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Multi-Criteria Group Decision-making based Sustainability Measurement of Wastewater Treatment Processes

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Abstract: There are various processes which can be used for wastewater treatment (WT), and the selection of the most sustainable one among different processes is a hard task. This study aims at helping the decision-makers (DM) to address this by developing an intuitionistic fuzzy set (IFS) theory based group multi-attribute decision analysis (MADA) method. Ten criteria in environment, economy, society-politic, and technology dimensions were employed to achieve sustainability measurement (SM) of WT processes. The multi-criteria sustainability assessment method developed in this study allow different experts to attend the SM, and enable the participants to employ the natural language/words to depict their intuitionistic opinions. Accordingly, the proposed method can achieve group SM under uncertainties. An illustrative case including four processes for wastewater treatment, namely Anaerobic-Anoxic-Oxic (AAO) process**,** Triple Oxidation Ditch (TOD) process **,** Anaerobic single-ditch oxidation (ASD) process**,** and Sequencing batch reactor activated sludge process (SBR), has been studied, and the results reveal that this method can determine sustainability sequence of different WT processes.

Keywords: Wastewater treatment; IFS; MADA; sustainability assessment

1. Introduction

The depletion, pollution and degradation of water resources become the severe problems worldwide (Wu et al., *2015*). The pollution of water resources has become more and more severe recently because of population increase, and industrialization. As for this problem, scientists developed various processes for wastewater treatment, i.e. advanced oxidation process, membrane distillation bioreactor, emerging desalination processes, and physical and chemical method, etc. (Neoh *et al*., 2016; Ji *et al*., 2016; Subramani and Jacangelo, 2015). Wastewater treatment (WT) plants are usually highly energy-intensive and generate large amount of emissions (Chai *et al*., 2015). The selection of the most suitable technology for WT is usually difficult when facing multiple choices, because the accurate evaluation of these processes for WT has been a great challenge for the decision-makers (i.e. regulators and water companies) (Prasse *et al*., 2015).

Various studies have been carried to investigate and compare different processes for WT, and there are usually two most popular ways: one is environmental impact/economic feasibility assessment, and another is multi-criteria decision analysis. As for environmental impact/economic feasibility assessment, life cycle perspective analysis, referring to life cycle assessment, is one of the most popular way. For instance, Rodriguez-Garcia *et al.* (2012) developed a method for estimating the greenhouse gases emission of WT plants in life cycle perspective. Padilla-Rivera *et al.* (2016) used 25 indicators to evaluate the social concerns of WT facilities. There are also some other studies used life cycle assessment or economic analysis methods for investigating these processes (Meneses *et al.*, 2015; Hendrickson *et al.*, 2015; Mu *et al.*, 2016). However, the decision-makers (DM) also feel difficult to make a decision, because they usually have to face multiple conflict indicators. Accordingly, the selection of technology for WT among several different processes is a multi-attribute decision analysis problem.

There are also various studies focusing on using multi-attribute decision analysis (MADA) methods for comparing different processes for WT. A composite sustainability index based on the sum weighted method for comparing WT processes was developed by Plakas *et al.* (2016). Hadipour *et al*. (2016) developed a MADA method to rank the processes for wastewater reuse by employing AHP. Zorpas and SMranti (2016) employed MADA to investigate the processes for wastewater treatment in the field of winery. Ouyang *et al.* (2015) developed the a multi-criteria aid tool by combining the fuzzy AHP and multidimensional scaling (MDS) for the selection of natural WT alternatives. Macuada *et al*. (2015) developed a multi-criteria analysis framework based on AHP for evaluating of the facilities of water treatment. Lorenzo-Toja *et al*. (2016) employed eco-efficiency criteria based on LCA and LCC to assess the WT plants. Castillo et al. (2006) developed a decision support tool by determining the weighted score for WT selection. All these studies are useful promoting wastewater treatment; however there are still some research gaps. Almost all the studies need to know the exact data when selecting the most suitable technology for WT; however, sometime it is impossible to get the accurate data due to various reasons, i.e. lack of information and data uncertainties. Accordingly, some methods employed AHP and various methods derived from AHP to score the WT processes regarding some criteria. For instance, Molinos-Senante *et al.* (2015) employed the ANP to assess different processes for the WT for small communities. Meanwhile, various MADA methods based on fuzzy set theory have been employed to address this, beacuse fuzzy set theory has the advanatges of dealing with problems such as vaguness and ambiguity existed in human judgements. For instance, An *et al*. (2016) employed fuzzy AHP to score the processes for groundwater contamination remediation. This kind of fuzzy MADA methods are based on the fuzzy theory Zadeh (1965; 1975) in which the membership function is used to characterize the fuzzy set. Atanassov (1986) developed a more powerful tool- IFS (intuitionistic fuzzy set). Accordingly, various MADA methods based on the IFS were developed for its advantages of dealing with more complex problems which need IFS format, i.e. voting process, a portion of rejection, and a portion of approval, etc. Therefore, this study developed a multi-criteria sustainability measurement method to select WT processes based on the IFST.

All in all, this study has two objectives:

(1) developing the hierarchal evaluation criteria system with multiple dimensions for sustainability measurement of wastewater treatment processes, the characteristic of this system is inclusive, and the decision-makers are allowed to choose parts of the criteria in each dimension or add more criteria in each dimension according to their preferences;

(2) developing a generic multi-attribute decision analysis method based on

intuitionistic fuzzy set theory for helping the decision-makers to prioritize the alternative wastewater treatment processes.

