Ranking media for multi-pollutant removal efficiency in bioretention

Ying Mei, Long Gao, Hang Zhou, Kun-Hao Wei, Na-Qi Cui and Chein-Chi Chang

ABSTRACT

Bioretention is an effective best management practice for urban stormwater. This study aims to provide guidance for selecting the best bioretention medium in terms of pollutant removal capacity. Fuzzy set theory was applied with the improved analytic hierarchy process (IAHP) for weight determination, thus forming the fuzzy synthetic evaluation model, to assess the comprehensive efficiencies of certain sand media. This work is the first to use this method to study bioretention. Results demonstrated that the fuzzy synthetic evaluation model was a rational choice for the selection of bioretention media. The studied media were ranked by pollutant removal capacity as follows: Media III > Media V > Media I > Media VI > Media II > Media VII > Media IV. Media I had the best comprehensive removal efficiency and infiltration rate in bioretention. Moreover, the removal rates for Cd^{2+}, Zn^{2+} and Pb^{2+} were excellent (>80%), those for Cu^{2+} and NH_{4}^{+}-N fluctuated from 58.1% to 92.7% and 64.7% to 95.9%, respectively, and those for NO_{3}^{-}-N and TP of the seven media did not show distinct differences.

INTRODUCTION

Rapid industrialisation and urbanisation have led to increasing levels of impermeable surfaces, thereby causing enhanced stormwater runoff. This water may contain many pollutants, including nitrogen, phosphorus and heavy metals (Barrett et al. 1998; Wu et al. 1998; Brown et al. 2016). Therefore, urban surface water quality is emphasised because of the eutrophication and toxicity of contaminated water (Yang et al. 2014). Consequently, stormwater management practices are being designed to remove nutrients and heavy metals, especially nitrogen and phosphorus. Many stormwater treatment technologies have recently been developed, such as sand filters, permeable pavements, wetlands and bioretention (Dietz 2007). Among these technologies, bioretention is being increasingly adopted (Melbourne Water 2005).

Bioretention is a best management practice (BMP) for stormwater that effectively reduces water quality and quantity (Davis et al. 2009; De et al. 2017). The typical structure used for this method includes vegetation, a ponding area and mulch, sand and gravel layers (Rusciano & Obropta 2007; Milandri et al. 2012). In bioretention, sand media are used for treatment in numerous processes, including sedimentation, filtration and sorption. Although sand media are widely applied in this technique, only a few studies have attempted to identify sand media that are effective in simultaneous multi-pollutant removal. The selection of sand media is a multi-objective uncertainty problem. A credible and applicable method of selecting such media deserves emphasis.

Fuzzy set theory has been extensively applied since it was established in 1965 (Zadeh 1965). This theory was developed for modelling nonlinear, uncertain and complex systems (Ross 2004) and is widely used in environmental quality assessment (Afshar et al. 2007; Lu et al. 2010; Sowlat et al. 2011). The application of fuzzy set theory effectively solves the problems of fuzzy boundaries and effects of monitoring errors (Haiyan 2002). The analytic hierarchy process (AHP) is a popular multiple-criteria decision-making tool (Bahceci & Topkaya 2008). Nevertheless, limited information is available about the comprehensive assessment of the pollutant removal efficiency of bioretention media. In this work, an improved AHP (IAHP) is used to calculate
the weights of all indices. This study mainly aims to select the best bioretention medium using the fuzzy synthetic evaluation model.

This paper is organised as follows. The next section describes the materials and methods, then the following section constructs the theory frame of best medium selection on the basis of the fuzzy set evaluation. The subsequent section discusses the results obtained by the study case, and then the final section presents the conclusions.

MATERIALS AND METHODS

Materials

Seven media with different types and mean particle sizes and excavated from the coastal area of the Yongding River in Beijing were obtained from a local home supply store and used in this study. All media were washed thrice using deionised water prior to the experiments. The seven media were placed in 20 cm diameter PVC pipes (100 cm height), which were filled with 60 cm sand media. Effluent samples were collected from the bases of the pipes. To determine the effect of the sand media on pollutant removal from stormwater, every medium received 11 L synthetic stormwater in a 6 h experimental period. The experiment was run once per week, and six replicate experiments were conducted in total. The effluent samples were the compound samples in all the experiments. The characteristics of the media are shown in Tables 1 and 2.

Synthetic stormwater runoff

Synthetic stormwater runoff was used in all of the experiments to provide controlled input conditions. The utilised runoff comprised deionised water and contained the target pollutants sodium nitrate (NaNO₃), ammonium chloride (NH₄Cl), sodium dihydrogen phosphate (Na₂HPO₄), cadmium nitrate (Cd(NO₃)₂), zinc chloride (ZnCl₂), lead chloride (PbCl₂) and cupric sulfate (CuSO₄). The levels of the target pollutants in the synthetic stormwater are listed in Table 3. All target pollutant levels were determined by the actual levels in Beijing.

