies of the adsorption substrates and optimizing their synergistic effects when combined with nutrient substrates.

Key words | adsorption, extensive green roof, retention and interception effect, substrate layer

HIGHLIGHTS

- Vermiculite is a viable adsorption substrate in practical engineering applications.
- Vermiculite has an effective NH₄⁺ and TP interception capacity.
- Green zeolite has a good NH₄⁺, NO₃⁻, and TN interception capacity.
- Ceramsite, lava rock, and quartz sand have significant rainfall runoff retention capacities.
- This study provides reliable supporting for EGR adsorption substrates selection.

INTRODUCTION

With the rapid development of urbanization in China, the hardening rate of roads and roofs is increasing, and the amount of permeable area is decreasing. In recent years, extreme rainstorms have been occurring more frequently, leading to rapidly increasing runoff because the rainwater is unable to infiltrate. As urban drainage capacity is limited, this results in frequent urban waterlogging. Concurrently, due to atmospheric deposition and the flushing of roofs and roads by rainwater runoff, a large number of pollutants have entered the water body, resulting in non-point-source pollution (Muhammad et al. 2018). Low impact development (LID) is a technical method for controlling the rainwater...
runoff and pollution problems caused by rainstorm at the source, and makes a certain contribution towards meeting the urgent need for mitigating the effects of such rainstorms upon urban waterlogging and non-point-source pollution. The green roof (GR) is one example of such LID measures. In practical application, along with its ability to retain rainwater and alleviate non-point-source pollution, the GR can also make optimum use of the available roof space, reduce the urban heat island effect via roof insulation, and optimize the energy budget of the building, thus improving the living environment therein (Abualfaraj et al. 2018; Besir & Cuce 2018; Vanstockem et al. 2018; Vijayaraghavan et al. 2018; Schindler et al. 2019; Zhang et al. 2019).

An extensive GR (EGR) is a kind of GR with the advantages of low roof load, easy maintenance, and low cost. It can be applied to most flat roof renovations in cities without the need for structural adjustment (Johannessen et al. 2018; Christine & Nigel 2019). The main body of the EGR is generally composed of discrete vegetation, substrate, filter, drainage, and waterproof layers that jointly affect its capacity to retain and intercept rainwater runoff (Santos & Castilho 2018; Ladani et al. 2019). The majority of relevant literature indicates that the structure of the substrate layer (especially the type of material) is one of the most important factors affecting the rainwater retention and pollution interception capacity of the EGR (Gong et al. 2018; Cascone et al. 2019). According to their function, the materials in the substrate layer can be divided into nutrient substrates and adsorption substrates (Wang et al. 2017). Nutrient substrates mainly provide nutrients for the upper vegetation layer in order to maintain growth, while the main role of adsorption substrates is the interception and retention of rainwater runoff. In Pęczkowski’s study, an EGR device with zeolite as the adsorption substrate is constructed, an average rainwater runoff retention rate of 60.6% was shown during the entire rainfall process, and at the same time, it showed an inhibitory effect on total nitrogen leaching (Pęczkowski et al. 2018). Sang found that EGRs composed of perlite, ceramicite, maifan stone and other adsorption substrates can control pollutants leaching to a certain extent while ensuring the effect of runoff retention (Sang et al. 2018). The rainwater retention and pollution interception capabilities of the adsorption substrate depend on its physical properties and, hence, differ from one substrate to another (Hill et al. 2019; Liu et al. 2019a, 2019b). Therefore, it is necessary to conduct separate studies on a range of adsorption substrates. The majority of researchers generally examine the adsorption properties of various substrates via the adsorption isotherm and adsorption kinetic models in order to determine their adsorption efficiencies under varying conditions of pH, pollutant concentration, and time (Nie et al. 2003; Wang et al. 2019). However, the contact time between runoff and adsorption substrate is extremely short in actual rainfall, and adsorption substrate cannot show fully rainwater retention and pollutant interception. At the same time, the concentration of pollutants and the PH in rainfall are ever changing, so it is unreliable to select adsorption substrates for an EGR substrate layer according to their physical properties and theoretical adsorption capacities. Therefore, it is necessary to study the rainwater retention and pollution interception capacity of a single adsorption substrate in actual rainfall. This can provide a reference basis for selection of EGR substrate layer adsorption substrates in actual engineering applications and experimental research.

By collecting and examining the conclusions of the most relevant literature on the types of adsorption substrate used in the EGR (Liu et al. 2019a, 2019b; Eksi et al. 2020), eight common adsorption substrates were selected for the present experimental study. These were separately used in identical configurations in the construction of eight small-scale experimental devices, and their retention and interception capabilities were examined under various simulated rainstorm events and continuous rainfall periods.