Besides the introduction section, the remaining parts of this study has been structured as follows: the criteria system for sustainability measurement of wastewater treatment processes was developed in Section 2; the IFS theory based MADA method was developed (see Section 3); an illustrative case was investigated (see Section 4); finally, the discussions and conclusion were presented (see Section 5).

2. Criteria for sustainability measurement of WT processes

According to WCED (1987) and Othman et al. (2010), the criteria in the three dimensions of sustainability (namely, economy, environment, and society) are usually used for sustainability assessment. However, there is no unique criterion system for sustainability measurement as different decision-makers have different requirements. Besides the criteria in the three sustainability pillars, some other aspects are also widely used for sustainability including technological and political aspects as the criterion in both of the two aspects may have significant influences on the criteria that belong to the main sustainability pillars (Ren *et al*., 2013). Therefore, four aspects including environment, economy, society-politic, and technology dimensions are considered for sustainability measurement. According to the special characteristics of the processes for the treatment of wastewater derived from coal-fired power generation, ten criteria are used to measure the sustainability of the processes for WT based on literature reviews and focus group meeting, as presented in Table 1. These criteria are specified as follows:

Table 1: Criteria for SM of WT processes

Aspect	Criteria	Abbreviation	Reference
Economic	Capital costs	EC_1	Sadr et al., 2015
	Operation and maintenance costs	EC_2	Sadr et al., 2015
Environmental;	Effect on water quality improvement	EN_1	Ling and Hang, 1998
	Occupied land	EN_2	Ling and Hang, 1998
	Operability and simplicity	T_1	Meerholz and Brent, 2013
Technological	Maturity	T_2	Ling and Hang, 1998
	Reliability	T_3	Eisenberg et al., 2001
	Public acceptability	SP_1	Ren et al., 2015a
Social-political	Added jobs	SP_2	Ren et al., 2015b
	Governmental support	SP_3	Ren et al., 2015a

2.1 Economic aspect (EC)

There are two economic criteria, namely, capital cost, and operation & maintenance cost.

(1) Capital costs (EC_1)

The capital cost represents the initial investment of all the facilities for WT processes. Sadr et al. (2015) pointed out that the capital cost has significant influence on the implementation of the projects about the WT, because the initial investment cost can significantly influence the decision-makers.

(2) Operation & maintenance costs (EC_2)

The operation & maintenance costs include all the costs related to operation and maintenance of the wastewater treatment processes, and this criterion consists of all the costs about human resources, energy use, waste management and various costs during the operations as well as the costs during maintenance (Sadr et al., 2015).

2.2 Environmental aspect (EN)

The criteria in environmental aspect aims at measuring the "environmental efficiency" of WT processes regarding consumed resources, emitted waste/harmful gases, and the effluent (Molinos-Senante et al., 2015). Two criteria including effect on water quality improvement and occupied land were used to measure the environmental efficiency of the processes for WT.

(1) Effect on water quality improvement (EN_1)

This criterion is to measure the ability of different WT processes for removing the waste constituents (i.e. nitrogenous and phosphorous organic compounds) and hazardous materials existed in wastewater. As for the wastewater derived from coal-fired power generation, the effect on water quality improvement mainly refer to the ability of the processes for the removal of the suspended solid. It is worth pointing out that the users can define the meaning of effect on water quality improvement according to the actual conditions. In other words, the definitions are different for different wastewater systems.

(2) Occupied land (EN_2)

This criterion refers to the sum of the occupied land due to the implementation of the processes for WT, i.e. the land for building the plant for WT, and the land for building the supplementary infrastructure.

2.3 Technological aspect (T)

Operability and simplicity, duration of service, and reliability are used to measure technological performances.

(1) Operability and simplicity (T_1)

This criterion is to measure the ease of implementing the processed for wastewater treatment (Meerholz and Brent, 2013). The processes for WT having a good performance on operability and simplicity will be used widely.

(2) Maturity (T_2)

Maturity refers to the wide-utilization level that the technology can be used for WT nationally and internationally. The more mature the technology, the more superior the technology will be.

(3) Reliability (T_3)

The reliability of the processes for WT refers to the robustness against the failures when implementing different processes for wastewater treatment (Eisenberg et al., 2001).

2.4 Social-political aspect

There are three criteria in social-political aspect, including public acceptability, added job, and governmental support.

(1) Public acceptability (SP_1)

Public acceptability is to measure the acceptability of public, especially the residents living nearby the plants for WTs, on the processes for WT (Ren et al., 2015a).

(2) Added jobs (SP_2)

The criterion refers to the created jobs by the implementation of the processes for WT. This criterion is widely used for measuring social sustainability (Ren *et al.*, 2015b).

(3) Policy support ((SP_3)

The attitudes of the policy-makers on different processes for WT are different due to the development goals, and policy support refers to the consistency level of the technology for WT with the policy system related to the development direction of WT processes, i.e. fiscal support, and policy/regulation support (Ren et al., 2015a).

Note that an evaluation criterion system was developed in this study, but the users can add more criteria or delete some criteria for sustainability measurement of wastewater treatment processes according to the requirements and requirements of the stakeholders.

3. Methods

In this section, the intuitionistic fuzzy set (IFS) theory was firstly introduced, then, the group MADA method was presented based on IFS theory.

