Wastewater treatment evaluation for enterprises based on fuzzy-AHP comprehensive evaluation: a case study in industrial park in Taihu Basin, China

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Abstract
This paper applied the fuzzy comprehensive evaluation (FCE) technique and analytic hierarchy process (AHP) procedure to evaluate the wastewater treatment for enterprises. Based on the characteristics of wastewater treatment for enterprises in Taihu basin, an evaluating index system was established for enterprise and analysis hierarchy process method was applied to determine index weight. Then the AHP and FCE methods were combined to validate the wastewater treatment level of 3 representative enterprises. The results show that the evaluation grade of enterprise 1, enterprise 2 and enterprise 3 was middle, good and excellent, respectively. Finally, the scores of 3 enterprises were calculated according to the hundred-mark system, and enterprise 3 has the highest wastewater treatment level, followed by enterprise 2 and enterprises 1. The application of this work can make the evaluation results more scientific and accurate. It is expected that this work may serve as an assistance tool for managers of enterprise in improving the wastewater treatment level.

Keywords: Analytic hierarchy process (AHP), Fuzzy comprehensive evaluation (FCE), Wastewater treatment evaluation, Evaluating index, Membership function, Taihu basin

Background
As the third largest freshwater lake in China, Taihu plays an important role in flood control, water supply, and fishery in Yangtze River Delta region. Due to the rapid development of economy in Taihu Lake Basin and different construction level of surrounding industrial park, a large number of wastewater was discharged into the Taihu lakes, which has serious harmful on the water quality of Taihu. Therefore, it is important to carry out the wastewater treatment evaluation of enterprise in industrial park, which has practical significance for enterprise to strengthen pollution control.

In order to accurately evaluate the level of wastewater treatment of enterprise, it is important to choose the scientific and effective methods. Fuzzy Theory is a method used to study and deal with fuzzy phenomena; it has lasted 50 years since it was first proposed by Zadeh (1965, 1975). With development of fuzzy comprehensive evaluation method, the Fuzzy Analytical Hierarchy Process (FAHP) was developed based on the
theory of FCE and AHP, and has been extensively applied in the fields of safety and risk assessment (Lai et al. 2015; Li et al. 2015; Chen et al. 2014; Padma and Balasubramanie 2011), technological comparison (Chen et al. 2015; Liu et al. 2014; Gim and Kim 2014), environmental evaluation (Shi et al. 2014; Feng et al. 2014), market decisions (Lee et al. 2011; Ho 2012; Li et al. 2014; Tsai et al. 2008), appearance products design (Hsiao and Ko 2013; Hsiao 1995, 1998; Hsiao and Chen 1997; Hsiao and Wang 1998), and facility location applications (Choudhary and Shankar 2012; Kaya and Kahraman 2010; Kabir and Sumi 2014) etc. However, it is rarely applied in the field of wastewater treatment evaluation in industrial park.

On the basis of this background, this paper adopted fuzzy-AHP comprehensive evaluation approach to study the wastewater treatment evaluation for enterprises in Taihu Basin, China. It is expected that this work may serve as an assistance tool for managers of enterprise in improving the wastewater treatment level.

Theoretical background

Fuzzy comprehensive evaluation

Fuzzy comprehensive evaluation steps included five parts: establishing the evaluation parameter, determining factor weight, constructing a parameter evaluation, building a single factor evaluation matrix and conducting fuzzy evaluation, as follows:

1. Establishing the evaluation parameter
   For fuzzy evaluation, factors affected the evaluation parameter should first be constructed. If the affected factors are $u_1, u_2, \ldots, u_m$, the parameters set can define:
   \[ U = \{u_1, u_2, \ldots, u_m\} = \{u_i\}, \quad (i = 1, 2, \ldots, m). \]

2. Determining factor weight
   Each factor has a different impact on the parameters. So the factors have different weights for parameter values. The set composed of various weights of all factors is called the factor weight set, which is represented as $A = \{a_1, a_2, \ldots, a_n\}$. The weight of each factor must satisfy Eq. (1).
   \[ \sum_{i=1}^{n} a_i = 1, \quad a_i \geq 0, \quad i = 1, 2, \ldots, n \] (1)

   There are many methods to confirm the index weight, such as the expert evaluation method, least squares estimation, AHP method and etc. The AHP is much more widely used by the analyzers. This method can analyze the important degree of the index more logically than other methods, and correspondingly the result disposed by mathematics are more reliable. In this study, AHP method was used to determining the factor weight.