### MATERIALS AND METHODS

#### Device construction

In this study, eight small-scale devices consisting of commonly-used adsorption substrates were constructed in the laboratory of the School of Architecture and Engineering in Nanchang University, as shown schematically in Figure 1.

Each device consisted of an identical polyethylene terephthalate (PET) plastic bucket with a bottom diameter of 22.9 cm, a top diameter of 26 cm, and a height of 27 cm. A

![Figure 1](image-url)
water outlet with a diameter of 1 cm was opened on one side of each device at a height of 1 cm from the bottom and was fitted with a ball valve faucet and a suitable length of plastic hose to facilitate the collection of the outflow samples. Eight kinds of adsorption substrates with particle sizes of 3–6 mm were added into the experimental devices to the same volume of 5 L and substrate depth of 12 cm. To prevent the rainwater runoff from scouring the substrate with fine particles, which would increase the concentration of pollutants in the outflow and influence the experimental results, a non-woven geotextile was used to separate the adsorption substrate from the water outlet and the bottom of the experimental device. In addition, a hard drainage plate was set at the bottom of each device to ensure easy discharge of any rainfall runoff that could not be retained by the adsorption substrate.

The eight commonly-used GR adsorption substrates selected for the present study were perlite, vermiculite, green zeolite, Maifan stone, diatomite, lava rock, ceramsite, and quartz sand. The physical properties and cost of these adsorption substrates are given in Table 1. The volumetric weight, porosity and specific gravity of the eight adsorption substrates are measured by the ring knife method (Li & Zheng 2019) and the cost is calculated from the unit price of the adsorption substrates purchased by our testers.

Perlite is a vitreous rock with a pearl fissure structure formed by rapid cooling of an acid lava. It is a lightweight, multifunctional material that is widely used in soil amelioration and the adjustment of soil compaction. Vermiculite has a strong ion-exchange capacity, which assists with the regulation of soil nutrients. Green zeolite is an alumino-silicate mineral with typically strong water and fertility retention along with a high adsorption capacity for nitrogen in the form of ammonia. Maifan stone has a porous structure formed by weathering and alteration, thus providing good adsorption and pH neutralization capability in water. Diatomite is a biogenic siliceous sedimentary rock with the peculiar advantages of small bulk density, high porosity and good mixing uniformity. Lava rock is a dark-red porous filter material with nearly round particles. It is suitable for microorganisms to grow and multiply on its surface to form a biomembrane and is often used as a carrier in biological water treatment. Ceramsite is widely used in building materials and horticulture due to its unusually hard ceramic shell, water and gas retention capacities, and high strength. Quartz sand consists of particles of crushed quartz stone. It is a hard, wear-resistant, chemically stable silicate mineral and is the most widely-used industrial water purification material. The eight kinds of adsorption substrate devices are shown in Figure 2.

**Table 1 | Physical properties and cost of eight adsorption substrates**

<table>
<thead>
<tr>
<th>Adsorption substrate</th>
<th>Volumetric weight (g/cm³)</th>
<th>Porosity (%)</th>
<th>Specific gravity (g/cm³)</th>
<th>Cost (yuan/dm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perlite</td>
<td>0.083</td>
<td>78.3</td>
<td>0.382</td>
<td>0.133</td>
</tr>
<tr>
<td>Vermiculite</td>
<td>0.174</td>
<td>85.0</td>
<td>1.161</td>
<td>0.087</td>
</tr>
<tr>
<td>Green zeolite</td>
<td>1.076</td>
<td>49.6</td>
<td>2.133</td>
<td>0.538</td>
</tr>
<tr>
<td>Maifan stone</td>
<td>1.473</td>
<td>51.3</td>
<td>3.026</td>
<td>0.884</td>
</tr>
<tr>
<td>Diatomite</td>
<td>0.600</td>
<td>73.3</td>
<td>2.245</td>
<td>1.200</td>
</tr>
<tr>
<td>Lava rock</td>
<td>0.870</td>
<td>70.8</td>
<td>2.979</td>
<td>0.435</td>
</tr>
<tr>
<td>Ceramsite</td>
<td>0.400</td>
<td>64.7</td>
<td>1.130</td>
<td>0.120</td>
</tr>
<tr>
<td>Quartz sand</td>
<td>1.488</td>
<td>49.5</td>
<td>2.950</td>
<td>0.342</td>
</tr>
</tbody>
</table>

Simulated rainfall design

In this study, the simulated rainfall depth and rainwater quality were selected based on the local rainfall characteristics of Nanchang city. The daily rainfall depth data for Nanchang City over a recent five-year period were collected and used to classify the daily rainfall grade according to the Grade of Precipitation, GB/T 28592-2012. This classifies depths of 0.0–9.9 mm as light rain, 10.0–24.9 mm as moderate rain, 25.0–49.9 mm as heavy rain, 50.0–99.9 mm as torrential rain, and over 100 mm as downpour. The annual and total rainfall frequencies of each grade in Nanchang during the five-year period are shown in Figure 3.

