Performance analysis and experimental study on rainfall water purification with an extensive green roof matrix layer in Shanghai, China

Jiankang Guo, Yanting Zhang and Shengquan Che

ABSTRACT

Current research has validated the purification of rainwater by a substrate layer of green roofs to some extent, though the effects of the substrate layer on rainwater purification have not been adequately quantified. The present study set up nine extensive green roof experiment combinations based on the current conditions of precipitation characteristics observed in Shanghai, China. Different rain with pollutants were simulated, and the orthogonal design L9 (33) test was conducted to measure purification performance. The purification influences of the extensive green roof substrate layer were quantitatively analyzed in Shanghai to optimize the thickness, proportion of substrate, and sodium polyacrylate content. The experimental outcomes resulted in ammonium nitrogen (NH₄⁺-N), lead (Pb), and zinc (Zn) removal of up to 93.87%, 98.81%, and 94.55% in the artificial rainfall, respectively, and NH₄⁺-N, Pb, and Zn event mean concentration (EMC) was depressed to 0.263 mg/L, 0.002 mg/L and 0.018 mg/L, respectively, which were all well below the pollutant concentrations of artificial rainfall. With reference to the rainfall chemical characteristics of Shanghai, a combination of a 200 mm thickness, proportions of 1:1:2 of Loam: Perlite: Cocopeat and 2 g/L sodium polyacrylate content was suggested for the design of an extensive green roof substrate to purify NH₄⁺-N, Pb and Zn.

Key words | extensive green roof, orthogonal design, rainfall water purification, substrate layer

INTRODUCTION

The accelerated urbanization and industrialization in Shanghai has resulted in a rapid increase in the city’s population, a reduction in the urban afforestation rate, a sharp growth in energy consumption, and increased prominence of an air pollution problem (Jiecheng et al. 2009). As a result of air pollution, rain has become a major source of water pollution in Shanghai. Therefore, increased urban greening will both improve the urban ecological environment and significantly promote the urban landscape, habitats, and water environment. However, there is increasingly less urban land available for planting in dense urban areas (Berndtsson 2010) and the conflict between designating land for further urban expansion and for greening has become increasingly fierce. Conversely, roof areas, which represent about 45–50% (Liu & Cao 2009) of the urban impervious area in China, have not been used effectively, and the majority of urban roofs are exposed or barely planted (Dunnett & Kingsbury 2004). Green roofs represent an appropriate approach that provides space for urban greening and improves the urban ecological environment.

Green roof construction typically consists of a root barrier, drainage material layer, filter fabric, growing substrate, and vegetation (Getter & Rowe 2006; Clark et al. 2008; Berndtsson 2010). The results of previous studies show that the construction of a green roof can decrease 34–69% of rainfall by interception, retention, and evaporation (Gregoire & Clausen 2011). Some conditions increase green roof rainfall interception, such as the duration of dry weather before the experiment, the higher water holding capacities of the substrate, small intensity rainfall, high temperature, and evaporation (Carter & Rasmussen 2005; Berndtsson et al. 2006; Getter & Rowe 2006; Teemusk & Mander 2007; Hathaway et al. 2008; Simmons et al. 2008;...
Berndtsson 2010). Many studies have reported on the removal by green roofs of pollutants from roof runoff (Monterusso et al. 2002; Köhler & Schmidt 2003; MacMillan 2004; Berndtsson et al. 2006; Teemusk & Mander 2007; Hathaway et al. 2008). Soil composition and fertilizer use have been reported as two major factors that affect runoff pollution (Emilsson et al. 2007; Teemusk & Mander 2007; Hathaway et al. 2008; Berndtsson et al. 2009). Most green roof runoff studies have focused on metals, specifically copper (Cu) and zinc (Zn) (Steusloff 1998; MacMillan 2004; Alsup et al. 2010), whereas few comprehensive studies have been conducted on the effects on nitrogen (N) and phosphorus (P) in roof runoff (Berndtsson et al. 2006, 2009; Berndtsson 2010).

Previous studies indicated that roof greening considerably removes the concentration of pollutants in runoff, though the factors influencing extensive green roof rainfall runoff water quality have not been clearly defined yet. In this study, we determined the influence factors (amongst substrate thickness, substrate proportion and sodium polyacrylate content) of extensive green roofs for the removal of NH\textsubscript{4}–N, Pb, and Zn by simulating rainfall, which was artificially compounded by water and chemicals. A 3-factor, 3-level orthogonal array experiment was performed on the extensive green roof substrate layer for runoff purification to determine the factors influencing the removal of pollutants and metals by green roofs and to generate a suitable and effective design for the substrate structure of extensive green roofs in Shanghai.

