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Urban sewage sludge, sustainability, and transition for Eco-City: Multi-criteria sustainability assessment of technologies based on best-worst method

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ABSTRACT

The treatment of urban sewage sludge is of vital importance for mitigating the risks of environmental contaminations, and the negative effects on human health. However, there are usually various different technologies for the treatment of urban sewage sludge; thus, it is difficult for decision-makers/stakeholders to select the most sustainable technology among multiple alternatives. This study aims at developing a generic multi-criteria decision support framework for sustainability assessment of the technologies for the treatment of urban sewage sludge. A generic criteria system including both hard and soft criteria in economic, environmental, social and technological aspects was developed for sustainability assessment. The improved analytic hierarchy process method, namely Best-Worst method, was employed to determine the weights of the criteria and the relative priorities of the technologies with respect to the soft criteria. Three MCDM methods including the sum weighted method, digraph model, and TOPSIS were used to determine sustainability sequence of the alternative technologies for the treatment of urban sewage sludge. Three technologies including landfilling, composting, and drying incineration have been studied using the proposed framework. The sustainability sequence of these three technologies determined by these three methods was obtained, and finally the priority sequence was determined as landing filling, drying incineration and composting in the descending order.

1. Introduction

The treatment of urban sewage sludge is one of the most severe challenges in wastewater management because sewage sludge is the residue produced when separating the liquids and solids in wastewater treatment (Fytili and Zabaniotou, 2008). The treatment of urban sewage sludge is of vital importance with objective of reducing the volume, improving the character and reducing the health problems and environmental problems (Appels et al., 2008). Accordingly, the treatment of urban sewage sludge has become an important concern all over the world (Singh and Agrawal, 2008) as inappropriate treatment will cause serious environmental pollutions and human health problems. Therefore, the development of the technologies for the treatment of urban sewage sludge has become a hot topic recently.

Similar to groundwater remediation and the treatment of e-waste, there are also various technologies for the treatment of urban sewage sludge, i.e., landfilling (Koenig et al., 1996), compositing (Fang and Wong, 1999), incineration (Li et al., 2014), and anaerobic digestion for energy recovery (Karagiannidis and Perkoulidis, 2009), etc. However, different technologies have different economic, environmental and social performances. For instance, one technology may perform better in regard to capital cost than another technology, but may cause more environmental impacts. Therefore, it is usually difficult for decision-makers to choose the most suitable technology for the treatment of urban sewage sludge when considering the multiple criteria in facing multiple options, because this is a typical multi-criteria decision making (MCDM) problem in which there are usually multiple conflict criteria. Many scholars employed MCDM methods for the analysis of the technologies for the treatment of urban sewage sludge. For instance, Pokoo-Aikins et al. (2010) used the multi-criteria approach for screening the alternatives (four solvents, toluene, hexane, methanol and ethanol in the extraction process were compared) for converting sewage sludge to biodiesel. Flores-Alsina et al. (2008) employed a multi-criteria analysis method for investigating the priorities of wastewater treatment plant control strategies under uncertainties. Karagiannidis and Perkoulidis (2009) used the multi-criteria decision support method ELECTRE III for analyzing different technologies in anaerobic digestion for energy recovery of the organic fraction of municipal solid wastes. The applications of the methods presented in these studies can provide

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significant implications to the decision-makers to select the most suitable scenario for the treatment of urban sewage sludge among multiple alternatives. However there are also some problems to be solved:

(1) The lack of the incorporation of soft criteria for sustainability assessment: in most of the previous studies, only hard criteria that can be quantified with units were considered; however, they neglect to consider soft criteria that can only be depicted quantitatively, i.e. social acceptability, technology maturity, and technology generalizability, etc.
(2) The difficulty in the determinations of the weights of the criteria: Selecting the most suitable technology for the treatment of urban sewage sludge should consider the preferences and willingness of the decision-makers/stakeholders. Accordingly, the weights should reflect the preferences and willingness of the decision-makers/stakeholders. The analytic Hierarchy Process (AHP) is the most commonly used for weights determination as this method can reflect the preferences and willingness of the decision-makers/stakeholders, but it is usually difficult for the users of this method to establish a consistent comparison matrix by using numbers from 1 to 9 as human judgment usually involves vagueness, ambiguity, and subjectivity (Ren and Lützen, 2015; Ren et al., 2016).
(3) The lack of incorporation of the sustainability concept: pursuing sustainability aims at achieving sustainable development, and green operations initiatives have attracted more and more interest from industry for promoting sustainable development (Wang, 2015); however, there is a lack of a criteria system for sustainability assessment of the technologies for the treatment of urban sewage sludge.
(4) The reliability of MCDM methods: the priority sequences determined by different MCDM methods based on the same decision-making matrix are usually slightly different. Therefore, it is usually difficult for the decision-makers to make the correct decision.

With the objective of solving the above-mentioned four problems, this study aims at helping the decision-makers/stakeholders select the most sustainable technology for the treatment of urban sewage sludge for sustainability transition to an eco-city, and a generic criteria system for sustainability assessment of the technologies for the treatment of urban sewage sludge was developed. An improved AHP (Saaty, 1980) method, namely, the Best-Worst (BW) method (Rezaei, 2015; Rezaei, 2016), was employed to determine the weights of the criteria for sustainability assessment, and was also used to determine the relative performance of alternative technologies for the treatment of urban sewage sludge. Three MCDM methods, the sum weighted method, digraph model, and Technique for Order of Preference by Similarity to the Ideal Solution were employed to determine the sustainability sequence of these alternative technologies for the treatment of urban sewage sludge. The reminding parts of this paper have been organized as follows: the methods are presented in Section 2, three technologies for the treatment of urban sewage sludge are studied in Section 3, and the discussion and conclusions are given in Section 4.

2. Methods

In this section, the criteria system for sustainability assessment was firstly developed, then, the method for determining the weights of the criteria and the relative preferences of the alternative technologies for the treatment of urban sewage sludge with respect to soft criteria is presented, and finally the multi-criteria decision making (MCDM) methods including sum weighted method (SWM), digraph model, and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) for determining the sustainability indices of the alternative technologies for the treatment of urban sewage sludge is specified.

2.1. Criteria for sustainability assessment

Sustainable development emphasizes development with consideration of achieving economic profits, environmental cleanliness, and social effects, simultaneously (Ren et al., 2016). Accordingly, sustainability assessment is usually based on the simultaneous measure of economic performance, environmental impact, and social acceptability. Therefore, the criteria system for sustainability assessment usually consists of the criteria in economic, environmental, and social aspects which are the main three pillars of sustainability (Ren et al., 2015a). However, Manzardo et al. (2012) held the view that the criteria in some other aspects should also be incorporated in sustainability assessment, because these criteria may also have significant effects on the criteria belonging to the main three pillars of sustainability. For instance, technology development and progress will affect economic performance (i.e. reducing the cost and increasing the profit), environmental impact (i.e. mitigating CO_2 emission and decreasing occupied land), and also social acceptability (i.e. increasing vacancies and increasing social benefits) (Ren et al., 2015b). Therefore, a criteria system including four aspects, namely economic, environmental, social and technological aspects, has been developed for sustainability assessment of the technologies for the treatment of urban sewage sludge.