Thus, most of the rainfall in the five-year period was light or moderate, which accounted for 86.00–88.57% of the total rainfall frequency. However, some researchers have indicated that an EGR can achieve a retention rate of 75.0–99.6% during light rain and moderate rain, and that continuous rainfall events will not affect this retention performance (Gong et al. 2018; Todorov et al. 2018). It is suggested that more attention should be paid to the retention capacity of the GR substrate layer during large rainfall events. Therefore, to study the effect of the various adsorption substrates on the retention and interception of rainwater under large rainfall events, six heavy rains, two torrential rains, and one downpour were simulated in the present study based on the proportions of these three rainfall grades over the five-year period. The measured daily rainfall depths over the selected period were arranged in ascending order, and the depths of seven simulated rainfalls were selected according to the quantile and rainfall grades. In detail, the six heavy rains were 25.5 mm, 27.3 mm, 30.8 mm, 52.2 mm, 36.7 mm, and 43.3 mm, the two torrential rains were 68.8 mm and...
89.5 mm, and the one downpour was 128 mm. The simulated rainfall events in this study are rectangular distributions. According to the Nanchang short-duration and high-intensity rainfall characteristics, the antecedent dry period (ADP) of the devices was set to two days, and the simulated rainfall duration was 1 hour. In addition, the average concentration of pollutants in the 10 actual rainfall events from May to July was calculated in order to select a realistic simulated rainfall water quality and to facilitate the analysis and comparison of the experimental results, as indicated in Table 2.

The simulated rainfall water was then prepared by adding the corresponding ionic standard solutions in deionized water. Thus, ammonium ion (NH$_4^+$) was prepared by adding an ammonium chloride (NH$_4$Cl) standard solution containing 1 mg/ml of nitrogen in the form of ammonia; the nitrate (NO$_3^-$) was prepared by adding potassium nitrate (KNO$_3$) standard solution (containing 0.1 mg/ml of nitrogen in the form of nitrate), the total phosphorus (TP) was prepared by adding monopotassium phosphate (KH$_2$PO$_4$) standard solution (containing 50 μg/ml phosphorus). The pre-prepared simulated rainfall water was then stored in a 160 L plastic water storage tank.

In the experiment, a peristaltic pump was used to evenly drop the pre-prepared simulated rainfall water onto the receiving surface of each device. To avoid the interference of any extraneous factors, it was ensured that the ADP and climatic environment of each device was the same at the start of each simulated rainfall experiment. The peristaltic pump squeezes the hose as the latter passes through the head rotor, thus generating a negative pressure that causes the water to flow into the hose. Once the hose is full of pressurized water, this is sprayed uniformly through the 0.6-m diameter atomizing nozzle in order to simulate actual rainfall and, thus, provide reliable experimental data. Four peristaltic pumps were used in the rainfall simulation experiment, including three SIGNAL BS100-1A peristaltic pumps with a flow range of 0.008–460 ml/min, and one LEADFLUID BT100S peristaltic pump with a flow range of 0.008–460 ml/min.
0.006–420 ml/min. All the peristaltic pumps used a YZ15 rotor head with a suitably-sized 25# (4.8 × 8 mm) transparent silicone hose. The transparent silicone hose was connected to the atomizing nozzle via a suitable length of 9/12 PVC rubber tubular billet. The experimental platform and the atomizing nozzle are shown schematically in Figure 4.

Sample collection and measurement

Under the premise of ensuring the same dry period, the delayed outflow times, outflow volumes, and rainfall retention rates were recorded and calculated for each of the devices. In addition, the concentrations of SS, NH₄⁺, NO₃⁻, TN and TP in the outflow samples were measured at predetermined time intervals, and the EMC, the average EMC, and the cumulative quantity of each pollutant in each device outflow were calculated according to the relevant formulas to evaluate the ability of each adsorption substrate to intercept rainfall runoff. From the start of outflow, the volumes in the collection bottle were measured and recorded at 5 min, 10 min, and every subsequent 10-min interval up to 90 min of simulated rainfall. At each measurement time, outflow samples were taken and stored in sample bottles in a refrigerator at 4 °C, and the concentrations of SS, NH₄⁺, NO₃⁻, TN, and TP were measured and recorded within 24 h.

The experimental data were processed and analyzed using IBM SPSS Statistics 25.0, Microsoft Excel 2010, and Origin Pro 2018. Due to the uneven variation in the data, the Games-Howell test was used in the one-way analysis of variance to determine the statistical significance of the volume and concentration of pollutants in the various outflow samples. The results indicated that at all data were in accordance with the normal distribution at the level of α = 0.05.

