Sustainable Development of Sewage Sludge-to-Energy in China: Barriers Identification and Technologies Prioritization

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Abstract: In order to promote the sustainable development of sludge-to-energy industry and help the decision-makers/stakeholders to select the most sustainable technology for achieving the sludge-to-energy target, this study aims at using grey Decision Making Trial and Evaluation Laboratory (DEMATEL) to indentify the critical barriers that hinder the sustainable development of sludge-to-energy industry in China and to investigate the cause-effect relationships among these barriers. Accordingly, some policy implications for promoting the sustainable development of sludge-to-energy industry in China were proposed. After the grey DEMATEL analysis, a grey Multi-Criteria Decision Making (MCDM) framework which allows multiple decision-makers/stakeholders to use linguistic terms to participate in the decision-making for prioritizing the alternative technologies for sludge-to-energy was developed, and the evaluation criterion system for sustainability assessment of sludge-to-energy technologies was determined based on the results of grey DEMATEL analysis. Three alternative technologies for sludge-to-electricity were studied by the proposed MCDM method, and the results show that the proposed grey MCDM method is feasible for group decision-making and sustainability assessment of the alternative technologies for sludge-to-energy.

Keywords: Decision Making Trial and Evaluation Laboratory; Multi-Criteria Decision Making; sludge; energy

1. Introduction

The treatment of sewage sludge is of vital importance world widely though it is the secondary process after wastewater treatment, because the sewage sludge will lead to many environmental and health problems if inappropriate treatment, and the amount of sewage sludge increases significantly year by year in many countries [1-2]. Wang [3] pointed out that most of the sewage sludge in China has not been treated or disposed properly, and this leaded China to face severe environmental problems and health challenges. Therefore, it is necessary for China to promote the sustainable development of sewage sludge treatment. In order to address this issue, China also planned to take various alternative technologies/process for sewage sludge treatment, i.e. sludge incineration, sludge anaerobic digestion, compost, and ocean disposal, etc..[4]. Among these, the options that can transform sewage sludge into energy are very attractive to China's decision-makers/stakeholders as these options cannot only mitigate the environmental problems caused by sewage sludge, but also enhance China's energy security. Therefore, it is no doubt that the treatment of sewage sludge to energy in China will become emerging industry with the increase of the perceptions on environment protection of China's administrators and Chinese people.Therefore, the promotion of sustainable development of sludge-to-energy is of vital importance.

However, it is usually not easy for China's decision-makers/stakeholders to take the pertinent measures to promote as they are usually puzzled by two questions: (i) what are the most important barriers that hinder the sustainable development of sludge-to-energy? (ii) what are the cause-effect relationships among these barriers?

The answers of these two questions are of vital importance for China's decision-makers/stakeholders to draft effective policies/regulations and take effective measures for promoting the sustainable development of the sludge-to-energy industry. Moreover, it is also difficult for the decisions-makers to select the most suitable one among multiple alternative solutions for achieving the sludge-to-energy target. And more and more studies focus on analyzing the environmental impacts of sewage sludge treatment options to compare their relative environmental impacts and economic performance. For instance, emergy theory was applied to analyze the sustainability of municipal wastewater treatment for electricity generation through digestion [5]. The environmental and economic consequences of four recycling and disposal options for municipal sewage sludge including agricultural application, co-incineration with waste, incineration combined with phosphorus recovery, and fractionation including phosphorus recovery were evaluated [6]. Life cycle approach was employed to analyze the environmental and economic impacts of the six alternative scenarios for sewage sludge treatment in Japan including dewatering, composting, drying, incineration, incinerated ash melting and dewatered sludge melting [7-8].

There are also many studies focusing on the technologies for treating the sewage sludge for environment protection, resources recovery and energy production. Müller [9] provided an overview of the applications of wet disintegration in wastewater and sludge treatment, and the applied disintegration techniques including mechanical, thermal, chemical and biological methods were discussed. Neyens and Baeyens [10] had a comprehensive overview of the optimum treatment conditions to obtain enhanced dewaterability and digestibility of sludge for sludge pre-treatment. Weemaes and Verstraete [11] reviewed the current state of the art and compared different wet sludge disintegration techniques, including mechanical, chemical, thermochemical, biological and oxidative treatments. Siegrist et al. [12] presented a mathematical model to depict the the dynamic behavior of the anaerobic mesophilic digestion, and the acetate degradation kinetics were specified. Fytili and Zabaniotou [13] reviewed the methods for the utilization of sewage sludge including at thermal processes (e.g. pyrolysis, wet oxidation, gasification) and the utilization of sewage sludge in cement manufacture as a co-fuel. Werle and Wilk [14] reviewed the state of knowledge and technology in thermal methods for the utilization of municipal sewage sludge including pyrolysis, gasification, combustion, and co-combustion for energy production. Kelessidis and Stasinakis [15] analyzed the current situation and discussed future perspectives for sludge treatment and disposal in EU countries. Luostarinen et al. [16] investigated the feasibility of anaerobic co-digestion of sewage sludge and grease trap sludge from a meat-processing plant. Gao [17] investigated the development of legislation in waste disposal in German, the main subjects in sewage sludge ordinance of the European Community and that of Germany are compared. Wong et al. [18] focused on the efficacy of the microwave/hydrogen peroxide advanced oxidation process on the secondary sludge treatment; this novel technology is beneficial for both environment protection and energy security enhancement.

These studies are very useful for the decision-makers/stakeholders to understand the economic performances or environmental impacts of different technologies for sewage sludge treatment; however, it is also difficult for the decision-makers/stakeholders to make decisions directly as one alternative may perform better with respect to one criterion, but it may also be inferior with respect to another criterion. In addition, the selection of the most suitable or the most sustainable technology among multiple alternative scenarios is a multi-criteria decision-making problem. Besides the criteria in economic and environmental aspects, the criteria in some other aspects, i.e. technological, social and political aspects should also be incorporated in decision-making.

In order to address the above-mentioned issues, this study aims at achieving four objectives: (1) indentifying the critical barriers that hinder the sustainable development of sludge-to-energy industry in China; (2) analyzing the cause-effect relationships among these barriers, propose some policy implications for promoting the sustainable development of sludge-to-energy industry in China; (3) establishing the evaluation criterion system for sustainability assessment of sludge-to-energy technologies; and (4) developing a multi-criteria decision-making framework for prioritizing the alternative technologies for sludge-to-energy. Grey Decision Making Trial and Evaluation Laboratory (GDEMATEL) method and grey Multi-Criteria Decision Making (MCDM) method were employed to address these four objectives. The reminder parts of this study were organized as follows: Section 2 investigated the barriers hinder the sustainable development of sludge-to-energy China, then presented the grey Decision Making Trial and Evaluation Laboratory (DEMATEL) finally proposed the developed grey Multi-Criteria Decision Making (MCDM). The research framework of this study was presented; Case study was carried out in Section 3; and finally, this study was concluded and discussed.

2. Method

In this section, the barriers that hinder the sustainable development of sludge-to-energy China were firstly identified, subsequently the grey Decision Making Trial and Evaluation Laboratory (DEMATEL) was presented, then the grey Multi-Criteria Decision Making (MCDM) was developed. The research framework of this study is: grey DEMATEL was firstly used to identify the most important barriers that hinder the sustainable development of sludge-to-energy in China. Based on the results determined by grey DEMATEL, the users can conclude the most suitable criteria from the most important barriers for sustainability assessment of the technologies for sludge-to-energy, and the developed grey MCDM method was used to prioritize the alternative technologies for sludge-to-energy.

2.1 Barriers hindering sustainability assessment

In order to obtain the barriers that hinder the sustainable development of sewage sludge-to-energy, the authors firstly summarized the key difficulties for promoting the development of sewage sludge-to-energy in economic, environmental, technological, social-political aspects based on literature review [19-25], and then a focus group meeting in which two professors, two postdoctoral fellows, three PhD students, two senior researchers, one administrator and one engineer participated was carried out for aggregating these key points provided into criteria/barriers. A total of thirteen barriers hindering sustainable development of sewage sludge-to-energy in four aspects including economic, environmental, technological, social-political aspects were obtained, as presented in Table 1. There are four barriers in economic aspect, i.e. high capital cost, high operation and maintenance costs, lack of investment channel, and lack of funds for R&DD of sewage sludge-to-energy. Risk of secondary pollution is the barrier belonging to environmental aspect. The barriers in technological aspect consist of technology immaturity, lack of project experience, lack of complete and systematic inspection of groundwater pollution and sludge characteristics, and lack of technicians. The barriers in social-political aspect include low public perception on groundwater protection and sludge treatment, lack of governance on groundwater protection and sludge treatment, low governmental support, and lack of overall planning on groundwater exploitation belong to social-political aspect.

2.2 Grey DEMATEL

The Decision Making Trial and Evaluation Laboratory (DEMATEL) is a systematic analysis method, developed by the Science and Human Affairs Program of the Battelle Memorial Institute of Geneva between 1972 and 1976, for investigating the complicated and intertwined problem group [26]. The original purpose of Battelle Memorial Institute of Geneva for developing this method was to investigate the fragmented and antagonistic phenomena of world society and search for integrated solution [27]. And this method has been widely used in various fields for its advantages of improving the understanding of the intertwined problems, and identifying the workable solutions by visualization method [28-30].

However, the complicated systems in the real world are usually uncertainty or lack of information, and the traditional DEMATEL does not work well under this situation. Grey theory is a multi-disciplinary theory for addressing multi-criteria systems under the conditions of uncertainties or incomplete information, and it is able to conduct theoretical analysis of systems with imprecise information and incomplete samples [31]. Accordingly, many modified DEMATEL methods, so-called “grey DEMATEL”, have been developed by combining grey theory and DEMATEL thoughts [32-37]. The Grey DEMATEL method developed by Bai and Sarkis in 2013 [32] has been employed to study the cause-effect relationships among the barriers that hinder sustainable treatment of e-waste in China and the relative importance of these barriers in terms of their negative effects. Grey number was firstly presented in this part, subsequently the grey DEMATEL was developed..

