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Developing a Life Cycle Composite Footprint Index for Sustainability Prioritization of Sludge-to-Energy Alternatives

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Abstract

Sludge-to-energy technologies can achieve sewage sludge treatment and energy recovery simultaneously. Having a comprehensive assessment for the related technologies can contribute to the decision-making process and sustainable development of sludge management industry. In this paper, a life cycle composite footprint index was proposed, including energy recovery, carbon emissions, water consumptions, nitrogen and sulfur flows. Related methodology framework was constructed to evaluate the sustainability performance of sludge-to-energy alternatives on the composite footprint index. Fuzzy Best-Worst Method (BWM) and fuzzy AHP method were applied to obtain the weights and the overall scores. A case study was carried out applying the established framework to assess six sludge-to-energy scenarios, covering dewatering, composting, drying, incineration, incinerated ash melting, and dewatered sludge melting by the life cycle composite energy-carbon-water index. Results showed that dewatered sludge melting was the most preferred option owing to the considerable quantity of energy production, while drying process was the undesired one because of the unsatisfactory performance on energy recovery and carbon emissions. Sensitivity analysis and uncertainty analysis were carried out to study the impacts of changing weights on different aspects and the influence of changing energy recovery amount from anaerobic digestion, lower heating value and carbon content in sewage sludge toward the sustainability assessment of the sludge-to-energy technologies.

Keywords: life cycle assessment; sludge-to-energy technology; fuzzy best-worst method; fuzzy analytic hierarchy process; sludge treatment

Abbreviations Table

Abbreviation	Full title	Abbreviation	Full title
AD	anaerobic digestion	LHV	lower heating value
AHP	analytic hierarchy process	N	nitrogen
BWM	best-worst method	P	phosphorus
C	carbon	S	sulfur
DS	dry sludge	SCWG	supercritical water gasification
LCA	life cycle assessment	SCWO	supercritical water oxidation

1 Introduction

Sewage sludge generated from wastewater treatment plants can lead to various environmental and social problems if it cannot be treated appropriately (Yang et al., 2015). Typical compositions of sludge consist of nontoxic organic carbon substances, the organics with nitrogen (N) and phosphorus (P), toxic chemical matters, microbiological pollutants, inorganic components, and water (generally $\geq 95\%$) (Rulkens, 2008). Considering the harmful components in sludge, proper treatment is required to reduce or eliminate the negative effects on the environment. Conventional disposal methods majorly include landfilling, agricultural usage, and incineration (Fytili and Zabaniotou, 2008). However, the conventional management methods may not be suitable for current situation due to the increasing production of sewage sludge and improving requirement on sludge discharge standards (Fytili and Zabaniotou, 2008; Yang et al., 2015). Meanwhile, various valuable matters which are worthy to recycle also exist in sludge. Accordingly, sludge treatment technologies for simultaneous waste reduction and energy recovery were proposed and developed (Grosser and Neczaj, 2018; Syed-Hassan et al., 2017). These technologies include anaerobic digestion (AD), incineration, pyrolysis, gasification, supercritical water oxidation (SCWO) and co-treatment with other wastes. Bio-fuels and electricity can be generated directly or indirectly during the treatment process (Rulkens, 2008; Syed-Hassan et al., 2017).