Evaluation methods

In this study, the retention capacity of the eight adsorption substrates is evaluated based on the delayed outflow time (DOT) and runoff reduction rate (RRR) of the eight adsorption substrate devices under seven different rainfall depths. The difference start time between the device outflow and the simulated rainfall is the DOT. The runoff reduction rate can be calculated by the following formula:

\[
\text{RRR} = \frac{D \times S - V}{D \times S} \times 100\% \tag{1}
\]

where RRR is the runoff reduction rate (%), D is the depth of the simulated rainfall (mm), S is the device receiving surface area (m²), and V is the volume of the device outflow (L).

In this study, the interception capacity of the eight adsorption substrates is evaluated based on the event measurement concentration (EMC) and the cumulative pollutant quantity (CPQ) of each pollutant in the outflow of eight adsorption substrate devices under nine different rainfall depths, and the average EMC during the entire simulated rainfall process. The EMC of each pollutant can be calculated by the following formula:

\[
\text{EMC} = \frac{\int_{0}^{T} C(t)Q(t)dt}{\int_{0}^{T} Q(t)dt} \approx \sum_{i=1}^{n} \frac{C_i V_i}{\sum_{i=1}^{n} V_i} \tag{2}
\]

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

\[
\text{CPQ} = \int_{0}^{T} C(t)Q(t)dt \approx \sum_{i=1}^{n} C_i V_i \tag{3}
\]

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

\[
\text{Average EMC} = \frac{\sum_{j=1}^{m} \int_{0}^{T} C_j(t)Q(t)dt}{\sum_{j=1}^{m} \int_{0}^{T} Q(t)dt} \approx \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} C_j V_i}{\sum_{j=1}^{m} \sum_{i=1}^{n} V_i} \tag{4}
\]

where EMC is the event mean concentration (mg/L); CPQ is the cumulative pollutant quantity (mg); C(t) is the pollutant concentration distribution in a rainfall runoff with time t (mg/L); Q(t) is the device outflow volume with time t (m³/s); T is the total rainfall duration (s); n is the number of rainfall time segments; m is the number of rainfall events. C_i is the concentration of a given pollutant in a device outflow sample collected during the i-th segment time of a rainfall (mg/L), and V_i is the device outflow volume in the i-th segment of a rainfall (m³).
RESULTS AND DISCUSSION

Rainfall runoff retention capacity

The obtained outflow curves for the eight experimental devices under simulated rainfall of nine different depths are presented in Figure 5.

Here, the delayed outflow times and the corresponding outflow volumes of the experimental devices are seen to gradually decrease with increasing rainfall time. All eight devices generate outflow at the simulated rainfall depth of 30.8 mm, with the ceramsite device showing the maximum delayed outflow time of 47 min, and the green zeolite device showing the minimum delayed outflow time of 28.5 min. At a rainfall depth of 128.05 mm, however, the delayed outflow time of the green zeolite device is only 9.33 min, while the ceramsite device gives the maximum delay of only 10.92 min. This is because the volume of rainwater increases with increasing rainfall depth, such that the water-retention capacity of the substrate quickly reaches saturation. At the same time, due to the constant rainfall duration, the rainfall intensity and rainwater seepage rate both increase, thus leading to a reduction in the delayed outflow time. Further, the ceramsite device displays no outflow under the simulated rainfall depths of 25.5 mm and 27.3 mm, and exhibits a better ability to delay outflow than the other substrates at rainfall depths other than 68.8 mm and 89.5 mm. By comparison, the lava rock device generates
Figure 5  |  Continued.
no outflow under a simulated rainfall depth of 25.5 mm, and delayed outflow times of 50.08, 22.00, and 15.92 min at rainfall depths of 27.3, 68.8 mm, and 89.5 mm, respectively. Thus, overall, the lava rock outperforms the ceramsite to display the best ability to delay outflow under the widest range of rainfall depths. Moreover, both ceramsite and volcanic rock have stronger abilities to delay outflow than the other investigated substrates at various rainfall depths and throughout the entire simulated rainfall process due to their unique physical properties. Averaged over the entire simulated rainfall experiment, the delayed outflow times of the perlite, green zeolite, maifan stone, and diatomite devices are 27.22, 24.90, 24.72, and 27.01 min, respectively, which are all lower than the delayed outflow time averaged over all the experimental devices (including ceramsite and lava rock); that is, 28.11 min.