3.1 Fuzzy set（FS）theory and IFS theory

Fuzzy set theory developed by Zadeh (Zadeh, 1965) was defined as follows:

Definition 1. Fuzzy sets (FS)

Assume that X is a object collection of x, a fuzz set α can be represented by Eq.1. and the membership function $\mu_\alpha(x)$ indicates the degree of x belonging to α.

$$\alpha = \{(x, \mu_\alpha(x)) \mid x \in X\} \quad (1)$$

Definition 2. Intuitionistic fuzzy set (IFS)

The traditional fuzzy set was extended by Atanassov (1986), and the IFS was defined in Eq.2.

$$\alpha = \{(x, \mu_\alpha(x), \upsilon_\alpha(x)) \mid x \in X\} \quad (2)$$

where $\mu_\alpha(x): X \to [0,1], x \in X \to \mu_\alpha(x) \in [0,1]$ and $\upsilon_\alpha(x): X \to [0,1], x \in X \to \upsilon_\alpha(x) \in [0,1]$ satisfy the condition of $0 \le \mu_\alpha(x) + \upsilon_\alpha(x) \le 1$ for all $x \in X$.

The numbers $\mu_\alpha(x)$ and $\upsilon_\alpha(x)$ represent the degree of membership and the degree of nonmembership of the element $x \in X$ to the set α.

The degree of indeterminacy of $x \in X$ to the set α is

$$\pi_\alpha(x) = 1 - \mu_\alpha(x) - \upsilon_\alpha(x), x \in X \quad (3)$$

An intuitionistic fuzzy number α can usually be denoted by $\alpha = (\mu_\alpha, \upsilon_\alpha, \pi_\alpha)$, where $\mu_\alpha \in [0,1], \upsilon_\alpha \in [0,1], \mu_\alpha(x) + \upsilon_\alpha(x) \le 1$, and $\pi_\alpha = 1 - \mu_\alpha - \upsilon_\alpha$

Definition 3. Linguistic variables

The linguistic terms which can qualitatively depict human judgments and their corresponding intuitionistic fuzzy numbers (IFM) were presented in Table 2. It is worth pointing out that these linguistic terms are allowed to be used by the decision-makers to depict the relative score of the wastewater treatment processes regarding each of the evaluation criteria, and these linguistic variables can also be used to determine the criteria weights. For instance, 'EP' was employed to describe the relative performance of a WT technology with respect to a criterion if the decision-makers held the view that the relative performance is extreme poor, and the corresponding intuitionistic fuzzy number is (0.05, 0.95, 0.00). Similarly, EL will be used to depict the relative importance (weight) of an evaluation criterion if the decision-makers thought that the relative importance is extreme low, and the corresponding intuitionistic fuzzy number is also (0.05, 0.95, 0.00).

Table 2: The linguistic variables and corresponding intuitionistic fuzzy numbers

Linguistic terms	Abbreviation	IFN
Extreme poor-Extreme low	EP-EL	(0.05,0.95,0.00)
Very poor-Very low	VP-VL	(0.15,0.80,0.05)
Poor –Low	P-L	(0.25,0.65,0.10)
Medium poor –Medium low	MP-ML	(0.35,0.55,0.10)
Fair –Medium	F-M	(0.50,0.40,0.10)
Medium good-Medium high	MG-MH	(0.65,0.25,0.10)

Good –High	G-H	(0.75,0.15,0.10)
Very good –Very high	VG-VH	(0.85,0.10,0.05)
Extreme good –Extreme high	EG-EH	(0.95,0.05,0.00)

Sources: Zhang and Liu (2011).

Definition 4. Distance between

Suppose $\alpha = \left(\mu_\alpha, \upsilon_\alpha, \pi_\alpha\right)$ and $\beta = \left(\mu_\beta, \upsilon_\beta, \pi_\beta\right)$, the distance between α and β can be determined by Eq.4

$$d\left(\alpha,\beta\right) = \frac{1}{2}\left(\left|\mu_\alpha - \mu_\beta\right| + \left|\upsilon_\alpha - \upsilon_\beta\right| + \left|\pi_\alpha - \pi_\beta\right|\right) \tag{4}$$

4. Group MADA method

There are total six steps in this group MADA method,.

Step 1: Determining the relative performances of the wastewater treatment processes regarding each criterion by each decision-maker (DM). The linguistic terms including “extreme poor”, “very poor”, “poor”, “medium poor”, “fair”, “medium good”, “good”, “very good”, and “extreme good” can be used to rate the alternative wastewater treatment processes with respect to each criterion.

Step 2: Weights determination for the criteria by each DM. The linguistic terms including “extreme low”, “very low”, “low”, “medium low”, “medium”, “medium high”, “high”, “very high”, and “extreme high” can be used to describe the relative importance of the evaluation criteria for sustainability measurement of wastewater treatment processes.

Step 3: Weights determination for the DMs in the decision-making. The linguistic terms, including “very important”, “important”, “medium”, “unimportant”, and “very unimportant” (see Table 3) can be used to describe the role of the DMs in the decision-making.

Step 4: Establishing the aggregated decision-making matrix and the aggregated weight of each criterion.

Step 5: Determining the integrated priorities of the alternatives by using intuitionistic fuzzy numbers.

Step 6: Determine the priority sequence of the alternatives by comparing their relative priorities.