3. Constructing a parameter evaluation
   An evaluation set is the set of various possible evaluation results given by evaluators for the evaluation objects, shown as $V = \{v_1, v_2, \ldots, v_n\} = \{v_j\}, \quad (j = 1, 2, \ldots, n)$, where $v_j$ is the grade of evaluation. The purpose of fuzzy evaluation is to obtain an optimal evaluation result from the evaluation set.
(4) Building a single factor evaluation matrix

A single factor fuzzy evaluation system was used to determine the membership of an evaluation object. The evaluation result of No. i factor U_i can be expressed as:

\[ R_i = (r_{i1}, r_{i2}, \ldots, r_{in}) \]
\[ R_2 = (r_{21}, r_{22}, \ldots, r_{2n}) \]
\[ \vdots \]
\[ R_m = (r_{m1}, r_{m2}, \ldots, r_{mn}) \]

where \( r_{mn} \) represents the membership degree of j factors to comment V_i, \( R_m \) is called single factor evaluation set.

(5) Conducting fuzzy evaluation

If the fuzzy evaluation matrix of an evaluation object is:

\[
R = \begin{bmatrix}
R_1 \\
R_2 \\
\vdots \\
R_m
\end{bmatrix} = \begin{bmatrix}
r_{11} & r_{12} & \cdots & r_{1n} \\
r_{21} & r_{22} & \cdots & r_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
r_{m1} & r_{m2} & \cdots & r_{mn}
\end{bmatrix}
\]

Then the comprehensive fuzzy evaluation matrix is:

\[
B = A \cdot R = (a_1, a_2, \ldots, a_n) \cdot \begin{bmatrix}
r_{11} & r_{12} & \cdots & r_{1n} \\
r_{21} & r_{22} & \cdots & r_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
r_{m1} & r_{m2} & \cdots & r_{mn}
\end{bmatrix} = (b_1, b_2, \ldots, b_n)
\]

where B is the evaluation result based on all factors in the index system U. In the above equation, the symbol “•” represent fuzzy composition. This study will use \( M(\cdot, +) \) algorithm to work out various evaluation results for comparison and analysis.

**Analytic hierarchy process**

Analytical Hierarchy Process (AHP), first introduced by Saaty (1980), is a systematic approach to solving complex and multi-level decision-making problems. Based on the expert judgments, the criteria are compared in a pairwise fashion to assess how they contribute to the target. However, in many cases the preference model of the human decision-maker is uncertain and fuzzy, and the comparison ratios are relatively difficult to be provided. The decision-maker may be uncertain due to incomplete information or knowledge, inherent complexity and uncertainty within the decision environment. Therefore, some researchers have improved the fuzzy pairwise comparison judgements. In Rezaei’s study (Rezaei et al. 2013), they improve a fuzzy AHP and then apply it using the pairwise comparisons of three experts to evaluate the entrepreneurship orientation of 59 small to medium-sized enterprises (SMEs) and rank the firms based on their entrepreneurship orientation score. In Mikhailov’s study (Mikhailov 2003), a new approach for deriving priorities from fuzzy pairwise comparison judgements is proposed, based on \( \alpha \)-cuts decomposition of the fuzzy judgements into a series of interval comparisons. Meanwhile, a modification of the linear fuzzy preference programming method is also proposed to derive priorities directly from fuzzy judgements, without applying \( \alpha \)-cut transformations. Both proposed methods are illustrated by numerical examples and compared to some of the existing fuzzy prioritisation methods. Leung and Cao (2000)
proposes a fuzzy consistency definition with consideration of a tolerance deviation, and
determined the fuzzy local and global weights via the extension principle.

The AHP method can be divided into the five steps:
Step 1: Defining the decision-making problem.
Step 2: Constructing a hierarchical structure.
Step 3: Building a pairwise comparison matrix.
Step 4: Calculate eigenvalues.
Step 5: Conformance test.
A consistency ratio (CR) must be computed [Eq. (5)] to check the discordances
between the pairwise comparisons and the reliability of the obtained weights. The value
must be <0.1 to be accepted; otherwise, it is necessary to recalculate the weight.

\[
CR = \frac{CI}{RI}
\]  

(5)

where RI is a random index represented the consistency of a randomly generated pair-
wise comparison matrix. Its reference standard, shown in Table 1, was computed and
recommended by Saaty (1980). CI represents the consistency index computation:

\[
CI = \frac{\lambda_{max} - n}{n - 1}
\]  

(6)

where \(\lambda_{max}\) is the largest eigenvalue of the matrix, n is matrix order (number of
parameters).