**MATERIALS AND METHODS**

**Substrate composition**

Most extensive green roofs are constructed on poor load-bearing roofs, so light weight was an essential requirement for the substrate. Moreover, the selection of substrate should take important factors into account, such as maintenance of the plant growth, good ventilation and drainage performance, and use of non-toxic materials (Teemusk & Mander 2007). Currently, artificial substrates are primarily selected for the study and building of extensive green roof plant growth substrates. Artificial substrates are broadly classified into two categories: modified soil and ultra-lightweight substrate. Modified soil is mainly composed of light aggregates, drainage materials, fertilizers, and soil mixes. Ultra-light weight substrates have three layers: the surface layer, plant growing layer, and drainage layer (Gregoire & Clausen 2011).

Substrates can be divided into two classes according to their composition: inorganic substrate and organic substrate. Inorganic substrates include vermiculite, perlite, gravel, sand, whereas organic substrates include organic peat, rice husk, bagasse, cocopeat, and bark.

The basic physical and chemical properties of extensive green roof substrates are presented in Table 1. The ideal extensive green roof growing substrate is suitable for growing various plants and has a density of 100–800 kg/m\textsuperscript{3}, with an ideal density of 500 kg/m\textsuperscript{3}, a total porosity of about 60\%, and a pH value within the range of 5.5–7.0 (Snodgrass & Snodgrass 2006; Gregoire & Clausen 2011).

Based on previous studies, the substrate chosen for this study was composed of three parts: loam, inorganic perlite, and organic cocopeat. Extensive green roofs require a higher amount of water to support plant growth compared with plant growth on the ground because thin substrates have more efficient plant transpiration and evaporation of soil moisture. Therefore, sodium polyacrylate was added in the present study, which is a superabsorbent polymer, given its strong water retention characteristics and slow water release capacity. Experiments were conducted using sodium polyacrylate contents of 0, 2, and 4 g/L to follow a report previously published by Cui et al. (2006).

**Physical and chemical properties of the substrate**

Single substrates generally have shortcomings in quality such as a weight that is greater or smaller than required or poor ventilation (Monterusso et al. 2005). To overcome these shortcomings, an inorganic substrate (perlite) and
organic substrate (cocopeat) were proportionately mixed with loam to form the test substrate. The pH value, total porosity, and wet bulk density of soil were measured according to the *Soil physical and chemical analysis* (Institute of Soil Science of China 1978). Each index had three repetitions and the mean values were analyzed subsequently. The substrate parameters are presented in Table 2. Also, to clarify the naming of combinations, we coded the substrate proportions of 1:1:1, 1:2:1 and 1:1:2 as A, B and C.

**Experimental platform**

A total of nine experimental combinations were examined on 685 × 525 × 390 mm HDPE material platforms, which were set to a slope angle of about 5° by planks and were placed on bricks at a height of 0.5 m. The basic platform structures were all identical and included vegetation (*Sedum Lineare*) and sodium polyacrylate, which was sprinkled 50 mm under the substrate surface, a substrate layer (thickness of 10, 200, and 300 mm), a filter layer (non-woven fabrics), and a drainage layers (50 mm height). Excess water was drained from an overflow tube and purified water samples were collected on the lower side of the platform (Figure 1).

**Orthogonal arrays experiment design**

In the present study, a 3-factor, 3-level orthogonal array experiment was performed. The factors included the substrate thickness, substrate proportion, and sodium polyacrylate content. The levels are presented in Table 3.

The substrate thickness (Table 4) refers to the technical specifications of the Shanghai green roof Technical Manual (Shanghai 2010). A substrate thickness of 100–300 mm was selected for the vegetation (ground cover plants). The test factor designs are presented in Figure 2.

The experiment was conducted according to L9 (3^3) orthogonal arrays (Taguchi 2007), where ‘L9’ indicates nine tests overall, ‘3’ indicates that there were three factors (substrate thickness, substrate proportion and sodium polyacrylate content), and ‘3’ indicates that each factor has three levels (substrate thickness of 100, 200, and 300 mm; substrate proportion of 1:1:1, 1:1:2, and 1:1:2 (loam: perlite: cocopeat); and sodium polyacrylate content of 0, 2, and 4 g/L). Nine possible test design combinations were generated, as presented in Table 5.