The development of sewage sludge treatment technologies has been reviewed by plenty of previous studies. AD for biogas production and further electricity generation from sludge has been developed maturely and applied at different scales in the worldwide (Liu et al., 2019). Sludge incineration has been studied and utilized as an important sludge treatment technique in many developed countries (Li et al., 2013; Zhou et al., 2008). Pyrolysis and gasification are relatively new methods for hydrogen production from sewage sludge (Gai et al., 2016; Xiong et al., 2009). Supercritical water gasification (SCWG) for sludge treatment and hydrogen production is an emerging technology which shares the similar principles with those of SCWO, while the latter owns longer development history (He et al., 2014). The potential of energy and resources recovery from sewage sludge has gradually recognized by more and more researchers (Fytili and Zabaniotou, 2008). It is important to investigate the energy recovery efficiency because it is one of the major concerns of the feasibility and potential of sludge-to-energy technologies. High organic matters content in sludge can result in high emissions of carbon dioxide during sludge treatment process. Meanwhile, high moisture content leads to the necessity of water recycling from sludge treatment process, otherwise a vast amount of water would be wasted. It is also necessary to analyze the behaviors of some elements which may pollute the environment or be recovered, such as nitrogen, sulfur (S) and phosphorus, for better treatment or recovery. Thus, energy and matters flow analysis, especially energy recovery, water consumptions and carbon emissions, are important to consider when studying the performance of various sludge treatment technologies. Nevertheless, different technologies have different advantages and drawbacks due to the various features, which make it difficult to make a suitable choice among the diverse options. Hence, sustainability assessment to evaluate the performances in different aspect is highly necessary. Assessment focused on the production processes may be questionable since it would ignore the environmental and economic influence of energy and materials input to the sludge treatment system. Reversely, life cycle assessment (LCA) considering the full life stages of a product or a process makes the objective comparison between different technologies be possible.

LCA is a powerful tool for environmental and economic influence evaluation (ISO 14040, 2006). The application on sustainability assessment for targeted systems, including sewage sludge management, has been gradually recognized during the past decades (Yoshida et al., 2013). Current assessment work focused more on the environmental and economic performances of several common sludge treatment technologies, majorly including anaerobic digestion, incineration (Hong et al., 2009; Xu et al., 2014), pyrolysis (Kim and Parker, 2008; Li and Feng, 2018), and wet air oxidation (Svanström et al., 2004; Tarpani and Azapagic, 2018). According to the specific hypotheses in each paper, assessment results can be different from each other. The quantity of energy recovery from AD was 12500 MJ/t dry sludge (DS) according to the report of Xu et al. (2014) while the data from the study of Hong et al. (2009) was much lower than the former with only 261.72MJ/t-DS. However, both studies confirmed the benign effect on the environment and economic of digested sludge incineration. Pyrolysis combined with anaerobic digestion was found to have acceptable environmental impacts and energy efficiency under certain conditions (Li and Feng, 2018). Economic estimations recognized the profits created by pyrolysis and AD (Tarpani and Azapagic, 2018). Evaluation work for gasification and SCWG are scarce which means that more efforts are still needed in this field. An environmental assessment for SCWO suggested that it is environmental benign from the life cycle perspective (Svanström et al., 2004) and more suitable for large scale of sludge treatment compared with incineration (Xu et al., 2012). Although there are plenty of evaluation work for sludge treatment technologies, few studies investigated the aspects beyond environment and economy, such as technical maturity, social acceptability, and some important footprints analysis.

To fill the above-mentioned research gaps, this study built up a methodology framework to discuss and analyze a composite footprint index for sludge-to-energy technologies by life cycle thinking. The footprints described in this paper included energy, water, carbon (C), nitrogen, and sulfur, while the similar core thought can also be promoted to other matters and elements footprints analysis. Fuzzy Best-Worst Method (BWM) and Fuzzy Analytic Hierarchy Process (AHP) method were applied to integrate the considered footprints together and obtain an overall evaluation result for the investigated scenario. A case study was conducted by applying the proposed framework to evaluate six selected sludge treatment technologies by life cycle composite energy-carbon-water footprint index. The entire framework of this paper is illustrated in Figure 1.