2.2.1 Grey numbers

Let x denote a closed and bounded set of real numbers. A grey number $\otimes x$ is defined as an interval with known upper and lower bounds but unknown distribution information for x [38-39]. The grey operations have been summarized in Table 2.

$$\otimes x = \left[x^{-}, x^{+} \right] = \left\{ x \in \otimes x \middle| x^{-} \le x \le x^{+} \right\} \quad (1)$$

where x^{-} and x^{+} represent the lower and upper bound of the interval.

2.2.2 Grey DEMATEL

The procedures of grey DEMATEL have been specified as follows based on Refs.

[32]:

Step 1: Determining the influential factors and the participants in the decision-making. The objective of this step is to determine all the relevant influential factors that affect the studied problem and all the participants in the decision-making that can represent different stakeholders. In order to help the participants to have a good understanding of the studied object, focus group meetings or teleconferences will be held, and a coordinator will be nominated in each meeting/teleconference, he/she is responsible to introduce the objective of the studied problems and the concepts of the influential factors.

Step 2: Establishing the direct-influenced matrices using linguistic terms. The objective is to determine the direct relationships among the influential factors by using the linguistic terms. The participants are asked to present their opinions and views on how a factor influences other factors. Assuming that there are a total of K participants (k=1,2,.., K), and a total of n factors (C_1, C_1,…,C_n) to be studied. The participants are asked to judge how a criterion affects the other criteria by using linguistic terms including “No influence ([0, 0])”, “Very low influence ([0, 1])”, “Low influence ([1, 2])”, “High influence ([2, 3])”, “Very high influence ([3, 4])”, and “Extremely high influence ([4, 5])”, respectively. Accordingly, a total of K direct-influenced matrices using linguistic terms can be obtained after the focus group meetings.

Step 3: Transforming the direct-influenced matrices by using linguistic terms into grey direct-influenced matrices. All these linguistic terms in the direct-influenced matrices determined in **Step 3** can be transformed into grey numbers according to Table 2. Therefore, a total of K grey direct-influenced matrices can be obtained, as presented in Eq.8

$$\otimes X^{k}=\begin{bmatrix}[0,0] & \otimes x_{12}^{k} & \cdots & \otimes x_{1n}^{k} \\ \otimes x_{21}^{k} & [0,0] & \cdots & \otimes x_{2n}^{k} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes x_{n1}^{k} & \otimes x_{n2}^{k} & & [0,0]\end{bmatrix}, for \quad k=1,2,\cdots,\mathrm{K} \tag{8}$$

where $\otimes X^{k}$ is the grey direct-influenced matrix determined by the k-th stakeholders, $\otimes x_{ij}^{k}=\left[x_{ij}^{k-}, x_{ij}^{k+}\right]$ represents the relative influence of the i-th factor on the j-th factor, it is the element in cell (i,j) of $\otimes X^{k}$, and x_{ij}^{k-} and x_{ij}^{k+} are the lower and upper bounds of the grey number $\otimes x_{ij}^{k}$, respectively.

Step 4: Determining the initial direct-influenced matrix. The initial direct-influenced matrix can be determined by combining all the grey direct-influenced matrices into an aggregating matrix according to Eqs.2-3

$$\otimes X=\begin{bmatrix}[0,0] & \otimes x_{12} & \cdots & \otimes x_{1n} \\ \otimes x_{21} & [0,0] & \cdots & \otimes x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes x_{n1} & \otimes x_{n2} & & [0,0]\end{bmatrix} \tag{9}$$

$$\otimes x_{ij}=\sum_{k=1}^{K} \otimes x_{ij}^{k} \Big/ K \tag{10}$$

Step 5: Determining the normalized direct-influenced matrix. The normalized direct-influenced matrix can be obtained by Eqs.11-13.

$$s=\left[s^{-}, s^{+}\right]=1 \Big/ \max_{1 \leq i \leq n} \sum_{j=1}^{n} \otimes x_{ij} \tag{11}$$

$$\left[\left(n_{ij}^{-}, n_{ij}^{+}\right)\right]=\otimes s \otimes x_{ij}=\left[s^{-}, s^{+}\right] \times\left[x_{ij}^{-}, x_{ij}^{+}\right] \tag{12}$$

$$\otimes N=\left[\otimes n_{ij}\right]_{n \times n}=\left[\left(n_{ij}^{-}, n_{ij}^{+}\right)\right]_{n \times n} \tag{13}$$

Step 6: Calculating the total relation matrix. The total relation matrix $\otimes T$ can be calculated by Eqs.15-19.

$$\otimes T = \left[\otimes t_{ij}\right]_{n\times n} = \left[\left(t_{ij}^{-}, t_{ij}^{+}\right)\right]_{n\times n} = \otimes N + \left(\otimes N\right)^{2} + \cdots + \left(\otimes N\right)^{\infty} = N(I-N)^{-1} \tag{15}$$

$$T^{-} = \left[t_{ij}^{-}\right]_{n\times n} = N^{-}(I-N^{-})^{-1} \tag{16}$$

$$T^{+} = \left[t_{ij}^{+}\right]_{n\times n} = N^{+}(I-N^{+})^{-1} \tag{17}$$

$$N^{+} = \left[n_{ij}^{-}\right]_{n\times n} \tag{18}$$

$$N^{-} = \left[n_{ij}^{+}\right]_{n\times n} \tag{19}$$

where $\otimes T$ represents the total relation matrix, and I is the identity matrix.

Step 7: Determining the overall importance or prominence of each factor and the net influence of each factor.

The total effect that directly and indirectly exerted by the i-th factor, is denoted by $\otimes R_i$, could be determined by calculating the sum of the elements in the i-th row, as presented in Eq.20.

$$\otimes R_i = \sum_{j=1}^{n} \otimes t_{ij} \tag{20}$$

The total effect including direct and indirect effects received by the i-th factor, is denoted by $\otimes C_i$ could be calculated could be determined by calculating the sum of the elements in the i-th column, as presented in Eq.21.

$$\otimes C_j = \sum_{i=1}^{n} \otimes t_{ij} \tag{21}$$

Subsequently, the overall importance or prominence ($\otimes P_i$) of each factor and net effect ($\otimes E_i$) of each factor can be calculated by Eqs. 22-23, respectively.

$$\otimes P_i = \otimes R_i + \otimes C_i \tag{22}$$

$$\otimes E_i = \otimes R_i - \otimes C_i \tag{23}$$

It is worth pointing out that $\otimes P_i$ and $\otimes E_i$ are grey numbers. Their whitened mid-values can be determined according to Eq. 7, denoted by P_i and E_i, respectively. The value of P_i represents the total effects given and received by the i-th factor. The larger the value, the greater the overall prominence of the i-th factor among all the factors.

The value of E_i measures the net effect that contributed by the *i*-th factor to the studied objects. When $E_i > 0$, the i-the factor is a net cause, and it belongs to the 'cause' group. In the contrary, $E_i < 0$, the i-the factor is a net receiver or result, and it belongs to the 'effect' group.

According to the coordinate values (P_i, E_i) with respect to all the factors, they could be drawn out in the cause-effect diagram. Before drawing the cause-effect diagram, the threshold value is allowed to be set, if the sum (r_i +c_i) with respect to the i-th criterion is smaller the threshold value, it means that the influence of the i-th criterion is relatively small, then the *i*-th criterion could be deleted in the cause-effect diagram.

After the grey DEMATEL analysis, the criteria for sustainability assessment of the technologies of sludge-to-energy can be determined according to the critical barriers that have been recognized to have significant influence on the sustainable development of China's sludge-to-energy industry, the cause-effect relationships among these barriers, and the actual conditions.

2.3 Linguistic Grey Multi-Criteria Decision Making (MCDM) Method

The traditional grey rational analysis (GRA) can only address the decision-making matrix with crisp numbers, thus, sometime it is usually difficult or impossible for the decision-makers to provide accurate data of the alternatives with respect to the criteria in the decision-making. This study developed an improved GRA method which allows the decision-makers to use linguistic terms to express their opinions on the alternatives with respect to each criterion. The improved grey relational analysis with grey numbers has been developed, as presented in the following eight steps. The traditional grey analysis has been popularized to address interval problems [40].

Step 1: Determining the decision-making matrix by each decision-maker and the integrated decision-making matrix. Assume that there are a total of L experts who have participated in the decision-making, and there are m alternative characterized by n criteria, each expert is asked to use the linguistic terms presented in Table 4 to evaluate the relative priorities of the alternatives with respect to each criterion.

Then, the linguistic terms can be transformed into grey numbers according to Table 4, and the grey decision making matrix (X^k) established by the k-th decision-maker can be expressed by Eq.24.

$$\otimes X^k = \begin{vmatrix} \otimes x_{11}^k & \otimes x_{12}^k & \cdots & \otimes x_{1n}^k \\ \otimes x_{21}^k & \otimes x_{22}^k & \cdots & \otimes x_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ \otimes x_{m1}^k & \otimes x_{m2}^k & & \otimes x_{mn}^k \end{vmatrix} \tag{24}$$

$$\otimes x_{ij}^k = \left[x_{ij}^{k,-}, x_{ij}^{k,+} \right], i = 1,2,\cdots,m; j = 1,2,\cdots,n \tag{25}$$

where $\otimes x_{ij}$ represents the value of the i-th alternative with respect to the j-th criterion determined by by the k-th expert.

