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Runoff quality and quantity after usage of layered or mixed substrate green roofs: a laboratory study

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ABSTRACT

Usage of green roofs is a major technique for urban stormwater management. In this study, layered and mixed substrate green roof platforms, using perlite or vermiculite as adsorption substrates, were established to investigate rainwater retention and pollutant leaching. The platforms were subjected to 12 simulated rainfall events. The average rainwater retention of layered substrate with perlite (30.95% ± 17.20%) was significantly higher than mixed substrate with perlite (21.66% ± 12.91%). However, there was no significant difference in rainwater retention between layered and mixed substrates with vermiculite ($p > 0.05$). The layered substrate effectively controlled total phosphorus (TP), phosphate (PO_4^{3-}–P) and ammonia (NH_4^+–N) leaching and layered substrate with perlite also exhibited better chemical oxygen demand (COD), total nitrogen (TN) and nitrate (NO_3^-–N) leaching control than the mixed substrate with perlite. The cumulative leaching masses of layered substrate with perlite were lower (COD: 44.77%, TN: 19.60%, TP: 45.51%, NH_4^+–N: 20.27%, NO_3–N: 21.47%) than mixed substrate; the TP and NH_4^+–N cumulative leaching masses of layered substrate with vermiculite decreased by 51.49% and 25.34% compared with mixed substrate. Moreover, layered and mixed substrates with vermiculite showed better TP, NH_4^+–N and PO_4^{3-}–P leaching control than perlite. The layered substrate improved pollutant leaching overall, but the selection of adsorption substrate plays an important role in the leaching control of green roofs.

Keywords: Extensive green roof; Layered substrate; Mixed substrate; Rainwater retention; Pollutant leaching

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1. Introduction

Rapid urbanization leads to a series of environmental problems, such as urban runoff pollution and flooding [1,2]. Urban stormwater management provides an effective way to mitigate these problems and green roofs are a major technical practice for urban stormwater management [3,4]. Green roofs provide additional ecological and economic benefits, including energy conservation, noise reduction, mitigation of the urban heat island effect and increased roofing membrane longevity, as well as providing a more esthetically pleasing environment [5–7]. They are usually classified into three categories: extensive, semi-intensive and intensive. The extensive green roof is the most common and has greater potential for application as it has a simple structure and is easy to implement [8–10].

Previous research has indicated that green roofs effectively capture rainwater by reducing peak runoff and runoff volume [10,11]. The rainwater retention capacity of

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green roofs depends on several factors, such as rainfall characteristics, substrate type and composition, substrate depth, vegetation cover and the age of the green roof [10]. Substrate type, depth and composition are commonly considered the main influencing factors [12,13]. The rainwater retention capacity of a green roof is significantly improved with increasing substrate depth [14]. Both intra-particle and inter-particle pore space distribution, determined by particle size, are important factors for water-holding capacity and rainwater retention [11]. Biochar and other porous materials, such as perlite and vermiculite, have been investigated as green roof substrates and can significantly improve rainwater retention [15,16].

While green roofs can control rainwater runoff, their impact on the quality of infiltrating water can be either positive or negative [17–20]. A green roof controls runoff pollution through soil interception, plant absorption and microbial utilization [9,15]. Two different types of green roofs in Japan and Sweden showed that extensive and intensive green roofs are sinks for nitrate (NO_3^-–N) and ammonia nitrogen (NH_4^+–N) [9] and a subsequent study confirmed that a green roof can control NO_3^-–N [21]. However, green roofs can also act as a source of pollutants from soil erosion, substrate release, fertilization and bio-corruption that decrease runoff quality [22–24]. Based on an investigation of four full-scale green roofs in southern Sweden, the green roofs acted as a source of metals, total phosphorus (TP) and phosphate (PO_4^{3-}–P) [25]. Moreover, a large number of monitoring results showed that runoff quality from green roofs exhibited different degrees of deterioration [24,26,27].

In recent years, control of pollutant leaching has still been the main application of a green roof [28]. To decrease the leaching of nutrients, Beck et al. [15] showed that the addition of 7% biochar to green roof soil increased water retention and significantly decreased the discharge of total nitrogen (TN), TP, NO_3^-–N, PO_4^{3-}–P and organic carbon. River sediment can be used as a substrate additive in green roofs to control leaching for chemical oxygen demand (COD), TN and TP [20]. Vijayaraghavan and Joshi [29] incorporated a brown seaweed (*Turbinaria conoides*) in the growth substrate to enhance sorption capacity of various metal ions and water retention. Gong et al. [30] and Wang et al. [31] introduced a new type of green roof, called a dual-substrate layer green roof, and it used a commercial controlled-release fertilizer or local grass charcoal soil as the nutrient substrate and a perlite and vermiculite mixture (1:1) as the adsorption substrate. Wang et al. [31] found that the dual-substrate layer green roofs behaved as a sink for TN, NH_4^+–N and COD, and acted as a source of contaminants for TP. In a subsequent study, dual-substrate layer green roofs, which used mixtures of activated charcoal with perlite and vermiculite as the adsorption substrate, showed better rainfall retention (65.9% and 55.4%, respectively) than a single-substrate layer green roof (52.5%). These green roofs appeared to be sinks for organics, heavy metals and all forms of nitrogen in all cases [32,33].