Each step of the group MADA method was specified as follows:

Step 1: Determining the data of the wastewater treatment processes regarding each criterion by each DM. Assume that a total of K experts (the expert panel should include all the representative stakeholders, and one member in each representative stakeholder group was invited in this study) and m wastewater treatment processes $\{A_1, A_2, \cdots, A_m\}$ to be assessed by using n criteria $\{C_1, C_2, \cdots, C_m\}$, and the decision-making matrix by the *k*-th decision-maker can be defined in Eq.5. x_{ij}^k is the data of the *i*-th wastewater treatment process regarding the *j*-th criterion. The users can firstly use the nature language phrases presented in Table 2 to determine the data of the wastewater treatment processes and the weights of the criteria; then the decision-making matrix composed by the intuitionistic fuzzy numbers can be obtained, as presented in Eq.5.

$$
\begin{array}{cccccc}
 & C_1 & C_2 & & C_n \\
A_1 & x_{11}^k & x_{12}^k & \cdots & x_{1n}^k \\
A_2 & x_{21}^k & x_{22}^k & \cdots & x_{2n}^k \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
A_m & x_{m1}^k & x_{m2}^k & \cdots & x_{mn}^k
\end{array} \tag{5}
$$

where $x_{ij}^k = (\mu_{ij}^{x,k}, \upsilon_{ij}^{x,k}, \pi_{ij}^{x,k})$ represents the score of the *i*-th wastewater treatment process regarding the *j*-th criterion by the *k*-th decision-maker.

Step 2: Determining the criteria weights by each of the decision-makers. Use the intuitionistic fuzzy numbers to establish the weights vector.

Let $c_j^k = (\mu_j^{c,k}, \upsilon_j^{c,k}, \pi_j^{c,k})$ be the weight of the *j*-th criterion given by the *k*-th decision-maker, and the weights vector given by the *k*-th decision-maker obtained, as presented in Eq.6.

$$
W = \begin{bmatrix} c_1^k & c_2^k & \cdots & c_n^k \end{bmatrix} \quad j = 1, 2, \cdots, n \tag{6}
$$

where $c_j^k = (\mu_j^{c,k}, \upsilon_j^{c,k}, \pi_j^{c,k})$

The weight of the *j*-th criterion by the k-th decision-maker could be calculated by Eq.7.

$$
\tilde{\omega}_j^k = \frac{\left(\mu_j^{c,k} + \pi_j^{c,k} \left(\frac{\mu_j^{c,k}}{\mu_j^{c,k} + \upsilon_j^{c,k}} \right) \right)}{\sum_{j=1}^{n} \left(\mu_j^{c,k} + \pi_j^{c,k} \left(\frac{\mu_j^{c,k}}{\mu_j^{c,k} + \upsilon_j^{c,k}} \right) \right)} \tag{7}
$$

Step 3: Weights determination for the DMs in the decision-making. The users can employ the intuitionistic fuzzy numbers presented in Table 3 to determine the weights vector regarding the role importance of the decision-makers.

Let $D_k = (\mu_k^D, \upsilon_k^D, \pi_k^D)$ be the *k*-th role importance of decision-maker, and the role importance of each decision-maker could be calculated by Eq.8 (Boran et al., 2009).

$$\lambda_k = \frac{\left(\mu_k^D + \pi_k^D\left(\frac{\mu_k^D}{\mu_k^D + \upsilon_k^D}\right)\right)}{\sum_{k=1}^{K}\left(\mu_k^D + \pi_k^D\left(\frac{\mu_k^D}{\mu_k^D + \upsilon_k^D}\right)\right)} \tag{8}$$

where λ_k is the role weight of the *k*-th decision-maker, and $\lambda_1 + \lambda_2 + \cdots + \lambda_K = 1$.

Table 3: Linguistic variables for rating the role of the decision-makers

Linguistic terms	Abbreviation	IFN
Very important (VI)	VI	(0.90,0.05,0.05)
Important (I)	I	(0.75,0.20,0.05)
Medium (M)	M	(0.50,0.40,0.10)
Unimportant (U)	U	(0.25,0.60,0.15)
Very unimportant (VU)	VU	(0.10,0.80,0.10)

Source: Zhang and Liu, 2011

Step 4: Establishing the aggregated decision-making matrix and the aggregated weight (AW) of each criterion. Intuitionistic fuzzy weighted averaging (IFWA) operator proposed by Xu (2007) was utilized to aggregate all individual decision makers' opinions into a group opinion, as presented in Eq.9 and Eq.10.

$$\begin{aligned} x_{ij} &= IFWA_{\lambda}(x_{ij}^1, x_{ij}^2, \cdots, x_{ij}^K) \\ &= \left(1 - \prod_{k=1}^{K}(1-\mu_{ij}^{x,k})^{\lambda_k}, \prod_{k=1}^{K}\left(\upsilon_{ij}^{x,k}\right)^{\lambda_k}, \prod_{k=1}^{K}(1-\mu_{ij}^{x,k})^{\lambda_k} - \prod_{k=1}^{K}\left(\upsilon_{ij}^{x,k}\right)^{\lambda_k}\right) \end{aligned} \tag{9}$$

$$\begin{array}{cccccc} & C_1 & C_2 & & C_n \\ A_1 & x_{11} & x_{12} & \cdots & x_{1n} \\ A_2 & x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & x_{m1} & x_{m2} & \cdots & x_{mn} \end{array} \tag{10}$$

where $x_{ij} = (\mu_{ij}^x, \upsilon_{ij}^x, \pi_{ij}^x)$ represents the aggregated score of the *i*-th wastewater treatment technologies regarding the *j*-th criterion.

The AW of each criterion can be calculated by Eq.11,

$$\tilde{\omega}_j = \left(\prod_{k=1}^{K} \left(\tilde{\omega}_j^k \right)^{\lambda_k} \right)^{\frac{1}{\sum_{k=1}^{K} \lambda_k}} \tag{11}$$

where $\tilde{\omega}_j$ is the AW of the *j*-th criterion.