There have been many studies focusing on developing the criteria for sustainability assessment of the treatment of urban sewage or urban sewage sludge. For instance, Balkema et al. (2002) proposed a complete set of sustainability indicators for selecting sustainable wastewater treatment systems. Hiessl et al. (2001) established a criteria system including 44 criteria in economic, social, and ecological aspects for sustainability assessment of scenarios of urban water infrastructure systems. Muga and Mihelcic (2008) developed various criteria including economic indicators (including capital, operation and management, and user costs), environmental indicators (energy use, resource utilization, and performance of the technology in removing conventional wastewater constituents), and societal indicators (capture cultural acceptance of the technology, better education, or an improved local environment, etc.) for sustainability assessment of wastewater treatment technologies. An et al. (2016a) employed ten criteria including capital cost and running cost in economic aspects, occupied land, environmental risk, and resource utilization efficiency in environmental aspect, social acceptability in social aspect, such as operability, site selection, applicability, and management level requirement in the technological aspect to assess the sustainability of the technologies for the treatment of urban sludge. Meanwhile, An et al. (2016b) used a total of eight criteria for sustainability assessment of the technologies for groundwater remediation, capital cost, detection and analysis costs, and operation and maintenance costs in economic aspects, effect of secondary pollution in environmental aspect, effectiveness for water quality, improvement and time for remediation in technological aspect, the effect on public health in social aspect, and policy support in political aspect. Mels et al. (1999) developed five sustainability criteria based on the Life Cycle Assessment methodology, including energy balance, final sludge production, effluent quality, the use of chemicals and space requirement (footprint) to evaluate the sewage treatment scenarios. Based on the literature review, it is apparent that there are no uniform standards for selecting the criteria for sustainability assessment of the technologies for the treatment of urban sewage sludge. In this study, six criteria in regard to economic, environmental, social, and technological aspects have been used to measure the sustainability of the technologies for the treatment of urban sewage sludge based on a focus group meeting in which seven experts, including two professors, three Ph.D students, and two senior researchers were invited to participate. These six criteria are specified as follows.

2.1.1. Economic aspect (EC)

I. Capital cost (EC_1): this criterion refers to the initial capital cost for a plant adopting a particular technology for the treatment of urban sewage sludge including the purchase of land, building, construction, equipment and facilities, etc.
II. Running cost (EC_2): this running cost represents the total costs for running the plant for the treatment of urban sewage sludge.

2.1.2. Environmental aspect (EN)

I. Occupied land (EN_1): this criterion refers to the total occupied land for the construction of the plant for the treatment of urban sewage sludge.
II. Environmental risk (EN_2): urban sewage sludge usually contains heavy metals, pathogens, and some other harmful elements that have high potential to cause environmental risk.

2.1.3. Social aspect

I. Social acceptability: this is the criterion to measure the acceptability level of the technologies for the treatment of urban sewage sludge.

2.1.4. Technological aspect (T)

I. Generalizability (T_1): this criterion is to measure the maturity level of the technology for the treatment of urban sewage sludge.

It is worth pointing out that this study aims at developing a generic criteria system for sustainability assessment of the technology for the treatment of urban sewage sludge; thus, the users can add new criteria or delete some criteria according to the actual conditions and their preferences when selecting the criteria for sustainability assessment. These six criteria can be categorized into two groups according to the effects of the criteria on the priorities of the technologies for the treatment of urban sewage sludge: benefit-type criteria (BT) and cost-type criteria (CT). The benefit-type criteria are the criteria that have the characteristics that the greater the value of the criteria, the better the technology will be. On the contrary, the cost-type criteria are criteria that have the characteristic that the lower the values of the criteria, the better the technologies will be. Accordingly, capital cost, running cost, occupied land, and environmental risk are cost-type criteria. Social acceptability and generalizability are benefit-type criteria. Meanwhile, these criteria can also be divided into two groups according to the method for describing them: soft criteria and hard criteria. The hard criteria are the criteria that can be measured quantitatively with units; however, soft criteria are the criteria that can only be described qualitatively. Accordingly, capital cost, running cost, occupied land, and environmental risk are usually recognized as hard criteria. Social acceptability and generalizability are soft criteria.

Assuming there are a total of m alternative technologies for the treatment of urban sewage sludge ($A_1, A_2, A_3, \ldots, A_m$) and a total of n criteria for sustainability assessment of these technologies (C_1, C_2, C_3, …, C_n), the decision-making matrix can be determined as presented in Eq. (1)

$$\begin{array}{ccccc} & C_1 & C_2 & \cdots & C_n \\ \mathrm{A}_1 & x_{11} & x_{12} & \cdots & x_{1n} \\ \mathrm{A}_2 & x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathrm{A}_m & x_{m1} & x_{m2} & \cdots & x_{mn} \\ W & \omega_1 & \omega_2 & \cdots & \omega_n \end{array} \tag{1}$$

where $W$is the weight vector, $\omega_j$and x_{ij} represents the value of the i-th alternative with respect to the j-th criterion.

Note that the units of the criteria are different, and it is impossible to compare the alternatives with respect to different criteria with different units. In order to make all the criteria dimensionless, a method for normalizing the data is presented as follows:

$$y_{ij} = \begin{cases} \dfrac{x_{ij}}{\sum_{j=1}^{n} x_{ij}}, & C_j \in \mathrm{BT} \\[2ex] \dfrac{1/x_{ij}}{\sum_{j=1}^{n} 1/x_{ij}}, & C_j \in \mathrm{CT} \end{cases}, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \tag{2}$$

After normalization of the data, all the criteria have been transformed into benefit-type criteria, and all the data in the decision-making matrix can be transformed into values between 0 and 1. Accordingly, the normalized decision-making matrix can also be obtained, as presented in Eq. (3):

$$\begin{array}{ccccc} & C_1 & C_2 & \cdots & C_n \\ \mathrm{A}_1 & y_{11} & y_{12} & \cdots & y_{1n} \\ \mathrm{A}_2 & y_{21} & y_{22} & \cdots & y_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathrm{A}_m & y_{m1} & y_{m2} & \cdots & y_{mn} \\ W & \omega_1 & \omega_2 & \cdots & \omega_n \end{array} \tag{3}$$

In this study, the sustainability index of each technology for the treatment of urban sewage sludge can be determined by combination of Best-Worst (BW) method and three MCDM methods. The BW method was applied to determine both the weights of the criteria for sustainability assessment of the technologies for the treatment of urban sewage sludge and the relative performances of these technologies with respect to the soft criteria. SWM, graph theory and TOPSIS were then used to determine the sustainability indices of these alternative technologies after determining the digraph model. The sustainability assessment framework of technologies for the treatment of urban sewage sludge is presented in Fig. 1. In this section, the BW method is presented in Section 2.2, and SWM, graph theory and TOPSIS methods are presented in Sections 2.3–2.5.

2.2. BW method

The Best-Worst (BW) developed by Rezaei (2015) is a modified AHP method which can determine the relative weights of factors/elements by establishing the vectors of the relative preferences of the most important criterion over all the other criteria and that of all the other criteria over the least important criterion. This method has been widely used recently for the advantage of ease of handling in achieving consistency compared to the traditional AHP method. For instance, Gupta and Barua (2016) employed this method to investigate the enablers of technological innovation for Indian Micro-small and Medium Enterprises. Annema et al. (2015) used the BW method to study the politicians' perspective on transport policy appraisal. Nispeling (2015) adopted the BW method for supplier selection in the Edible Oil Industry.