Given the specific local conditions and the randomness of rainfall events in these previous studies, it is unclear whether the layered substrate green roof results are applicable to other localities with different rainfall conditions. It is also unclear whether there would be significant differences in rainwater retention and nutrient leaching control between layered substrate and mixed substrate green roofs. In this laboratory study, layered substrate (dual-substrate layer) and mixed substrate (single-substrate layer) extensive green roof platforms were established to assess the performance of extensive green roofs. The study objectives were: (1) to evaluate the difference in rainwater retention between layered and mixed substrate green roofs; (2) to compare the nutrient leaching control between layered and mixed substrate green roofs; (3) to verify the results about dual-substrate layer green roofs regarding their applicability to other localities with different rainfall characteristics.

2. Materials and methods

2.1. Green roof platforms

Five laboratory-scale green roof platforms (external dimensions: 27 cm wide × 37 cm long × 28 cm high) were established in the greenhouse of the stormwater laboratory building at the Beijing University of Civil Engineering and Architecture, China (Fig. 1a). This set-up provided proper sunlight and avoided interference from natural rainfall during the experiment.

The green roof platforms had a longitudinal slope of 5% and the lower end of the platform was fitted with an outflow pipe (DN 25 mm). Each of the mixed substrate green roofs consisted of the following layers: concave-convex plastic drainage plate (25 mm), geotextile filter preventing the loss of substrate particles, mixed substrate (150 mm) and vegetation on the top (Fig. 1b). Each of the layered substrate green roofs consisted of the following layers: concave-convex plastic drainage plate (25 mm), geotextile filter preventing the loss of substrate particles, adsorption substrate (45 mm), nutrition substrate (105 mm) and vegetation on the top (Fig. 1c). A geotextile material was used between the nutrition and adsorption layers to separate them. *Sedum lineare Thunb.* was selected as the vegetation because it is commonly used in green roofs in northern China and planted with a density of 240 strains/m^2.

The green roof substrates, including local soil, peat soil, perlite and vermiculite, were selected according to green roof standards (DB11/T 281-2015) in Beijing [34]. Perlite and vermiculite were selected as lightweight inorganic materials to reduce the effective load per unit area of the green roof; they also have good adsorption capacities for several contaminants. The compositions of the green roof substrates are shown in Table 1.

Platform LS was filled with only local soil and platforms MV, MP, LV and LP were filled with various substrate combinations to evaluate differences in pollutant leaching control (Table 1). Seven kinds of substrates or combinations were tested for organic matter content via oxidation with dichromate in a strong sulfuric acid medium, particle density, available phosphorous via the Olsen ($NaHCO_3$) method and alkali solution N via an alkaline hydrolysis-diffusion method (Table 2) [35–37].

2.2. Simulated rainfall

Tap water has been used to simulate rain events in similar studies [38,39]. Thus, local tap water was used to simulate rainwater here. The tap water characteristics were: pH: 7.30 ± 0.02, COD: 5.00 ± 0.82 mg/L, TP: 0.01 ± 0.00 mg/L, TN: 9.32 ± 0.95 mg/L, NH_4^+–N: 0.03 ± 0.01 mg/L, NO_3^-–N: 6.84 ± 0.04 mg/L, PO_4^{3-}–P: 0.01 ± 0.00 mg/L.

The rainfall simulations used peristaltic pumps to control the rainfall intensity and the water was sprayed onto the platform surface to simulate rainfall. The rainfall amount in an event was 50 mm, basically equivalent to the rainfall depth for 1-year return period in Beijing. The average rainfall rate was 12.5 mm/h with 4 h duration for each simulation. The antecedent dry period was 7 d and the experiment lasted 3 months (12 rainfall events with total rainfall of approximately 600 mm) according to rainfall characteristics in Beijing [39].