Then, the integrated decision-making matrix can be determined by Eqs.26-27,

$$\otimes X = \begin{vmatrix} \otimes x_{11} & \otimes x_{12} & \cdots & \otimes x_{1n} \\ \otimes x_{21} & \otimes x_{22} & \cdots & \otimes x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes x_{m1} & \otimes x_{m2} & & \otimes x_{mn} \end{vmatrix} \tag{26}$$

$$\otimes x_{ij} = \sum_{k=1}^{L} \otimes x_{ij}^{k} \Big/ L = \left[\sum_{k=1}^{L} x_{ij}^{k,-}, \sum_{k=1}^{L} x_{ij}^{k,+} \right], i = 1,2,\cdots,m; j = 1,2,\cdots,n \tag{27}$$

Step 2: Normalizing the data in the integrated decision making matrix. There are two methods for data processing for different types of the criteria. If the larger the criteria, the better the alternative will be, the criteria belong to benefit-type, on the contrary, the larger the criteria, the worse the alternative will, the criteria belong to cost-type.

The benefit-criteria can be normalized by Eq.28:

$$\otimes y_{ij} = \frac{\otimes x_{ij}}{\max_{i=1}^{m}\left\{ x_{ij}^{k,+} \right\}}, i = 1,2,\cdots,m; j = 1,2,\cdots,n \tag{28}$$

The cost-criteria can be normalized by Eq.29:

$$\otimes y_{ij} = \frac{\min_{i=1}^{m}\left\{ x_{ij}^{k,-} \right\}}{\otimes x_{ij}}, i = 1,2,\cdots,m; j = 1,2,\cdots,n \tag{29}$$

Step 3: Determining the reference alternative. According to the normalized matrix, as presented in Eq.30, the reference alternative can be determined by Eq.31 and Eq.32. Reference alternative is the ideal best solution.

$$\otimes Y = \begin{vmatrix} \otimes y_{11} & \otimes y_{12} & \cdots & \otimes y_{1n} \\ \otimes y_{21} & \otimes y_{22} & \cdots & \otimes y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes y_{m1} & \otimes y_{m2} & & \otimes y_{mn} \end{vmatrix} \tag{30}$$

$$y^{0} = \left\{ y_{1}^{0}, y_{2}^{0}, \cdots, y_{n}^{0} \right\} \tag{31}$$

$$\otimes y_{j}^{0} = \max_{i=1}^{m} y_{ij}^{+}, j = 1,2,\cdots,n \tag{32}$$

where y_j^0 is the reference value in relation to the j-th criterion

Step 4: Calculating the difference between the alternatives and the reference alternative. The difference matrix can be determined by Eq.33 and Eq.34.

$$\otimes\Delta = \begin{vmatrix} \otimes\Delta_{11} & \otimes\Delta_{12} & \cdots & \otimes\Delta_{1n} \\ \otimes\Delta_{21} & \otimes\Delta_{22} & \cdots & \otimes\Delta_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes\Delta_{m1} & \otimes\Delta_{m2} & & \otimes\Delta_{mn} \end{vmatrix} \quad (33)$$

$$\otimes\Delta_{ij} = \left[y_j^0 - y_{ij}^+, y_j^0 - y_{ij}^- \right], i = 1,2,\cdots,m; j = 1,2,\cdots,n \quad (34)$$

Step 5: Determining the weights of the criteria. The weight of each criterion can be determined according to the overall importance or prominence of the criterion determined by grey DEMATEL, as presented in Eq.35.

$$\otimes\omega_j = \otimes P_j \Big/ \sum_{j=1}^{n} \otimes P_j \quad (35)$$

where $\otimes\omega_j$ is the weight of the *j*-th criterion, and $\otimes P_j$ represents the overall importance or prominence determined with respect to the *j*-th criterion determined in grey DEMATEL analysis.

Step 6: Calculating the grey relational coefficients of the alternatives with respect to the criteria. The grey relational coefficients of the alternatives with respect to the criteria can be determined by Eqs.36-37, and the grey relational coefficient matrix can be determined by Eq.38.

$$\varepsilon_{ij}^- = \frac{\min_{i=1}^{m} \min_{j=1}^{n} \Delta_{ij}^- + \rho \times \max_{i=1}^{m} \max_{j=1}^{n} \Delta_{ij}^+}{\Delta_{ij}^+ + \rho \times \max_{i=1}^{m} \max_{j=1}^{n} \Delta_{ij}^+} \quad (36)$$

$$\varepsilon_{ij}^+ = \frac{\min_{i=1}^{m} \min_{j=1}^{n} \Delta_{ij}^- + \rho \times \max_{i=1}^{m} \max_{j=1}^{n} \Delta_{ij}^+}{\Delta_{ij}^- + \rho \times \max_{i=1}^{m} \max_{j=1}^{n} \Delta_{ij}^+} \quad (37)$$

$$\otimes E = \left\{ \otimes \varepsilon_{ij} \right\}_{m \times n} \tag{38}$$

where $\otimes \varepsilon_{ij} = \left[\varepsilon_{ij}^{-}, \varepsilon_{ij}^{+} \right]$ is the grey relational coefficient, ρ represents the distinguishing coefficient, it takes the value of 0,5 in this study.

Step 7: Determining the grey relational degree. The grey relational degree with respect to each alternative is a weighted sum of the grey relational coefficients, as shown in Eq.39.

$$\otimes \gamma_i = \sum_{j=1}^{n} \otimes \varepsilon_{ij} \times \otimes \omega_j \tag{39}$$

where $\otimes \omega_j$ represents the grey weight (weighting coefficient) of the j-th criterion, and $\otimes \gamma_i$ is the grey relational degree with respect to the i-th alternative.

Step 7: Whitening the grey relational degree and prioritizing the alternatives. The whitening relational degree can be determined by Eq.40 and Eq.41. The alternatives can be prioritized according to the rule that the bigger the whitening relational degree, the better the corresponding alternative will be.

$$\otimes \gamma_i = [\gamma_i^{-}, \gamma_i^{+}] \tag{40}$$

$$\gamma_i = \frac{\gamma_i^{-} + \gamma_i^{+}}{2} \tag{41}$$

where $\otimes \gamma_i$ and γ_i represent the grey relational degree and whitening relational degree of the i-th alternative, respectively.

3. Case study

In this section, grey DEMATEL method was firstly employed to identify the critical factors that hinder the sustainable development of sewage sludge-to-energy in

China, to analyze the case-effect relationships among these factors, and to propose some policy implications for the decision-makers/policy-makers in China to draft effective policies/regulations and to take effective measures for promoting the sustainable development of sewage sludge-to-energy in China. Meanwhile, the criteria for sustainability assessment of the technologies for sewage sludge-to-energy can be determined according to the critical factors identified by grey DEMATEL analysis. Moreover, the relative importance (weight) of each criteria can also be determined according to the overall importance or prominence ($\otimes P_i$) of the criterion. Then, the proposed linguistic grey multi-criteria decision making was used to propose the following three technologies for sewage sludge to electricity [41]:

(1) Sludge incineration to electricity (SIE, denotes by T_1);

(2) Sludge anaerobic digestion for biogas to electricity through gas engine (SADBEGE, denotes by T_2);

(3) Sludge anaerobic digestion for biogas to electricity through fuel cell (SADBEFC, denotes by T_3).

3.1 Grey DEMATEL analysis

There are a total of thirteen influential factors (barriers) hindering sustainable development of China's sewage sludge-to-energy that have been identified in section 2, and three top representative experts represent three groups of stakeholders have been invited to participate in determining the direct-influenced matrices. The first expert group (DM#1) consists of two professor , three postdoctoral fellows, three PhD students and two senior researchers , and their research interests mainly focus on environmental engineering, management science, or sustainable development, a professor from a public university which is a key university in China was nominated as the coordinator of this expert group . The second expert group (DM#2) include six experienced environmental engineer who has abundant experience on waste management, and an engineer from the factory for urban wastewater treatment was nominated as the coordinator of this expert group. The third expert group (DM#3) has many three administrators as decision-makers/policy-makers who worked in the environmental protection section of the local governments in China, and an administrator from a regional water company of China was nominated as the coordinator of this expert group. The authors have provided all the related technical reports, literature, papers, and surveys to them for the coordinator of each expert group to have a good understanding of the objectives of this study and the concepts of all the influential factors. Moreover, a focus group meeting and two teleconferences with the coordinators have been held to supervise him/her to firstly determine the direct-influenced matrix using linguistic terms, then he/she will discuss with his/her colleagues of his/her expert group to modify the determined direct-influenced matrix until achieving a consistency. The results are presented in Tables 5-7. Taking Table 5 as an example, this is the direct-influenced matrix using linguistic terms determined by DM#1, cell (1.3) in this matrix is 'VH' which means that the effect of 'capital cost(EC_1)' on 'lack of investment channels (EC_3)' is 'very high (VH)'. Subsequently, the linguistic terms in the direct-influenced matrices determined by DM#1, DM#2 and

DM#3 (see Tables 5-7) can be transformed into grey numbers according to Table 3. For instance, 'N', 'VL','L', 'H', and 'VH' in Table 5 can be transformed into [0, 0], [0, 1], [1, 2], [2, 3], [3, 4] and [4, 5], respectively. Accordingly, the direct-influenced matrix using grey numbers determined by DM#1 can be obtained, as presented in Table 8. Similarly, the direct-influenced matrices using grey numbers determined by DM#2 and DM#3 can also be obtained, as presented in Tables 9-10.

Then, the initial direct-influenced matrix can be obtained by aggregating Tables 8-10 according to Eq.10, and the results are presented in Table 11. According to Table 10 and Eq.11, $s=\left[s^{-},s^{+}\right]=1/[19.0000,29.0000]=[0.0345,0.0526]$. Then, the normalized direct-influenced matrix can be obtained according to Eqs.12-13, as presented in Table 12. Finally, the total relation matrix $\otimes T$ can be calculated by Eq.15-19, as presented in Table 13.