In this study, the Best-Worst method was applied to determine the relative importance of the criteria for sustainability assessment of the technologies for the treatment of urban sewage sludge and the relative performances of the alternative technologies with respect to the soft criteria. It consists of four steps (Rezaei, 2015; Rezaei, 2016):

2.2.1. Step 1

Determining the best and the worst criteria, denotes by C_B and C_W, respectively. It is worth pointing out that users have to determine the most important and the least important criteria, denoted by C_M and C_L when using this method to determine the relative weights of the criteria.

2.2.2. Step 2

Determining the relative preferences of the most important criterion over all the other criteria and that of all the other criteria over the least important criterion by using the scales used on Saaty method (Saaty, 1980), see Table 1. Then, the Best-to-Others (BO) vector and the

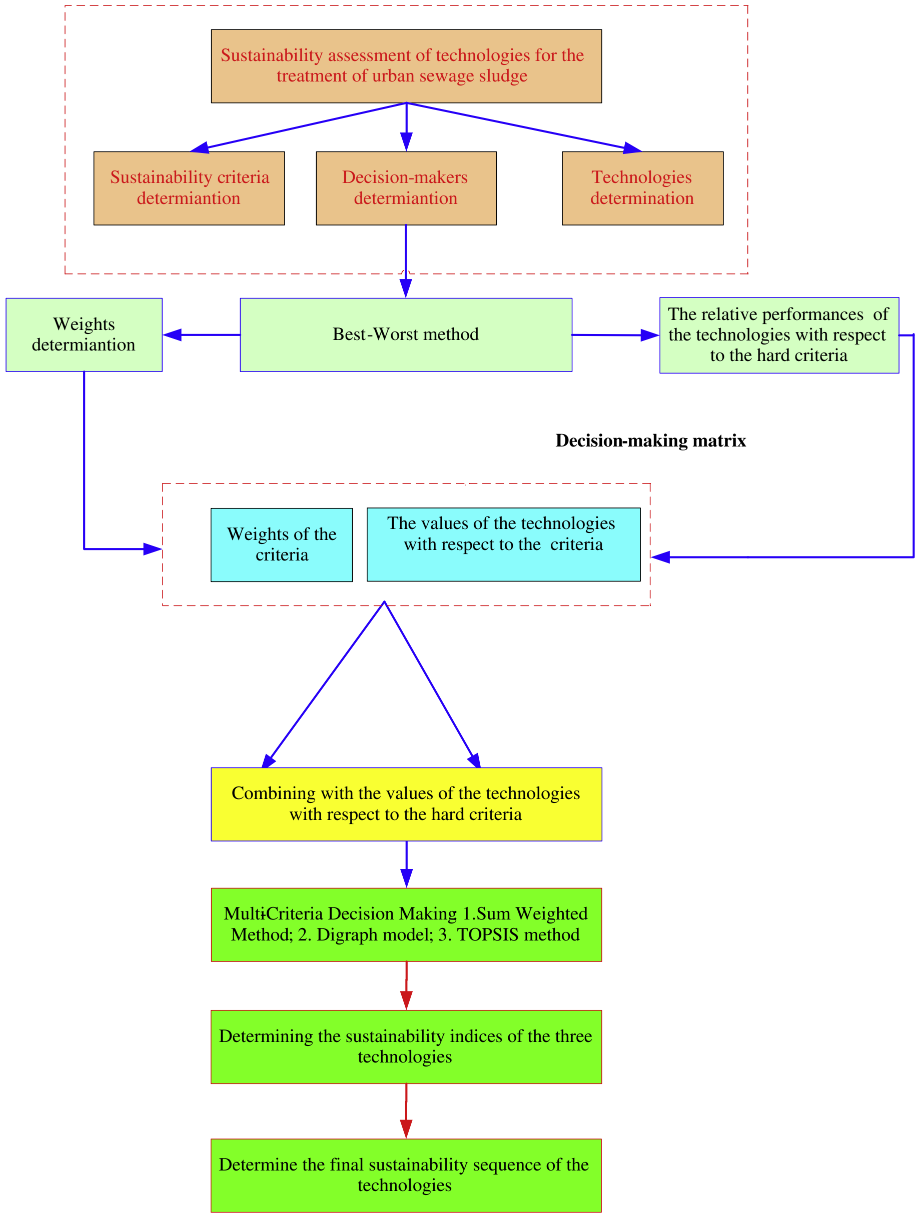

Fig. 1. The sustainability assessment framework of technologies for the treatment of urban sewage sludge.

Table 1
Comparison scale in Saaty method (Saaty, 1980).

Scales	Definition	Note
1	Equal importance	*i* is equally important to *j*
3	Moderate importance	*i* is moderately important to *j*
5	Essential importance	*i* is essentially important to *j*
7	Very strong importance	*i* is very strongly important to *j*
9	Absolute importance	*i* is very absolutely important to *j*
2, 4, 6, 8	Intermediate value	The relative importance of *i* to *j* is between to adjacent judgment
Reciprocal	Reciprocals of above	The value had been assigned to *i* when compared to *j*, then *j* has the reciprocal value compared to *i*

Others-to- Worst (OW) vector can be obtained, as presented in Eqs. (4) and (5), respectively.

$$\mathrm{BO(MO)} = [\, a_{B1} \quad a_{B2} \quad \ldots \quad a_{Bn} \,] \tag{4}$$

$$\mathrm{OW(OL)} = [\, a_{1W} \quad a_{2W} \quad \ldots \quad a_{nW} \,] \tag{5}$$

where $a_{Bj}(j = 1,2,\ldots,n)$ and $a_{jW}(j = 1,2,\ldots,n)$ represent the relative preference of the most important criterion and the least important criterion over the *j*-th criteria.

It is apparent that when $j = B(M)$, then $a_{B(M)j} = 1$, and when $j = W(L)$, then $a_{jW(L)} = 1$.

2.2.3. Step 3

2.2.3.1. Determining the weights of the criteria. The optimal weights of the criteria should satisfy the conditions presented in Eqs. (6–7)

$$\frac{\omega_{B(M)}}{\omega_j} = a_{B(M)j}(j = 1,2,\ldots,n) \tag{6}$$

$$\frac{\omega_j}{\omega_{W(L)}} = a_{jW(L)}(j = 1, 2, \ldots, n) \tag{7}$$

To satisfy all these conditions, the solution which satisfies that the maximum absolute difference is $|\frac{\omega_{B(M)}}{\omega_j} - a_{B(M)j}|$ and $|\frac{\omega_j}{\omega_{W(L)}} - a_{jW(L)}|$ for all j is the minimized item. Then, the weights of the criteria can be determined by solving the following:

$$\begin{aligned} &\min \max_j \left\{ \left| \frac{\omega_B}{\omega_j} - a_{Bj} \right|, \left| \frac{\omega_j}{\omega_W} - a_{jW} \right| \right\} \\ &s.t. \\ &\sum_{j=1}^{n} \omega_j = 1 \\ &\omega_j \geq 0, j = 1, 2, \ldots, n \end{aligned} \tag{8}$$

Eq.(8) can be transferred into the following problem:

$$\begin{aligned} &\min \xi \\ &s.t. \\ &\left| \frac{\omega_B}{\omega_j} - a_{Bj} \right| \leq \xi, j = 1, 2, \ldots, n \\ &\left| \frac{\omega_j}{\omega_W} - a_{jW} \right| \leq \xi, j = 1, 2, \ldots, n \\ &\sum_{j=1}^{n} \omega_j = 1 \\ &\omega_j \geq 0, j = 1, 2, \ldots, n \end{aligned} \tag{9}$$

where ω_B represents the weight of the best criterion, ω_W represents the weight of the worst criterion, and ω_j denotes the weight of the j-th criterion.