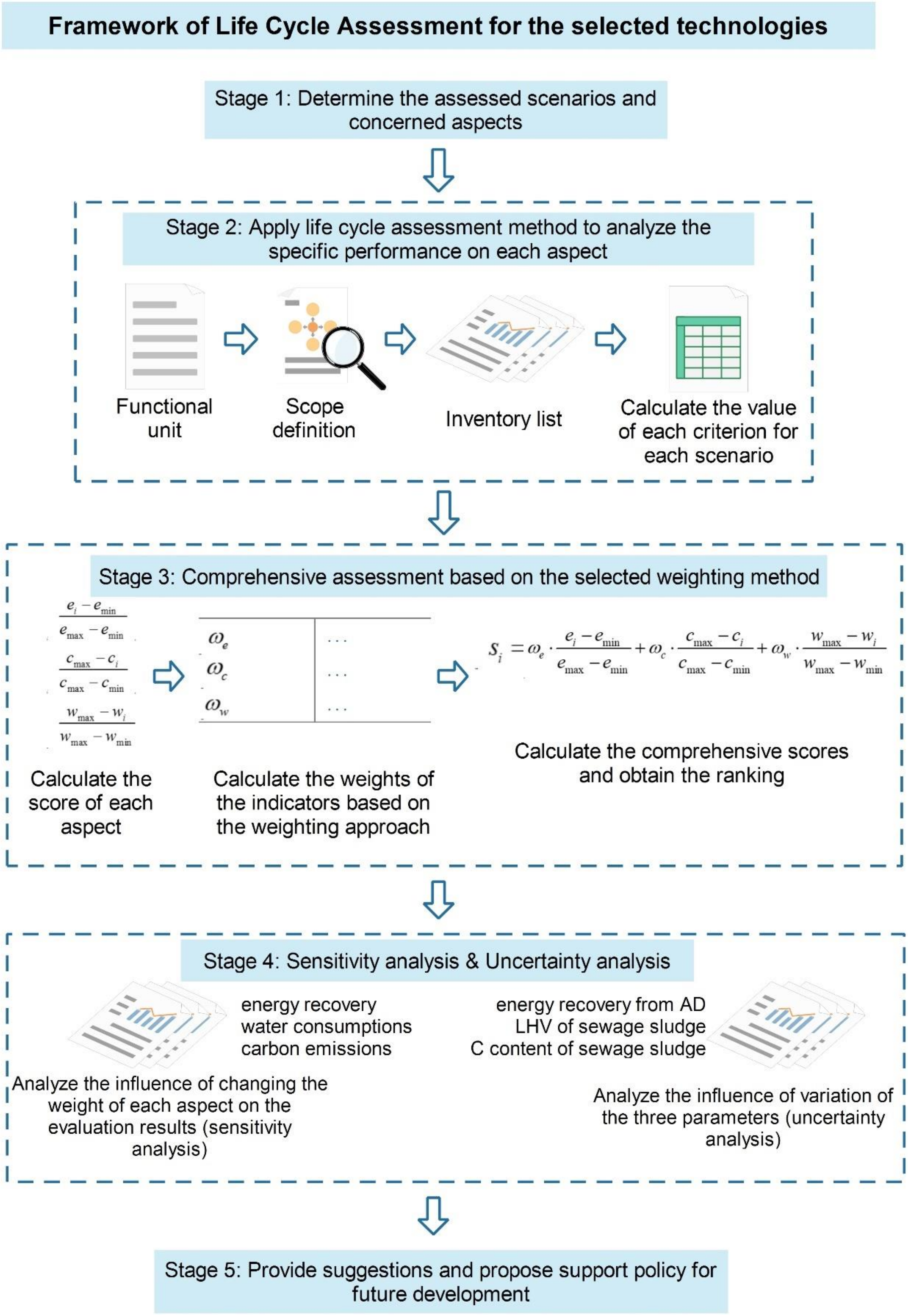


Figure 1 The framework of life cycle assessment for the selected technologies in this study

2 Methodology

In this section, a methodology framework with life cycle thinking was established to investigate the different footprints of sludge management technologies aiming to provide decision-making reference for stakeholders. The footprints of energy, carbon and water were introduced in detailed in Sections 2.1.1 – 2.1.3 and the similar calculation approach for other types of footprints were presented in Section 2.1.4. The investigated footprints were then integrated together to generate an overall assessment score for each scenario by weighting method. The weighting methods applied in this work were fuzzy BWM and fuzzy AHP, which were introduced in Section 2.2. The integration method for life cycle composite footprint index was included in Section 2.3.