Based on the total relation matrix (Table 13), $\otimes R_i$, $\otimes C_i$, $\otimes P_i$, and $\otimes E_i$ with respect to each barrier can be obtained. Then, the whitened mid-values of $\otimes P_i$, and $\otimes E_i$ with respect each barrier can also be obtained according to Eq.7, as presented in Table 14. Accordingly, the cause-effect diagram can be obtained, as presented in Figure 1. According to the values of P_i, a critical line was set to identify the critical factors, 'lack of project experience (T_2)' is the most important barrier that hinder the sustainable development of sewage sludge-to-energy in China, followed by 'low governmental support (SP_3)' , 'lack of investment channels (EC_3)', 'technology immaturity (T_1)', 'high capital cost (EC_1)', 'lack of funds for R&DD of sewage sludge-to-energy(EC_4)', 'high operation and maintenance costs (EC_2)', 'lack of governance on groundwater protection and sludge treatment (SP_2)', 'lack of complete and systematic inspection of groundwater pollution and sludge characteristics (T_3)', and 'risk of secondary pollution (EN_1)' in the descending order. The other barriers are less important. According to the values of E_i, the 'cause' group consists of 'low governmental support (SP_3)', 'technology immaturity (T_1)', 'high capital cost (EC_1)', 'lack of funds for R&DD of sewage sludge-to-energy(EC_4)', 'high operation and maintenance costs (EC_2)', 'lack of governance on groundwater protection and sludge treatment (SP_2)', and 'lack of overall planning on groundwater exploitation SP_4' as the values of E_i with respect to these barriers are greater than zero; the 'effect' group consist of 'lack of project experience (T_2)', 'lack of complete and systematic inspection of groundwater pollution and sludge characteristics (T_3)', 'risk of secondary pollution (EN_1)', 'Low public perception on groundwater protection and sludge treatment (SP_1)', and 'lack of technicians (T_4)' as the values of E_i with respect to these barriers are less than zero. However, the values of E_i with respect to the barriers in the 'cause' group and the 'effect' group are near zero, and it means that these barriers in the 'cause' group have high possibility of turning into 'effect' group, and these barriers in the 'effect' group have high possibility of turning into 'cause' group. Thus, the barriers in the cause-effect diagram have been further divided into three regions including the 'cause' group, the 'linkage' group, and the 'effect' group, as presented in Figure 1. The barrier 'lack of investment channels (EC_3)' belongs to the 'linkage' group.

3.2 MCDM on the three technologies for sewage sludge to electricity

As mentioned-above, the barriers including 'lack of project experience (T_2)', governmental support (SP_3)' , 'lack of investment channels (EC_3)', 'technology immaturity (T_1)', 'high capital cost (EC_1)', 'lack of funds for R&DD of sewage sludge-to-energy(EC_4)', 'high operation and maintenance costs (EC_2)', 'lack of governance on groundwater protection and sludge treatment (SP_2)', 'lack of complete and systematic inspection of groundwater pollution and sludge characteristics (T_3)', and 'risk of secondary pollution (EN_1)' are the most important that hinder the sustainable development of sewage sludge-to-energy in China, and they should be selected as the criteria for sustainability assessment of the technologies for sewage sludge to electricity; however, with the considerations of the similarity of some factors among the technologies and the cause-effect relationships existed in some factors, five criteria in four aspects were determined for sustainability assessment, as presented in Table 15. There are two criteria in economic aspect, including capital cost (C_1), and operation and maintenance costs (C_2) corresponding to the barriers EC_1 and EC_2, respectively. The other three criteria are environmental impacts belonging to environmental aspect (C_3), technology maturity (C_4) belonging to technological, and governmental support (C_5) belonging to social-political aspect, and they correspond to the barriers $EN_{1,}$ T_1, and $SP_{3,}$ respectively.

The decision-makers are asked to use the linguistic terms presented in Table 4 to determine the decision-making matrices by using linguistic terms, and the decision-making matrices determined by DM#1, DM#2, and DM#3 were presented in

Table 16. The decision-making matrix determined by DM#1, DM#2, and DM#3 using grey numbers can be determined by transforming the linguistic terms in Table 16 into grey numbers according to Table 4, and the results were presented in Table 17.

According to Table 17 and Eqs.26-27, the integrated decision-making matrix can be determined, as presented in Table 18. According to Eq.28, the integrated decision-making matrix can be normalized; it is worth pointing out that all the criteria can be recognized as benefit-criteria as they have been scored by using the grey numbers. Taking cell (1,1) in Table 18 as an example:

$$\otimes y_{11} = \frac{\otimes x_{11}}{\max_{i=1}^{m}\left\{x_{i1}^{k,+}\right\}} = \frac{[2.0,3.5]}{\max\{3.5,6.5,7.0\}} = [0.2857,0.5000]$$

Similarly, other elements in Table 17 can also be normalized, and the normalized integrated decision-making matrix was presented in Table 19. The reference alternatives can be determined by Eqs.31-32 $y^0 = \{1,1,1,1,1\}$. Subsequently, the difference matrix can be calculated by Eqs.33-34, as presented in Table 20.

The weight of each criterion can be determined according to the overall importance or prominence of the criterion determined by grey DEMATEL, and the weights of the five criteria were presented in Table 21 according to Eq.35. After the determination of the weights of the criteria, the grey relational coefficient matrix can be determined by Eqs.36-38. Then, the grey relational degrees of the three technologies for sewage sludge to electricity can be determined by Eq.39, the results were presented in Table 23. Finally, whitening relational degrees of the technologies can be determined, as presented in Figure 2. Therefore, the priority of the three technologies according to their sustainability in descending order is T_2 , T_3 , and T_1.

3.3 Policy implications

According to the results of grey DEMATEL and the prioritization of the technologies for sludge-to-electricity, the following policy implications are proposed for China's decision-makers/stakeholders:

(1) According to the results determined by grey DEMATEL that the most important six barriers that hinder the sustainable development of sludge-to-energy consist of lack of project experience, low governmental support, lack of investment channels, technology immaturity, high capital cost, and lack of funds for R&DD of sewage sludge-to-energy, thus, China's decision-makers/stakeholders should:

I. enhance the project experience on sludge-to-energy in China by inviting foreign investors or technology providers to participate technologically in the reclamation of sludge to energy in China;

II. extend the investment channels on sludge-to-energy projects in China by encouraging the foreign and private investors to participate in these projects through various fiscal supporting approaches (i.e. subsidies and zero interest rate loan), regulations, and policies;

III. enhance government's functions by taking effective measures to be business incubator for attracting investments on the projects of sludge-to-energy;

IV. set special funds R&DD of the technologies for sludge-to-energy to improve technology maturity and reduce the capital costs.

(2) According to the results determined by grey DEMATEL that the cause group consists of seven barriers. Among these, the four barriers including low governmental support, technology immaturity, high capital cost, and lack of funds for R&DD of sewage sludge-to-energy are not only important, but also the root of the problems existed in sludge-to-energy industry in China, thus, China's decision-makers/stakeholders should take more pertinent measures for overcoming these four barriers.

(3) According to the results of prioritization of the technologies for sludge-to-energy, it is apparent that different technologies perform different in sustainability aspect, thus, the decision-makers/stakeholders should invest more on the technologies that have better sustainability performance.

4. Conclusions and discussion

The treatment of sewage sludge in China faces both opportunities and challenges as the sustainable development of sludge treatment industry is a good opportunity for reclamation, while the inappropriate treatment will lead to severe environmental pollutions and human health problems. This study aims at analyzing the barriers that hinder the sustainable development of sewage sludge-to-energy in China and proposing a multi-criteria decision-making method for prioritizing the technologies for sludge-to-energy, and thirteen barriers in four aspects including economic, environmental, technological, and social-political aspects have been obtained. In order to investigate the roles of these barriers and the interrelationships among them, grey

DEMATEL has been employed to analyze these barriers, three top experts of e-waste recycling representing the three groups of stakeholders have been invited to participate the determination of the direct-influenced matrices that can describe the direct relationships among the barriers, the most important barriers have been determined, and the 'cause' and 'effect' groups have also been identified. The results provide insights for the stakeholders to take appropriate measures for overcoming the barriers and promoting the sustainable development of sewage sludge-to-energy in China. Therefore, some recommendations for promoting the sustainable sludge-to-energy in China have been proposed for China's stakeholders.

Moreover, a multi-criteria decision-making method for prioritizing the technologies for sewage sludge-to-energy was developed by modifying the traditional grey relational analysis, and this improved grey relational analysis allows the users to use linguistic terms to evaluate the performances of the technologies with respect to each criterion. In order to illustrate the proposed MCDM method, three technologies for sludge to electricity has been studied by the proposed method, and the results show that the proposed MCDM method is feasible for the decision-makers to rank the alternatives.

All in all, this study provides a modular approach (grey DEMATEL) for analyzing the barriers existed in sustainable development of sludge-to-energy in China and a generic MCDM method for prioritizing the technologies for sludge-to-energy. Grey DEMATEL allows the users to analyze more barriers that have not been mentioned in this study. Besides the advantages, there are also two drawbacks in this study: (i) this study only select the barriers that are significantly important, while more barriers should be analyzed; (ii) this study only incorporate the opinions of three experts though they have discussed with their colleagues for determining the direct-influenced matrix, and more stakeholders in each group should be invited to participate in this process. Thus, the future work of the authors is to analyze more barriers that affect the sustainable development of sludge-to-energy in China and incorporate the opinions of more stakeholders. Meanwhile, the proposed MCDM method allows multiple decision-makers to participate in the decision-making and it also allows the users to use linguistic terms to express their opinions; however, the difference of the decision-makers on the weight of each criterion has never been considered, thus, the future work will develop a MCDM method which can incorporate the difference of the decision-makers on the weight of each criterion for sustainability assessment.