In addition, the results in Figure 5 indicate that the outflow volume of each device increases and the corresponding rainfall runoff retention rate gradually decreases with increasing rainfall depth. For a given input volume of water, the retention capacity of each substrate is determined by its physical properties and is, therefore, expected to be largely unaffected by changes in rainfall volume. However, because the dry period between two successive simulated rainfall events is short, the previous heavy rainfall will affect the rainfall retention capacity of each device in the next rainfall event. Therefore, as the receiving area of each device remains invariant, and the rainfall runoff increases with increasing rainfall depth, the rainfall runoff retention rate of each device will continuously decrease. In detail, the runoff retention rates of the various devices are seen to range from 33.86 to 77.24% during the four heavy rain events, from 19.41 to 39.97% during the two torrential rain events, and from 9.36 to 16.72% during the single downpour event. This demonstrates that the runoff retention rate of each substrate layer is more strongly affected by the actual rainfall depth than by the different physical properties of the various substrates or by the different rainfall retention capacities. Moreover, the ceramsite and lava rock devices exhibit no outflow at a rainfall depth of 25.5 mm, and the ceramsite device continues to produce no runoff at 27.3 mm. Thus, under these conditions, the rainfall runoff volumes do not exceed the runoff retention capacity of the ceramsite and lava rock devices and, hence, the runoff retention rates are 100%. In the heavy rain events, the green zeolite device exhibits a good runoff retention capacity that is higher than the average runoff retention capacity of all other devices for the same rainfall event. However, the runoff retention rate of this device is seen to decrease rapidly during torrential rain and downpour events. This may be due to the low porosity of green zeolite and the inability to rapidly reduce the moisture content of the substrate layer after the continuous heavy rainfall event. By contrast, the vermiculite device displays the opposite performance, with a better runoff retention capacity in torrential rain and downpour events compared with the average runoff retention capacity over all devices for the same rainfall event. The perlite device shows the worst runoff retention effect during the entire simulated rainfall process, with an average runoff retention capacity of 29.29% compared to 47.15% for the ceramsite device. In addition, the average runoff retention capacities of vermiculite (51.65%), green zeolite (31.73%), Maifan stone (29.62%), and diatomite (30.83%) during the entire simulated rainfall process are also lower than the runoff retention capacity averaged over all devices.

Throughout the simulated rainfall experiment, there is a significant correlation between the delayed outflow time and the runoff retention capacity of each device under the various rainfall depths. This is because the actual retention capacity of the substrate layer is influenced by the physical properties of the substrate, the intervening dry period between rainfall events, and rainfall depth, so that both the delayed outflow time and runoff retention capacity are affected by these factors. Therefore, a device with a strong ability to delay outflow also shows a higher runoff retention rate, and vice versa. Thus, the outflow curves of the eight experimental devices under nine different depths of simulated rainfall allow an evaluation of the retention capacity of each device according to the delayed outflow time and runoff retention rate. The results demonstrate that ceramsite, lava rock, and quartz sand have stronger retention capacities for use as EGF substrate layer materials. Consequently, these three materials are considered to be more suitable for use in future studies on EGR substrate layer structure. In particular, ceramsite has a low bulk density and cost, but a high runoff retention capacity. It can be flexibly configured in practical engineering applications and is a high-quality substrate layer material.

Rainfall runoff interception capacity

The EMC, average EMC, and CPQ of each pollutant in the eight experimental devices are indicated in Figures 6–10. The EMC of the SS in the eight experimental device outflows under nine different rainfall depths, along with the corresponding average EMC and CPQ over the entire experimental process, are presented in Figure 6.
Here, each device exhibits its own distinct trend in the EMC of SS in its outflow for the various rainfall depths. For example, the SS EMC in the Maifan stone outflow generally increases with increasing rainfall depths (except for the 27.3-to-30.8-mm depth increase). This is because the Maifan stone has abundant fine sand particles that are easily washed away as the intensity of runoff flushing increases with increased rainfall depth. By comparison, the outflows of other devices, such as the lava rock, green zeolite, vermiculite, and perlite devices, show more erratic trends in which the SS EMC initially increases, then becomes relatively stable, and then decreases. However, the SS EMC in the outflows of the diatomite, ceramsite, and quartz sand devices is seen to increase significantly during the first simulated rainfall experiment, but remains low and stable during the subsequent simulated rainfall experiments. This may be because these materials have fewer fine particles, so that the SS concentration in the outflow is only notably affected by the first flush. Nevertheless, the average SS EMC in the outflow of each experimental device over the entire experiment is higher than the concentration of SS in the simulated rainfall water, with the Maifan device giving the worst performance, and the ceramsite device the best. This is because the adsorption substrates contain different amounts of particulate impurities, the removal of SS into the device outflows primarily depends on the geotextile, and the SS interception capacities of the adsorption substrates are weak. Therefore, the concentration of SS in the device outflows increases under the strong rainfall runoff flushing. The Maifan stone device maintains a higher outflow SS EMC than the other substrates and has a weaker rainfall runoff retention capacity.