Analytical methodology

All samples were filtered by a 0.45 μm membrane filter, and the total phosphorus, ammonium, nitrate, copper, lead, zinc from stormwater, every medium received 11 L synthetic stormwater in a 6 h experimental period. The experiment was run once per week, and six replicate experiments were conducted in total. The effluent samples were the compound samples in all the experiments. The characteristics of the media are shown in Tables 1 and 2.

Table 1 Physical characteristics of bioretention media

<table>
<thead>
<tr>
<th></th>
<th>d₁₀ mm</th>
<th>d₆₀ mm</th>
<th>PH</th>
<th>Sand %</th>
<th>Silt %</th>
<th>Clay %</th>
<th>OM %</th>
<th>CEC cmol/kg</th>
<th>Infiltration rate cm/h</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Media I</td>
<td>0.072</td>
<td>0.22</td>
<td>9.05</td>
<td>96</td>
<td>4</td>
<td>0</td>
<td>0.37</td>
<td>3</td>
<td>28.5</td>
<td>Sand</td>
</tr>
<tr>
<td>Media II</td>
<td>0.05</td>
<td>0.1</td>
<td>9.11</td>
<td>90</td>
<td>10</td>
<td>0</td>
<td>0.3</td>
<td>3</td>
<td>9.9</td>
<td>Sand</td>
</tr>
<tr>
<td>Media III</td>
<td>0.005</td>
<td>0.088</td>
<td>8.68</td>
<td>61</td>
<td>37</td>
<td>2</td>
<td>1.31</td>
<td>16.4</td>
<td>0.37</td>
<td>Sandy clay</td>
</tr>
<tr>
<td>Media IV</td>
<td>0.05</td>
<td>0.25</td>
<td>9.17</td>
<td>89</td>
<td>11</td>
<td>0</td>
<td>0.55</td>
<td>3.71</td>
<td>3.94</td>
<td>Loamy sand</td>
</tr>
<tr>
<td>Media V</td>
<td>0.02</td>
<td>0.11</td>
<td>8.79</td>
<td>72</td>
<td>28</td>
<td>0</td>
<td>0.35</td>
<td>4.28</td>
<td>1.1</td>
<td>Sandy clay loam</td>
</tr>
<tr>
<td>Media VI</td>
<td>0.026</td>
<td>0.246</td>
<td>9.03</td>
<td>85</td>
<td>15</td>
<td>0</td>
<td>0.27</td>
<td>2</td>
<td>5.08</td>
<td>Loamy sand</td>
</tr>
<tr>
<td>Media VII</td>
<td>0.009</td>
<td>0.061</td>
<td>8.28</td>
<td>52</td>
<td>44</td>
<td>4</td>
<td>0.42</td>
<td>10.4</td>
<td>0.27</td>
<td>Sandy clay</td>
</tr>
</tbody>
</table>

*Effective sizes: d₁₀ = 10th percentile diameter; d₆₀ = 60th percentile diameter.

Table 2 Chemical characteristics of bioretention media (g/kg)

<table>
<thead>
<tr>
<th></th>
<th>As</th>
<th>Cd</th>
<th>Co</th>
<th>Cr</th>
<th>Cu</th>
<th>Fe</th>
<th>Mn</th>
<th>P</th>
<th>Pb</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Media II</td>
<td>4.7</td>
<td>0.29</td>
<td>7.56</td>
<td>50.4</td>
<td>9.16</td>
<td>22,449</td>
<td>391</td>
<td>471.8</td>
<td>12.2</td>
<td>35.2</td>
</tr>
<tr>
<td>Media III</td>
<td>6.4</td>
<td>0.43</td>
<td>11.83</td>
<td>54.0</td>
<td>26.73</td>
<td>29,745</td>
<td>596</td>
<td>482.9</td>
<td>16.1</td>
<td>57.6</td>
</tr>
<tr>
<td>Media IV</td>
<td>ND</td>
<td>0.11</td>
<td>4.12</td>
<td>21.3</td>
<td>4.62</td>
<td>8,709</td>
<td>126</td>
<td>147.3</td>
<td>12.3</td>
<td>17.4</td>
</tr>
<tr>
<td>Media V</td>
<td>5.0</td>
<td>0.29</td>
<td>7.41</td>
<td>44.5</td>
<td>12.02</td>
<td>20,424</td>
<td>370</td>
<td>503.0</td>
<td>11.8</td>
<td>35.4</td>
</tr>
<tr>
<td>Media VI</td>
<td>1.7</td>
<td>0.13</td>
<td>3.53</td>
<td>18.9</td>
<td>4.71</td>
<td>10,621</td>
<td>173</td>
<td>174.8</td>
<td>9.5</td>
<td>16.6</td>
</tr>
<tr>
<td>Media VII</td>
<td>6.6</td>
<td>0.33</td>
<td>8.08</td>
<td>50.4</td>
<td>11.44</td>
<td>22,596</td>
<td>407</td>
<td>602.6</td>
<td>12.7</td>
<td>37.4</td>
</tr>
</tbody>
</table>
and cadmium contents were analysed. Nitrate and ammonium were analysed using a Seal-Auto Analyzer. Total phosphorus, copper, lead, zinc and cadmium contents were analysed using inductively coupled plasma-atomic emission spectrometry.