**Case study**

**Construction of evaluation index system**
The wastewater treatment for enterprises evaluation system is a big system, which can
be divided into economy, society and environment subsystems. Due to the abundant
factors contained, it is necessary to choose several representative factors as evaluation
index. The choice of index should pay attention to the comprehensive, representative,
reasonable and realistic aspects of factor. Both comprehensive and particular features of
the wastewater treatment for enterprises should be indicated.

According to the above principles, and combined with the characteristics of industrial
wastewater treatment in Taihu Basin, 12 index of wastewater treatment evaluation sys-
tem for enterprises was constructed from three aspects (environmental protection ben-
efit, resource utilization benefit and recycling benefit) in this paper, as shown in Table 2.

**Data collection and analysis**
Measurement methods of COD, NH\textsubscript{3}-N, TP, TN and colority pollutant concentration
are carried out in accordance with the Chinese national standard method, which are
shown in Table 3.

| n  | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| RI | 0   | 0   | 0.58| 0.90| 1.12| 1.24| 1.32| 1.41| 1.45| 1.49| 1.51| 1.48| 1.56| 1.57| 1.58|
Effluent pollutant concentration of COD, NH$_3$-N, TP, TN and colority comes from the monthly routine monitoring data of enterprises, while unit product water consumption, unit product wastewater discharge, wastewater treatment cost per ton, operating load of sewage treatment, recycling rate of industrial water and reuse rate of tail water comes from the statistical data of enterprise. The statistical results of 12 indexes of 3 enterprises were seen in Tables 4, 5 and 6 in 2014. It can be seen from the Tables 4, 5 and 6 that the average value of the 12 indexes of enterprise 3 was relatively low, followed by enterprise 2 and enterprise 1.
Table 4 Summary of index actual values for enterprise 1 in 2014

| Index                                | Jan  | Feb  | Mar  | Apr  | May  | Jun  | Jul  | Aug  | Sep  | Oct  | Nov  | Dec  | Average |
|--------------------------------------|------|------|------|------|------|------|------|------|------|------|------|------|---------|
| COD effluent concentration           | 347  | 358  | 388  | 410  | 401  | 329  | 337  | 420  | 360  | 372  | 380  | 313  | 368     |
| NH$_3$-N effluent concentration      | 294  | 27.8 | 36.6 | 26.3 | 28.7 | 25.8 | 28.4 | 33.5 | 29   | 32.5 | 34.7 | 37.1 | 30.8    |
| TP effluent concentration            | 1.7  | 1.8  | 2.3  | 2    | 1.6  | 2.7  | 2.8  | 1.8  | 2.5  | 2.1  | 2.3  | 1.5  | 2.1     |
| TN effluent concentration            | 50.7 | 41.1 | 37.2 | 346  | 35.6 | 53.3 | 50.5 | 42.4 | 48   | 47   | 38.5 | 45.4 | 43.7    |
| Effluent colority                    | 80   | 50   | 60   | 50   | 60   | 60   | 60   | 70   | 50   | 70   | 60   | 60   | 60      |
| Unit product water consumption       | 213.7| 279.3| 203.5| 219.7| 243.2| 199.3| 195.5| 286.5| 217.8| 225.4| 268.6| 190.8| 228.6   |
| Unit product wastewater discharge    | 161.1| 150.6| 140.8| 205.6| 198.5| 133.7| 173.6| 224.2| 139.5| 193.4| 152.4| 183.3| 171.4   |
| Wastewater treatment cost per ton    | 1.12 | 0.8  | 0.91 | 1.04 | 1.59 | 1.16 | 1.25 | 1.06 | 1.21 | 1.37 | 1.17 | 1.23 | 1.16    |
| Operating load of sewage treatment   | 72   | 54   | 57   | 63   | 46   | 81   | 54   | 72   | 59   | 48   | 65   | 48   | 60      |
| Recycling rate of industrial water   | 20   | 32   | 27   | 23   | 36   | 16   | 31   | 23   | 24   | 30   | 22   | 17   | 25      |
| Reuse rate of tail water             | 63   | 56   | 89   | 82   | 64   | 73   | 58   | 61   | 78   | 82   | 69   | 64   | 70      |
| Stability compliance rate of wastewater treatment | 98.8 | 99   | 98.4 | 99.2 | 99.4 | 98.6 | 98.9 | 98.9 | 99.3 | 98.8 | 98.5 | 99.1 | 98.9    |
Table 5  Summary of index actual values for enterprise 2 in 2014