Step 5: Determining the integrated priorities of the alternatives. The priorities of the wastewater treatment processes could be calculated by Eq.12,

$$\begin{aligned} P_i &= IFWA_{\omega}(x_{i1}, x_{i2}, \cdots, x_{in}) \\ &= \left(1 - \prod_{j=1}^{n} (1 - \mu_{ij}^x)^{\tilde{\omega}_j}, \prod_{j=1}^{n} \left(\upsilon_{ij}^x \right)^{\tilde{\omega}_j}, \prod_{j=1}^{n} (1 - \mu_{ij}^x)^{\tilde{\omega}_j} - \prod_{j=1}^{n} \left(\upsilon_{ij}^{x,k} \right)^{\tilde{\omega}_j} \right) \end{aligned} \tag{12}$$

where $P_i = (\mu_{P_i}, \upsilon_{P_i}, \pi_{P_i})$ represents the integrated priority of the *i*-th alternative.

Step 6: Determine the priority sequence. The score and the accuracy degree of P_i were calculated by Eq.13 and Eq.14, respectively (Hong and Choi, 2000; Chen and Tan, 1994).

$$S_i = \mu_{P_i} - \upsilon_{P_i} \tag{13}$$

$$H_i = \mu_{P_i} + \upsilon_{P_i} \tag{14}$$

The priority order of $P_i = (\mu_{P_i}, \upsilon_{P_i}, \pi_{P_i})$ and $P_j = (\mu_{P_j}, \upsilon_{P_j}, \pi_{P_j})$ can be determined according to the following rules (Xu and Yager, 2006).

(1) $S_i > S_j \Rightarrow P_i > P_j$, the i-th scenario is better than the j-th scenario, denotes by $i \succ j$;

(2) $S_i < S_j \Rightarrow P_i < P_j$, the i-th scenario is worse than the j-th scenario, denotes by $i \prec j$;

(3) $S_i = S_j \cap H_i = H_j$, the i-th alternative is no difference to the j-th alternative, denotes by $i \sim j$;

(4) $S_i = S_j \cap H_i > H_j$, the i-th scenario is better than the j-th scenario, denotes by $i \succ j$; and

(5) $S_i = S_j \cap H_i < H_j$, the i-th scenario is worse than the j-th scenario, denotes by $i \prec j$.

5. Case study

An illustrative case including four processes for WT, namely Anaerobic-Anoxic-Oxic (AAO) process**,** Triple oxidation ditch (TOD) process **,**Anaerobic single-ditch oxidation (ASD) process, and Sequencing batch reactor activated sludge process (SBR), has been investigated. The advantages and disadvantages of these four processes were summarized in Table 4.

Table 4: The advantages and disadvantages of these four processes for wastewater treatment

	Advantages	Disadvantages
AAO	good performances on removing nitrogenous and phosphorous organic compounds	High capital cost
TOD	high reliability and easy for operations	bad performance on sludge treatment, large occupied land
ASD	good performances on removing nitrogenous and phosphorous organic compounds and high	large occupied land
SBR	low capital cost and less occupied land	low maturity and reliability, bad performances on removing nitrogenous and phosphorous organic compounds

Reference: Ling and Hang (1998)

Eight criteria including capital costs (EC_1), operation and maintenance costs (EC_2), effect on water quality improvement (EN_1), occupied land (EN_2), operability and simplicity (T_1), maturity (T_2), reliability (T_3), and public acceptability (SP_1) were employed for sustainability measurement of the four processes. Note that the users can of course employed all the ten criteria or add more criteria in each of the four dimensions for sustainability assessment in some other cases; however, the decision-makers held the view that there is no difference among these four WT processes with respect to the other criteria in social-political dimension, so eight criteria were used in this case.

Three representative stakeholder groups attended in this SM process, and they are researchers (DM#1), administrators (including the managers from coal-fired power company) (DM#2), and local residents of this city (DM#3). There are eight researchers in DM#1 including two professors, two PhD researchers whose research includes industrial water treatment, one postdoctoral researcher who is an expert of environment protection, and three senior researchers focusing on wastewater treatment and chemical engineering from Chongqing University (China) . DM#2 consists of three administrators including two officials from the local Environmental Protection Bureau and one project manager from the sector of wastewater treatment of the state-owned coal-fired power company. Six local residents from different regions of this city were invited as the representative participants in DM#3. A director in each group was firstly selected to collect the data.

Step 1: The relative performances of the wastewater treatment processes regarding each criterion by each decision-maker could be obtained in this step, as presented in the Appendix (Table A1). It is worth pointing out that the data were collected by the authors directly in the focus groups meeting of each representative stakeholder group. According to Table 1, the linguistic variables can be transformed into IFS, and the results were presented in Appendix (Table A2).

Step 2: The weights of the four dimensions of sustainability and that of the criteria in each dimension by the three groups of DMs were obtained in this step. The weight vectors determined by the three groups of DMs were presented in Table 6. According to Eq.7, the dimension weights can be obtained based on normalizing the weight vectors determined. Taking the weight vector (by DM#1) as an example, the weights of the economic dimension based on the requirements of DM#1 can be determined by:

$$\omega_{EC}^{1} = \frac{\left(0.50 + 0.10\left(\frac{0.50}{0.50 + 0.40}\right)\right)}{\left(0.50 + 0.10\left(\frac{0.50}{0.50 + 0.40}\right)\right) + \cdots + \left(0.35 + 0.10\left(\frac{0.35}{0.35 + 0.55}\right)\right)} = 0.2222$$

(15)

In a similar way, the weights of the four dimensions determined by each group of DMs can also be obtained, (see Appendix (Table A3).