### THEOREY FRAME OF BEST MEDIUM SELECTION BASED ON FUZZY SET EVALUATION MODEL

#### Select assessment parameters

Selecting representative rational parameters is crucial to the comprehensive assessment of bioretention media. The assessment parameter set \( U \) is established on the basis of their characteristics of affecting water body quality. Seven indices of pollutants are selected, namely, NO\(_3\)-N, NH\(_4\)-N, TP, Cd\(^{2+}\), Cu\(^{2+}\), Pb\(^{2+}\) and Zn\(^{2+}\). The assessment parameter set \( U \) is expressed as

\[
U = \{u_1, u_2, \ldots, u_n\}
\]

where \( n \) is the number of selected assessment parameters (\( n = 7 \)).

#### Establish assessment criteria

The assessment criterion set \( V \) is constructed by the experimental results of the pollutant removal rates of the bioretention media. According to the experimental results, the degrees of pollutant removal can be divided into five grades: high (1), higher (2), medium (3), lower (4) and low (5). The assessment criterion set \( V \) is expressed as

\[
V = \{v_1, v_2, \ldots, v_m\}
\]

where \( m \) is the number of assessment criterion categories. The assessment criteria are classified into five levels.

The construction process is as follows. First, the minimum removal rate is subtracted from the maximum removal rate. Next, the rates are equally divided into five sections (\( m = 5 \)). Finally, the assessment standard of the five grades is obtained by the seven indices (\( n = 7 \)) for all the bioretention media. Table 4 shows the values of the assessment standard.

#### Establish membership functions of fuzzy pollutant removal efficiencies

The membership functions represent the membership degrees to which specified pollutant removal efficiencies belong to the fuzzy set. The larger the membership function, the better for the pollutant removal efficiency assessment parameters. For example, the membership functions for NH\(_4\) are

\[
\pi_{ij}(c_i) = \begin{cases} 
1 & c_i \geq v_{i1} \\
\frac{(c_i - v_{i2})}{v_{i1} - v_{i2}} & v_{i2} < c_i < v_{i1}, \\
0 & c_i \leq v_{i2}
\end{cases}
\]

where

\[
v = \frac{1}{m} \sum_{i=1}^{m} v_i
\]

Table 3 | Characteristics of synthetic stormwater used in experiments

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>Chemical</th>
<th>Concentration (mg/L except pH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>HCl or NaOH</td>
<td>7.0 ± 0.5</td>
</tr>
<tr>
<td>Nitrate (mg/L as N)</td>
<td>NaNO(_3)</td>
<td>15 (as N)</td>
</tr>
<tr>
<td>Ammonium (mg/L as N)</td>
<td>NH(_4)Cl</td>
<td>12 (as N)</td>
</tr>
<tr>
<td>Phosphorus (mg/L as P)</td>
<td>Na(_3)HPO(_4)</td>
<td>0.28 (as P)</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Cd(NO(_3))(_2)</td>
<td>0.0007 (as Cd(^{2+}))</td>
</tr>
<tr>
<td>Zinc</td>
<td>ZnCl(_2)</td>
<td>0.92 (as Zn(^{2+}))</td>
</tr>
<tr>
<td>Lead</td>
<td>PbCl(_2)</td>
<td>0.016 (as Pb(^{2+}))</td>
</tr>
<tr>
<td>Copper</td>
<td>CuSO(_4)</td>
<td>0.017 (as Cu(^{2+}))</td>
</tr>
</tbody>
</table>

Table 4 | Medium assessment standard based on experimental data (%)

<table>
<thead>
<tr>
<th>Class</th>
<th>Criterion</th>
<th>NO(_3)-N</th>
<th>NH(_4)-N</th>
<th>TP</th>
<th>Cd(^{2+})</th>
<th>Cu(^{2+})</th>
<th>Pb(^{2+})</th>
<th>Zn(^{2+})</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Excellent</td>
<td>&gt;19</td>
<td>&gt;86</td>
<td>&gt;84</td>
<td>&gt;99.6</td>
<td>&gt;88</td>
<td>&gt;96</td>
<td>&gt;98.6</td>
</tr>
<tr>
<td>Higher</td>
<td>Good</td>
<td>15–19</td>
<td>79–86</td>
<td>81–84</td>
<td>99.3–99.6</td>
<td>82–88</td>
<td>92–96</td>
<td>97.9–98.6</td>
</tr>
<tr>
<td>Medium</td>
<td>Ordinary</td>
<td>11–15</td>
<td>72–79</td>
<td>78–81</td>
<td>99–99.5</td>
<td>76–82</td>
<td>88–92</td>
<td>97.2–97.9</td>
</tr>
<tr>
<td>Lower</td>
<td>Poor</td>
<td>7–11</td>
<td>65–72</td>
<td>75–78</td>
<td>98.7–99</td>
<td>70–76</td>
<td>84–88</td>
<td>96.5–97.2</td>
</tr>
<tr>
<td>Low</td>
<td>Bad</td>
<td>&lt;7</td>
<td>&lt;65</td>
<td>&lt;75</td>
<td>&lt;98.7</td>
<td>&lt;70</td>
<td>&lt;84</td>
<td>&lt;96.5</td>
</tr>
</tbody>
</table>
where \( c_i \) denotes the actual pollutant removal data of the \( i \)-th assessment parameter and \( v_{ij} \) is the criterion value of the \( i \)-th assessment parameter at the \( j \)-th level (\( i = 1, 2, \ldots, n \); \( j = 1, 2, \ldots, m \)).