| Index                                | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Average |
|--------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|---------|
| COD effluent concentration           | 248 | 216 | 194 | 173 | 224 | 256 | 237 | 208 | 183 | 165 | 151 | 195 | 204     |
| NH$_3$-N effluent concentration      | 18.5| 19.2| 23.6| 22.6| 24.8| 26.3| 16.4| 17.9| 18.8| 19.5| 27.2| 15.9| 20.9    |
| TP effluent concentration            | 1.2 | 1.5 | 0.7 | 0.8 | 1.1 | 0.9 | 0.6 | 1.8 | 2   | 1.4 | 0.8 | 1.7 | 1.2     |
| TN effluent concentration            | 267 | 23.7| 35.1| 39  | 41.5| 25.4| 22.9| 29.3| 33.5| 38.7| 36.2| 30.6| 31.9    |
| Effluent colority                    | 30  | 40  | 40  | 50  | 60  | 40  | 30  | 40  | 30  | 40  | 40  | 50  | 40      |
| Unit product water consumption       | 125.3| 148.7| 203.6| 224.8| 131 | 154.7| 1604| 138.5| 134.6| 221.5| 178.3| 142 | 163.6   |
| Unit product wastewater discharge    | 117.5| 158.4| 138.9| 126.5| 190.3| 105.8| 1483| 170.6| 163.5| 98.7 | 102.5| 115.6| 136.4   |
| Wastewater treatment cost per ton    | 1.38 | 1.49 | 1.63 | 1.32 | 1.17 | 1.06 | 1.43 | 1.85 | 1.42 | 1.51 | 1.47 | 1.3  | 1.42    |
| Operating load of sewage treatment   | 58  | 70  | 62  | 44  | 38  | 49  | 45  | 36  | 38  | 62  | 53  | 44  | 50      |
| Recycling rate of industrial water   | 37  | 36  | 26  | 22  | 32  | 30  | 28  | 25  | 21  | 36  | 40  | 25  | 30      |
| Reuse rate of tail water             | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0       |
| Stability compliance rate of wastewater treatment | 99.5 | 99.2 | 99.8 | 99.4 | 98.8 | 99.3 | 99.7 | 98.9 | 99.1 | 99.5 | 99.3 | 99.2 | 99.3    |
Table 6  Summary of index actual values for enterprise 3 in 2014

| Index                                | Jan   | Feb   | Mar   | Apr   | May   | Jun   | Jul   | Aug   | Sep   | Oct   | Nov   | Dec   | Average |
|--------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------|
| COD effluent concentration           | 89    | 81    | 172   | 111   | 153   | 110   | 68    | 99    | 140   | 124   | 132   | 163   | 120     |
| NH₃-N effluent concentration         | 9.5   | 16.4  | 7.5   | 11.1  | 8.1   | 18.8  | 10.4  | 14.3  | 17.9  | 10.8  | 15.2  | 10.1  | 12.5    |
| TP effluent concentration             | 0.8   | 0.4   | 0.3   | 1.2   | 1.4   | 1     | 0.3   | 1.2   | 0.4   | 1.2   | 0.7   | 0.8   |         |
| TN effluent concentration             | 27    | 11.3  | 24.5  | 18.9  | 17.6  | 12.1  | 21.9  | 13.7  | 27.2  | 29.8  | 23.5  | 15    | 20.2    |
| Effluent colority                     | 30    | 10    | 20    | 40    | 20    | 10    | 20    | 30    | 20    | 20    | 20    | 10    | 20      |
| Unit product water consumption        | 190   | 1174  | 121   | 124.9 | 164.6 | 207.9 | 211.3 | 141.1 | 128.5 | 135.2 | 146.8 | 111.7  | 150     |
| Unit product wastewater discharge     | 694   | 134.2 | 79.2  | 111.9 | 62.3  | 127.4 | 102.5 | 66.1  | 154   | 90.1  | 81.7  | 122   | 100     |
| Wastewater treatment cost per ton     | 1.42  | 1.54  | 1.29  | 1.18  | 1.59  | 1.97  | 1.63  | 1.75  | 1.44  | 1.56  | 1.53  | 1.61  | 1.54    |
| Operating load of sewage treatment    | 19    | 13    | 24    | 20    | 28    | 13    | 36    | 37    | 33    | 19    | 14    | 45    | 25      |
| Recycling rate of industrial water    | 20    | 18    | 15    | 26    | 15    | 26    | 31    | 16    | 22    | 12    | 11    | 27    | 20      |
| Reuse rate of tail water              | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |         |
| Stability compliance rate of wastewater treatment | 99.8  | 99.6  | 100   | 999   | 997   | 998   | 99.5  | 100   | 99.9  | 99.6  | 99.7  | 100   | 99.8    |
Grading standard
According to the comprehensive consideration of the actual situation of enterprise wastewater treatment in the industrial park of the Taihu basin, the evaluating set is divided into four grades in this study: excellent, good, middle, bad. The grading standard is based on the accessing standard of sewage treatment plant, the field survey, the expert consultation and the cleaner production evaluation index system of the industry in China.