Hence, this device exhibits significant SS leaching throughout the experiment. In addition, the average SS EMC in the outflow of the green zeolite device is found to be lower than that of the lava rock device. Moreover, the SS CPQ in the outflow of the green zeolite device during the first seven simulated rainfall experiments is higher than that of the lava rock device. This is because lava rock has a stronger rainfall runoff retention capacity than green zeolite. Similarly, the ceramsite and quartz sand have significant abilities to control the leaching of SS and significant rainfall runoff retention capacities; hence, the SS CPQ in the outflows of both of these devices is lower than that in the other devices.

The EMC of NH\textsubscript{4}\textsuperscript{+} in the outflows of the eight experimental devices under the nine different rainfall depths, along with the corresponding average EMC and CPQ values over the entire experimental process, are presented in Figure 7. Here, the NH\textsubscript{4}\textsuperscript{+} EMC in the outflows of most of the devices exhibit small-range fluctuations under heavy rain events, and relatively higher values under torrential rain and downpour events. This is because the decrease in the amount of NH\textsubscript{4}\textsuperscript{+} in the rainfall runoff primarily depends on its adsorption by the substrates. Thus, as the rainfall runoff seepage velocity increases with increasing rainfall intensity, the contact time between the rainfall runoff and the substrate decreases and, hence, the substrates’ adsorption efficiency for NH\textsubscript{4}\textsuperscript{+} decreases, thus increasing the NH\textsubscript{4}\textsuperscript{+} EMC in the device outflow. The Maifan stone, perlite, and quartz sand devices perform particularly well in this respect, with only minor NH\textsubscript{4}\textsuperscript{+} EMC reduction rates of 3.20, 19.13, and 3.20\% at rainfall depths of 129 mm. However, the outflow of the vermiculite device maintains a low