<table>
<thead>
<tr>
<th>Code</th>
<th>Substrate proportion (Loam: Perlite: Cocopeat)</th>
<th>pH value</th>
<th>Total porosity (%)</th>
<th>Wet bulk density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1:1:1</td>
<td>8.32</td>
<td>70.05</td>
<td>1,440</td>
</tr>
<tr>
<td>B</td>
<td>1:2:1</td>
<td>8.19</td>
<td>74.38</td>
<td>1,180</td>
</tr>
<tr>
<td>C</td>
<td>1:1:2</td>
<td>8.05</td>
<td>73.60</td>
<td>1,240</td>
</tr>
</tbody>
</table>

Figure 1 | Sketch of experiment equipment.
The test was conducted at Shanghai Jiao Tong University, Shanghai, China. The artificial rainfall equipment NLJY-10-01 (NFUE, Nanjing, China) is presented in Figure 3. Three artificial rainfall simulation tests were performed.

The representative studied pollutants of the rainfall in Shanghai were NH$_4^+$-N, Pb, and Zn, and the maximum measured concentration of these three pollutants in previous studies was 4.490, 0.067, and 0.263 mg/L, respectively (Ai 2014). Referring to the results of a previous study of pollutant concentration (Huang et al. 2015) and the compound method (Wang et al. 2008) of artificial rainfall, the water that flowed into the rainfall simulator system was artificial rainwater with target concentrations of 5.000, 0.100, and 0.300 mg/L for NH$_4^+$-N, Pb, and Zn, respectively, and was prepared with ammonium chloride (pure), lead chloride, and zinc.

**Sampling collection and measurement method**

The sampling methods followed the United States National Pollutant Discharge Elimination System (NPDES) guidelines for the sampling of water (EPA 1992), which specifies the following methods:

1. Three artificial rainfall events were conducted, each sustained for 30 min and with a 7-day interval between events. Five rain gauges were placed under the artificial rainfall generator to measure the quantity of rainwater.

### Artificial rainfall simulator

The test was conducted at Shanghai Jiao Tong University, Shanghai, China. The artificial rainfall equipment NLJY-10-01 (NFUE, Nanjing, China) is presented in Figure 3. Three artificial rainfall simulation tests were performed.

#### Table 3 | Factors and levels of substrate

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Substrate thickness (mm)</td>
<td>100</td>
</tr>
<tr>
<td>2. Substrate proportion (Loam: Perlite: Cocopeat)</td>
<td>1:1:1</td>
</tr>
<tr>
<td>3. Sodium polyacrylate (g/L)</td>
<td>0</td>
</tr>
</tbody>
</table>

#### Table 4 | Different plant types in substrate thickness

<table>
<thead>
<tr>
<th>Plant types</th>
<th>The minimum substrate thickness for the survival of plants (mm)</th>
<th>The minimum substrate thickness for plant growth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large shrub</td>
<td>300–600</td>
<td>600–900</td>
</tr>
<tr>
<td>Small shrubs</td>
<td>200–450</td>
<td>450–600</td>
</tr>
<tr>
<td>Ground cover plants</td>
<td>100–300</td>
<td>300–450</td>
</tr>
</tbody>
</table>

**Figure 2** | Photograph of orthogonal test design.
(2) Following runoff generation, instantaneous water samples from the point labeled 'Sample' in Figure 2 were collected for 1 min at the 0, 10, 20, 30, and 40 min mark. Five instantaneous water samples were then mixed, of which 1 L of the mixed water was placed into PET bottles and nine mixed samples were taken from the nine test combinations.

(3) After the artificial rainfall, the volume of five rain gauges was immediately measured and 1 L of the rainwater mixture was collected as the rainfall sample.

(4) The platform number and sampling date for each of the 10 sample bottles (nine sample bottles from (2) and one sample bottle from (3)) were recorded, respectively.

The three simulated rainfall experiments lead to the collection of 50 mixed samples, of which each mixed sample was measured in triplicate for each individual indicator. The amount of NH4+-N, Pb, and Zn was determined based on the Chinese Standards.

**Event mean concentration determination method**

To present the pollutant changes during rainfall, the event mean concentration (EMC) (Athayde et al. 1985) of the rain pollutants was characterized as the main parameter to evaluate the given pollutant concentration changes observed for the same rainfall event. The EMC is the weighted average concentration of rainfall runoff for the entire process, the expression of which is presented as follows:

\[
EMC = \frac{M}{V} = \frac{\int (C(t)Q(t))}{\int Q(t)} \approx \frac{\sum (C(t)Q(t))}{\sum Q(t)}
\]

(1)

where \(M\) is the mass of pollutants in a certain runoff process, \(V\) is the total volume of the runoff process, \(C(t)\) is the concentration of a certain pollutant as a function of time, and \(Q(t)\) is the runoff flow as a function of time.