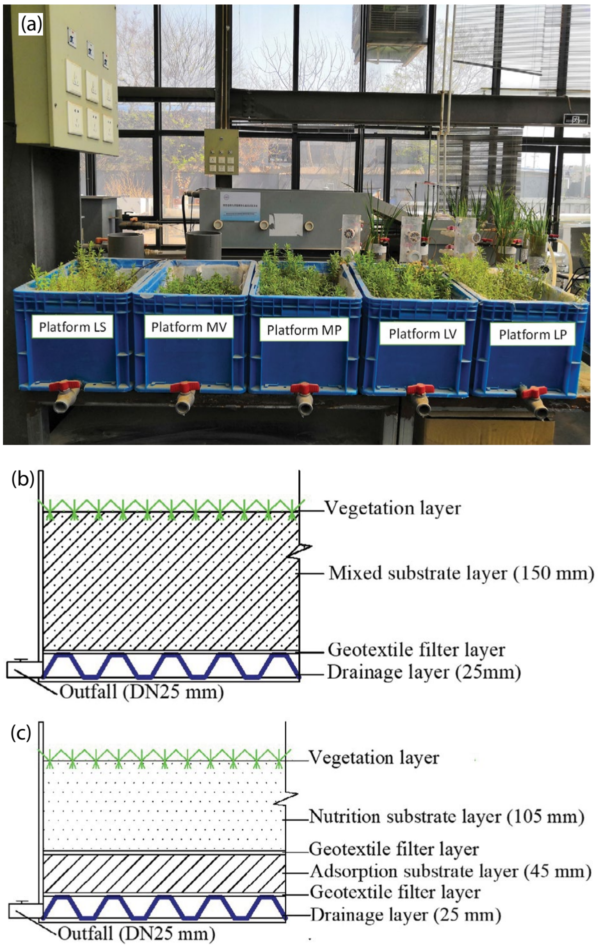

Fig. 1. Photographs and cross-section schematics of the green roof platforms used in this study. (a) Photo of green roof platforms, (b) Cross-section of the mixed substrate green roof (platforms LS, MV and MP), and (c) Cross-section of the layered substrate green roof (platforms LV and LP).

During the experiment, the recorded minimum and maximum temperatures were 16°C and 31°C, respectively, and the relative humidity averaged 25.72% ± 10.16%. There were no large fluctuations in temperature or relative humidity during the experiment.

2.3. Sampling and analysis

A drain hole with polyvinyl chloride piping was installed at the lower end of each test plot to collect runoff from individual platforms. The runoff was sampled manually at fixed 30 min intervals from the time it first appeared. Runoff samples were tested for COD, TN, TP, NH_4^+–N, NO_3^-–N and PO_4^{3-}–P using standard methods [40].

2.4. Data analysis

Rainwater retention was used to evaluate the water retention capacity of a green roof:

$$Q = \frac{Q_i - Q_e}{Q_i} \times 100\% \qquad (1)$$

The cumulative runoff depth was used to evaluate the runoff process of the green roofs:

$$\text{CRD} = \sum_{i=1}^{n} R_p \qquad (2)$$

Repeated analysis of variance tests were performed to investigate the significant differences in runoff quantity and quality from different platforms (significance level $p = 0.05$). The statistical analyses were performed with IBM SPSS Statistics 22.0 and Origin Pro 9.1 software.

3. Results and discussion

3.1. Rainfall retention

The rainwater retention for 12 rainfall simulations is illustrated in Fig. 2a. The average rainwater retention of

Table 1
Compositions of green roof substrates

No.	Depth(cm)	Composition (volume ratio)
LS	15	Local soil 100%
MV	15	Local soil 40% + peat soil 30% + vermiculite 30%
MP	15	Local soil 40% + peat soil 30% + perlite 30%
LV	Nutrition substrate layer 10.5 + adsorption substrate layer 4.5	Nutrition substrate layer: local soil 40% + peat soil 30%; adsorption substrate layer: vermiculite 30%
LP	Nutrition substrate layer 10.5 + adsorption substrate layer 4.5	Nutrition substrate layer: local soil 40% + peat soil 30%; adsorption substrate layer: perlite 30%

Table 2
Physical and chemical properties of the substrates

Substrates	Organic matter content (%)	Particle density (kg/m^3)	Available phosphorous (mg/kg)	Alkali solution N (mg/kg)
Local soil	0.95	1,210	4.32	44.15
Peat soil	9.69	770	30.25	377.86
Vermiculite	0.35	181	0.57	39.16
Perlite	0.16	95	1.28	34.15
Nutrition substrate layer (local soil: peat soil = 4:3)	5.58	1,115	14.36	174.57
Local soil 40% + peat soil 30% + vermiculite 30%	5.03	957	13.83	161.02
Local soil 40% + peat soil 30% + perlite 30%	3.58	864	13.94	138.42