### Calculate membership function matrix

By substituting the data of the assessment parameters at the monitoring sites and the national standards into the membership functions, we can obtain the fuzzy matrix \( R \), which is expressed as

\[
R = (r_{ij})_{n \times m} = \begin{pmatrix}
    r_{11} & r_{12} & \cdots & r_{1m} \\
    r_{21} & r_{22} & \cdots & r_{2m} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{n1} & r_{n2} & \cdots & r_{nm}
\end{pmatrix},
\]

where \( r_{ij} \) (\( i = 1, 2, \ldots, n \); \( j = 1, 2, \ldots, m \)) is the membership degree of the \( i \)-th assessment parameter at the \( j \)-th level.

### Calculate weight matrix

In this study, the IAHP method is used for calculating the weights of all indices as follows.

**Step 1:** Constructing hierarchical structure. The hierarchy comprises two levels. The first level contains the goal weights of the indices, and the second contains the given indices.

**Step 2:** Constructing judgment matrix. Pairwise comparisons are conducted, and the judgment matrix is obtained. The comparisons are used to form a matrix of pairwise comparisons called the ‘judgment matrix \( A \)’ (Ashtari & Barzegar 2011). The pairwise comparison for \( n \) indices is as follows:

\[
A = \begin{pmatrix}
    1 & \cdots & a_{1n} \\
    \vdots & \ddots & \vdots \\
    a_{n1} & \cdots & 1
\end{pmatrix},
\]

where \( a_{ij} \) is the preferable or importance ratio of index \( i \) over index \( j \). Each entry \( a_{ij} \) of the judgment matrix is governed by three rules: \( a_{ij} > 0 \), \( a_{ij} = 1 / a_{ji} \), and \( a_{ii} = 1 \) for all \( i \).

**Step 3:** Calculating local weights. The local weights of the indices are calculated by the judgment matrices using the accelerating genetic algorithm (AGA) method. The AGA is calculated as shown in Figure 1.

### Determining evaluation results

Evaluation results can be obtained from the fuzzy matrix algorithm of \( WR \), the fuzzy matrix \( R = (r_{ij})_{n \times m} \), and the weight matrix \( W = (w_i)_{1 \times n} \). The matrix algorithm results \( B \) can be calculated as follows:

\[
B = WR = (b_1, b_2, \ldots, b_m),
\]

where \( b_j = \sum_{i=1}^n w_i a_{ij}, j = 1, 2, \ldots, m \). The evaluation result is

\[
Class = \max (b_j), j = 1, 2, \ldots, m,
\]

where the maximum value of \( b_j \) determines the comprehensive removal rate class of the bioretention media.

### Other comprehensive assessment models

In this work, set pair analysis–IAHP (SPAIAHP) (Mei et al. 2015) and a back propagation (BP) dynamic neural network (Yang et al. 2014) are also applied to select the bioretention medium with the best multi-pollutant removal capacity.
SPAIAHP is implemented as follows. Firstly, an IAHP model is established for the weights. ① A hierarchical structure is built. ② The judgment matrix is constructed. ③ Local weights are established. ④ The judgment matrix is checked for consistency. Secondly, an SPAIAHP model is established to address the complex assessment problem. ① Two sets are constructed. ② The connection degree of each layer is determined. ③ The connection number of each layer is calculated. Finally, the evaluation degrees of the bioretention media are calculated.

The BP neural network is a multilayer feedforward nonlinear mapping network with BP algorithm training. In detail, the assessment procedure for the dynamic neural network is as follows. ① The input and output vectors are established. ② Samples are generated. ③ The BP dynamic neural network is trained. ④ The BP dynamic neural network is tested. ⑤ Finally, the actual monitoring samples are inputted into a BP dynamic neural network to obtain the comprehensive removal efficiency of each medium. The BP algorithm program is illustrated in Figure 2.

RESULTS AND DISCUSSION

Status of pollutant removal efficiency of sand media in bioretention

The effects of the seven soil media on the removal of pollutants were tested through a medium optimisation experiment in a bioretention system, and the results are shown in Figure 3.