In a similar way, the local criteria weights within each dimension were calculated, as presented in Appendix (Table A4).

After determining the dimensions weight and the local criteria weights, the global criteria weights for SM by DM#1, DM#2 and DM#3 can also be determined. For example, the global weight EC_1 in economic aspect (EC) determined by DM#1 can be calculated by: $0.2222 \times 0.5357 = 0.1190$ .Similarly, all the global criteria weights by each group of DMs can obtained, and the results were shown in Appendix (Table A5).

Step 3: Weights determination for the DMs in the decision-making. The role weights of the three decision-making groups are "important (I)", " very important (VI)", and "medium (M)", respectively. Then, the role weight of GM#1 was presented in Eqs.16.

$$\lambda_1 = \frac{\left(0.90 + 0.05\left(\frac{0.90}{0.90+0.05}\right)\right)}{\left(0.90 + 0.05\left(\frac{0.90}{0.90+0.05}\right)\right) + \cdots + \left(0.50 + 0.10\left(\frac{0.50}{0.50+0.40}\right)\right)} = 0.4133$$

(16)

In a similar way, the relative importance of DM#2 and DM#3 can also be determined, and they are 0.3444 and 0.2424, respectively.

Step 4: The aggregated decision-making matrix and the aggregated weight of each criterion were obtained in this step. According to Eq.10, the aggregated relative priority of AAO with respect to EC_1 by incorporating the opinions of all the three groups of DMs can be obtained by Eq.17.

$$\begin{aligned} x_{11} &= IFWA_{\lambda}(x_{11}^{DM\#1}, x_{11}^{DM\#2}, x_{11}^{DM\#3}) \\ &= \begin{pmatrix} 1-(1-0.35)^{0.4133}(1-0.25)^{0.3444}(1-0.25)^{0.2424}, \\ 0.55^{0.4133}0.65^{0.3444}0.65^{0.2424}, \\ (1-0.35)^{0.4133}(1-0.25)^{0.3444}(1-0.25)^{0.2424} - 0.55^{0.4133}0.65^{0.3444}0.65^{0.2424} \end{pmatrix} \\ &= (0.2931, 0.6066, 0.1003) \end{aligned}$$

(17)

In a similar way, all the other data in the aggregated decision-making matrix can be determined, as presented in Appendix (Table A5).

According to Eq.11, the aggregated weight of EC_1 can be determined by Eq.18.

$$\tilde{\omega}_{EC_1}=\left((0.1190)^{0.4133}\times(0.1534)^{0.3444}\times(0.1743)^{0.2424}\right)^{\frac{1}{0.4133+0.3444+0.2424}}=0.1425$$

(18)

In a similar, the aggregated weights of other criteria can also be determined (see Table 5).

Table 5: The aggregated weights of the criteria

Criteria	EC_1	EC_2	EN_1	EN_2	T_1	T_2	T_3	SP_1
Weights	0.1425	0.1015	0.1812	0.0946	0.0658	0.1294	0.1112	0.1596

Step 5: The priorities of the four alternatives can be determined according to Eq.12 (see Table 6).

Step 6: The score S_i and the accuracy degree H_i of P_i can be determined, and the sustainability sequence of the four alternatives for WT can then be determined. It is apparent that anaerobic single-ditch oxidation (ASD) process has been recognized as the most sustainable, followed by AAO process, TOD process, and SBR process in the descending order.

Table 6: The priorities of the four alternatives for WT

Alternatives	AAO	TOD	ASD	SBR
P_i	(0.6339,0.2729,0.0932)	(0.5794,0.3143,0.1063)	(0.6678,0.2386,0.0936)	(0.5681,0.3440,0.0879)
S_i	0.3610	0.2651	0.4292	0.2241
H_i	0.9068	0.8937	0.9064	0.9121

Anaerobic single-ditch oxidation was determined as the best process for WT according to their sustainability, this result determined by the model presented in this study is consistent to that determined by Ling and Hang (1998). However, triple oxidation ditch (TOD) process was recognized as the secondly most sustainable scenario by Ling and Hang (1998), followed by a AAO process and SBR process in the descending order. There are several reasons leading the difference: (1) the results determined by the proposed method have incorporated the requirements and opinions of three groups of decision-makers; (2) the MADA method based on IFST was applied in this study; however Ling and Hang (1998) used a MADA method which is different from that used in this study; (3) the criteria system for SM of the processes for WT is different from that used in the work of Ling and Hang (1998).

5. Conclusions and policy implications

This study aims at developing an IFST based MADA method which allows multiple DMs to participate in the process and allows them to employ the intuitionistic fuzzy instead of crisp data for sustainability prioritization of the processes for wastewater treatment. An illustrative case including four alternative processes for wastewater treatment has been investigated, and the sequence of the alternative process for wastewater treatment can be successfully obtained. Anaerobic single-ditch oxidation was recognized as the most sustainable technology for wastewater treatment, thus, some insights and policy implications can be obtained for the decision-makers:

(1) Setting special subsidies for anaerobic single-ditch oxidation technology to the wastewater treatment companies for vigorously expanding the market share of

this technology;

(2) Education and training on the engineers of wastewater treatment companies for building a team of quality people skilling in anaerobic single-ditch oxidation technology;

(3) Publicizing the comprehensive sustainability performance and advantages of the stakeholders/decision-makers of wastewater treatment.