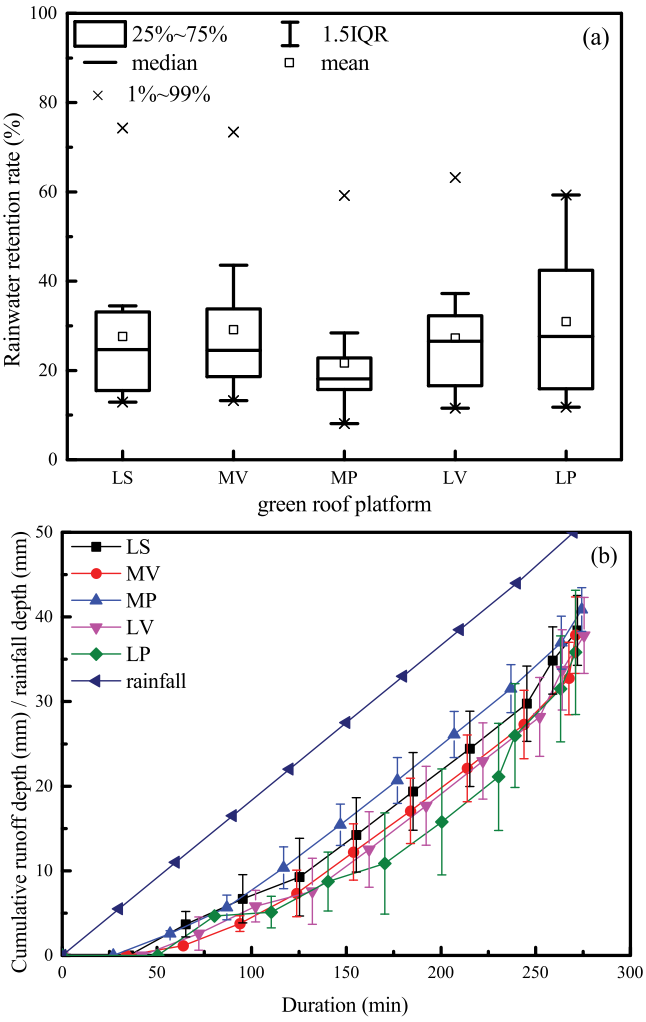

Fig. 2. Rainwater retention and runoff depth of each platform. The runoff depth (mm) from green roofs is the average data from 12 rainfall simulations. The cumulative runoff depth (mm) is the mean data from 12 repetitions of each simulated rainfall event; the error bars are standard deviations of 12 repetitions of each event.

platform LP (30.95% ± 17.20%) was significantly higher than platform MP (21.66% ± 12.91%). However, there was no significant difference in rainwater retention between platforms LV and MV ($p > 0.05$). The layered substrate green roof with perlite showed significantly increased rainwater retention compared with the mixed substrate green roofs. Wang et al. [32] found that layered substrate green roofs, which used mixtures of activated charcoal with perlite and vermiculite as the adsorption substrates, showed better rainfall retention (65.9% and 55.4%, respectively) than mixed substrate green roofs (52.5%). Perlite has high porosity and low particle density (Table 2), and the intergranular voids of a mixed substrate green roof are easily filled with fine particles of soil and peat soil. However, the structure of a layered substrate green roof makes it easier to use the pore space between perlite particles to store rainwater. Therefore, a layered substrate green roof with perlite has better rainwater retention than layered substrate with vermiculite. Although vermiculite has high porosity and low particle density (Table 2), the particles are soft, so vermiculite fills as a single adsorption layer under the platform (above the drainage layer). Vermiculite substrate is, therefore, compacted due to gravity of the upper substrate layer. Hence, it does not result in better rainwater retention.

However, it is worth noting that the rainwater retention of MV (29.16% ± 16.55%) was higher than MP (21.66% ± 12.91%). The rainwater retention of LV and LP was similar. Vermiculite showed better rainwater retention than perlite when the mixed substrate green roof was filled with vermiculite.

The average accumulation runoff depth curve obtained from the 12 rainfall simulations is illustrated in Fig. 2b. For 50 mm rainfall, the runoff depth of each platform was arranged as MP (40.88 ± 2.59 mm) > LS (38.41 ± 4.14 mm) > MV (37.84 ± 4.52 mm) > LV (37.80 ± 4.49 mm) > LP (35.81 ± 7.35 mm). The layered substrate green roof with perlite (LP) showed the best rainfall retention with an average runoff depth decrease of 10.13% ± 12.69% compared with the mixed substrate green roof (MP). Moreover, the average runoff depth of the mixed substrate green roof with vermiculite (MV) decreased by 6.49% ± 6.48% compared with the mixed substrate green roof with perlite (MP). There was no significant difference in rainwater retention between the layered substrate green roof with vermiculite and the layered substrate with perlite. However, the layered substrate structure enhanced rainwater retention of green roofs with the same adsorption substrate. The hydrological performance of the layered substrate green roofs during the simulations was relatively good because of the porous structure and large specific surface area of the adsorptive materials employed, which helped absorb and hold water [32].