As shown in Figure 3(a), the removal rates for ammonia nitrogen by the seven soil media followed the following order: Media VI > Media II > Media III > Media V > Media I > Media VII > Media IV. Media VI (>90%) had the highest ammonia nitrogen removal rate. Davis et al.
and Hsieh & Davis (2005) found that the clay and silt content in soil media have a positive relationship with the capability of the soil media to adsorb ammonia nitrogen. However, Media V and VII had relatively low pollutant removal rates despite having high clay and silt contents. This finding was associated with the turbidity of the samples collected from the two media. Thus, media with low clay content should be selected. The ammonia adsorption capacity of a medium increases with the soil clay content, but the oxygen content of the medium decreases with an increase in soil clay content, thereby making the formation of aerobic environments difficult. The quantitative relationship among the removal rate, adsorption capacity and nitrification process of ammonia nitrogen in different
bioretention media is unclear and yet to be verified through future batch experiments.

The average removal rates of TP by the seven selected soil media were all more than 70% and followed this order: Media II > Media III > Media VII > Media VI > Media V > Media IV > Media I. Media I and IV achieved low TP removal rates. This result may be related to the low Fe content in Media I and IV (Table 2). The soil media with a high metal content (such as calcium, aluminium and iron) exhibit a significant adsorption of phosphorus (Arias et al. 2001).

The nitrate removal by seven soil media was low; this result is consistent with previous studies (Davis et al. 2001). The relations were: Media VI > Media I > Media V > Media VII > Media II > Media III > Media IV. Media IV achieved the lowest nitrate removal rate (less than 5%) among the soil media. The physical and chemical properties of the media may have influenced the removal effect on various pollutants.

In Figure 5(b), a high removal rate of cadmium (100%) is shown in all media except Media II (98.5%). The removal rate of Cu$^{2+}$ by the seven soil media followed the order: Media VII (99.5%) > Media III (97.2%) > Media V (92.2%) > Media IV (95.9%) > Media I (86.6%) > Media II (77.3%) > Media VI (64.7%). The result indicated that soil media with high silt and clay contents achieve a relatively high copper removal rate. The six soil media achieved a high removal rate of Pb$^{2+}$ (100%), except Media VI (80.6%).

The removal rate of Zn$^{2+}$ by seven soil media followed the following order: Media III (99.7%) > Media VII (99.4%) > Media V (99%) > Media IV (98.9%) > Media I (98.7%) > Media II (97%) > Media VI (95.9%). The result denoted that soil media with high silt and clay contents achieve a high removal rate for Zn$^{2+}$. The order of the removal rate of Zn$^{2+}$ was consistent with that of Cu$^{2+}$.

In general, the removal rates of NO$_3$-$N$ and TP varied from 3.7% to 23.9%, 72.1% to 86.9%, and averages of 13.8% and 81.4%, respectively. The removal rate of NO$_3$-$N$ and TP did not reflect any difference among the seven bioretention media. The removal rates of NH$_4$-$N$ and Cu$^{2+}$ changed from 58.1% to 92.7% and 64.7% to 95.9%, correspondingly, with an average of 80.7% and 85.5%, respectively. These results indicate various fluctuations in the removal rate of NH$_4$-$N$ and Cu$^{2+}$ by using seven media. The removal efficiency of Cd$^{2+}$, Pb$^{2+}$ and Zn$^{2+}$ ranged from 98.5% to 100%, 80.3% to 100% and 95.9% to 99.7%, correspondingly. Numerous studies have considered bioretention a BMP that can remove approximately 100% of lead and zinc (Davis et al. 2003; Li & Davis 2009; Chapman & Horner 2010).

**Correlation analysis of chemical characteristics and pollutant removal efficiency of bioretention media**

The relationship between chemical characteristics and pollutant removal efficiency of bioretention media was analysed by Pearson’s correlation (Table 5). A high positive correlation ($p < 0.01$) was observed between the removal rates of Cu$^{2+}$ and Zn$^{2+}$ ($F = 0.979$, $R^2 = 0.673$). Moreover, a significant positive correlation ($p < 0.05$) was also observed between the removal rates of Cu$^{2+}$ and Pb$^{2+}$ ($F = 0.838$, $R^2 = 0.63$) and Pb$^{2+}$ and Zn$^{2+}$ ($F = 0.780$, $R^2 = 0.479$). These results suggest that a synergistic effect which can be effectively removed by the bioretention media occurs in Cu$^{2+}$ and Zn$^{2+}$.