The innovations of the proposed method in this study can be summarized as follows:

(1) Different decision-makers can participate in the sustainability measurement process, the opinions, requirements and willingness of theirs can all be incorporated in the sustainability measurement process.

(2) Sustainability measurement can also be carried out even the decision-makers do not have the corresponding data for decision-making. Thus, the proposed method can achieve sustainability assessment under uncertainties.

Besides the advantages, there are also some limitations:

(1) Some data of the technologies for wastewater treatment regarding some criteria for sustainability cannot be fully used in the developed method. For instance, this intuitionistic fuzzy set based multi-attribute decision analysis method cannot use the exact data of the wastewater treatment processes with respect to capital cost even the decision-makers know;

(2) It is assumed that all the criteria for sustainability assessment are independent; however, there are usually various independences, interdependences and interactions among them.

Accordingly, the future work of the authors is to develop an intuitionistic fuzzy set theory based MADA method which cannot use exact data if some data can be obtained, but also incorporate the independences, interdependences and interactions among the criteria.

Appendix

Table A 1: The data of the wastewater treatment processes regarding each criterion by each decision-maker (DM) using linguistic variables

DM#1	AAO	TOD	ASD	SBR
Capital costs (EC_1)	MP	MG	F	G
Operation and maintenance costs (EC_2)	VG	VP	F	MP
Effect on water quality improvement (EN_1)	G	F	VG	F
Occupied land(EN_2)	MG	MP	MP	G
Operability and simplicity (T_1)	P	G	F	P
Maturity (T_2)	VG	G	G	MP
Reliability (T_3)	MG	G	G	MG
Public acceptability (SP_1)	MP	F	G	P
DM#2	AAO	TOD	ASD	SBR
Capital costs (EC_1)	P	F	MP	VG
Operation and maintenance costs (EC_2)	G	MP	F	P
Effect on water quality improvement (EN_1)	MG	MP	G	MP
Occupied land(EN_2)	G	F	F	VG
Operability and simplicity (T_1)	MP	MG	F	MP
Maturity (T_2)	VG	VG	VG	F
Reliability (T_3)	G	MG	MG	VG
Public acceptability (SP_1)	P	G	VG	VP

DM#3	AAO	TOD	ASD	SBR
Capital costs (EC_1)	P	G	MP	EG
Operation and maintenance costs (EC_2)	G	VP	MG	MP
Effect on water quality improvement (EN_1)	F	MP	MG	MP
Occupied land(EN_2)	G	VP	VP	VG
Operability and simplicity (T_1)	VP	F	MP	VP
Maturity (T_2)	EG	G	VG	F
Reliability (T_3)	F	MG	MG	F
Public acceptability (SP_1)	P	F	MG	EP

Table A2: The data of the wastewater treatment processes regarding each criterion by each decision-maker (DM) using IFS

DM#1	AAO	TOD	ASD	SBR
EC_1	(0.35,0.55,0.10)	(0.65,0.25,0.10)	(0.50,0.40,0.10)	(0.75,0.15,0.10)
EC_2	(0.85,0.10,0.05)	(0.15,0.80,0.05)	(0.50,0.40,0.10)	(0.35,0.55,0.10)
EN_1	(0.75,0.15,0.10)	(0.50,0.40,0.10)	(0.85,0.10,0.05)	(0.50,0.40,0.10)
EN_2	(0.65,0.25,0.10)	(0.35,0.55,0.10)	(0.35,0.55,0.10)	(0.75,0.15,0.10)
T_1	(0.25,0.65,0.10)	(0.75,0.15,0.10)	(0.50,0.40,0.10)	(0.25,0.65,0.10)
T_2	(0.85,0.10,0.05)	(0.75,0.15,0.10)	(0.75,0.15,0.10)	(0.35,0.55,0.10)
T_3	(0.65,0.25,0.10)	(0.75,0.15,0.10)	(0.75,0.15,0.10)	(0.65,0.25,0.10)
SP_1	(0.35,0.55,0.10)	(0.50,0.40,0.10)	(0.75,0.15,0.10)	(0.25,0.65,0.10)
DM#2	AAO	TOD	ASD	SBR
EC_1	(0.25,0.65,0.10)	(0.50,0.40,0.10)	(0.35,0.55,0.10)	(0.85,0.10,0.05)
EC_2	(0.75,0.15,0.10)	(0.35,0.55,0.10)	(0.50,0.40,0.10)	(0.25,0.65,0.10)
EN_1	(0.65,0.25,0.10)	(0.35,0.55,0.10)	(0.75,0.15,0.10)	(0.35,0.55,0.10)
EN_2	(0.75,0.15,0.10)	(0.50,0.40,0.10)	(0.50,0.40,0.10)	(0.85,0.10,0.05)
T_1	(0.35,0.55,0.10)	(0.65,0.25,0.10)	(0.50,0.40,0.10)	(0.35,0.55,0.10)
T_2	(0.85,0.10,0.05)	(0.85,0.10,0.05)	(0.85,0.10,0.05)	(0.50,0.40,0.10)
T_3	(0.75,0.15,0.10)	(0.65,0.25,0.10)	(0.65,0.25,0.10)	(0.85,0.10,0.05)
SP_1	(0.25,0.65,0.10)	(0.75,0.15,0.10)	(0.85,0.10,0.05)	(0.15,0.80,0.05)
DM#3	AAO	TOD	ASD	SBR