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Figures

Figure Captions

Figure 1: The cause-effect diagram

Figure 2: The whitening relational degrees of the three technologies

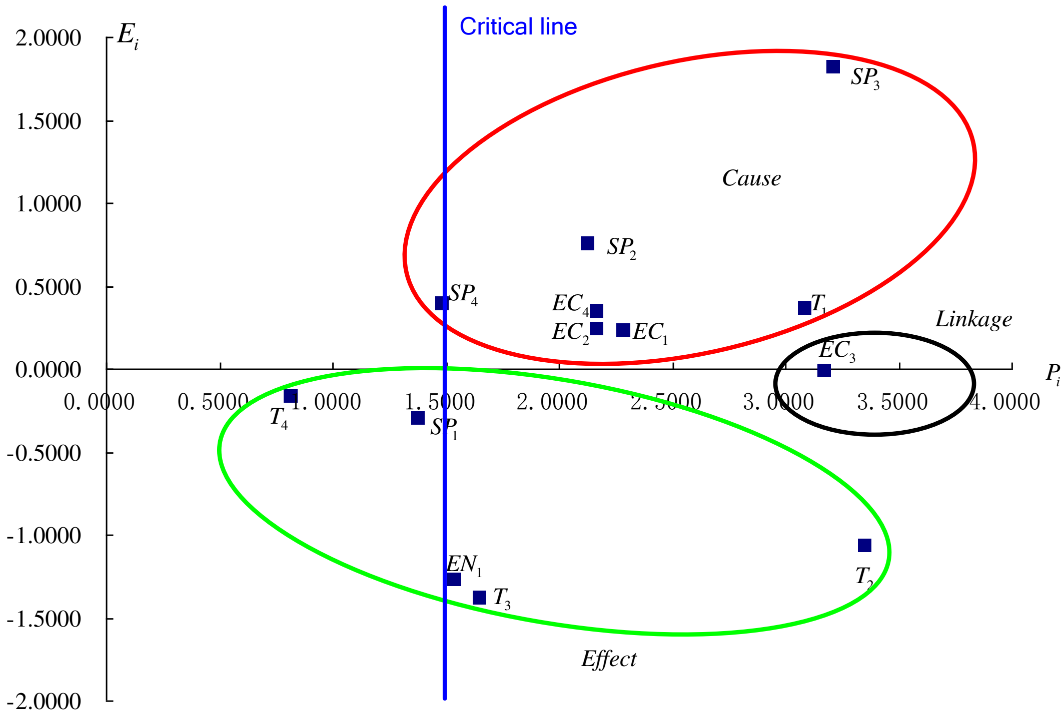

Figure 1: The cause-effect diagram

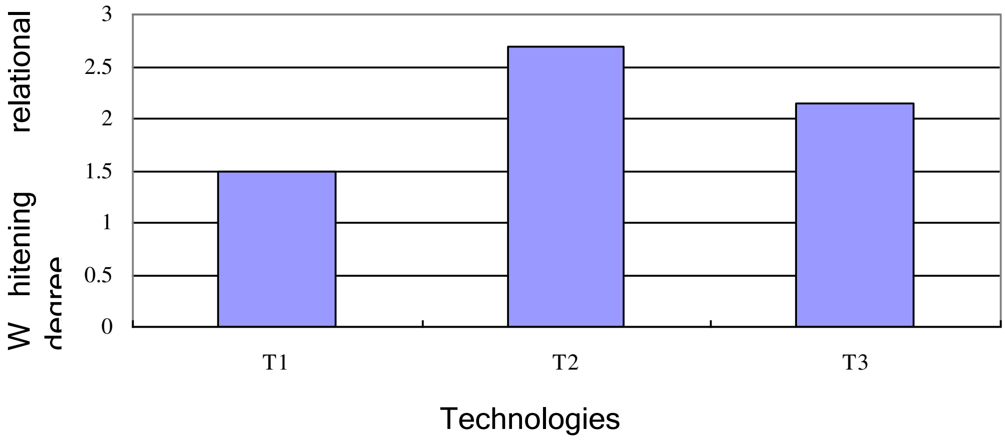

Figure 2: The whitening relational degrees of the three technologies

Tables

Table 1: Criteria for sustainability assessment of sewage sludge-to-energy

Aspect	Criteria	Abbreviation
Economic	High capital cost	EC_1
	High operation and maintenance costs	EC_2
	Lack of investment channels	EC_3
	Lack of funds for R&DD of sewage sludge-to-energy	EC_4
Environmental	Risk of secondary pollution	EN_1
Technological	Technology immaturity	T_1
	Lack of project experience	T_2
	Lack of complete and systematic inspection of groundwater pollution and sludge characteristics	T_3
	Lack of technicians	T_4
Social-political	Low public perception on groundwater protection and sludge treatment	SP_1
	Lack of governance on groundwater protection and sludge treatment	SP_2
	Low governmental support	SP_3
	Lack of overall planning on groundwater exploitation	SP_4

Table 2: The grey operations

Item	Formulas and explanation	Equation
ADDITION	$\otimes x_1 + \otimes x_2 = \left[x_1^-, x_1^+\right] + \left[x_2^-, x_2^+\right] = \left[x_1^- + x_2^-, x_1^+ + x_2^+\right]$ The addition law between two grey numbers $\otimes x_1 = \left[x_1^-, x_1^+\right]$ and $\otimes x_2 = \left[x_2^-, x_2^+\right]$.	Eq.2
SUBTRACTION	$\otimes x_1 - \otimes x_2 = \left[x_1^-, x_1^+\right] - \left[x_2^-, x_2^+\right] = \left[x_1^- - x_2^+, x_1^+ - x_2^-\right]$ The subtraction law between two grey numbers $\otimes x_1 = \left[x_1^-, x_1^+\right]$ and $\otimes x_2 = \left[x_2^-, x_2^+\right]$.	Eq.3
MULTIPLICATION	$\otimes x_1 \otimes x_2 = \left[\min\left\{x_1^- x_2^-, x_1^- x_2^+, x_1^+ x_2^-, x_1^+ x_2^+\right\}, \max\left\{x_1^- x_2^-, x_1^- x_2^+, x_1^+ x_2^-, x_1^+ x_2^+\right\}\right]$ The multiplication law between two grey numbers $\otimes x_1 = \left[x_1^-, x_1^+\right]$ and $\otimes x_2 = \left[x_2^-, x_2^+\right]$.	Eq.4
MULTIPLICATION	$k \otimes x = x \otimes k = k\left[x^-, x^+\right] = \left[kx^-, kx^+\right]$ The multiplication law between a grey number $\otimes x = \left[x^-, x^+\right]$ and the real number k.	Eq.5
DIVISION	$\frac{\otimes x_1}{\otimes x_2} = \left[\min\left\{\frac{x_1^-}{x_2^-}, \frac{x_1^-}{x_2^+}, \frac{x_1^+}{x_2^-}, \frac{x_1^+}{x_2^+}\right\}, \max\left\{\frac{x_1^-}{x_2^-}, \frac{x_1^-}{x_2^+}, \frac{x_1^+}{x_2^-}, \frac{x_1^+}{x_2^+}\right\}\right]$ The multiplication law between two grey numbers $\otimes x_1 = \left[x_1^-, x_1^+\right]$ and $\otimes x_2 = \left[x_2^-, x_2^+\right]$.	Eq.6
WHITENED MID-VALUE	The whitened mid-value (WMV) of $\otimes x = \left[x^-, x^+\right]$ is $x^M = \left(x^- + x^+\right)/2$	Eq.7

Source: adapted form [38-39]

Table 3: Linguistic terms and grey numbers

Linguistic terms	Code	Grey numbers
No influence	N	[0, 0]
Very low influence	VL	[0, 1]
Low influence	L	[1, 2]
High influence	H	[2,3]
Very high influence	VH	[3, 4]

Sources: adapted from [32]

Table 4: The scale of grey number for the assessment of the alternative

Performance	Abbreviation	Scale of grey number
Very Poor	VP	(1.5,3.0)
Poor	P	(3.0,4.5)
Medium	M	(4.5,6.0)
Good	G	(6.0,7.5)
Very Good	VG	(7.5,9.0)

Source: [40]

Table 5: The direct-influenced matrix using linguistic terms by DM#1

	EC_1	EC_2	EC_3	EC_4	EN_1	T_1	T_2	T_3	T_4	SP_1	SP_2	SP_3	SP_4
EC_1	N	N	VH	VL	N	L	H	N	N	N	VL	L	N
EC_2	N	N	H	VL	N	VL	L	N	N	N	VL	VL	N
EC_3	N	N	N	VH	N	VL	VH	L	VL	VL	L	H	VL
EC_4	VL	VL	N	N	VH	VH	VH	H	L	VL	N	VL	N
EN_1	N	N	N	VL	N	N	N	N	N	N	N	N	VL
T_1	VH	VH	L	N	VH	N	VH	N	VL	N	N	N	VL
T_2	H	H	N	N	H	VL	N	L	VL	L	N	N	N
T_3	N	N	N	N	L	N	N	N	VL	L	N	N	N
T_4	N	N	VL	N	VL	VL	VL	L	N	N	N	N	VL
SP_1	N	N	VL	VL	N	N	N	N	N	N	L	VL	VL
SP_2	N	N	L	L	H	VL	L	H	N	H	N	VL	L
SP_3	N	N	H	H	H	L	H	VH	VL	H	H	N	H
SP_4	N	N	L	VL	L	N	N	N	VL	N	L	N	N

Table 6: The direct-influenced matrix using linguistic terms by DM#2

	EC_1	EC_2	EC_3	EC_4	EN_1	T_1	T_2	T_3	T_4	SP_1	SP_2	SP_3	SP_4
EC_1	N	N	H	N	N	H	VH	VL	VL	N	L	L	N
EC_2	N	N	VH	VL	N	L	H	N	N	N	VL	L	N
EC_3	N	N	N	L	VL	VH	VH	H	N	L	L	L	VL
EC_4	N	N	N	N	L	VH	H	L	VL	N	N	VL	N
EN_1	N	N	N	VL	N	N	N	N	N	N	N	N	VL
T_1	VH	VH	VH	N	H	N	VH	N	L	N	N	N	VL
T_2	VH	H	N	N	VH	VL	N	H	N	VL	N	N	N
T_3	N	N	N	N	N	N	N	N	VL	VL	N	N	N
T_4	N	N	VL	N	N	VL	N	VL	N	N	N	N	N
SP_1	N	N	N	N	N	N	N	N	N	N	VL	L	L
SP_2	N	N	L	VL	VH	VL	L	H	N	VH	N	N	VL
SP_3	VL	VL	VH	VH	VH	H	VH	VH	L	VH	VH	N	VH
SP_4	N	N	VL	VL	VL	N	N	N	N	N	VL	N	N