Usually, for the normal operation of the sewage treatment plant, the enterprise’s wastewater must be pretreatment before entering in the sewage treatment plant. Thus the influent concentration of pollutants has an accessing standard, and the accessing standard of COD, NH₃-N, TP, TN and colority of sewage treatment plant were 500, 45, 8, 70 and 70 respectively in this study. Taking the COD as an example, the COD accessing concentration of sewage treatment plant must be less than 500 mg/L, or the sewage treatment plant will be overloaded operation if exceed 500 mg/L. According to the many year operation experiences of sewage treatment plant, the lower influent concentration of COD were, the better treatment effect of sewage treatment plant achieved.

In addition, the expert consultation method was used to determine the grading standard. The designed table for expert consultation was shown in Table 7. 30 copies of the expert consultation form were sent and all of it was recovered. The statistical results of the 30 expert consultation was shown that 4 grading was chosen by 23 experts, 3 grading by 4 experts and 5 grading by 3 experts for question 1. Furthermore, in the 23 consultation table with choice of 4 grading, 20 experts believed that the grading standard of COD were appropriate for 100, 200, 300 and 400. So the COD grading standard was divided into four grades in this study: excellent, good, middle, bad, and the grading standard were 100, 200, 300 and 400 respectively.

Similarly, the grading standard of NH₃-N, TP, TN and colority index can be obtained. At the same time, grading standard of unit product water consumption, unit product wastewater discharge, wastewater treatment cost per ton, operating load of sewage treatment, recycling rate of industrial water and reuse rate of tail water index were obtained by consulting Chinese printing and dyeing industry cleaner production evaluation index system and expert consultation results. Finally, the critical values of the grading standard in this study are shown in Table 8.

Membership function
Since indices vary in range and dimension values, a unified standard is needed in the same evaluation system, which can be solved by membership function. In general, the

Table 7  Designed table for expert consultation

| Expert name | Work unit | Title |
|-------------|-----------|-------|
| Question 1  | What grading number do you think is appropriate? 3, 4, 5, or others? Please write down in the right blank place |
| Question 2  | According to the COD accessing standard of sewage treatment plant and the grading number determined in question 1, what values of each grading do you think is appropriate? Please write down the values of each grading in the right blank place |
membership degree of each level can be determined by the piecewise linear function in fuzzy mathematics and descending semi-trapezoid function was used in this study. According to the critical value of the grading standard (Table 3), the membership degrees of the twelve single evaluation factors to the grading level set were calculated applying the above calculating method given in “Fuzzy comprehensive evaluation” section, and the single-factor evaluation matrices were produced. Taking the enterprise 1 as an example, the membership degree of COD effluent concentration index is calculated as follows:

\[
\begin{align*}
  r_1 &= 0 \\
  r_2 &= 0 \\
  r_3 &= \frac{400 - 368}{400 - 300} = \frac{32}{100} = 0.32 \\
  r_4 &= \frac{368 - 300}{400 - 300} = \frac{68}{100} = 0.68
\end{align*}
\]