EC_1	(0.25,0.65,0.10)	(0.75,0.15,0.10)	(0.35,0.55,0.10)	(0.95,0.05,0.00)
EC_2	(0.75,0.15,0.10)	(0.15,0.80,0.05)	(0.65,0.25,0.10)	(0.35,0.55,0.10)
EN_1	(0.50,0.40,0.10)	(0.35,0.55,0.10)	(0.65,0.25,0.10)	(0.35,0.55,0.10)
EN_2	(0.75,0.15,0.10)	(0.15,0.80,0.05)	(0.15,0.80,0.05)	(0.85,0.10,0.05)
T_1	(0.15,0.80,0.05)	(0.50,0.40,0.10)	(0.35,0.55,0.10)	(0.15,0.80,0.05)
T_2	(0.95,0.05,0.00)	(0.75,0.15,0.10)	(0.85,0.10,0.05)	(0.50,0.40,0.10)
T_3	(0.50,0.40,0.10)	(0.65,0.25,0.10)	(0.65,0.25,0.10)	(0.50,0.40,0.10)
SP_1	(0.25,0.65,0.10)	(0.50,0.40,0.10)	(0.65,0.25,0.10)	(0.05,0.95,0.00)

Table A3: The dimension weight by each group of decision-makers

	EC	EN	T	SP
DM#1	M-(0.50,0.40,0.10)	MG-(0.65,0.25,0.10)	H-(0.75,0.15,0.10)	ML-(0.35,0.55,0.10)
DM#2	H-(0.75,0.15,0.10)	VH-(0.85,0.10,0.05)	VH-(0.85,0.10,0.05)	MH-(0.65,0.25,0.10)
DM#3	MH-(0.65,0.25,0.10)	MH-(0.65,0.25,0.10)	H-(0.75,0.15,0.10)	L-(0.25,0.65,0.10)
Weights DM#1	0.2222	0.2889	0.3333	0.1556
Weights DM#2	0.2488	0.2678	0.2678	0.2156
Weights DM#3	0.2826	0.2826	0.3261	0.1087

Table A4: The criteria weights within each dimension by each group of decision-makers

	EC_1	EC_2	EN_1	EN_2
DM#1	H-(0.75,0.15,0.10)	MH-(0.65,0.25,0.10)	VH-(0.85,0.10,0.05)	MH-(0.65,0.25,0.10)
DM#2	VH-(0.85,0.10,0.05)	M-(0.50,0.40,0.10)	MH-(0.65,0.25,0.10)	L-(0.25,0.65,0.10)
DM#3	H-(0.75,0.15,0.10)	M-(0.50,0.40,0.10)	VH-(0.85,0.10,0.05)	M-(0.50,0.40,0.10)
Weights DM#1	0.5357	0.4643	0.5540	0.4460
Weights DM#2	0.6167	0.3824	0.7222	0.2778
Weights DM#3	0.6000	0.4000	0.6176	0.3824
	T_1	T_2	T_3	SP_1
DM#1	L-(0.25,0.65,0.10)	MH-(0.65,0.25,0.10)	M-(0.50,0.40,0.10)	/
DM#2	M-(0.50,0.40,0.10)	VH-(0.85,0.10,0.05)	H-(0.75,0.15,0.10)	/
DM#3	MH- (0.65,0.25,0.10)	M-(0.50,0.40,0.10)	VH-(0.85,0.10,0.05)	/
Weights DM#1	0.1786	0.4643	0.3572	1.0000
Weights DM#2	0.2430	0.3925	0.3645	1.0000
Weights DM#3	0.3320	0.2554	0.4125	1.0000

Table A5: The global weights of the eight criteria for sustainability measurement

Global weights by	DM#1	DM#2	DM#3
EC_1	0.1190	0.1534	0.1743
EC_2	0.1032	0.0951	0.1081
EN_1	0.1601	0.1934	0.2041
EN_2	0.1288	0.0744	0.0785
T_1	0.0595	0.0651	0.0792
T_2	0.1548	0.1051	0.1280
T_3	0.1191	0.0976	0.1189
SP_1	0.1556	0.2156	0.1087

Table A6: The aggregated intuitionistic fuzzy decision-making matrix

	AAO	TOD	ASD	SBR
EC_1	(0.2931,0.6066,0.1003)	(0.6353,0.2597,0.1051)	(0.4168,0.4821,0.1010)	(0.8581,0.0999,0.0420)
EC_2	(0.7976,0.1268,0.0756)	(0.2250,0.7031,0.0718)	(0.5414,0.3569,0.1017)	(0.3172,0.5825,0.1003)
EN_1	(0.6680,0.2268,0.1052)	(0.4168,0.4821,0.1010)	(0.7804,0.1436,0.0760)	(0.4168,0.4821,0.1010)
EN_2	(0.7127,0.1852,0.1020)	(0.3663,0.5397,0.0940)	(0.3663,0.5397,0.0940)	(0.8148,0.1182,0.0670)
T_1	(0.2641,0.6453,0.0906)	(0.6680,0.2268,0.1052)	(0.4672,0.4321,0.1007)	(0.2641,0.6453,0.0906)
T_2	(0.8851,0.0845,0.0304)	(0.7904,0.1304,0.0792)	(0.8148,0.1182,0.0670)	(0.4428,0.4562,0.1010)
T_3	(0.6602,0.2349,0.1049)	(0.6955,0.2024,0.1021)	(0.6955,0.2024,0.1021)	(0.7150,0.2043,0.0807)
SP_1	(0.2931,0.6066,0.1003)	(0.6062,0.2853,0.1085)	(0.7725,0.1476,0.0798)	(0.1708,0.7654,0.0638)

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