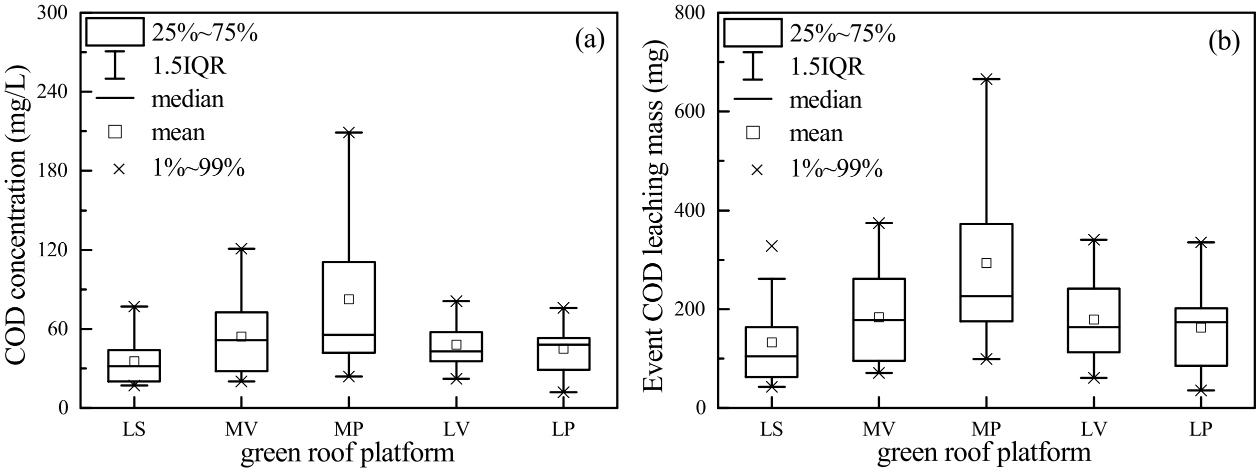

Fig. 3. Concentrations and event leaching masses of chemical oxygen demand (COD) substances in runoff from green roofs during 12 rainfall simulations. Inter-quartile range: IQR.

The average time for runoff initiation of LV (42.09 ± 23.20 min) was longer than MV (33.82 ± 16.97 min). The average time for the initiation of runoff of LP (50.36 ± 34.22 min) was longer than MP (26.91 ± 17.01 min). The layered substrate green roofs delayed the runoff initiation time compared with mixed substrate green roofs. Moreover, we found that higher green roof retention capacity meant a longer runoff initiation time [32], which was consistent with our general expectations.

3.2. COD leaching

The COD concentrations from the runoff of different green roofs during 12 rainfall simulations are illustrated in Fig. 3a. The average COD concentration in runoff from LP (44.83 ± 18.04 mg/L) was significantly lower than MP (82.25 ± 62.24 mg/L) ($p < 0.05$). There was no significant difference in the average COD concentrations between platforms LV (48.00 ± 18.58 mg/L) and MV (54.00 ± 29.89 mg/L) ($p > 0.05$). The layered substrate with perlite (LP) significantly reduced COD leaching. For the layered substrate green roofs, this may be because the adsorptive materials in the green roofs possess relatively strong buffering capacities and rapid adsorption rates [32]. However, when vermiculite was used, the layered substrate green roof did not show significant improvement in COD leaching. The event leaching mass confirmed the COD leaching control of platform LP (Fig. 3b). The average event COD leaching mass of LP (162.11 ± 91.45 mg) was significantly lower than MP (293.51 ± 174.26 mg) ($p < 0.05$). The layered substrate green roof with perlite reduced COD cumulative leaching mass by 44.77% compared with the corresponding mixed substrate green roof. There was no significant difference for average event COD leaching mass between LV and MV ($p > 0.05$). While the layered substrate green roof with perlite effectively reduced COD leaching, the mechanism of this from green roofs with vermiculite and perlite should be investigated further.

3.3. Nitrogen leaching

The concentrations of TN, NH_4^+–N and NO_3^-–N during the rainfall simulations are illustrated in Fig. 4. The TN concentrations in runoff from platforms MV, LV, MP and LV were relatively higher than platform LS. Conventional fertilizers or nutrient-rich material can lead to obvious nutrient leaching [41]. The organic matter in green roof substrates in MV, LV, MP and LV was much higher than LS, which led to serious TN leaching from them. There was no significant difference in average TN concentrations between layered and mixed substrate green roofs (LV and MV, LP and MP) ($p > 0.05$) (Fig. 4a). Wang et al. [31] found that when the volume ratio of adsorption to nutrient substrates was 2:1, the green roofs acted as a sink for TN. Because the proportion of adsorption substrate was much lower in this study, the TN leaching control of the layered substrate green roof was not significantly improved. The average event TN leaching mass of platform LP (91.08 ± 123.96 mg) was slightly less than MP (113.29 ± 128.88 mg) (Fig. 4b). The layered substrate green roof with perlite decreased TN cumulative leaching mass during the simulations by 19.60% compared with the corresponding mixed substrate green roof. There was no significant difference in average event TN leaching mass between LV (86.01 ± 106.65 mg) and MV (81.28 ± 57.15 mg) ($p > 0.05$).