**Pollutant removal efficiency of different depths of soil media**

Figure 4(a) illustrates that the removal rate of ammonia nitrogen increases with soil media depth, except Media VII. Media I, II and III had a rapid increase in ammonia nitrogen removal rate with the increase in the soil media depth. By contrast, the growth rates of Media IV, V and VI were relatively slow. The increase in media depth was helpful to increasing the removal rate of ammonia nitrogen. Figure 4(b) depicts that media depth has the most significant effect on the removal rate of nitrate nitrogen, thereby obviously increasing the nitrate removal efficiency. This result may be related to the robust anaerobic condition in deep soil media. Figure 4(c) demonstrates that the removal rates of TP and media depth are unrelated. Overall, the removal rate of TP increased with the media depth. That is, depth is important for an effective P removal, and deep media will result in significant P removal. However, the extent of concentration reduction for P is minimal with the increase in depth (Li & Davis 2016). In Figure 4(d), the removal rate of Cd$^{2+}$ increased with the media depth. Thus, the removal rates of Cd$^{2+}$ in the soil media depth between 40 and 60 cm change slightly because Cd$^{2+}$ has a robust tendency to accumulate on the surface of the bioretention column. This result is consistent with the research conducted by Wang et al. (2016).

In Figure 4(e), the removal rate of Cu$^{2+}$ obviously changed with the different soil media depth which increased with the media soil depth. In Figure 4(f), the removal rate of Pb$^{2+}$ reached 100% in Media II, IV and VII at the depth of 40 and 60 cm. The removal rate of Pb$^{2+}$ was lowest in Media V which was 83.26% at the depth of 60 cm. Media V was sandy clay loam. Figure 4(g) exhibits that the removal rate...
Table 5 | Pearson’s correlation coefficient of chemical characteristics and pollutant removal efficiency of bioretention media

| Pearson’s correlation coefficient | As | Cd | Co | Cr | Cu | Fe | Mn | Ni | P | Pb | Zn | NO₃ | NH₄⁺ | TP | Cd | Cu | Pb | Zn |
|----------------------------------|----|----|----|----|----|----|----|----|----|----|----|-----|-----|-----|----|----|----|----|----|
| As                               | 1  |    |    |    |    |    |    |    |    |    |    |     |     |     |    |    |    |    |    |
| Cd                               | 0.927** | 1  |    |    |    |    |    |    |    |    |    |     |     |     |    |    |    |    |    |
| Co                               | 0.835*  | 0.979** | 1  |    |    |    |    |    |    |    |    |     |     |     |    |    |    |    |    |
| Cr                               | 0.903** | 0.947** | 0.906** | 1  |    |    |    |    |    |    |    |     |     |     |    |    |    |    |    |
| Cu                               | 0.736   | 0.892** | 0.936** | 0.719 | 1  |    |    |    |    |    |    |     |     |     |    |    |    |    |    |
| Fe                               | 0.913** | 0.994** | 0.973** | 0.958** | 0.872* | 1  |    |    |    |    |    |     |     |     |    |    |    |    |    |
| Mn                               | 0.910** | 0.993** | 0.979** | 0.922** | 0.919** | 0.992** | 1  |    |    |    |    |    |     |     |    |    |    |    |    |
| Ni                               | 0.803*  | 0.958** | 0.992** | 0.861*  | 0.964** | 0.945** | 0.963** | 1  |    |    |    |    |     |     |    |    |    |    |    |
| P                                | 0.914** | 0.868*  | 0.779*  | 0.945** | 0.565   | 0.861*  | 0.815*  | 0.722 | 1  |    |    |    |     |     |    |    |    |    |    |
| Pb                               | 0.507   | 0.764*  | 0.873*  | 0.673   | 0.852*  | 0.748   | 0.764*  | 0.892** | 0.480 | 1  |    |    |     |     |    |    |    |    |    |
| Zn                               | 0.845*  | 0.977** | 0.994** | 0.878** | 0.962** | 0.966** | 0.982** | 0.995** | 0.756 | 0.854* | 1  |    |     |     |    |    |    |    |    |
| NO₃                              | −0.123  | −0.201  | −0.282  | −0.244  | −0.255  | −0.195  | −0.210  | −0.308  | −0.063 | −0.534 | −0.249 | 1  |    |     |     |    |    |    |    |    |
| NH₄⁺                             | 0.323   | 0.307   | 0.235   | 0.255   | 0.244   | 0.368   | 0.362   | 0.193   | 0.216  | −0.131 | 0.257 | 0.608 | 1  |    |     |     |    |    |    |    |    |
| TP                               | 0.589   | 0.459   | 0.592   | 0.413   | 0.453   | 0.475   | 0.520   | 0.404   | 0.216  | 0.174  | 0.425  | −0.424 | 0.273 | 1  |    |     |     |    |    |    |    |    |
| Cd                               | −0.162  | −0.123  | −0.082  | −0.329  | 0.102   | −0.217  | −0.158  | −0.018  | −0.193 | 0.068  | −0.025 | 0.291  | −0.334 | −0.492 | 1  |    |     |     |    |    |    |    |    |
| Cu                               | 0.455   | 0.544   | 0.584   | 0.555   | 0.490   | 0.480   | 0.474   | 0.608   | 0.578  | 0.686  | 0.567  | −0.450 | −0.555 | −0.74  | 0.331 | 1  |    |     |     |    |    |    |    |    |
| Pb                               | 0.357   | 0.504   | 0.564   | 0.641   | 0.361   | 0.496   | 0.448   | 0.559   | 0.566  | 0.679  | 0.503  | −0.590 | −0.445 | −0.25  | 0.167 | 0.838* | 1  |    |     |     |    |    |    |    |    |
| Zn                               | 0.397   | 0.541   | 0.611   | 0.500   | 0.564   | 0.474   | 0.481   | 0.647   | 0.490  | 0.763* | 0.601  | −0.428 | −0.535 | −0.128 | 0.435 | 0.979** | 0.78* | 1  |    |     |     |    |    |    |    |    |