The ξ^* is the value of the objective function in programming (Eq. (15)) under the optimum conditionsω_1^*, ω_2^*, ω_3^*, and ω_4^*.

2.2.4. Step 4

2.2.4.1. Consistency check. Similar to the traditional AHP method, users of the Best-Worst method need to check the consistency of the comparison matrix to ensure the overall consistency. The comparison is fully consistent when $a_{Bj}a_{jW} = a_{BW}(j = 1, 2, \ldots, n)$, however this ideal condition cannot always be achieved due to the ambiguity and vagueness existing in human judgment. The consistency ratio can be calculated for consistency check, as presented in Eq. (10),

$$\mathrm{CR} = \frac{\xi^*}{\mathrm{CI}} \tag{10}$$

where CR represents the consistency ratio, and CI represents the consistency index.

The consistency index can be obtained according to Table 2, and the value of consistency ratio belonging to the interval [0 1] indicates the consistency level, and the closer the value to zero, the more consistent the comparison is; on the contrary, the closer the value to one, the more consistent the comparison is.

2.3. Sum weighted method (SWM)

After determining the normalized decision-making matrix in Eq. (3), the sum weighted method (Triantaphyllou and Sánchez, 1997; Ren and Lützen, 2015) was applied to determine the sustainability sequence of these alternative technologies for the treatment of the urban sewage sludge.

$$S_i(\mathrm{SWM}) = \sum_{j=1}^{n} \omega_j x_{ij} \quad i = 1, 2, \ldots, n \tag{11}$$

where S_i(SWM) represent sustainability index of the i-th technology for the treatment of urban sewage sludge determined by SWM method.

2.4. Digraph model

Each of the technologies for the treatment of urban sewage sludge can be represented in a graphical representation approach which consists of the sustainability attributes, the performance of each technology with respect each sustainability attributes, and the interrelationships among these attributes. The digraph consists of nodes and directed edges, where a node N_j ($j = 1,2, \ldots, n$) represents the j-th sustainability attribute, and edges ($i = 1,2, \ldots, n$, k $= 1,2, \ldots, n$, and k $\neq j$) represents the relative importance of the j-th sustainability attribute over the k-th sustainability attribute (Lanjewar et al., 2015). For instance, the i-th technology for the treatment of urban sewage sludge can be represented by the digraph model, as presented in Fig. 2.

However, the visual representation becomes more and more difficult with increase of the number of the attributes and complexity of the interrelationships among the attributes. The matrix approach can be used to address. Accordingly, the digraph model can be transformed into an equivalent matrix X_i, as presented this issue in Eq. (12).

$$X_i = \begin{array}{ccccccc} (T_i) & C_1 & C_2 & C_3 & \cdots & C_{n-1} & C_n \\ C_1 & y_{i1} & e_{12} & e_{13} & \cdots & e_{1(n-1)} & e_{1n} \\ C_2 & e_{21} & y_{i2} & e_{23} & \cdots & e_{2(n-1)} & e_{2n} \\ C_3 & e_{31} & e_{32} & y_{i3} & \cdots & e_{3(n-1)} & e_{3n} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ C_{n-1} & e_{(n-1)1} & e_{(n-1)2} & e_{(n-1)3} & \cdots & y_{i(n-1)} & e_{(n-1)n} \\ C_n & e_{n1} & e_{n2} & e_{n3} & \cdots & e_{n(n-1)} & y_{in} \end{array} \tag{12}$$

where T_i represents the i-th technology, the diagonal element y_{ij} represents the normalized value the i-th alternative technology with respect to the j-th criterion/attribute, the non-diagonal element e_{jk} represents the relative importance of the j-th sustainability attribute over the k-th sustainability attribute.

The weight of the j-th ($j = 1.2, \ldots, n$) criterion ω_j and that of the k-th ($k = 1.2, \ldots, n$, and $k \neq$ j) ω_k criterion can be determined by the BW

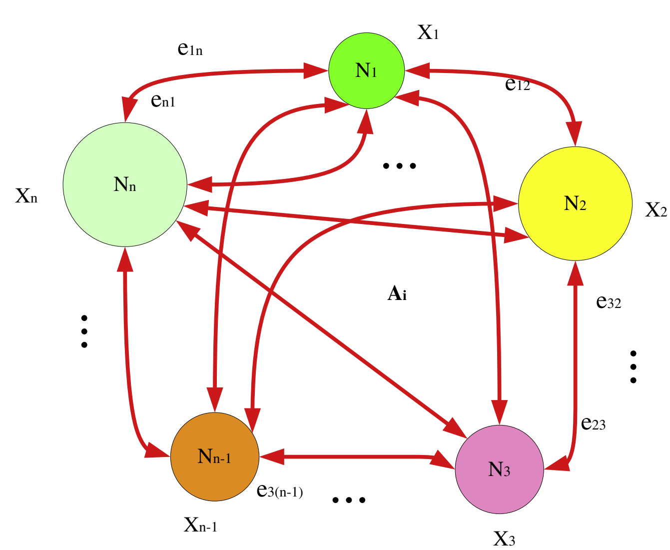

Fig. 2. Digraph model for technologies for the treatment of urban sewage sludge.

Table 2
Consistency index (CI) table.

a_{ML}	1	2	3	4	5	6	7	8	9
Consistency index (max ξ)	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

method. Accordingly, the relative importance of the j-th sustainability attribute over the k-th sustainability attribute e_{jk} can be determined by Eq. (13).

$$e_{ij} = \frac{\omega_j}{\omega_k} \tag{13}$$

As for the diagonal elements y_{ij}, they can be determined according to Eq. (2), and y_{ij} can be determined in the following two ways:

I. If the j-th criterion/attribute is a soft criterion, the value the i-th alternative technology with respect to the j-th criterion/attribute x_{ij} ($i = 1,2, \ldots, m$) can be determined by calculating the relative performances of the m technologies with respect to the j-th criterion/attribute.
II. If the j-th criterion/attribute is a hard criterion, the value the i-th alternative technology with respect to the j-th criterion/attribute x_{ij} ($i = 1,2, \ldots, m$) can be determined according to the results of real measurements.

The sustainability index of each technology can be determined by determining the permanency of the matrix X_i according to the rule presented in Eq. (14). The permanency of an n × n matrix $A = (a_{ij})_{n \times n}$ is:

$$Perm(A) = \sum_{\sigma \in S_n} \prod_{i=1}^{n} a_i \delta(i) \tag{14}$$

Note that the sum here extends over all elements σ of the symmetric group S_n; i.e. over all permutations of the numbers 1, 2, …, n.

Simply, the permanent function of the matrix can be determined in a similar way to its determinant, but the negatives in the process for calculating the determinant should be changed into positives (Lanjewar et al., 2016).

For instance, $A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$, its determinant is: $|A| = a_{11}a_{22} - a_{12}a_{21}$ then, its permanency should be: $perm(A) = a_{11}a_{22} + a_{12}a_{21}$.

Similarly, if $A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$, its determinant is: $|A| = a_{11}\begin{vmatrix} a_{22} & a_{23} \\ a_{32} & \end{vmatrix} a_{33}| + a_{21}\begin{vmatrix} a_{12} & a_{13} \\ a_{32} & a_{33} \end{vmatrix} + a_{31}\begin{vmatrix} a_{12} & a_{13} \\ a_{22} & a_{23} \end{vmatrix} = a_{11} a_{22}a_{33} - a_{11}a_{23}a_{32} + a_{21}a_{12}a_{33} - a_{21}a_{13}a_{32} + a_{31}a_{12}a_{23} - a_{31}a_{13}a_{22}$.