Although there was no significant difference between platforms LP and LV in runoff TN concentrations, LP exhibited high rainwater retention; thus, the layered substrate green roof with perlite still showed TN leaching control. When a deeper adsorption substrate layer is used (e.g., 10 cm), the TN leaching control may improve [32]. It is worth noting that the mixed substrate green roof with vermiculite (MV) had a lower event TN leaching mass than the mixed substrate green roof with perlite (MP); MV controlled TN leaching from substrate compared with MP with a cumulative leaching mass decrease of 28.25%. Thus, vermiculite had more effective TN leaching control than perlite when used as an adsorption substrate. This is consistent with the results of Jiang et al. [42] that showed vermiculite had a good adsorption effect on TN (largest amount of adsorbed TN was 1.75 g/kg).

The NH_4^+–N concentration in runoff from LV (0.55 ± 0.48 mg/L) was significantly lower than MV (0.78 ± 0.52 mg/L);

LP (0.73 ± 0.76 mg/L) was significantly lower than MP (0.90 ± 0.61 mg/L) ($p < 0.05$) (Fig. 4c). The average event NH_4^+–N leaching masses of the different platforms also confirmed that layered substrate green roofs effectively improved NH_4^+–N leaching (Fig. 4d); the cumulative leaching masses of NH_4^+–N decreased by 25.34% (vermiculite) and 20.27% (perlite). Soil permeability and porosity and the concentration of nitrifying bacteria in the nutrient substrate or soil also had a great impact on ammonia removal efficiency [31,43]. The two layered substrate green roofs have higher particle densities and lower porosity than the mixed substrate green roofs. This may be the main reason that layered substrates have better NH_4^+–N leaching control. Additionally, the green roofs with vermiculite (LV and MV) had better NH_4^+–N leaching control than perlite (LP and MP). In addition to a porous structure, the high cation exchange capacity of