2.1 Methods for footprint family

There are different methods for estimating different types of footprints in an investigated system, such as LCA-based approaches and simple spread sheet-based models. CML 2000 and Eco-Indicator 99 assessment tool are frequently used in LCA-based models (Singh et al., 2016). Emission factors and the corresponding embodied factor of the examined energy or element can also be applied to calculate the emissions in each stage accordingly (Moussavi Nadoushani and Akbarnezhad, 2015; Zhuang et al., 2020). In this study, emission factors and data collected from literature review were employed to estimate the energy and materials flows in different alternatives.

2.1.1 Energy footprint

Energy consumption was calculated based on the energy and materials input within the entire process provided from the life cycle inventory list and the corresponding lower heating values or energy equivalent of the materials, which are shown in Eq. (1).

$$E = \sum_{i=1}^{n} \sum_{j=1}^{k_i} m_j^{k_i} \cdot e^j \qquad (1)$$

where i refers to the ith process in the entire technology route; n represents the total amount of processes in the technical route; j is the jth material in the ith process and there are k_i types of input materials in the ith process. Hence, $m_j^{k_i}$ means the amount of jth material in the ith process. e^j is the energy equivalent or lower heating value (LHV) of the jth input material. E refers to the total amount of input energy in the investigated technical route.

2.1.2 Carbon footprint

Carbon emissions usually includes direct carbon emissions and indirect carbon emissions. Direct carbon emissions refer to the emissions from full combustion of different materials, including dried sewage sludge, natural gas, and coal. Indirect carbon emissions majorly refer to the emissions during the generation process of input energy, i.e., the process of coal-combustion for electricity production, acquisition of natural gas, and coal mining (Man et al., 2018; Man et al., 2019). The calculation for carbon emissions was based on the energy consumptions and corresponding life cycle CO_2 eq emissions from literature review, which is described by Eq. (2).

$$C=\sum_{i=1}^{n}\sum_{j=1}^{k_i}E_j^{k_i}\cdot c^j \tag{2}$$

where C refers to carbon emissions in the analyzed scenario; $E_j^{k_i}$ is the equivalent energy consumptions during the process i from the j th input material; c^j is the carbon emissions (kg CO_2 eq) for the j th material per gigajoule. Indirect carbon emissions can be calculated in the same way. In this work, the conversion rate of coal combustion to steam for incineration is considered. Hence, the values obtained from Eq. (2) need to be divided by the efficiency 90% as the final results for the part of heat supply in incineration.

2.1.3 Water footprint

Similar to carbon emissions, water consumptions also cover direct water consumptions and indirect water consumptions. The generation of direct water consumptions and indirect water consumptions can similarly refer to the source of direct and indirect carbon emissions. Direct water consumptions are the water originally contained in the materials or generated from the materials during the treatment process, like combustion. The water consumptions during the generation process of input energy contribute to the indirect water consumptions. The water consumptions can be calculated by the life cycle water consumptions from literature review, as shown in Eq. (3).

$$W=\sum_{i=1}^{n}\sum_{j=1}^{k_i}E_j^{k_i}\cdot w^j \tag{3}$$

where W represents water consumptions in the analyzed scenario; w^j refers to the water consumptions (kg) from the process of j th material per gigajoule. Indirect water consumptions can be obtained by the same equation. Similar to the calculation of carbon emissions, the values obtained from Eq. (3) should be divided by the conversion efficiency. In this research, it is assumed that the water can be completely recycled during the process of machine thickening and dewatering.