**Pollutant removal rate determination method**

The pollutant removal rate is defined as follows (Hou et al. 2009):

\[
RR = \frac{C_i - C_o}{C_i} \times 100\%
\]

(2)

where \(RR\) is the pollutant removal rate (here the \(RR\) was the average removal rate), \(C_i\) is the artificial rainfall concentration of the pollutant, and \(C_o\) is the average runoff concentration of the pollutant.

**Method of analysis of the factors influencing pollutant reduction by green roofs**

Analysis of variance (ANOVA) is a collection of statistical models used to analyze the differences among group means and their associated procedures (such as ‘variation’ among and between groups) and was conducted to determine whether there are significant differences among the factors of purification capacity. When the ANOVA result revealed that there were differences among group means,
Duncan’s new multiple range test, which is a post multiple comparison for observed means, was applied to test whether there was a statistically significant difference in the EMC and removal rate value between the levels.

Range analysis is a way to evaluate which factor has the most important impact on the result (EMC in this research). The R value is the difference between the maximum value and the minimum value of k. And k is the average EMC value of each level (Table 7), where k1 represents the average EMC value of 100 mm (100A-0, 100B-2 and 100C-4), k2 represents the average EMC value of 1:2:1 (100B-2, 200B-4 and 300B-0) and so on. The highest R value indicates that the variety of the levels in the identified factor has the most important impact on the result. Also, the level with the highest R value means it’s the best choice to remove the pollutants.

### RESULTS AND DISCUSSION

#### Artificial rainfall data

The three artificial rainfall experiments were performed on October 12, 19, and 26, 2015. The specific rainfall conditions presented in Table 6 indicate that the three artificial rainfall events all reached heavy rain intensity (Huschke 1960).

#### EMC and removal rate of pollutants

The EMC represent the average value of the runoff pollutants. According to Figure 4, the value of NH$_4$\textsuperscript{+}-N EMC of rainfall in Shanghai (4.490 mg/L) (based on Ai (2014) and Huang et al. (2015)) and artificial rainfall (5.380 mg/L) in the present study was beyond class V of the standards (MEP of China 2002). The NH$_4$\textsuperscript{+}-N EMCs of the nine combinations were between 0.450 and 1.485 mg/L (Figure 4). In addition, the combination of 300C-2 had the lowest NH$_4$\textsuperscript{+}-N value, which reveals that 300C-2 (Figure 4) was the optimal combination to reduce the EMC of NH$_4$\textsuperscript{+}-N.

According to the results of Figures 5 and 6, the Pb and Zn EMC of rainfall in Shanghai (0.067 and 0.263 mg/L, respectively), as provided by Ai (2014) and Huang et al. (2015), and artificial rainfall (0.090 and 0.333 mg/L, respectively) in the present study were within Class V and Class II & III in the

![Table 6](https://iwaponline.com/wst/article-pdf/77/3/670/212386/wst077030670.pdf)

<table>
<thead>
<tr>
<th>Date (year/month/day)</th>
<th>Total rainfall height (mm)</th>
<th>Total rainfall duration (min)</th>
<th>Grade of precipitation (refers to Chinese Standard GB/T 28592-2012)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015/10/12</td>
<td>51.85</td>
<td>30</td>
<td>Heavy rain</td>
</tr>
<tr>
<td>2015/10/19</td>
<td>69.30</td>
<td>30</td>
<td>Heavy rain</td>
</tr>
<tr>
<td>2015/10/26</td>
<td>71.59</td>
<td>30</td>
<td>Heavy rain</td>
</tr>
</tbody>
</table>

![Table 7](https://iwaponline.com/wst/article-pdf/77/3/670/212386/wst077030670.pdf)