*Correlation is significant at the 0.05 level (two-tailed).
**Correlation is significant at the 0.01 level (two-tailed).
of \( Zn^{2+} \) obviously changed with the soil media depth. The removal rate of \( Zn^{2+} \) increased with the increase in the soil media depth. Media V had a minimal \( d_{10} \) and \( d_{60} \), thereby improving the residence time of pollutants in the media and demonstrating a robust capability for removing pollutants. Media VII and IV achieved a poor capability on the removal of comprehensive pollutants, considering the high clay content. The sand that flowed with water resulted in a relatively low pollutant removal capacity.

**FSE**

The FSE model is used to assess the removal efficiency of the bioretention media based on the monitoring data and the constructed index standards. The \( NO_3^- - N \), \( NH_4^+ - N \), TP, \( Cd^{2+} \), \( Cu^{2+} \), \( Pb^{2+} \) and \( Zn^{2+} \) are selected as assessment parameters to form the assessment factor set \( U \), \( U = \{ NO_3^- - N, NH_4^+ - N, TP, Cd^{2+}, Cu^{2+}, Pb^{2+}, Zn^{2+} \} \). An assessment criteria set \( V \) is also established in accordance with equally dividing the removal rate of pollutants. The removal rates by the seven bioretention media of the seven assessment parameters are presented in Figure 3.

Based on Equations (3)–(5), the membership functions of \( NO_3^- - N \), \( NH_4^+ - N \), TP, \( Cd^{2+} \), \( Cu^{2+} \), \( Pb^{2+} \) and \( Zn^{2+} \) under the five-level standards are established. The membership functions of \( NO_3^- - N \), \( NH_4^+ - N \), TP, \( Cd^{2+}, Cu^{2+} \), \( Pb^{2+} \) and \( Zn^{2+} \) are expressed in Equations (3)–(5).

We obtained the fuzzy matrices of \( R_1 \text{--} R_7 \) for the seven bioretention media after substituting the actual pollutant removal data from each sampling site into the membership...
functions. For example, the fuzzy matrix for Media I is

\[
R_1 = \begin{pmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 0.93 & 0.07 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0.47 & 0.53 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0
\end{pmatrix}
\]

The normalisation values of all the original monitoring data are substituted into Equation (7). We obtain the weights of NO$_3$-N, NH$_4$-N, TP, Cd$^{2+}$, Cu$^{2+}$, Pb$^{2+}$ and Zn$^{2+}$. The weight matrix is 

\[
W = (0.3596, 0.1650, 0.1764, 0.0921, 0.0583, 0.0921, 0.0565).
\]

The fuzzy matrixes for the other sampling sites are disregarded in this paper. The fuzzy algorithm \(B \cdot R\) expresses the following result of Media I:

\[
W \cdot R_1 = (0.3596 \ 0.1650 \ 0.1764 \ 0.0921 \ 0.0583 \ 0.0921 \ 0.0565).
\]

\[
R_1 = W \cdot \begin{pmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 0.93 & 0.07 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0.47 & 0.53 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0
\end{pmatrix}
\]

\[
= (0.5356 \ 0.1843 \ 0.0116 \ 0.2685)
\]
The assessment result can be obtained from the results of fuzzy operation \( W \cdot R_1 \) and Equation (9). The multi-pollutant removal efficiency of Media I belongs to Class I because the membership degree is higher in Class I (0.5356) than in Class II (0.1843), Class III (0.0116), Class IV (0) and Class V (0.2685).

We obtain the FSE results for the multi-pollutant removal efficiency of the other bioretention media by using the same process. The fuzzy comprehensive assessment results of the multi-pollutant removal efficiency of the seven types of media follow the order: Media III (0.6510) > Media V (0.6428) > Media I (0.5356) > Media VI (0.5130) > Media II (0.4315) > Media VII (0.3282) > Media IV (0.3036). Media III achieves the high comprehensive removal capacities, which may be due to the high contents of OM (1.31%) and CEC (16.42 cmol/kg) in Media III. The result of the fuzzy comprehensive evaluation is consistent with the experimental result of the pollutant removal efficiency of bioretention media.