2.1.4 Other footprints

Considering the complex compositions of sewage sludge, there are still many types of components or material flows which are worthy to investigate, such as the heavy metals (Cr, Pb, Hg, Zn, etc.), N- and S- contained chemical matters (Hong et al., 2009; Liu et al., 2019). N- and S- contained components can be converted into poisonous and harmful gases, like N_2O, NO_x, and SO_x (Hong et al., 2009). Heavy metals can be discharged into the air as the dust is produced from incineration process or into the soil along with the final landfilling, which can put negative impact to the environment. Therefore, it is necessary to discuss these types of footprints to provide a clearer recognition of the material flows in different processes. In this section, the analysis for the footprints of N and S is briefly introduced to provide a basic thought for the related calculation. The analysis for heavy metals and other elements may also use the similar methods and refer to the ecological risks analysis for sewage sludge agricultural application to cropland (Seleiman et al., 2020).

To analyze the footprints of N and S, it is essential to know about the corresponding content in each kind of material, such as sewage sludge and the input fuels for energy supply. Indirect N and S input should also be noticed since the input electricity may be generated accompanied with considerable amount of N and S contained gases. The related data can be obtained through detection and records in the literature review. Considering the waste combustion is a complex physical and chemical process, it can be assumed that the N- and S- containing chemicals have been sufficiently reacted during the combustion to simplify the analysis. Once the N and S input from different raw materials and energy in each process are clearly analyzed, the footprints of N and S can be correspondingly calculated by the similar approach with carbon and water, as shown in Eq. (4) and Eq. (5).

$$\bar{N} = \sum_{i=1}^{n} \sum_{j=1}^{k_i} E_j^{k_i} \cdot \bar{n}^j \tag{4}$$

$$S = \sum_{i=1}^{n} \sum_{j=1}^{k_i} E_j^{k_i} \cdot s^j \tag{5}$$

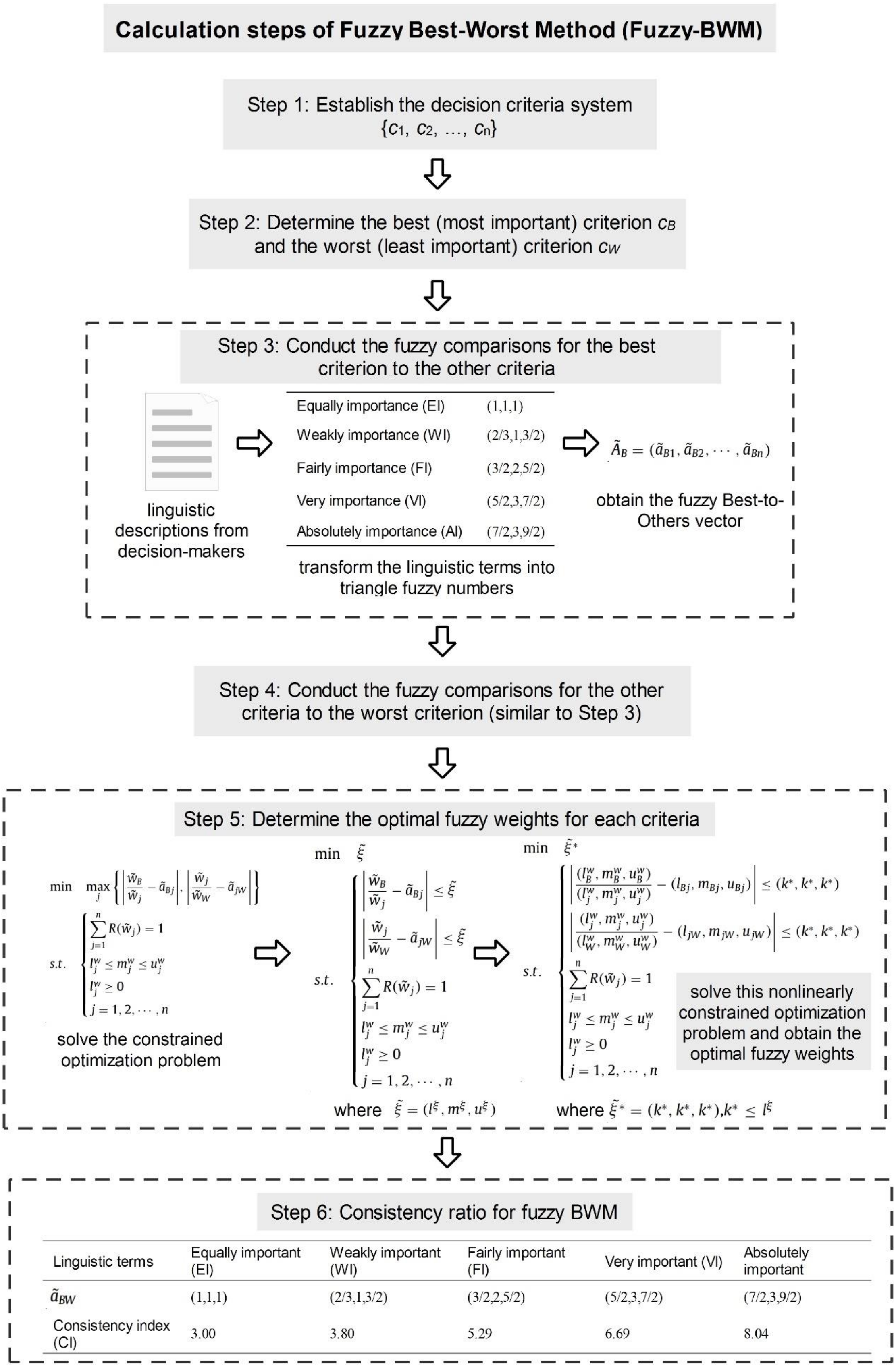
where $\bar{N}$ and S represent the amount of nitrogen and sulfur contained matters in the examined scenario, respectively; $\bar{n}^j$ and s^j refer to the amount of generation of nitrogen and sulfur contained chemical matters from the process of the j th material per gigajoule.