Table 7: The direct-influenced matrix using linguistic terms by DM#3

	EC_1	EC_2	EC_3	EC_4	EN_1	T_1	T_2	T_3	T_4	SP_1	SP_2	SP_3	SP_4
EC_1	N	N	L	N	N	L	L	VL	N	N	N	N	N
EC_2	N	N	H	N	N	VL	H	N	N	N	L	L	N
EC_3	N	N	N	VL	N	H	VH	H	N	VL	N	N	N
EC_4	N	N	N	N	N	VH	VH	L	N	N	N	N	VL
EN_1	N	N	VL	N	N	N	N	N	N	N	N	N	N
T_1	H	VH	H	N	L	N	VH	VL	N	N	N	N	N
T_2	VH	H	L	N	L	N	N	VH	N	N	N	N	N
T_3	N	N	N	N	N	N	N	N	N	VL	N	N	N
T_4	N	N	VL	N	N	VL	N	L	N	N	N	N	N
SP_1	N	N	VL	VL	N	N	N	N	N	N	VL	VL	VL
SP_2	VL	VL	H	H	H	N	L	H	VL	VH	N	N	VL
SP_3	L	L	H	VH	H	VH	VH	VH	H	VH	H	N	H
SP_4	N	N	L	L	VL	VL	VL	L	N	N	N	N	N

Table 8: The direct-influenced matrix using grey numbers by DM#1

	EC_1	EC_2	EC_3	EC_4	EN_1	T_1	T_2	T_3	T_4	SP_1	SP_2	SP_3	SP_4
EC_1	[0 0]	[0 0]	[3 4]	[0 1]	[0 0]	[1 2]	[2 3]	[0 0]	[0 0]	[0 0]	[0 1]	[1 2]	[0 0]
EC_2	[0 0]	[0 0]	[2 3]	[0 1]	[0 0]	[0 1]	[1 2]	[0 0]	[0 0]	[0 0]	[0 1]	[0 1]	[0 0]
EC_3	[0 0]	[0 0]	[0 0]	[3 4]	[0 0]	[0 1]	[3 4]	[1 2]	[0 1]	[0 1]	[1 2]	[2 3]	[0 1]
EC_4	[0 1]	[0 1]	[0 0]	[0 0]	[3 4]	[3 4]	[3 4]	[2 3]	[1 2]	[0 1]	[0 0]	[0 1]	[0 0]
EN_1	[0 0]	[0 0]	[0 0]	[0 1]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 1]
T_1	[3 4]	[3 4]	[1 2]	[0 0]	[3 4]	[0 0]	[3 4]	[0 0]	[0 1]	[0 0]	[0 0]	[0 0]	[0 1]
T_2	[2 3]	[2 3]	[0 0]	[0 0]	[2 3]	[0 1]	[0 0]	[1 2]	[0 1]	[1 2]	[0 0]	[0 0]	[0 0]
T_3	[0 0]	[0 0]	[0 0]	[0 0]	[1 2]	[0 0]	[0 0]	[0 0]	[0 1]	[1 2]	[0 0]	[0 0]	[0 0]
T_4	[0 0]	[0 0]	[0 1]	[0 0]	[0 1]	[0 1]	[0 1]	[1 2]	[0 0]	[0 0]	[0 0]	[0 0]	[0 1]
SP_1	[0 0]	[0 0]	[0 1]	[0 1]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[1 2]	[0 1]	[0 1]
SP_2	[0 0]	[0 0]	[3 4]	[0 1]	[0 0]	[1 2]	[2 3]	[0 0]	[0 0]	[0 0]	[0 1]	[1 2]	[0 0]
SP_3	[0 0]	[0 0]	[2 3]	[0 1]	[0 0]	[0 1]	[1 2]	[0 0]	[0 0]	[0 0]	[0 1]	[0 1]	[0 0]
SP_4	[0 0]	[0 0]	[0 0]	[3 4]	[0 0]	[0 1]	[3 4]	[1 2]	[0 1]	[0 1]	[1 2]	[2 3]	[0 1]

Table 9: The direct-influenced matrix using grey numbers by DM#2

	EC_1	EC_2	EC_3	EC_4	EN_1	T_1	T_2	T_3	T_4	SP_1	SP_2	SP_3	SP_4
EC_1	[0 0]	[0 0]	[2 3]	[0 0]	[0 0]	[2 3]	[3 4]	[0 1]	[0 1]	[0 0]	[1 2]	[1 2]	[0 0]
EC_2	[0 0]	[0 0]	[3 4]	[0 1]	[0 0]	[1 2]	[2 3]	[0 0]	[0 0]	[0 0]	[0 1]	[1 2]	[0 0]
EC_3	[0 0]	[0 0]	[0 0]	[1 2]	[0 1]	[3 4]	[3 4]	[2 3]	[0 0]	[1 2]	[1 2]	[1 2]	[0 1]
EC_4	[0 0]	[0 0]	[0 0]	[0 0]	[1 2]	[3 4]	[2 3]	[1 2]	[0 1]	[0 0]	[0 0]	[0 1]	[0 0]
EN_1	[0 0]	[0 0]	[0 0]	[0 1]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 1]
T_1	[3 4]	[3 4]	[3 4]	[0 0]	[2 3]	[0 0]	[3 4]	[0 0]	[1 2]	[0 0]	[0 0]	[0 0]	[0 1]
T_2	[3 4]	[2 3]	[0 0]	[0 0]	[3 4]	[0 1]	[0 0]	[2 3]	[0 0]	[0 1]	[0 0]	[0 0]	[0 0]
T_3	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 1]	[0 1]	[0 0]	[0 0]	[0 0]
T_4	[0 0]	[0 0]	[0 1]	[0 0]	[0 0]	[0 1]	[0 0]	[0 1]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]
SP_1	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 1]	[1 2]	[1 2]
SP_2	[0 0]	[0 0]	[1 2]	[0 1]	[3 4]	[0 1]	[1 2]	[2 3]	[0 0]	[3 4]	[0 0]	[0 0]	[0 1]
SP_3	[0 1]	[0 1]	[3 4]	[3 4]	[3 4]	[2 3]	[3 4]	[3 4]	[1 2]	[3 4]	[3 4]	[0 0]	[3 4]
SP_4	[0 0]	[0 0]	[0 1]	[0 1]	[0 1]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 1]	[0 0]	[0 0]

Table 10: The direct-influenced matrix using grey numbers by DM#3

	EC_1	EC_2	EC_3	EC_4	EN_1	T_1	T_2	T_3	T_4	SP_1	SP_2	SP_3	SP_4
EC_1	[0 0]	[0 0]	[1 2]	[0 0]	[0 0]	[1 2]	[1 2]	[0 1]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]
EC_2	[0 0]	[0 0]	[2 3]	[0 0]	[0 0]	[0 1]	[2 3]	[0 0]	[0 0]	[0 0]	[1 2]	[1 2]	[0 0]
EC_3	[0 0]	[0 0]	[0 0]	[0 1]	[0 0]	[2 3]	[3 4]	[2 3]	[0 0]	[0 1]	[0 0]	[0 0]	[0 0]
EC_4	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[3 4]	[3 4]	[1 2]	[0 0]	[0 0]	[0 0]	[0 0]	[0 1]
EN_1	[0 0]	[0 0]	[0 1]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]
T_1	[2 3]	[3 4]	[2 3]	[0 0]	[1 2]	[0 0]	[3 4]	[0 1]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]
T_2	[3 4]	[2 3]	[1 2]	[0 0]	[1 2]	[0 0]	[0 0]	[3 4]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]
T_3	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 1]	[0 0]	[0 0]	[0 0]
T_4	[0 0]	[0 0]	[0 1]	[0 0]	[0 0]	[0 1]	[0 0]	[1 2]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]
SP_1	[0 0]	[0 0]	[0 1]	[0 1]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]	[0 1]	[0 1]	[0 1]
SP_2	[0 1]	[0 1]	[2 3]	[2 3]	[2 3]	[0 0]	[1 2]	[2 3]	[0 1]	[3 4]	[0 0]	[0 0]	[0 1]
SP_3	[1 2]	[1 2]	[2 3]	[3 4]	[2 3]	[3 4]	[3 4]	[3 4]	[2 3]	[3 4]	[2 3]	[0 0]	[2 3]
SP_4	[0 0]	[0 0]	[1 2]	[1 2]	[0 1]	[0 1]	[0 1]	[1 2]	[0 0]	[0 0]	[0 0]	[0 0]	[0 0]

Table 11: The initial direct-influenced matrix ($\otimes X$)