Therefore, the membership degree of the COD effluent concentration was \((0, 0, 0.32, 0.68)\). Similarly, the membership degree of other’s index can be obtained. The evaluation matrices of indexes were then formed in follows:

\[
R_1 = \begin{bmatrix}
  0 & 0 & 0.32 & 0.68 \\
  0 & 0 & 0.42 & 0.58 \\
  0.9 & 0.1 & 0 & \\
  0.13 & 0.87 & 0 \\
  0 & 0 & 0.5 & 0.5
\end{bmatrix}
\]

\[
R_2 = \begin{bmatrix}
  0 & 0 & 0.572 & 0.428 \\
  0 & 0 & 0.715 & 0.285 \\
  0.2 & 0.8 & 0 & 0 \\
  0 & 0 & 1 & 0
\end{bmatrix}
\]

| Index                        | Grading standard |
|------------------------------|------------------|
|                              | Excellent | Good | Middle | Bad  |
| COD effluent concentration   | 100       | 200  | 300    | 400  |
| NH₃-N effluent concentration | 5         | 15   | 25     | 35   |
| TP effluent concentration    | 1         | 2    | 3      | 4    |
| TN effluent concentration    | 25        | 35   | 45     | 55   |
| Effluent colority            | 10        | 30   | 50     | 70   |
| Unit product water consumption | 100     | 150  | 200    | 250  |
| Unit product wastewater discharge | 80     | 120  | 160    | 200  |
| Wastewater treatment cost per ton | 1       | 1.2  | 1.4    | 1.6  |
| Operating load of sewage treatment | 80     | 70   | 60     | 50   |
| Recycling rate of industrial water | 40     | 30   | 20     | 10   |
| Reuse rate of tail water     | 40        | 30   | 20     | 10   |
| Stability compliance rate of wastewater treatment | 100    | 99.5 | 99     | 98.5 |
Weight analysis

30 peoples including college students from wastewater treatment-related majors, scholars and experts filled in the questionnaire. The determination of weight is built into a pairwise comparison matrix by AHP. The total sum of what the coefficients related to the pairwise comparison matrix multiply each part’s weight is the $\lambda$ value of each part, and it is incorporated to calculate $\lambda_{max}$. Taking T-U judgment matrix as an example, the calculation process is shown in Table 9.

By using of square root method, the maximum eigenvalue ($\lambda_{max}$) is obtained:

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} b_{ij} W = \frac{1}{3} \times 9.163 = 3.054.$$ 

Consistency index is:

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{3.054 - 3}{3 - 1} = 0.027.$$

Random consistency rate is:

$$CR = \frac{CI}{RI} = \frac{0.027}{0.58} = 0.047 < 0.1.$$ 

Similarly, each index weight can be determined, random consistency rate can also be confirmed. The calculating process is omitted, and results are shown in Table 10. Due to all the random consistency rates are less than 0.1, so all the judgment matrix are satisfactory. Therefore, the index weight vectors are: $A = (0.413 \; 0.327 \; 0.260); \; A_1 = (0.168 \; 0.168 \; 0.306 \; 0.306 \; 0.052); \; A_2 = (0.227 \; 0.227 \; 0.423 \; 0.123); \; A_3 = (0.25 \; 0.25 \; 0.5)$, respectively.

Fuzzy comprehensive evaluation

(1) First order fuzzy comprehensive evaluation.

Taking enterprise 1 as an example, first order fuzzy comprehensive evaluation on $B_1$ (environmental protection benefit) factor can be calculated as follow:

$$B_1 = A_1R_1 = (0.1680.1680.3060.3060.052) = (0.3150.4470.238)$$

Table 9 Weight of T-U judgment matrix using square root method

| T | U_1 | U_2 | U_3 | M = \prod \mathbf{M}_j | W'_i = \sqrt{M} | W'_i = W'_i \times W_i | (AW)_i | (AW)_i/W_i |
|---|-----|-----|-----|-----------------------|----------------|------------------------|----------|--------|
| U_1 | 1   | 1   | 2   | 2                     | 1.260          | 0.413                  | 1.260    | 3.051  |
| U_2 | 1   | 1   | 1   | 1                     | 0.327          | 1                      | 3.058    |
| U_3 | 1/2 | 1   | 0.5 | 0.794                 | 0.260          | 0.794                  | 3.054    |
| \_ | \_  | \_  | \_  | Total \Sigma           | \_             | \_                     | 9.163    |
Similarly, we got the evaluation result of $B_2$ (resource utilization benefit) and $B_3$ (recycling benefit) through calculations:
\[
B_2 = A_2 \cdot R_2 = (0.085 \ 0.338 \ 0.415 \ 0.162).
\]
\[
B_3 = A_3 \cdot R_3 = (0.25 \ 0.125 \ 0.525 \ 0.1).
\]

(2) Second order fuzzy comprehensive evaluation.