<table>
<thead>
<tr>
<th>k value</th>
<th>EMC of NH$_4$\textsuperscript{+}-N</th>
<th>EMC of Pb</th>
<th>EMC of Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Substrate thickness</td>
<td>Substrate proportion</td>
<td>Sodium polyacrylate</td>
</tr>
<tr>
<td>k1</td>
<td>1.428 1.037 1.267</td>
<td>0.018 0.008 0.016</td>
<td>0.025 0.021 0.027</td>
</tr>
<tr>
<td>k2</td>
<td>0.925 1.533 0.812</td>
<td>0.003 0.014 0.008</td>
<td>0.025 0.030 0.023</td>
</tr>
<tr>
<td>k3</td>
<td>1.013 0.976 1.288</td>
<td>0.010 0.009 0.008</td>
<td>0.029 0.028 0.028</td>
</tr>
<tr>
<td>R</td>
<td>0.503 0.378 0.476</td>
<td>0.015 0.006 0.008</td>
<td>0.004 0.008 0.005</td>
</tr>
<tr>
<td>Advantage Level</td>
<td>200 mm 1:1:2 2 g/L</td>
<td>200 mm 1:1:1 2 g/L</td>
<td>200 mm 1:1:1 2 g/L</td>
</tr>
</tbody>
</table>

K1 represents the average EMC value of level 100 mm (100A-0, 100B-2 and 100C-4), 1:1:1 (100A-0, 200A-2 and 300A-4), and 0 g/L (100A-0, 200C-0 and 300B-0). K2 represents the average EMC value of level 200 mm (200A-2, 200B-4 and 200C-0), 1:2:1 (100B-2, 200B-4 and 300B-0) and 2 g/L (100B-2, 200A-2 and 300C-2). K3 represents the average EMC value of level 300 mm (300A-4, 300B-0 and 300C-2), 1:1:2 (100C-4, 200C-0 and 300C-2) and 4 g/L (100C-4, 200B-4 and 300A-4). R represents the Range value which is the difference between the maximum value of k1, k2, k3 and the minimum value of k1, k2, k3. Advantage Level represents the highest value of k1, k2, k3. Dominant factors rank represents the R value in descending order.
**Figure 4** | NH₄⁺-N EMC of different rainfall and combinations. Note: The Class of NH₄⁺-N was quoted from the Environmental quality standards for surface water (MEP of China 2002). The value of Class I is ≤0.15 mg/L, Class II is ≤0.5 mg/L, Class III is ≤1.0 mg/L, Class IV is ≤1.5 mg/L, Class V is ≤2 mg/L.

**Figure 5** | Pb EMC of different rainfall and combinations. Note: The Class of Pb was quoted from the Environmental quality standards for surface water (MEP of China 2002). The values of Class I and Class II are ≤0.01 mg/L, the values of Class III and Class IV are ≤0.05 mg/L, the value of Class V is ≤0.10 mg/L.
standards (MEP of China 2002, the values of Class I & Class II in the standards of Pb are the same, the values of Class III & IV in the standards of Pb are the same, the values of Class II & III in the standards of Zn are the same, the values of Class IV & V in the standards of Zn are the same). The Pb EMCs of the nine combinations were between 0.003 and 0.022 mg/L (Figure 5), and the Zn EMCs of the nine combinations were between 0.018 and 0.034 mg/L (Figure 6).

Moreover, combination 200A-2 had the lowest value of Pb and Zn EMC, which reveals that 200A-2 (Figures 5 and 6) was the best option to reduce Pb and Zn. Meanwhile, all of the nine combinations reduced the Zn EMC to Class I, which indicates that extensive green roofs have a great effect on the decrease of Zn concentration of rainfall.

Removal rates of NH$_4^+$-N, Pb and Zn are shown in Figure 7. Similar to EMC, and as expected, these results indicated that combination 300C-2 was the best option to remove NH$_4^+$-N, while combination 200A-2 was the best option to remove Pb and Zn.

Range analysis of the EMC

Range analysis of the impact on EMC of NH$_4^+$-N, and the heavy metals Pb and Zn from the nine combinations are presented in Table 7. The results indicate that the best options to reduce NH$_4^+$-N were levels 200 mm, 1:2:1 and 2 g/L, the dominant factor was substrate thickness, and the descending order of most important influencing factor was: substrate thickness > sodium polyacrylate > substrate proportion. In addition, the best options to reduce both Pb and Zn were levels 200 mm, 1:1:1 and 2 g/L, the dominant factor to reduce Pb was substrate thickness and the descending order of most important influence level was: substrate thickness > sodium polyacrylate > substrate proportion. The dominant factor to reduce Zn was substrate proportion and the descending order of most important influence level was: substrate proportion > sodium polyacrylate > substrate thickness.