		EC_1	EC_2	EC_3	EC_4	EN_1	T_1	T_2	T_3	T_4	SP_1	SP_2	SP_3	SP_4	Sum
EC_1	Lower	0.0000	0.0000	2.0000	0.0000	0.0000	1.3333	2.0000	0.0000	0.0000	0.0000	0.3333	0.6667	0.0000	6.3333
	Upper	0.0000	0.0000	3.0000	0.3333	0.0000	2.3333	3.0000	0.6667	0.3333	0.0000	1.0000	1.3333	0.0000	12.0000
EC_2	Lower	0.0000	0.0000	2.3333	0.0000	0.0000	0.3333	1.6667	0.0000	0.0000	0.0000	0.3333	0.6667	0.0000	5.3333
	Upper	0.0000	0.0000	3.3333	0.6667	0.0000	1.3333	2.6667	0.0000	0.0000	0.0000	1.3333	1.6667	0.0000	11.0000
EC_3	Lower	0.0000	0.0000	0.0000	1.3333	0.0000	1.6667	3.0000	1.6667	0.0000	0.3333	0.6667	1.0000	0.0000	9.6667
	Upper	0.0000	0.0000	0.0000	2.3333	0.3333	2.6667	4.0000	2.6667	0.3333	1.3333	1.3333	1.6667	0.6667	17.3333
EC_4	Lower	0.0000	0.0000	0.0000	0.0000	1.3333	3.0000	2.6667	1.3333	0.3333	0.0000	0.0000	0.0000	0.0000	8.6667
	Upper	0.3333	0.3333	0.0000	0.0000	2.0000	4.0000	3.6667	2.3333	1.0000	0.3333	0.0000	0.6667	0.3333	15.0000
EN_1	Lower	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Upper	0.0000	0.0000	0.3333	0.6667	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6667	1.6667
T_1	Lower	2.6667	3.0000	2.0000	0.0000	2.0000	0.0000	3.0000	0.0000	0.3333	0.0000	0.0000	0.0000	0.0000	13.0000
	Upper	3.6667	4.0000	3.0000	0.0000	3.0000	0.0000	4.0000	0.3333	1.0000	0.0000	0.0000	0.0000	0.6667	19.6667
T_2	Lower	2.6667	2.0000	0.3333	0.0000	2.0000	0.0000	0.0000	2.0000	0.0000	0.3333	0.0000	0.0000	0.0000	9.3333
	Upper	3.6667	3.0000	0.6667	0.0000	3.0000	0.6667	0.0000	3.0000	0.3333	1.0000	0.0000	0.0000	0.0000	15.3333
T_3	Lower	0.0000	0.0000	0.0000	0.0000	0.3333	0.0000	0.0000	0.0000	0.0000	0.3333	0.0000	0.0000	0.0000	0.6667
	Upper	0.0000	0.0000	0.0000	0.0000	0.6667	0.0000	0.0000	0.0000	0.6667	1.3333	0.0000	0.0000	0.0000	2.6667
T_4	Lower	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6667	0.0000	0.0000	0.0000	0.0000	0.0000	0.6667
	Upper	0.0000	0.0000	1.0000	0.0000	0.3333	1.0000	0.3333	1.6667	0.0000	0.0000	0.0000	0.0000	0.3333	4.6667
SP_1	Lower	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3333	0.3333	0.3333	1.0000
	Upper	0.0000	0.0000	0.6667	0.6667	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.3333	1.3333	1.3333	5.3333

SP_2	Lower	0.0000	0.0000	2.0000	0.6667	1.6667	0.3333	1.3333	1.3333	0.0000	2.0000	0.0000	0.3333	0.0000	9.6667
	Upper	0.3333	0.3333	3.0000	1.6667	2.3333	1.0000	2.3333	2.0000	0.3333	2.6667	0.3333	0.6667	0.6667	17.6667
SP_3	Lower	0.3333	0.3333	2.3333	2.0000	1.6667	1.6667	2.3333	2.0000	1.0000	2.0000	1.6667	0.0000	1.6667	19.0000
	Upper	1.0000	1.0000	3.3333	3.0000	2.3333	2.6667	3.3333	2.6667	1.6667	2.6667	2.6667	0.3333	2.3333	29.0000
SP_4	Lower	0.0000	0.0000	0.3333	1.3333	0.0000	0.0000	1.0000	0.6667	0.0000	0.0000	0.3333	0.6667	0.0000	4.3333
	Upper	0.0000	0.0000	1.0000	2.3333	0.6667	0.6667	1.6667	1.3333	0.3333	0.3333	1.0000	1.0000	0.3333	10.6667

Table 12: The normalized direct-influenced matrix ($\otimes N$)

		EC_1	EC_2	EC_3	EC_4	EN_1	T_1	T_2	T_3	T_4	SP_1	SP_2	SP_3	SP_4
EC_1	Lower	0.0000	0.0000	0.0690	0.0000	0.0000	0.0460	0.0690	0.0000	0.0000	0.0000	0.0115	0.0230	0.0000
	Upper	0.0000	0.0000	0.1579	0.0175	0.0000	0.1228	0.1579	0.0351	0.0175	0.0000	0.0526	0.0702	0.0000
EC_2	Lower	0.0000	0.0000	0.0805	0.0000	0.0000	0.0115	0.0575	0.0000	0.0000	0.0000	0.0115	0.0230	0.0000
	Upper	0.0000	0.0000	0.1754	0.0351	0.0000	0.0702	0.1404	0.0000	0.0000	0.0000	0.0702	0.0877	0.0000
EC_3	Lower	0.0000	0.0000	0.0000	0.0460	0.0000	0.0575	0.1034	0.0575	0.0000	0.0115	0.0230	0.0345	0.0000
	Upper	0.0000	0.0000	0.0000	0.1228	0.0175	0.1404	0.2105	0.1404	0.0175	0.0702	0.0702	0.0877	0.0351
EC_4	Lower	0.0000	0.0000	0.0000	0.0000	0.0460	0.1034	0.0920	0.0460	0.0115	0.0000	0.0000	0.0000	0.0000
	Upper	0.0175	0.0175	0.0000	0.0000	0.1053	0.2105	0.1930	0.1228	0.0526	0.0175	0.0000	0.0351	0.0175
EN_1	Lower	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Upper	0.0000	0.0000	0.0175	0.0351	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0351
T_1	Lower	0.0920	0.1034	0.0690	0.0000	0.0690	0.0000	0.1034	0.0000	0.0115	0.0000	0.0000	0.0000	0.0000
	Upper	0.1930	0.2105	0.1579	0.0000	0.1579	0.0000	0.2105	0.0175	0.0526	0.0000	0.0000	0.0000	0.0351
T_2	Lower	0.0920	0.0690	0.0115	0.0000	0.0690	0.0000	0.0000	0.0690	0.0000	0.0115	0.0000	0.0000	0.0000
	Upper	0.1930	0.1579	0.0351	0.0000	0.1579	0.0351	0.0000	0.1579	0.0175	0.0526	0.0000	0.0000	0.0000
T_3	Lower	0.0000	0.0000	0.0000	0.0000	0.0115	0.0000	0.0000	0.0000	0.0000	0.0115	0.0000	0.0000	0.0000
	Upper	0.0000	0.0000	0.0000	0.0000	0.0351	0.0000	0.0000	0.0000	0.0351	0.0702	0.0000	0.0000	0.0000
T_4	Lower	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0230	0.0000	0.0000	0.0000	0.0000	0.0000
	Upper	0.0000	0.0000	0.0526	0.0000	0.0175	0.0526	0.0175	0.0877	0.0000	0.0000	0.0000	0.0000	0.0175
SP_1	Lower	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0115	0.0115	0.0115
	Upper	0.0000	0.0000	0.0351	0.0351	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0702	0.0702	0.0702

SP_2	Lower	0.0000	0.0000	0.0690	0.0230	0.0575	0.0115	0.0460	0.0460	0.0000	0.0690	0.0000	0.0115	0.0000
	Upper	0.0175	0.0175	0.1579	0.0877	0.1228	0.0526	0.1228	0.1053	0.0175	0.1404	0.0175	0.0351	0.0351
SP_3	Lower	0.0115	0.0115	0.0805	0.0690	0.0575	0.0575	0.0805	0.0690	0.0345	0.0690	0.0575	0.0000	0.0575
	Upper	0.0526	0.0526	0.1754	0.1579	0.1228	0.1404	0.1754	0.1404	0.0877	0.1404	0.1404	0.0175	0.1228
SP_4	Lower	0.0000	0.0000	0.0115	0.0460	0.0000	0.0000	0.0345	0.0230	0.0000	0.0000	0.0115	0.0230	0.0000
	Upper	0.0000	0.0000	0.0526	0.1228	0.0351	0.0351	0.0877	0.0702	0.0175	0.0175	0.0526	0.0526	0.0175

Table 13: The total relation matrix ($\otimes T$)

		EC_1	EC_2	EC_3	EC_4	EN_1	T_1	T_2	T_3	T_4	SP_1	SP_2	SP_3	SP_4
EC_1	Lower	0.0133	0.0119	0.0787	0.0059	0.0126	0.0536	0.0877	0.0134	0.0016	0.0049	0.0152	0.0266	0.0016
	Upper	0.1363	0.1273	0.3134	0.1118	0.1621	0.2614	0.3857	0.2060	0.0744	0.0964	0.1222	0.1389	0.0583
EC_2	Lower	0.0088	0.0073	0.0870	0.0063	0.0092	0.0193	0.0730	0.0129	0.0012	0.0049	0.0153	0.0266	0.0016
	Upper	0.1259	0.1168	0.3255	0.1353	0.1584	0.2157	0.3682	0.1750	0.0564	0.1002	0.1427	0.1581	0.0604
EC_3	Lower	0.0178	0.0158	0.0133	0.0498	0.0198	0.0668	0.1226	0.0728	0.0026	0.0182	0.0260	0.0363	0.0023
	Upper	0.1609	0.1500	0.1866	0.2190	0.2179	0.2978	0.4583	0.3299	0.0891	0.1794	0.1457	0.1623	0.1046
EC_4	Lower	0.0195	0.0183	0.0115	0.0006	0.0614	0.1054	0.1066	0.0544	0.0128	0.0021	0.0008	0.0013	0.0001
	Upper	0.1576	0.1498	0.1540	0.0656	0.2543	0.3120	0.3792	0.2549	0.1034	0.0882	0.0526	0.0881	0.0658
EN_1	Lower	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Upper	0.0114	0.0107	0.0318	0.0478	0.0182	0.0213	0.0301	0.0216	0.0074	0.0093	0.0079	0.0095	0.0414
T_1	Lower	0.1050	0.1137	0.0887	0.0048	0.0799	0.0123	0.1290	0.0153	0.0120	0.0036	0.0051	0.0082	0.0005
	Upper	0.3330	0.3366	0.3699	0.1147	0.3211	0.1869	0.4904	0.2172	0.1098	0.0991	0.0957	0.1065	0.0949
T_2	Lower	0.0940	0.0708	0.0249	0.0016	0.0718	0.0070	0.0145	0.0720	0.0003	0.0133	0.0029	0.0048	0.0004
	Upper	0.2620	0.2231	0.1808	0.0690	0.2477	0.1467	0.1796	0.2563	0.0568	0.1134	0.0632	0.0698	0.0419
T_3	Lower	0.0000	0.0000	0.0000	0.0000	0.0115	0.0000	0.0000	0.0000	0.0000	0.0115	0.0001	0.0001	0.0001
	Upper	0.0047	0.0044	0.0120	0.0091	0.0429	0.0089	0.0116	0.0110	0.0380	0.0751	0.0085	0.0083	0.0098
T_4	Lower	0.0000	0.0000	0.0000	0.0000	0.0003	0.0000	0.0000	0.0230	0.0000	0.0003	0.0000	0.0000	0.0000
	Upper	0.0327	0.0315	0.0895	0.0237	0.0571	0.0844	0.0765	0.1258	0.0160	0.0249	0.0164	0.0180	0.0314
SP_1	Lower	0.0005	0.0004	0.0021	0.0018	0.0018	0.0012	0.0025	0.0021	0.0004	0.0018	0.0124	0.0120	0.0122
	Upper	0.0447	0.0421	0.1108	0.0943	0.0744	0.0734	0.1114	0.0836	0.0294	0.0530	0.1091	0.1049	0.1037