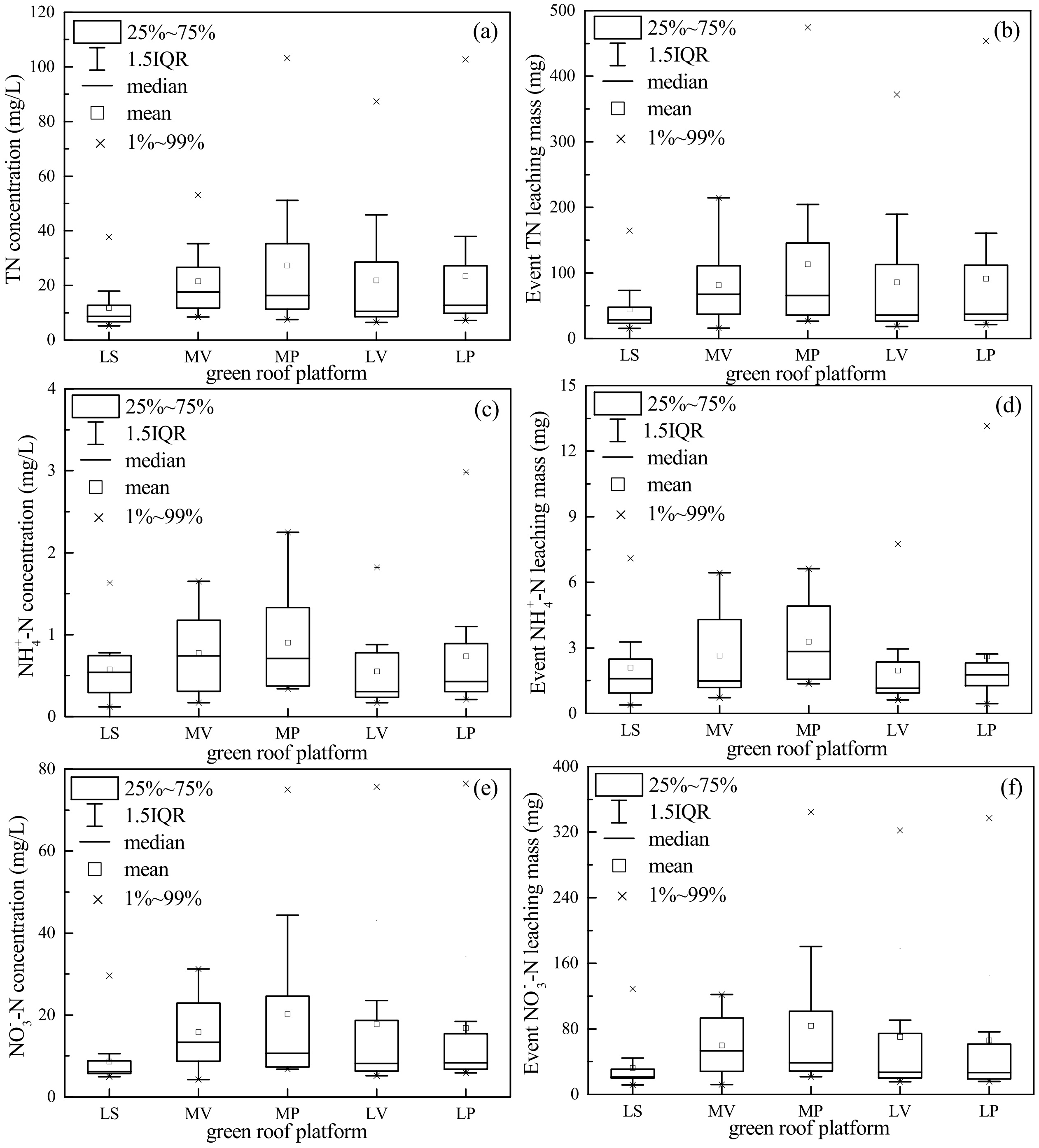

Fig. 4. Concentrations and event leaching masses of nitrogen substances in runoff from green roofs during 12 rainfall simulations. Inter-quartile range: IQR.

vermiculite is also likely responsible for the high retention of NH_4^+–N [32,44].

There was no significant difference in average NO_3^-–N concentrations in runoff from the layered and mixed substrates (LV and MV, LP and MP). The NO_3^-–N concentration in runoff from each platform was high. It is worth noting that the layered substrate green roof with perlite showed a 21.47% decrease in NO_3^-–N cumulative leaching mass during the simulations compared with the corresponding mixed substrate green roof. NH_4^+–N or organic nitrogen is converted to NO_3^-–N by nitrifying and nitrosating soil bacteria through aerobic nitrification. Because NO_3^- is a negatively charged anion that is difficult to adsorb, the converted NO_3^-–N accumulates in the substrate until accumulated NO_3^- is released from the medium when rainfall occurs [45–47].

3.4. Phosphorus leaching

The concentrations of TP and PO_4^{3-}–P during 12 rainfall simulations are illustrated in Fig. 5. The TP concentration in runoff from platform LV (0.11 ± 0.04 mg/L) was significantly lower than platform MV (0.24 ± 0.12 mg/L); platform LP (0.15 ± 0.03 mg/L) was significantly lower than platform MP (0.25 ± 0.09 mg/L) ($p < 0.05$). The average event TP leaching masses of different platforms also confirmed that layered substrate green roofs effectively improved TP leaching control (Fig. 5b). The results indicate that layered substrate green roofs exhibit better TP leaching control, especially the layered substrate green roof with vermiculite (LV). The layered substrates with vermiculite and perlite decreased the TP cumulative leaching mass by 51.49% and 45.51%, respectively, compared with the corresponding mixed substrates. The leaching of phosphorus in green roofs is mainly controlled through substrate adsorption, as well as microbial and plant uptake [48]. Perlite and vermiculite have strong water absorption capacities and retain phosphorus because of the numerous pores on the particle surfaces [32,49]. The layered substrate green roof effectively improved PO_4^{3-}–P leaching control (Figs. 5c and d).

The green roofs with vermiculite (LV and MV) had lower average event TP and PO_4^{3-}–P leaching masses than green roofs with perlite (LP and MP). Vermiculite leachate was found to contain higher Ca (3.7 mg/L) than perlite (0.4 mg/L) [50] and Ca-P complexes can precipitate out of solution [48,51]. This may explain why vermiculite has a significant effect on TP leaching.

4. Conclusions

The average rainwater retention of layered substrate green roofs with perlite (30.95% ± 17.20%) was significantly