Then, its permanency should be $Perm(A) = a_{11}a_{22}a_{33} + a_{11}a_{23}a_{32} + a_{21}a_{12}a_{33} + a_{21}a_{13}a_{32} + a_{31}a_{12}a_{23} + a_{31}a_{13}a_{22}$.

2.5. TOPSIS

The technique for order sequence by the similarity to the ideal solution (TOPSIS) (Hwang and Yoon, 2012;Yoon, 1987) is a multi-criteria decision making method which holds that the best solution should have the shortest distance to the ideal solution and the furthest distance to the anti-ideal solution (Gumus, 2009; Yue, 2011). The method of the traditional TOPSIS method has been introduced in (Lin et al., 2008; Dagdeviren et al., 2009).

After determining the normalized decision-making matrix (see Eq. (3)), the weighted normalized decision-making matrix can be obtained by Eq. (15)

$$y'_{ij} = \omega_j y_{ij} \tag{15}$$

where y'_{ij} represents the value of the i-th alternative with respect to the j-th criterion the weighted normalized decision-making matrix.

The ideal point (ideal best scheme) can be acquired with Eq. (16) and (17)

$$Y_j^+ = \left\{ \max\left(y_{ij}\right) \right\} (i = 1, 2, \ldots, m) \tag{16}$$

$$Y^+ = \{Y_1^+, Y_2^+, \ldots, Y_n^+\} \tag{17}$$

The anti-ideal point can be acquired in Eqs. (18) and 19

$$Y_j^- = \left\{ \min\left(y_{ij}\right) \right\} (i = 1, 2, \ldots, m) \tag{18}$$

$$Y^- = \{Y_1^-, Y_2^-, \ldots, Y_n^-\} \tag{19}$$

If the alternative approaches the ideal point and is far away from anti-ideal point, the sample will be more superior. Minkowski distance methodology can be used to measure the distance from the i-th alternative to the ideal point and anti-ideal point, as shown in Eq. (20) and (21), respectively.

$$D_i^+ = \left\{ \sum_{j=1}^{n} \left(y_{ij} - Y_j^+\right)^p \right\}^{1/p} \tag{20}$$

$$D_i^- = \left\{ \sum_{j=1}^{n} \left(y_{ij} - Y_j^-\right)^p \right\}^{1/p} \tag{21}$$

where D_i^+ represents the distance from the i-th alternative to the ideal point, D_i^- represents the distance from the i-th alternative to the anti-ideal point, $\omega_j$represents the weights of index j, p represents exponential coefficient taking the value of 2 in this paper.

The closeness coefficient is defined in Eq. (22), and indicates the closeness level of the alternative to the ideal point and the farness level of the alternative to the anti-ideal point. Therefore, the bigger the first coefficient, the more superior the alternative will be.

$$C_1^i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{22}$$

where C_1^i represents the first closeness coefficient with respect to the i-th alternative.

3. Case study

In order to illustrate the proposed framework for sustainability assessment of the technologies for the treatment of urban sewage sludge, a hypothetical case has been studied in this study. This case study aims at helping the stakeholders/decision-makers of a medium-sized city in the south of China to select the most sustainable scenario for treating urban sewage sludge among three technologies: Landfilling, Composting, and Drying Incineration. The pollution caused by the urban sewage sludge in the sewage disposal plants of this city is a severe problem, thus, the government is planning to choose the most sustainable technology for urban sewage sludge treatment using limited funds, for an annual total amount of urban sewage sludge around 1.50E + 5 tonnes.

A brief description of these three technologies is specified as follows:

(1) Landfilling (A_1): this technology is easy in operation and the cost is also low; however, the technology has high risk to cause soil pollution.
(2) Composting (A_2): this technology produces products that are suitable for land use through organic matter degradation and stabilization by the effects of microorganisms.
(3) Drying incineration (A_3): this technology treats sewage sludge by incineration after drying, and the incineration technology has the

Table 3
The solutions of programming (Eq. (23)).

Item	ω_1	ω_2	ω_3	ω_4	ω_5	ω_6	ξ^*
Values	0.4144	0.1496	0.0441	0.1938	0.0832	0.1149	0.3944

advantages of a large reduction of sludge volume, thermal destruction of toxic organic compounds, high potential for energy recovering, and minimization of odor generation (Fytili and Zabaniotou, 2008).

3.1. Weights determination for sustainability assessment

In this study, six criteria, capital cost (C_1), running cost (C_2), occupied land (C_3), environmental risk (C_4), social acceptability (C_5), and generalizability (C_6), have been used for sustainability assessment of the technologies for the treatment of urban sewage sludge. The BW method was applied to determine the weights of the six criteria, and the procedures are presented as follows:

3.1.1. Step 1

This step is to determine the most important and the least important criteria for sustainability assessment among these six criteria. In order to determine these two criteria, a focus group meeting in which six participants including two professors whose research focused on environmental engineering, two senior researchers skilled in groundwater remediation, and two PhD students whose research focused on sustainability engineering have participated. The focus was on determining the most important and the least important criteria, with capital cost (C_1) identified as the most important criterion, and occupied land (C_3) identified as the least important Accordingly, M = 1 and L = 3.

3.1.2. Step 2

The MO and OL vectors in which the relative importance of the most important criterion over the other criteria and that of the other criteria over the lease important criterion were also determined based on focus group meeting. For instance, the relative importance of the best technology (capital cost, C_1) over all the other criteria (C_1, C_2, C_3, C_5 and C_6) were recognized as 'equally important' (corresponding to 1), 'moderately important' (corresponding to 3), 'absolutely important' (corresponding to 9), between 'equally important' and 'moderately important' (corresponding to 2), 'essential importance' (corresponding to 5), between 'moderately important' and 'essential importance' (corresponding to 4). Accordingly, the BO vector is $\text{BO} = [1 \quad 3 \quad 9 \quad 2 \quad 5 \quad 4]$. In a similar way, the relative preferences of other criteria over the least important criterion (occupied land, C_3) were also determined: $\text{OL} = [9 \quad 3 \quad 1 \quad 4 \quad 2 \quad 3]$.

Table 4
BW method for determining the relative performances of the three technologies for the treatment of urban sewage sludge with respect to generalizability.
Reference: Jin and Li, 2009.

Best technology: A_3		Worst technology: A_1	
a_{3j}	7	3	1
a_{j1}	1	2	7
Relative performances	A_1	A_2	A_3
	0.1000	0.2162	0.6838
$\xi^*=0.1623$, $a_{BW}=7$, CI = 3.73, so $\text{CR} = \frac{\xi^*}{\text{CI}} = \frac{0.1623}{3.73} = 0.0435$			

3.1.3. Step 3

Determining the weights of the criteria by solving the following programming:

$$
\begin{aligned}
&\min \xi \\
&s.t. \\
&\left|\frac{\omega_1}{\omega_2}-3\right| \le \xi \\
&\left|\frac{\omega_1}{\omega_3}-9\right| \le \xi \\
&\left|\frac{\omega_1}{\omega_4}-2\right| \le \xi \\
&\left|\frac{\omega_1}{\omega_5}-5\right| \le \xi \\
&\left|\frac{\omega_1}{\omega_6}-4\right| \le \xi \\
&\left|\frac{\omega_2}{\omega_3}-3\right| \le \xi \\
&\left|\frac{\omega_4}{\omega_3}-4\right| \le \xi \\
&\left|\frac{\omega_5}{\omega_3}-2\right| \le \xi \\
&\left|\frac{\omega_6}{\omega_3}-3\right| \le \xi \\
&\omega_1+\omega_2+\omega_3+\omega_4+\omega_5+\omega_6=1 \\
&\omega_j \ge 0,\ j=1,2,3,4,5,6
\end{aligned}
\tag{23}
$$

The solutions were presented in Table 3.