SP_2	Lower	0.0076	0.0064	0.0736	0.0276	0.0660	0.0199	0.0605	0.0569	0.0011	0.0725	0.0036	0.0153	0.0017
	Upper	0.1342	0.1256	0.3026	0.1887	0.2748	0.2011	0.3463	0.2738	0.0750	0.2336	0.0944	0.1158	0.1028
SP_3	Lower	0.0289	0.0271	0.0966	0.0781	0.0791	0.0739	0.1143	0.0916	0.0365	0.0773	0.0623	0.0076	0.0588
	Upper	0.2574	0.2443	0.4485	0.3255	0.3948	0.3936	0.5727	0.4309	0.1851	0.3001	0.2616	0.1527	0.2282
SP_4	Lower	0.0051	0.0042	0.0161	0.0487	0.0084	0.0078	0.0446	0.0316	0.0015	0.0036	0.0134	0.0240	0.0014
	Upper	0.0867	0.0805	0.1580	0.1872	0.1547	0.1465	0.2493	0.1947	0.0623	0.0878	0.0992	0.1008	0.0611

Table 14: The results of $\otimes R_i$, $\otimes C_i$, $\otimes P_i$, $\otimes E_i$, P_i and E_i

		EC_1	EC_2	EC_3	EC_4	EN_1	T_1	T_2	T_3	T_4	SP_1	SP_2	SP_3	SP_4
$\otimes R_i$	Lower	0.3269	0.2735	0.4640	0.3948	0.0000	0.5780	0.3783	0.0236	0.0235	0.0512	0.4126	0.8321	0.2104
	Upper	2.1941	2.1387	2.7015	2.1255	0.2682	2.8757	1.9103	0.2444	0.6281	1.0348	2.4688	4.1953	1.6688
$\otimes C_i$	Lower	0.3005	0.2759	0.4926	0.2251	0.4216	0.3671	0.7555	0.4460	0.0699	0.2140	0.1571	0.1628	0.0808
	Upper	1.7476	1.6429	2.6834	1.5917	2.3782	2.3498	3.6592	2.5808	0.9030	1.4606	1.2192	1.2339	1.0042
$\otimes P_i$	Lower	0.6274	0.5494	0.9566	0.6199	0.4216	0.9451	1.1338	0.4696	0.0934	0.2652	0.5698	0.9949	0.2911
	Upper	3.9417	3.7815	5.3850	3.7172	2.6465	5.2255	5.5695	2.8252	1.5311	2.4955	3.6880	5.4292	2.6731
$\otimes E_i$	Lower	-1.4206	-1.3694	-2.2195	-1.1969	-2.3782	-1.7717	-3.2809	-2.5572	-0.8794	-1.4094	-0.8066	-0.4018	-0.7938
	Upper	1.8936	1.8628	2.2090	1.9004	-0.1534	2.5086	1.1547	-0.2016	0.5582	0.8209	2.3117	4.0325	1.5881
P_i	WMV	2.2846	2.1654	3.1708	2.1685	1.5341	3.0853	3.3517	1.6474	0.8122	1.3803	2.1289	3.2120	1.4821
E_i	WMV	0.2365	0.2467	-0.0053	0.3518	-1.2658	0.3685	-1.0631	-1.3794	-0.1606	-0.2943	0.7526	1.8153	0.3971

Table 15: Criteria for sustainability assessment of technologies for sewage sludge to electricity

Aspect	Criteria	Abbreviation	Corresponding to the barriers
Economic	Capital cost,	C_1	EC_1
	Operation and maintenance costs	C_2	EC_2
Environmental	Environmental impacts	C_3	EN_1
Technological	Technology maturity	C_4	T_1
Social-political	Governmental support	C_5	SP_3

Table 16: Decision-making matrix determined by DM#1, DM#2, and DM#3 using linguistic terms

DM#1	C_1	C_2	C_3	C_4	C_5
T_1	P	VP	P	G	P
T_2	G	P	VG	VG	G
T_3	VG	G	G	VP	M
DM#2	C_1	C_2	C_3	C_4	C_5
T_1	VP	P	VP	M	G
T_2	P	P	G	VG	VG
T_3	P	G	P	P	G
DM#3	C_1	C_2	C_3	C_4	C_5
T_1	VP	P	VP	P	P
T_2	G	M	G	VG	G
T_3	G	G	P	VP	M

Table 17: Decision-making matrix determined by DM#1, DM#2, and DM#3 using grey numbers

DM#1	C_1	C_2	C_3	C_4	C_5
T_1	[3.0 4.5]	[1.5 3.0]	[3.0 4.5]	[6.0 7.5]	[3.0 4.5]
T_2	[6.0 7.5]	[3.0 4.5]	[7.5 9.0]	[7.5 9.0]	[6.0 7.5]
T_3	[7.5 9.0]	[6.0 7.5]	[6.0 7.5]	[1.5 3.0]	[4.5 6.0]
DM#2	C_1	C_2	C_3	C_4	C_5
T_1	[1.5 3.0]	[3.0 4.5]	[1.5 3.0]	[4.5 6.0]	[6.0 7.5]
T_2	[3.0 4.5]	[3.0 4.5]	[6.0 7.5]	[7.5 9.0]	[7.5 9.0]
T_3	[3.0 4.5]	[6.0 7.5]	[3.0 4.5]	[3.0 4.5]	[6.0 7.5]
DM#3	C_1	C_2	C_3	C_4	C_5
T_1	[1.5 3.0]	[3.0 4.5]	[1.5 3.0]	[3.0 4.5]	[3.0 4.5]
T_2	[6.0 7.5]	[4.5 6.0]	[6.0 7.5]	[7.5 9.0]	[6.0 7.5]
T_3	[6.0 7.5]	[6.0 7.5]	[3.0 4.5]	[1.5 3.0]	[4.5 6.0]

Table 18: The integrated decision-making matrix

	C_1	C_2	C_3	C_4	C_5
T_1	[2.0 3.5]	[2.5 4.0]	[2.0 3.5]	[4.5 6.0]	[4.0 5.5]
T_2	[5.0 6.5]	[3.5 5.0]	[6.5 8.0]	[7.5 9.0]	[6.0 8.0]
T_3	[5.5 7.0]	[6.0 7.5]	[4.0 5.5]	[2.0 3.5]	[5.0 6.5]

Table 19: The normalized integrated decision-making matrix

	C_1	C_2	C_3	C_4	C_5
T_1	[0.2857 0.5000]	[0.3333 0.5333]	[0.2500 0.4375]	[0.5000 0.6667]	[0.5000 0.6875]
T_2	[0.7143 0.9286]	[0.4667 0.6667]	[0.8125 1.0000]	[0.8333 1.0000]	[0.8125 1.0000]
T_3	[0.7857 1.0000]	[0.8000 1.0000]	[0.5000 0.6875]	[0.2222 0.3889]	[0.6250 0.8125]

Table 20: The difference matrix $\otimes\Delta$

	C_1	C_2	C_3	C_4	C_5
T_1	[0.5000 0.7143]	[0.4667 0.6667]	[0.5625 0.7500]	[0.3333 0.5000]	[0.3125 0.5000]
T_2	[0.0714 0.2857]	[0.3333 0.5333]	[0.0000 0.1875]	[0.0000 0.1667]	[0.0000 0.1875]
T_3	[0.0000 0.2143]	[0.0000 0.2000]	[0.3125 0.5000]	[0.6111 0.7778]	[0.1875 0.3750]

Table 21: The weights of the five criteria

	EC_1	EC_2	EN_1	T_1	SP_3
$\otimes P_i$	[0.6274 3.9417]	[0.5494 3.7815]	[0.4216 2.6465	[0.9451 5.2255]	[0.9949 5.4292
$\otimes \omega_i$	[0.0298 1.1140]	[0.0261 1.0687]	[0.0201 0.7479]	[0.0450 1.4768]	[0.0473 1.5344]

Table 22: The grey relational coefficient matrix $\otimes E$

	C_1	C_2	C_3	C_4	C_5
T_1	[0.3525 0.4375]	[0.3684 0.4545]	[0.3415 0.4088]	[0.4375 0.5385]	[0.4375 0.5545]
T_2	[0.5765 0.8448]	[0.4217 0.5385]	[0.6747 1.0000]	[0.7000 1.0000]	[0.6747 1.0000]
T_3	[0.6447 1.0000]	[0.6604 1.0000]	[0.4375 0.5545]	[0.3333 0.3889]	[0.5091 0.6747]

Table 23: The grey relational degrees $\otimes\gamma_i$

Technologies	T_1	T_2	T_3
$\otimes\gamma_i$	[0.0674 2.9248]	[0.1051 5.2757]	[0.0843 4.2069]