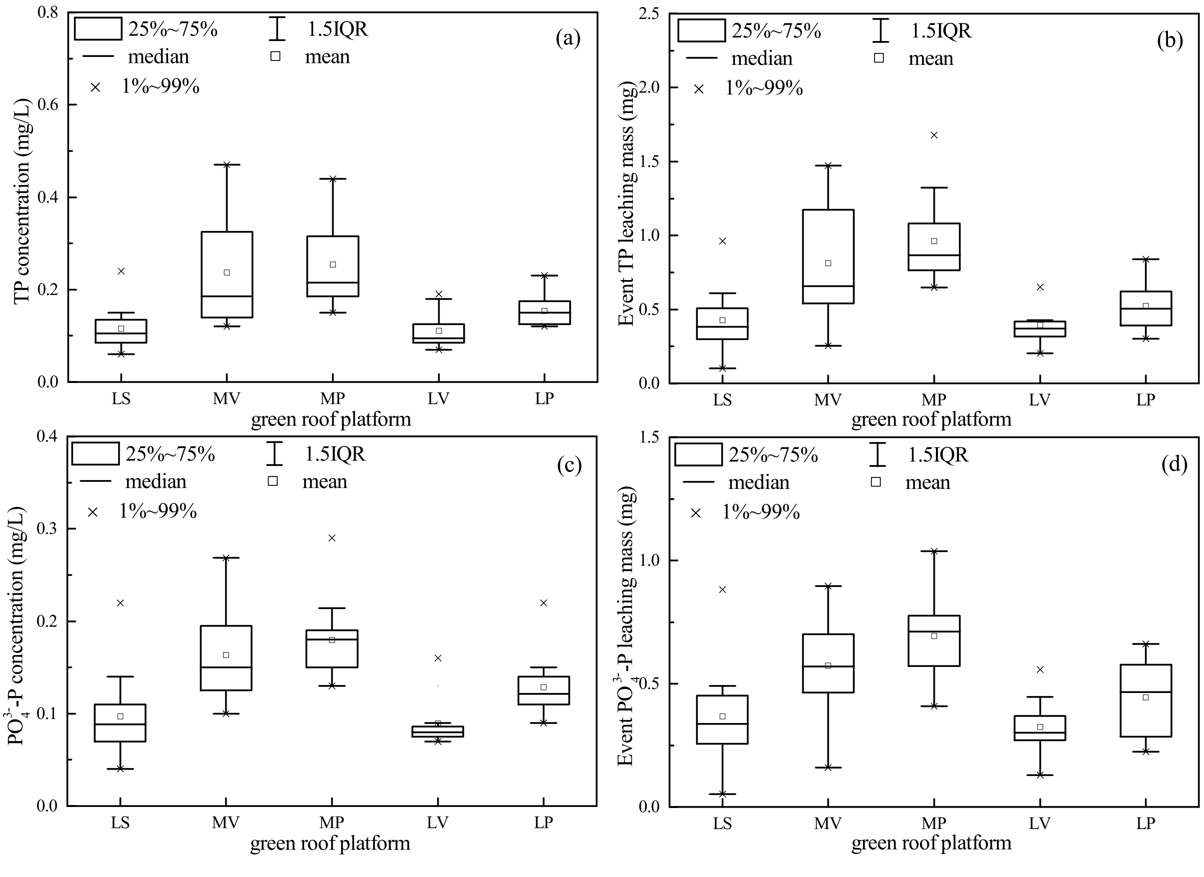

Fig. 5. Concentrations and event leaching masses of phosphorus substances in runoff from green roofs during 12 rainfall simulations. Inter-quartile range: IQR.

higher than mixed green roofs filled with the same substrate (21.66% ± 12.91%). After simulating 12 rainfall events, the average runoff depth of the layered substrate green roof with perlite was assessed and decreased 10.13% ± 12.69% compared with the mixed substrate green roof. Overall, the layered substrate green roofs delayed the runoff initiation time compared with the mixed substrate green roofs.

The layered substrate green roofs significantly controlled TP, PO_4^{3-}–P and NH_4^+–N leaching. Additionally, the layered substrate green roof with perlite exhibited better COD, TN and NO_3^-–N leaching control. The cumulative leaching masses of COD, TN, TP, NH_4^+–N and NO_3^-–N in the layered substrate with perlite decreased by 44.77%, 19.60%, 45.51%, 20.27% and 21.47%, respectively, compared with the mixed substrate. Moreover, the cumulative leaching masses of TP and NH_4^+–N in the layered substrate with vermiculite decreased by 51.49% and 25.34%, respectively, compared with the mixed substrate green roof. The green roofs that used vermiculite as the adsorption substrate (LV and MV) showed lower average leaching masses of TP, NH_4^+–N and PO_4^{3-}–P than the green roofs with perlite (LP and MP).

Improvements in rainwater retention and pollutant leaching control by layered substrate green roofs were confirmed in this study. However, the selection of an adsorption substrate still plays an important role for the control of leached pollutants, even though a layered substrate structure more effectively improves performance. However, determining the leaching control mechanisms from different adsorption substrates needs to be investigated in further research to promote layered substrate green roof applications.

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Symbols

CRD — Cumulative runoff depth, mm
n — Runoff process sampling time
Q — Rainwater retention rate, %
Q_e — Total runoff, L
Q_i — Total rainfall, L
R_p — Runoff depth at a fixed 30 min interval, mm

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