3.1.4. Step 4

As $a_{BW}=9$, CI = 5.23, it could be obtained that the consistent ratio $\text{CR} = \frac{\xi^*}{\text{CI}} = \frac{0.3944}{5.23} = 0.0754$, a value near zero. Therefore, the established comparisons in the BO and OW vectors are consistent.

Therefore, the weights of capital cost (C_1), running cost (C_2), occupied land (C_3), environmental risk (C_4), social acceptability (C_5), and generalizability (C_6) are 0.4144, 0.1496, 0.0441, 0.1938, 0.0832, and 0.1149, respectively.

After determining the weights of the criteria for sustainability, the relative performance of the three alternative technologies for the treatment of urban sewage sludge with respect to the sustainability criteria were determined in Section 3.2. The relative performances of the three alternative technologies with respect to the hard criteria were determined based on the literature review; however, the relative performances of the three alternative technologies with respect to the soft criteria were determined by BW method.

3.2. Relative performances determination

The capital cost, running cost, occupied land, and environmental risk are usually recognized as hard criteria, and social acceptability and generalizability are usually recognized soft criteria, but the occupied land and environmental risk cannot be determined with the values and units based on literature review. However, the status of these three technologies with respect to the occupied land and environmental risk were depicted qualitatively in some schemes. Accordingly, the relative performances of the three technologies with respect to capital cost and running cost were determined from the data provided in the literature, and that with respect to occupied land, environmental risk, social acceptability, and generalizability were determined by using BW method to determine their relative priorities with respect to these four criteria.

As for the two hard criteria in the economic aspect, Yu et al. (2007) estimated the capital costs of Landfilling, Composting, and Drying Incineration were 30,000–55,000, 300,000, and 350,000–450,000 Yuan per tonne of sewage sludge, respectively. In this study, the average values, namely 42,500, 300,000, and 400,000 Yuan per tonne, are used to depict the capital costs of these three technologies for the treatment of urban

Table 5
BW method for determining the relative performances of the three technologies for the treatment of urban sewage sludge with respect to social acceptability.
Reference: Jin and Li, 2009.

Best technology: A_2		Worst technology: A_3	
a_{2j}	3	1	7
a_{j3}	3	7	1
Relative performances	A_1 0.2456	A_2 0.6635	A_3 0.0909
$\xi^*=0.2984$, $a_{BW}=7$, CI = 3.73, so $\text{CR}=\frac{\xi^*}{\text{CI}}=\frac{0.1623}{3.73}=0.0800$			

sewage sludge. Similarly, the running costs of Landfilling, Composting, and Drying Incineration are 22.5, 60, and 500 Yuan per tonne of sewage sludge, respectively (Yu et al., 2007).

As for the four soft criteria of occupied land, environmental risk, social acceptability, and generalizability, BW was applied to address this. Taking the relative performances of the three technologies, Landfilling, Composting, and Drying Incineration, with respect to occupied land as an example, the four steps of BW method for determining the relative performances of the three technologies are illustrated as follows:

3.2.1. Step 1

Drying Inclination and Landfilling are recognized as the best and the worst technologies for the treatment of sewage sludge with respect to occupied land. Accordingly, B = 3 and W = 1.

3.2.2. Step 2

The BO and OW vectors can be determined based on focus group meeting. For instance, the relative preferences of the best technology (Drying Incineration, A_3) over all the other technologies (A_1, A_2, and A_3) are recognized as 'absolutely important' (corresponding to 9), 'absolutely important' (corresponding to 9), and 'equally important' (corresponding to 1) based on literature reviews (Jin and Li, 2009) and focus group meeting. Accordingly, the BO vector is $\text{BO}=[9\quad 9\quad 1]$. In a similar way, the relative preferences of other technologies over the worst technology (landfilling, A_1) with respect to occupied land can also be determined: $\text{OW}=[1\quad 2\quad 9]$.

3.2.3. Step 3

Determining the relative performances of the three technologies with respect to occupied land by solving the following programming:

$$\begin{aligned}
&\min\xi\\
&s.t.\\
&\left|\frac{\omega_3}{\omega_1}-9\right|\le\xi\\
&\left|\frac{\omega_3}{\omega_2}-9\right|\le\xi\\
&\left|\frac{\omega_2}{\omega_1}-2\right|\le\xi\\
&\omega_j+\omega_2+\omega_3=1\\
&\omega_j\ge 0\,,j=1,2,3
\end{aligned}\tag{24}$$

The solutions are:
$\omega_1=0.0909$, $\omega_2=0.0909$, $\omega_3=0.8182$, and $\xi^*=0$.

3.2.4. Step 4

As $a_{BW}=9$, CI = 5.23, gives $\text{CR}=\frac{\xi^*}{\text{CI}}=\frac{0}{5.23}=0$. Therefore, the established comparisons in the BO and OW vectors are consistent.

Similarly, the relative performances of the three technologies, Landfilling, Composting, and Drying Incineration, with respect to generalizability, social acceptability, and environmental risk can also be determined, as presented in Tables 4-6. Accordingly, the data of the technologies for the treatment of urban sewage sludge with respect to these six criteria can be summarized, as presented in Table 7.

3.3. Sustainability sequence determination

According to Eq. (2), the data in Table 7 can be normalized, and the results are presented in Table 8. It is worth pointing out that the values of the three technologies with respect to occupied land, environmental risk, social acceptability, and generalizability are determined by the BW method according to their relative priorities, thus, these four criteria have been transformed into benefit-type criteria. However, the capital cost and running cost are cost-type criteria.

The sum weighted method (SWM) (Ren and Lützen, 2015) was firstly used to determine the sustainability sequence of these three alternatives. Taking the sustainability index of landfilling (A_1) as an example:

$$\begin{aligned}
S_1(\text{SWM}) &= \sum_{j=1}^{6}\omega_j x_{1j} = 0.4144\times{}`0.8013+0.1496\times{}`0.7042+0.0441\\
&\times{}`0.0909+0.1938\times{}`0.0909+0.0832\times{}`0.1000+0.1149\\
&\times{}`0.2456=0.4956
\end{aligned}$$

Similarly, the sustainability of the other two technologies can also be determined, and the results are presented in Table 9.