Additional experiment and results

The range analysis result indicated that the best option to decrease Pb and Zn was 200A-2 for which the EMC values of Pb and Zn were 0.002 and 0.018 mg/L, respectively. However, the best option, (200 mm thickness, 1:1:2 proportion of Loam: Perlite: Cocopeat and 2 g/L sodium polyacrylate content) to remove NH$_4^+$-N was not in the list of combinations (Table 5). Thus, an additional experiment, which was called combination 200C-2 (200 mm thickness,
1:1:2 proportion of loam: perlite: cocopeat and 2 g/L sodium polyacrylate content was conducted on July 27, 2017 in triplicate to verify if this was really the optimum combination of levels. The result of the extra experiment is presented in Figures 8 and 9.

Figure 8 demonstrates that the NH$_4^+$-N EMC of 200C-2 was less than for 300C-2, indicating that the combination 200C-2 is a better option to reduce NH$_4^+$-N. However, the EMC value of NH$_4^+$-N was still Class II of the standards (MEP of China 2002). Moreover, the EMC of Pb and Zn of 200C-2 was larger than with 200A-2, indicating that 200A-2 is the best option to reduce Pb and Zn. As expected, the results for the removal rate showed the same trend as for EMC (Figure 9). The optimum approach to reduce NH$_4^+$-N is 200C-2 with a removal rate of 93.87%, and the optimum to reduce Pb and Zn remains 200A-2, with removal rates of 98.81% and 94.55%.

**ANOVA for the EMC and removal rate of pollutants**

The ANOVA results for the EMC and pollutant removal rates of NH$_4^+$-N and Zn are presented in Table 8. No significant difference was observed between the experimental combinations for NH$_4^+$-N and Zn, whereas the substrate thickness exhibited a significant influence (p < 0.05) on the Pb removal rate.

Furthermore, the results (Table 9) of Duncan’s new multiple range test (Duncan 1955) revealed that the removal rate value of Pb 100 mm thickness was significantly lower than for 200 and 300 mm.

**CONCLUSION**

Based on the above test results, we can conclude that the extensive green roof experimental combinations significantly reduce the concentrations of storm water pollutants. When the substrate thickness of the extensive green roof was 200 mm, the substrate proportions of loam: perlite: cocopeat were 1:1:2 and the sodium polyacrylate content was 2 g/L of the substrate, the highest removal rate (the one for NH$_4^+$-N) reached 93.87%, and the EMC of NH$_4^+$-N exhibited a reduction to 0.263 mg/L, which was far less than the maximum concentration value (4.49 mg/L) of NH$_4^+$-N in rainfall in Shanghai (Huang et al. 2012) and achieved surface water Class II standard (MEP of China 2002). In addition, when the substrate thickness of the extensive green roof was 200 mm, the substrate proportions of loam: perlite: cocopeat were 1:1:1 and the sodium polyacrylate content was 2 g/L of the substrate, the heavy metals Pb and Zn exhibited a removal rate of up to 98.81% and 94.55%, respectively, and an EMC reduction to 0.002 and 0.018 mg/L, respectively. As a result, this substrate produced pollution that was far less than the maximum concentration value (0.067 and 0.263 mg/L) of Pb and Zn in rainfall in Shanghai (Ai 2011) and reached the surface water Class I standard (MEP of China 2002). The results of previous studies (Steusloff 1998; Wang et al. 2012; Berndtsson et al. 2006) revealed that the removal rates of a green roof for NH$_4^+$-N, Pb and Zn were 50–93%, 91–94%, and 72–92%, respectively, which represent the same trend as the present study.

The dominant factor for extensive green roofs to reduce NH$_4^+$-N and Pb is substrate thickness, whilst to reduce Zn
the dominant factor is substrate proportion. The purification capacity of the green roof was the best for all three pollutants at a substrate thickness of 200 mm and sodium polyacrylate content of 2 g/L. However, the best substrate proportion to reduce NH$_4^+$-N was 1:1:2, and the optimum was 1:1:1 for Pb and Zn.

Figure 8 | Comparison of NH$_4^+$-N, Pb, Zn EMC between additional combinations and pervious optimum ones. Note: Class standards were the same as Figures 4–6.
The chemical characteristics of rainfall in Shanghai indicate that the NH₄⁺-N concentration is far worse than the Class V standard (the lowest level of the standard). Therefore, the combination of a 200 mm thickness, 1:1:2 proportions of loam: perlite: cocopeat and 2 g/L sodium polyacrylate content was identified as the optimal combination for an extensive green roof substrate for the region of Shanghai.

ACKNOWLEDGEMENT

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