![Figure 6](image-url)
NH$_4^+$ EMC under all nine rainfall events, with a maximum NH$_4^+$ concentration of 0.36 mg/L at 89.5 mm (a reduction rate of 76.0%), and a minimum NH$_4^+$ concentration of 0.139 mg/L at 43.3 mm (a reduction rate of 90.73%). This is because vermiculite has a strong adsorption efficiency and a large adsorption capacity for NH$_4^+$ due to its unique physical properties and excellent ion-exchange capacity. The average NH$_4^+$ EMC in the device outflows of each experimental device over the entire experiment is lower than the NH$_4^+$ concentration in the simulated rainfall water, and every substrate exhibits a reduction in the concentration of NH$_4^+$ in the rainfall runoff. The worst-performing substrate was the ceramsite, with an average NH$_4^+$ EMC reduction rate of 16.7%, while the vermiculite device gave the best performance with an 80.6% reduction. This is because all eight adsorption substrates are silicate minerals which, in addition to the essential components of silicon and oxygen, also contain positively charged cations such as Mg$^{2+}$, Ca$^{2+}$, and Al$^{3+}$. In contact with the rainfall runoff, these metal cations exchange with the NH$_4^+$ and, thus, reduce the concentration of NH$_4^+$ in the rainfall runoff. In particular, ceramsite consists of elliptical particles generated by the high-temperature calcination of clay. Although this gives it a porous structure and a strong rainfall runoff retention capacity, its weak adsorption capacity for NH$_4^+$ prevents this material from intercepting a significant amount of NH$_4^+$ in the rainfall runoff. By contrast, the strong ion-exchange capacity of green zeolite makes it an excellent EGR adsorption substrate for removing NH$_4^+$ from the rainfall runoff. The average NH$_4^+$ EMC reduction rate in the outflow of this device over the entire experimental process is 62.1%. In addition, although the average NH$_4^+$ EMC in the outflows of the quartz sand and ceramsite devices is higher than that of the Maifan stone device, the NH$_4^+$ CPQ of values are lower. This is due to the excellent rainfall runoff retention capacity of the quartz sand and ceramsite. The EMC of the NO$_3^-$ in the outflows of the eight experimental devices under the nine different rainfall depths, along with the corresponding average EMC and CPQ values over the entire experimental process, are presented in Figure 8. Here, the NO$_3^-$ EMC in the outflows of each device (except for the vermiculite device) exhibit an initial increase followed by a decrease with increasing rainfall depth and over successive rainfall experiments. The latter outcome may be because the rainfall runoff in the initial simulated rainfall experiment flushes and leaches the substrates, thus affecting the results of subsequent rainfall events. Moreover, the rainfall runoff seepage velocity is lower during the heavy rain events than during the torrential rain and downpour, thus resulting in longer contact time between the rainfall runoff and the substrate. This intensifies the NO$_3^-$ leaching effect and increases the concentration of NO$_3^-$ in the outflow. In particular, the NO$_3^-$ EMC in the outflow of the vermiculite device shows a significant increase during the simulated torrential rain and downpour events. This may be due to the use of a single layer of vermiculite as the substrate, such that the vermiculite particles are destroyed by the larger-intensity runoff. The perlite device exhibits the highest NO$_3^-$ EMC of 5.17 mg/L at a rainfall depth of 30.8 mm, with an increase of 86.47%. Meanwhile, the Maifan stone device gives the lowest outflow NO$_3^-$ EMC value of 1.285 mg/L at a rainfall depth of 128.05 mm, with a reduction rate of 24.41%. The average NO$_3^-$ EMC in the outflow of each device over the entire
The experiment is higher than the NO$_3^-$ concentration in the simulated rainfall water, with every substrate leaching NO$_3^-$ into the rainfall runoff. This indicates that none of the eight materials that are commonly used as absorption substrates in EGRs can effectively reduce the NO$_3^-$ concentration in rainfall runoff. The worst performer in this respect is the vermiculite device, with an average increase of 52.06% in the NO$_3^-$ EMC. By contrast, the outflows of the Maifan stone device gives an average NO$_3^-$ EMC only 0.002 mg/L higher than that of the simulated rainfall water, with almost no pollution effect. Meanwhile, the outflows of the vermiculite and perlite devices show a slight leaching effect of NO$_3^-$ throughout the experiment due to the high average NO$_3^-$ EMC and weak rainfall runoff retention capacities of these materials. The NO$_3^-$ CPQ in the outflow of the vermiculite device is 39.94 mg, with a leaching rate of 3.96%, while that of the perlite device is 38.55 mg, which is almost the same as the simulated rainfall water. The NO$_3^-$ CPQ in the outflows of the other devices over the entire experiment is lower than that of the simulated rainfall water, and the experimental results are relatively similar from one device to another. This shows that although the substrates cannot effectively reduce the concentration of NO$_3^-$ in the device outflows, they nevertheless exhibit a good NO$_3^-$ interception effect due to their excellent rainfall runoff retention capacities.
The EMC of the total nitrogen (TN) in the outflows of the eight experimental devices under the nine different rainfall depths, along with the corresponding average values over the entire experimental process, are presented in Figure 9. Here, as in the case of NO$_3^-$, most of the devices exhibit trends of initially increasing and subsequently decreasing TN EMCs with increasing rainfall depth and with subsequent rainfall experiments. This is because the TN includes NH$_4^+$, NO$_3^-$, NO$_2^-$, and organic nitrogen, with NH$_4^+$ and NO$_3^-$ being the main components in rainfall runoff. In the present study, the effects of the substrates are to decrease the EMC of NH$_4^+$ but increase the EMC of NO$_3^-$ in the rainfall runoff. Thus, the concentration of NO$_3^-$ accounts for a larger proportion of the TN and, hence, the TN EMC in the outflow of each device will display a similar trend with varying rainfall depth. In detail, with the exception of the 89.5 mm rainfall event, the TN EMC in the outflow of the ceramsite device is significantly worse than that of the other devices. Further, the outflow of this device exhibits a TN EMC of 5.134 mg/L for the 32.2 mm event, which is 55.58% higher than that in the simulated rainfall water. This is because the ceramsite does not effectively decrease the concentrations of NH$_4^+$ and NO$_3^-$ in the rainfall runoff, thus leading to a high TN concentration in the device outflow. A consideration of the average TN EMC in the outflow of each experimental device over the entire experiment reveals that each device exhibits its own distinct interception effect on the TN in the rainwater runoff. In particular, the vermiculite, green zeolite, Maifan stone, and diatomite all decrease the TN concentration in the rainfall runoff, with reduction rates of 0.003, 10.91, 7.42, and 4.24%, respectively. By contrast, the perlite, lava rock, ceramsite, and quartz sand each increase the levels of TN in the rainfall runoff, with pollution rates of 9.97, 3.03, 31.9, and 8.52%, respectively. However, the green zeolite device exhibits a lower average TN EMC in its outflow compared to the other devices due to its excellent adsorption of NH$_4^+$ and NO$_3^-$. This demonstrates that the use of green zeolite as an EGR substrate layer can have a significant interception effect upon nitrogen in rainfall runoff. Meanwhile, due to its weak rainfall runoff retention capacity, the perlite device does not display the highest concentrating effect upon TN, although the device does exhibit the highest TN CPQ. Nevertheless, the CPQ of TN in the outflow of the perlite device is lower than that of the simulated rainfall water, giving a TN CPQ reduction of 22.2%. Finally, even though the EMC of TN in the outflow of the lava rock device is also higher than that of the simulated rainfall water, this substrate shows the best TN interception capacity due to its excellent rainfall runoff retention capacity, with an interception rate of 41.2%.