2.2 Weighting methods

Considering the vagueness resulted from the uncertainty in data and linguistic description from the stakeholders, it may be difficult to obtain the exact weight of each aspect directly from the preferences of decision-makers. Therefore, fuzzy theory was introduced to solve this problem. In the paper, two weighting methods, fuzzy BWM and fuzzy AHP, were selected and applied to decide the weight of each index. These two methods were selected since they are commonly used pairwise comparison approaches. Best-worst method was chosen because it can significantly reduce the times of comparison and has a better performance on consistency ratio compared with traditional AHP method (Rezaei, 2015). Fuzzy BWM possesses the advantages of BWM and the ability of processing vagueness. AHP method was employed since it is a classical pairwise comparison method for weighting and decision-making. The operation is simple and easy to understand even for the decision-makers without related professional knowledge. Fuzzy theory combined with AHP method also allows it to process the vague information generated from the subjective recognition of the stakeholders. Section 2.2.1 and 2.2.2 provide a brief introduction of the calculation principles of fuzzy BWM and fuzzy AHP applied in this work.

2.2.1 Fuzzy BWM

The calculation principles of fuzzy BWM in this work complied with the method provided in the study of Guo and Zhao (2017). The general calculation steps of fuzzy BWM to determine the fuzzy weights were shown in Figure 2 (Guo and Zhao, 2017).



Equally importance (EI)	(1,1,1)
Weakly importance (WI)	(2/3,1,3/2)
Fairly importance (FI)	(3/2,2,5/2)
Very importance (VI)	(5/2,3,7/2)
Absolutely importance (AI)	(7/2,3,9/2)

$$\tilde{A}_B = (\tilde{a}_{B1}, \tilde{a}_{B2}, \cdots, \tilde{a}_{Bn})$$

$$\min \max_j \left\{ \left| \frac{\tilde{w}_B}{\tilde{w}_j} - \tilde{a}_{Bj} \right|, \left| \frac{\tilde{w}_j}{\tilde{w}_W} - \tilde{a}_{jW} \right| \right\}$$
$$s.t. \begin{cases} \sum_{j=1}^{n} R(\tilde{w}_j) = 1 \\ l_j^w \le m_j^w \le u_j^w \\ l_j^w \ge 0 \\ j = 1, 2, \cdots, n \end{cases}$$