The digraph model was also applied to determine the sustainability sequence of these three technologies. According to Eq. (12) and (13), the matrix X_i in the digraph model with respect the three technologies (A_1, A_2, and A_3) can be determined, as presented in Eqs. (25–27).

$$X_1=\begin{array}{c}(A_1)\\C_1\\C_2\\C_3\\C_4\\C_5\\C_6\end{array}\begin{array}{cccccc}C_1&C_2&C_3&C_4&C_5&C_6\\0.8013&2.7701&9.3968&2.1383&4.9808&3.6066\\0.3610&0.7042&3.3923&0.7719&1.7981&1.3020\\0.1064&0.2948&0.0909&0.2276&0.5300&0.3838\\0.4677&1.2955&4.3946&0.0909&2.3293&1.6867\\0.2008&0.5561&1.8866&0.4293&0.1000&0.7241\\0.2773&0.7680&2.6054&0.5929&1.3810&0.2456\end{array}\tag{25}$$

$$X_2=\begin{array}{c}(A_2)\\C_1\\C_2\\C_3\\C_4\\C_5\\C_6\end{array}\begin{array}{cccccc}C_1&C_2&C_3&C_4&C_5&C_6\\0.1135&2.7701&9.3968&2.1383&4.9808&3.6066\\0.3610&0.2641&3.3923&0.7719&1.7981&1.3020\\0.1064&0.2948&0.0909&0.2276&0.5300&0.3838\\0.4677&1.2955&4.3946&0.1583&2.3293&1.6867\\0.2008&0.5561&1.8866&0.4293&0.2162&0.7241\\0.2773&0.7680&2.6054&0.5929&1.3810&0.6635\end{array}\tag{26}$$

$$X_3=\begin{array}{c}(A_3)\\C_1\\C_2\\C_3\\C_4\\C_5\\C_6\end{array}\begin{array}{cccccc}C_1&C_2&C_3&C_4&C_5&C_6\\0.0851&2.7701&9.3968&2.1383&4.9808&3.6066\\0.3610&0.0317&3.3923&0.7719&1.7981&1.3020\\0.1064&0.2948&0.8182&0.2276&0.5300&0.3838\\0.4677&1.2955&4.3946&0.7508&2.3293&1.6867\\0.2008&0.5561&1.8866&0.4293&0.6838&0.7241\\0.2773&0.7680&2.6054&0.5929&1.3810&0.0909\end{array}\tag{27}$$

The sustainability indices of these three technologies can then be determined after determining the permanent of these three matrix, giving perm (X_1) = 368.4961, perm (X_2) = 339.2667, and perm (X_3) = 394.4895. Accordingly, it can be concluded that the sustainability

Table 6
BW method for determining the relative performances of the three technologies for the treatment of urban sewage sludge with respect to environmental risk (EN_2).
Reference: Yang et al., 2012.

Best technology: A_3		Worst technology: A_1	
a_{3j}	8	5	1
a_{j1}	1	2	8
Relative performances	A_1 0.0909	A_2 0.1583	A_3 0.7508
$\xi^*=0.2583$, $a_{BW}=7$, CI = 4.47, so $\text{CR}=\frac{\xi^*}{\text{CI}}=\frac{0.2583}{4.47}=0.0578$			

Table 7
The data of the technologies for the treatment of urban sewage sludge with respect to the criteria.

		Landfilling	Composting	Drying incineration
EC_1	Yuan RMB·t^{-1}	42,500	300,000	400,000
EC_2	Yuan RMB·t^{-1}	22.5	60	500
EN_1	/	0.0909	0.0909	0.8182
EN_2	/	0.0909	0.1583	0.7508
T_1	/	0.1000	0.2162	0.6838
S_1	/	0.2456	0.6635	0.0909

sequence of these three technologies in the descending order is Drying Incineration (A_3), Landfilling (A_1), and Composting (A_2).

The TOPSIS method was then applied to determine the sustainability sequence of these three technologies for the treatment of urban sewage sludge according to the normalized data of the technologies for the treatment of urban sewage sludge with respect to the criteria presented in Table 8. The weighted normalized data of the technologies for the treatment of urban sewage sludge with respect to the criteria can be obtained by Eq. (15), and the results are presented in Table 10.

According to Eqs. (16–19), the ideal and the anti-ideal solutions could also be determined:

$$Y^{+} = \{0.3321 \quad 0.1053 \quad 0.0361 \quad 0.1455 \quad 0.0569 \quad 0.0762\} \tag{28}$$

$$Y^{-} = \{0.0353 \quad 0.0047 \quad 0.0040 \quad 0.0176 \quad 0.0083 \quad 0.0104\} \tag{29}$$

Then, the distance from the i-th alternative to the ideal point and anti-ideal point can be determined by Eqs. (20) and (21), and they are presented in Table 11.

Finally, the closeness coefficients of these three technologies can be determined by Eq. (22), as presented in Table 12.

4. Discussion

It is apparent that the results determined by TOPSIS are consistent to that determined by SWM, in which landing filling is the most sustainable technology for the treatment of urban sewage sludge, followed by Dry Incineration and Composting. However, the results determined by SWM and TOPSIS are different from that determined by the diagraph model. The main reason is that the digraph model determines the sustainability indices of these technologies by calculating the permanency of the corresponding matrices in which no negative sign appears in the permanency function and no information is lost (Lanjewar et al., 2011). However, it is worth pointing out that it is difficult to inform decision-makers which method is correct or more accurate, because different stakeholders have different preferences and willingness; then, decision-makers can use all the determined results as a reference for decision-making. For instance, a final consensus can achieved by the rule of "the minority is subordinate to the majority" (Ren et al., 2015c), thus, the final sustainability sequence of these three technologies in the descending order is landing filling, dry incineration, and composting.

In order to test the robustness of the results, sensitivity analysis has been carried by changing the weights of the criteria for sustainability

Table 9
Sustainability sequence of the three technologies for the treatment of urban sewage sludge by WSM.

	Landfilling (A_1)	Composting (A_2)	Incineration (A_3)
Weighted sum	0.4956	0.2155	0.2889
Ranking by WSM	1	3	2

assessment of the technologies for the treatment of the urban sewage sludge. The following seven cases have been studied:

(1) Case 1: Assigning equal weights to the six criteria, namely, $\omega_1 = \omega_2 = \ldots = \omega_6 = 0.1667$;
(2) Cases 2–7: A dominant weight-0.40 was assigned to the (i–l)-th criteria ($i = 2.3,4,5,6,7$), and the other criteria were assigned by an equal weight of 0.12. For instance, in Case 2, the first criterion, namely, capital cost (EC_1), was assigned with a weight of 0.40, and the other five criteria were assigned with a weight of 0.12.

SWM, the digraph model, and TOPSIS were used to determine the relative priorities of the three alternative technologies for the treatment of urban sewage sludge under each of the seven conditions, and the results are presented in Fig. 3. It is apparent that the results determined by SWM and TOPSIS were very sensitive to the weighting of the criteria for sustainability assessment. However, the results determined by the digraph model were robust to the weights of the criteria. Therefore, it could be concluded that the integrated priorities of the technologies for the treatment of urban sewage sludge by SWM and TOPSIS were sensitive to the weights of the criteria. Accordingly, the priority sequence of the alternative technologies for the treatment of urban sewage sludge determined by SWM and TOPSIS can reflect the preferences and willingness of the decision-makers. However, the result determined by digraph model seems insensitive to the weights of the sustainability criteria, because the weights of the sustainability criteria have little contribution to the permanency as the integrated priority with respect to each technology for the treatment of urban sewage sludge.

5. Conclusions

Sustainability assessment of the alternative technologies for the treatment of urban sewage sludge is of vital importance for decision-makers/stakeholders in selecting the most sustainable technology among multiple alternatives with consideration of economic performance, environmental cleanliness, and social responsibility simultaneously. A generic criteria system which incorporates both hard criteria and soft criteria in economic, environmental, social and technological aspects for sustainability assessment was developed. The improved AHP method, namely the BW method, was applied to determine the weights of the criteria and the relative performances of the alternative technologies for the treatment of urban sewage sludge with respect to the soft criteria. The three MCDM methods, SWM, digraph model, and TOPSIS, were applied to determine the sustainability sequence of the alternative technologies for the treatment of urban sewage sludge.