The total phosphorus (TP) EMC in the outflows of the eight experimental devices under the nine different rainfall depths, along with the corresponding average EMC and CPQ values over the entire experimental process, are presented in Figure 10. Here, the TP EMCs are seen to vary with increasing rainfall depth, although the change value is almost negligible. Since the TP EMC is predominantly determined by the quantity of phosphorus pollutants that can be leached from the rainwater by the substrates, this lack of any obvious discrepancy among the devices suggests that each substrate has only a weak adsorption capacity for phosphorus compounds. The results also indicate that the diatomite device exhibits the highest outflow TP EMC of
all the devices under all rainfall conditions, along with the highest average TP EMC over the entire experimental process. This may be because the diatomite contains a significant level of phosphorus pollutants that can be leached out, or has a weak interception capacity for TP, or both factors play a contributing role. With the exception of the diatomite device, the average TP EMC in the outflow of each device over the entire experiment is similar to that of the simulated rainfall water. This is probably due to the low content of TP in the rainfall runoff, and to the fact that most of it is in the form of soluble orthophosphate, which usually requires specialized treatment for effective removal. Hence, the concentration of TP in rainfall runoff is difficult to reduce effectively by only short-term contact with the various substrates. Among the eight devices, the vermiculite device exhibits the lowest average TP EMC in its outflow, with a reduction rate of 25%. The Maifan stone and perlite devices only show a slight TP reduction effect, with reduction rates of 4 and 3%, respectively. Regarding the CPQ of TP in each device outflow, all of the devices except for diatomite exhibit an interception effect on TP, with that of the vermiculite and ceramsite devices being significant. This is due to the strong ability of vermiculite to reduce the concentration of TP in the rainfall runoff, and to the excellent rainfall runoff retention capacity of ceramsite.

In general, the different physical properties and pollutant removal characteristics of the eight commonly-used EGR adsorption substrates result in different interception capacities for SS, NH₄⁺, NO₃⁻, TN, and TP in rainfall runoff. In particular, vermiculite has a very good ability to intercept NH₄⁺ and TP in rainfall runoff, but its ability to intercept NO₃⁻ is weaker than that of other substrates. Maifan stone and diatomite have good interception capacity for NO₃⁻, but the leaching of SS in the Maifan stone outflow is particularly serious and its NH₄⁺ adsorption capacity is weak. The diatomite device outflow exhibits a large amount of TP leaching, but the green zeolite has a good interception capacity for NH₄⁺, NO₃⁻, and TN in rainfall runoff.

(i) Vermiculite has an excellent retention capacity for NH₄⁺ and total phosphorus (TP) in rainfall runoff, and has the advantages of low bulk density, high porosity, and low cost. This makes vermiculite a suitable choice of substrate in practical engineering applications. In addition, vermiculite exhibits a better rainwater runoff retention capacity under torrential rain and downpour events, but its ability to intercept NO₃⁻ in rainfall runoff is weaker than that of other substrates. Therefore, in future research, the modification of vermiculite should be considered in order to enhance its ability to intercept NO₃⁻.

(ii) Green zeolite has a good interception capacity for NH₄⁺, NO₃⁻, and total nitrogen (TN) in rainfall runoff. However, the bulk density of green zeolite is relatively high, so the thickness of the substrate layer should be considered during application as an EGR substrate in order to meet the roof load requirements.

(iii) Ceramsite, lava rock, and quartz sand have significant rainfall runoff retention capacities and significantly delay the rainwater outflow. In addition, ceramsite and quartz sand show good interception capacity for SS as a pollutant. The lava rock has a good interception capacity for NH₄⁺, but has weak interception capacities for SS, NO₃⁻, TN and TP.

Hence, the present study provides reliable supporting and reference data for the selection of EGR adsorption substrates, both for subsequent related research and for practical engineering application. However, the improvements of the various deficiencies in these adsorption substrates, and the effects of their combination with nutrient substrates in the substrate layer, require further exploration to assist in the sustainable development of the GR. For example, thermal modification, metal modification and other material modification methods and the addition of amendments to promote the construction of the soil granular structure to achieve the purpose of inhibiting the pollutants leaching should be paid attention.

CONCLUSIONS

This present work compared the rainfall runoff retention and pollutant interception capacities of eight commonly-used extensive green roof (EGR) adsorption substrates under nine different simulated rainfall depths to draw the following conclusions:

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DATA AVAILABILITY STATEMENT

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

REFERENCES


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