$$\min \tilde{\xi}$$
$$s.t. \begin{cases} \left| \frac{\tilde{w}_B}{\tilde{w}_j} - \tilde{a}_{Bj} \right| \le \tilde{\xi} \\ \left| \frac{\tilde{w}_j}{\tilde{w}_W} - \tilde{a}_{jW} \right| \le \tilde{\xi} \\ \sum_{j=1}^{n} R(\tilde{w}_j) = 1 \\ l_j^w \le m_j^w \le u_j^w \\ l_j^w \ge 0 \\ j = 1, 2, \cdots, n \end{cases}$$
where $\tilde{\xi} = (l^{\xi}, m^{\xi}, u^{\xi})$

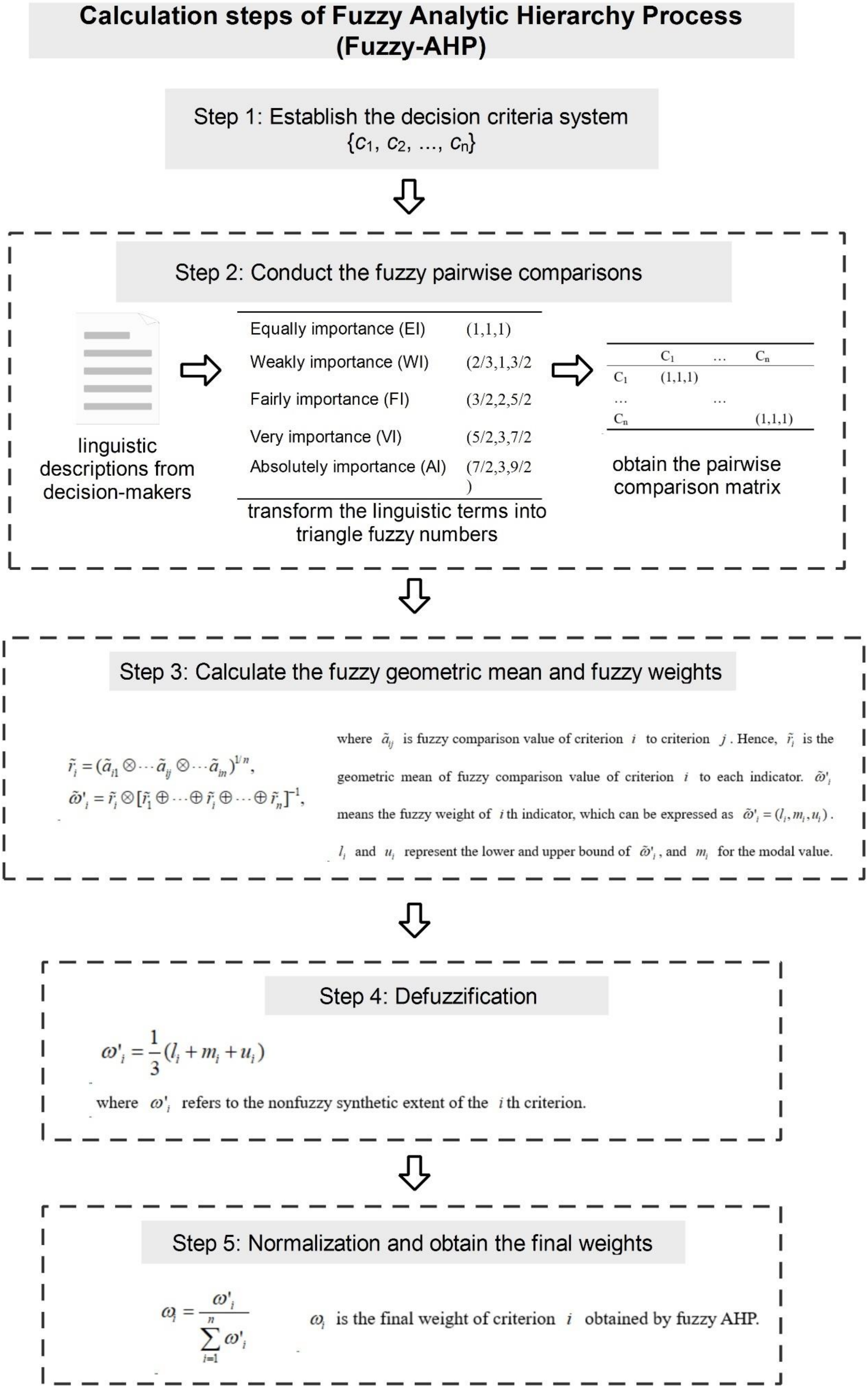
$$\min \tilde{\xi}^*$$
$$s.t. \begin{cases} \left| \frac{(l_B^w, m_B^w, u_B^w)}{(l_j^w, m_j^w, u_j^w)} - (l_{Bj}, m_{Bj}, u_{Bj}) \right| \le (k^*, k^*, k^*) \\ \left| \frac{(l_j^w, m_j^w, u_j^w)}{(l_W^w, m_W^w, u_W^w)} - (l_{jW}, m_{jW}, u_{jW}) \right| \le (k^*, k^*, k^*) \\ \sum_{j=1}^{n} R(\tilde{w}_j) = 1 \\ l_j^w \le m_j^w \le u_j^w \\ l_j^w \ge 0 \\ j = 1, 2, \cdots, n \end{cases}$$
where $\tilde{\xi}^* = (k^*, k^*, k^*), k^* \le l^{\xi}$