The comprehensive evaluation of wastewater treatment for enterprises is calculated as:
\[
B = A \cdot R = A \cdot \begin{bmatrix} 0.413 & 0.327 & 0.260 \\ 0.085 & 0.338 & 0.415 & 0.162 \\ 0.25 & 0.125 & 0.525 & 0.1 \end{bmatrix} = (0.0930.2730.4570.177).
\]

Through the above calculation, the evaluation grade of evaluation object is determined on maximum membership degree principle. The result shows that the probability of “excellent”, “good”, “middle” and “bad” is 0.093, 0.273, 0.457 and 0.177 respectively. According to the maximum membership degree principle, the evaluation result of the enterprise 1 is “middle.” Same to the calculating process of enterprise 1, the result vectors of other enterprise can be obtained, as shown in Table 11. It can be seen that evaluation grade of enterprise 1, enterprise 2 and enterprise 3 is middle, good and excellent respectively.

| Table 10 Comparison matrix and the consistency test |
|-----------------------------------------------|
| **Index** | **Comparison matrix B** | **Weight $A_i$** | **Consistency test** |
|----------|--------------------------|-----------------|----------------------|
| $u_{11}$ | 1 1 1/2 1/2 4           | 0.168           | $\lambda_{max} = 5.0354$ |
| $u_{12}$ | 1 1 1/2 1/2 4           | 0.168           | $\lambda_{max} = 4.01$ |
| $u_{13}$ | 2 2 1 1/5               | 0.306           | $\lambda_{max} = 3$ |
| $u_{14}$ | 2 2 1 1/5               | 0.306           | $\lambda_{max} = 0$ |
| $u_{15}$ | 1/4 1/4 1/5 1/5 1      | 0.052           | $\lambda_{max} = 0$ |
| $u_{21}$ | 1 1 1/2 2               | 0.227           | $\lambda_{max} = 0.003333$ |
| $u_{22}$ | 1 1 1/2 2               | 0.227           | $\lambda_{max} = 0.003333$ |
| $u_{23}$ | 2 2 1 3                | 0.423           | $\lambda_{max} = 0.003333$ |
| $u_{24}$ | 1/2 1/2 1/3 1          | 0.123           | $\lambda_{max} = 0$ |
| $u_{31}$ | 1 1 1/2                | 0.25            | $\lambda_{max} = 0.003333$ |
| $u_{32}$ | 1 1 1/2                | 0.25            | $\lambda_{max} = 0.003333$ |
| $u_{33}$ | 2 2 1                  | 0.5             | $\lambda_{max} = 0$ |

| Table 11 Fuzzy comprehensive evaluation results of wastewater treatment evaluation for enterprises |
|-----------------------------------------------|
| **Index** | **Membership degree** | **Evaluation grade** |
|----------|-----------------------|----------------------|
| Enterprise 1 | 0.093 0.273 0.457 0.177 | Middle |
| Enterprise 2 | 0.188 0.411 0.282 0.119 | Good |
| Enterprise 3 | 0.451 0.240 0.106 0.202 | Excellent |
And then calculate the value of comprehensive evaluation and determine the level of the evaluation, first, give the score of the set of evaluation according to the hundred-mark system, thus we can get the data of the set of evaluation by assign values: \( K = \{95, 85, 75, 65\} \), finally, got the scores of comprehensive evaluation of enterprise 1, enterprise 2 and enterprise 3 as follows:

\[
V_1 = B \times V^T = [0.0930.2730.4570.177] \times [95857565]^T = 77.8.
\]

Similarly, \( V_2 = 81.7 \), \( V_3 = 84.3 \), \( V_3 > V_2 > V_1 \), so we can think that the wastewater treatment evaluation result is enterprise 3 > enterprise 2 > enterprise 1.