Table 8
The normalized data of the technologies for the treatment of urban sewage sludge with respect to the criteria.

	Landfilling (A_1)	Composting (A_2)	Drying incineration (A_3)
EC_1	0.8013	0.1135	0.0851
EC_2	0.7042	0.2641	0.0317
EN_1	0.0909	0.0909	0.8182
EN_2	0.0909	0.1583	0.7508
T_1	0.1000	0.2162	0.6838
S_1	0.2456	0.6635	0.0909

Table 10
The weighted normalized data of the technologies for the treatment of urban sewage sludge with respect to the criteria.

	Landfilling (A_1)	Composting (A_2)	Drying incineration (A_3)
EC_1	0.3321	0.0470	0.0353
EC_2	0.1053	0.0395	0.0047
EN_1	0.0040	0.0040	0.0361
EN_2	0.0176	0.0307	0.1455
T_1	0.0083	0.0180	0.0569
S_1	0.0282	0.0762	0.0104

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Table 11
the distance from the i-th alternative to the ideal point and anti-ideal point.

	Landfilling (A_1)	Composting (A_2)	Dry incineration (A_3)
D_{i^+}	0.1485	0.3183	0.3202
D_i^-	0.3139	0.0771	0.1405

Three technologies, Landfilling, Composting, and Drying Incineration have been used to illustrate the developed sustainability assessment framework for determining the sustainability sequence of the technologies for the treatment of urban sewage sludge. The results of the sustainability sequence of these three technologies determined by SWM and TOPSIS are the same, with the sequence Landfilling, Drying Incineration and Composting in descending order. However, the sustainability sequence of these three technologies in descending order determined by the digraph model is Drying Incineration, Landfilling, and Composting. The results show that the results determined by different MCDM methods may be different. Accordingly, decision-makers should use more MCDM methods to obtain solutions and compare these solutions in order to make correct, reliable decisions.

Sensitivity analysis has been carried out by changing the weights of the criteria when using SWM, digraph model, and TOPSIS to determine the sustainability sequence of the alternative technologies for the treatment of the urban sewage sludge, and the results show that the sequences may change when using SWM and TOPSIS for ranking these alternatives if the weights of the criteria have been changed. In other words, the sustainability sequence of the alternative technologies for the treatment of the urban sewage sludge may change when using SWM and TOPSIS to rank these alternatives if the preferences and willingness of the stakeholders/decision-makers have been changed. However, changing the weights of the criteria has little effect on the integrated priorities of the alternative technologies for the treatment of the urban sewage sludge when using the digraph model to prioritize these alternatives. Therefore, the sustainability sequences determined by SWM and TOPSIS are sensitive to the weights of the sustainability criteria, because the weights can significantly influence the integrated priorities determined by these two methods. However, the digraph model which determines the integrated priority of each alternative by calculating the permanent with respect to each alternative cannot fully reflect the preferences and willingness of the stakeholders/decision-makers in the case study of this paper.

All in all, the proposed methodology for sustainability assessment has the following advantages:

(1) The criteria system for sustainability assessment of the technologies for the treatment of urban sewage sludge incorporates both hard and soft criteria in economic, environmental, social and technological aspects. It is a generic system, and the users are allowed to select the most suitable criteria by adding more criteria or deleting some of the criteria for sustainability assessment of the technologies for the treatment of urban sewage sludge;
(2) The BW method was applied to determine the weights of the criteria for sustainability assessment and the relative priorities of the technologies for the treatment of urban sewage sludge with respect to the soft criteria. This method is different from the traditional AHP method, which has to establish a consistent comparison matrix, and it only needs to determine the relative significance of the best element over all the other elements and that of all the other elements over the worst element.
(3) Three MCDM methods were applied to determine the sustainability sequence of these alternative technologies, and multiple solutions can be presented to the decision-makers as reference to help them to make correct decisions.

Table 12
the closeness coefficients of these three technologies.

	Landfilling (A_1)	Composting (A_2)	Dry incineration (A_3)
Closeness coefficients	0.6789	0.1949	0.3050
Ranking by	1	3	2

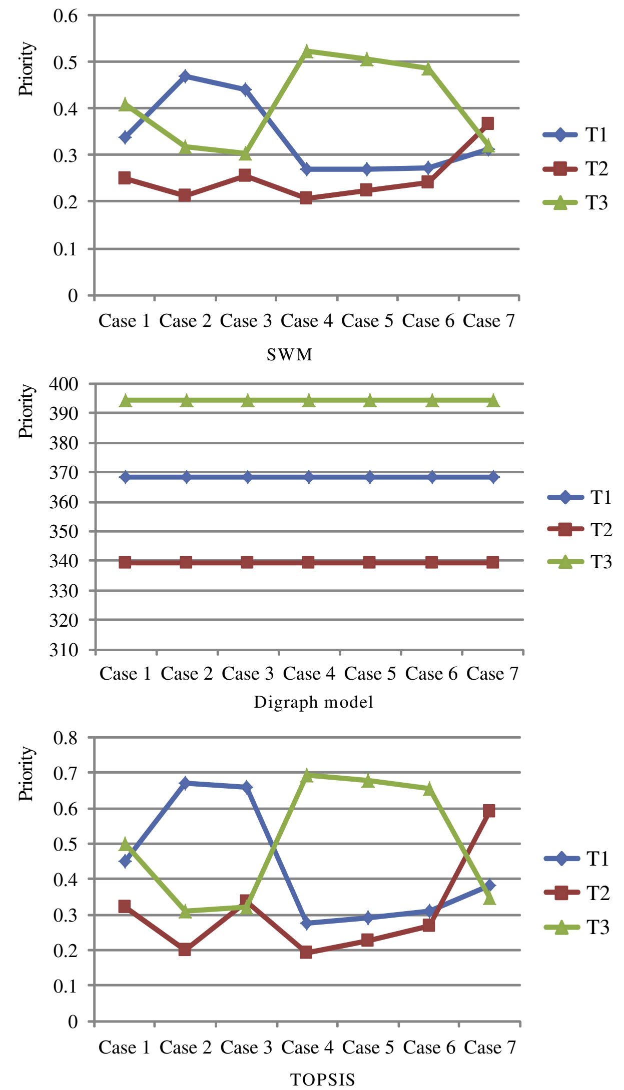

Fig. 3. Results of sensitivity analysis.

However, there is also some room for improving certain drawbacks in this study. The most severe drawback is that it is difficult for the users of the BW method to compare the relative performance of one factor over another using numbers from 1 to 9 due to the vagueness and ambiguity existing in human judgment. In addition, it demonstrates that the linear BW method is more efficient than the non-linear model according to literature review (Rezaei et al., 2015; Rezaei, 2016), because the non-linear BW model could result in multiple optimum solutions for the non-fully consistent problem with more than three criteria. Meanwhile, the linear BW model is as consistent as the no-linear method. Future work of the authors is to combine fuzzy set theory, linguistic evaluation (Wang et al., 2010) and linear BW method to modify the BW method for addressing this issue. Meanwhile, the ranking difference among the different MCDM methods often puzzles the decision-makers, and it is usually difficult for them to make correct decisions due to the inconsistency among these results. The authors plan to develop a model for providing the decision-makers with a final priority sequence by incorporating the different sequences determined by the different MCDM methods.

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