The bioretention system is a pollution control measure for the urban non-point source, and the effect of this system on the amount of water is also crucial. Soil media is a major component of the bioretention system and influences the performance of the entire system. Thus, the comprehensive pollutant removal efficiency and rainfall runoff infiltration effect are two important considerations in selecting soil media. We set a soil seepage rate of more than 1 inch/h in this study considering the foreign lowest infiltration standard (Dietz 2007). Media III and V achieve the optimal water quality comprehensive removal effect, and their percolation rates are lower than the lowest standard abroad. Thus, Media I is a favourable bioretention system soil medium considering water quantity and quality.

In this study, the FSE model is used to assess the comprehensive efficiency of the bioretention sand media. Simultaneously, the two other kinds of comprehensive assessment models are introduced to calculate the evaluation degree of bioretention media. The comparison results are summarised in Table 6.

In Table 6, the evaluation results of the FSE, SPAIAHP and BP neural network models are nearly uniform. The fuzzy analysis method is a mature evaluation method. In addition, the result of the FSE model is more credible and objective than the SPAIAHP model because the FSE model demonstrates a direct, credible and favourable application. The BP neural network model has the hidden layer which improved the uncertainty of the evaluation results. Therefore, the FSE model is a rational model for comprehensive assessment of the bioretention media and has the favourable functions of arrangement, objective and minimal uncertainty.

### CONCLUSION

The soil media of bioretention with high removal rates of nutrient and heavy metals were optimised through the experiment research combined with a comprehensive evaluation model. The main conclusions are as follows:

1. Among the seven selected soil media, Media VI demonstrated the highest removal rate of ammonia nitrogen (more than 90%). Media VII and IV with high clay and silt contents achieved a relatively low pollutant removal efficiency because of the sand that flowed with water. Thus, the soil media with high clay content were unsuitable. The removal rate of TP in all soil media was more than 70%. Media I and IV, with a low Fe content, achieved a low removal rate of TP. All selected soil media exhibited a low removal rate of nitrate and a high removal rate of \( \text{Cd}^{2+} \), \( \text{Pb}^{2+} \) and \( \text{Zn}^{2+} \). The removal rates of \( \text{Cu}^{2+} \) and \( \text{Zn}^{2+} \) increased.

<table>
<thead>
<tr>
<th>Types of media</th>
<th>Connection number of FSE</th>
<th>Degree of FSE</th>
<th>Connection number of SPAIAHP</th>
<th>Degree of SPAIAHP</th>
<th>Connection number of BP</th>
<th>Degree of BP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Media I</td>
<td>0.5356</td>
<td>2</td>
<td>0.5897</td>
<td>2</td>
<td>0.8745</td>
<td>2</td>
</tr>
<tr>
<td>Media II</td>
<td>0.4315</td>
<td>2</td>
<td>0.2249</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Media III</td>
<td>0.6510</td>
<td>1</td>
<td>0.3592</td>
<td>2</td>
<td>0.922</td>
<td>2</td>
</tr>
<tr>
<td>Media IV</td>
<td>0.3036</td>
<td>5</td>
<td>−0.2671</td>
<td>5</td>
<td>0.7834</td>
<td>5</td>
</tr>
<tr>
<td>Media V</td>
<td>0.6428</td>
<td>1</td>
<td>0.9042</td>
<td>1</td>
<td>0.9652</td>
<td>1</td>
</tr>
<tr>
<td>Media VI</td>
<td>0.5130</td>
<td>2</td>
<td>0.5192</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Media VII</td>
<td>0.3282</td>
<td>3</td>
<td>0.1789</td>
<td>3</td>
<td>0.7689</td>
<td>3</td>
</tr>
</tbody>
</table>
with the silt and clay contents in the soil media. The physical and chemical properties of media may influence the removal effect on various pollutants in different media. In general, the pollutant removal efficiency in the seven selected soil media increases with the soil media depth.

(2) The FSE model with the IAHP for weight determination was firstly used to assess the multi-pollutant removal efficiency of the bioretention media. The results indicated that the IAHP for weight determination is effective for the multi-pollutant removal efficiency evaluation. The results of the multi-pollutant removal efficiency assessment of the bioretention media indicated that all of the media belong to Class I. Simultaneously, the ranks of the bioretention media were Media III > Media V > Media I > Media VI > Media II > Media VII > Media IV. The assessment results were consistent with the actual characteristics of the bioretention media. Therefore, the FSE model is a rational model for evaluating the bioretention media and has the favourable functions of arrangement, objective and minimal uncertainty.

(3) Media I with an acceptable comprehensive removal capacity and infiltration rate was the favourable soil media of the bioretention system considering the water comprehensive evaluation results.

ACKNOWLEDGEMENTS

This work is supported by the Project of National Natural Science Foundation of China (No. 21667020), Project of Doctor Natural Science Foundation of Inner Mongolia (No. 2014BS0505), the Inner Mongolia Autonomous Region science and technology innovation project guide, Science and Research Projects of Inner Mongolia University of Technology (ZD201506).

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