The validation of the procedure steps with experimental data was shown in Table 12. It can be seen from data that enterprise 3 has the smallest values for unit product COD, NH$_3$-N, TP and TN discharge compared to enterprise 1 and enterprise 2, which means that the fuzzy AHP evaluation results of the enterprise 3 was in a better level, followed by enterprise 2 and enterprise 1. Thus the fuzzy AHP procedure steps were fulfilled by the experimental data.

(3) Fuzzy AHP results compared with real situation.

Unit product COD, NH$_3$-N, TP, TN charge and unit product sewage charge were used to characterize the actual situation of wastewater treatment effect for enterprise in industrial Park in China. In general, the lower unit product COD (NH$_3$-N, TP, TN) charge or unit product sewage charge, the better wastewater treatment effect of enterprise achieved. The unit product pollutant charge for enterprise was shown in Table 13. As can be seen from the Table 13, enterprise 3 has the smallest values for all indexes, with the largest values for enterprise 1. It means that the wastewater treatment effect of enterprise 3 is the best, followed by enterprise 2 and enterprise 1. On the other hand, the results indicates that the actual situation of wastewater treatment effect is corresponds to the experimental results.

### Table 12 Validation of the procedure steps with experimental data

| Index                  | Enterprise 1 | Enterprise 2 | Enterprise 3 |
|------------------------|--------------|--------------|--------------|
| Unit product COD discharge (kg/t) | 84.7         | 32.8         | 17.5         |
| Unit product NH$_3$-N discharge (kg/t) | 7.0          | 3.5          | 1.9          |
| Unit product TP discharge (kg/t)            | 0.5          | 0.2          | 0.1          |
| Unit product TN discharge (kg/t)            | 9.9          | 5.3          | 3.0          |

### Table 13 Unit product pollutant charge for enterprise

| Index                  | Enterprise 1 | Enterprise 2 | Enterprise 3 |
|------------------------|--------------|--------------|--------------|
| Unit product COD charge (RMB/t) | 98.3         | 77.9         | 54.4         |
| Unit product NH$_3$-N charge (RMB/t) | 47.6         | 30.7         | 24.5         |
| Unit product TP charge (RMB/t)          | 12.5         | 8.6          | 6.3          |
| Unit product TN charge (RMB/t)          | 10.2         | 5.4          | 4.7          |
| Unit product sewage charge (RMB/t)      | 185.6        | 143.8        | 110.5        |
Conclusions and future research

An integrated framework using a fuzzy comprehensive evaluation method and an AHP procedure was proposed and applied to wastewater treatment evaluation for enterprise in Taihu Basin, China. The main results of this study are summarized in the following points.

(1) According to the characteristics of industrial wastewater treatment in Taihu Basin, 12 index of wastewater treatment evaluation system for enterprises was constructed from three aspects (environmental protection benefit, resource utilization benefit and recycling benefit).

(2) The index weight was calculated according to AHP theory. Calculation results reflected that weight vectors were: 
\[ A = (0.413 \ 0.327 \ 0.260); \ A_1 = (0.168 \ 0.168 \ 0.306 \ 0.306 \ 0.052), \ A_2 = (0.227 \ 0.227 \ 0.423 \ 0.123) \] and 
\[ A_3 = (0.25 \ 0.25 \ 0.5). \]

(3) Fuzzy comprehensive evaluation results shown that the probability of "middle", "good", "bad" and "excellent" is 0.457, 0.273, 0.177 and 0.093 respectively for enterprise 1. According to the maximum membership degree principle, the comprehensive evaluation result of the enterprise 1 is "middle." Similarly, the evaluation grade of enterprise 2 and enterprise 3 is good and excellent respectively.

In future research, other MCDM and fuzzy approaches can be applied to assess the wastewater treatment evaluation for enterprises including ELECTRE (Benayoun et al. 1966), TOPSIS (Hawang and Yoon 1981), BWM (Birman and Wenzl 1989; Murakami 1987), VIKOR (Opricovic 1998) and so on. We think that the field of innovation and entrepreneurship can benefit from the experiences with fuzzy methods gained in the engineering sciences. Finally, we believe that fuzzy AHP approaches can be promoted in the wastewater treatment evaluation for enterprises in industrial park in China.

Authors' contributions
Conception and design: WH and GL; data collection: WH; writing of the manuscript: WH; final approval of the manuscript: WH, GL and YT. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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