Linguistic terms	Equally important (EI)	Weakly important (WI)	Fairly important (FI)	Very important (VI)	Absolutely important
$\tilde{a}_{BW}$	(1,1,1)	(2/3,1,3/2)	(3/2,2,5/2)	(5/2,3,7/2)	(7/2,3,9/2)
Consistency index (CI)	3.00	3.80	5.29	6.69	8.04

Figure 2 The calculation steps for fuzzy BWM (modified from Guo and Zhao (2017))

2.2.2 Fuzzy AHP

Fuzzy AHP applied in this paper complied with the method provided in the previous studies (Hsieh et al., 2004; Sun, 2010). The general calculation steps of fuzzy AHP to determine the fuzzy weights were shown in Figure 3 (Hsieh et al., 2004; Sun, 2010).



Equally importance (EI)	(1,1,1)
Weakly importance (WI)	(2/3,1,3/2
Fairly importance (FI)	(3/2,2,5/2
Very importance (VI)	(5/2,3,7/2
Absolutely importance (AI)	(7/2,3,9/2)

$$\begin{array}{c|ccc} & C_1 & \dots & C_n \\ \hline C_1 & (1,1,1) & & \\ \dots & & \dots & \\ C_n & & & (1,1,1) \end{array}$$

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \cdots \tilde{a}_{ij} \otimes \cdots \tilde{a}_{in})^{1/n},$$
$$\tilde{\omega}'_i = \tilde{r}_i \otimes [\tilde{r}_1 \oplus \cdots \oplus \tilde{r}_i \oplus \cdots \oplus \tilde{r}_n]^{-1},$$

where $\tilde{a}_{ij}$ is fuzzy comparison value of criterion i to criterion j. Hence, $\tilde{r}_i$ is the geometric mean of fuzzy comparison value of criterion i to each indicator. $\tilde{\omega}'_i$ means the fuzzy weight of i th indicator, which can be expressed as $\tilde{\omega}'_i = (l_i, m_i, u_i)$. l_i and u_i represent the lower and upper bound of $\tilde{\omega}'_i$, and m_i for the modal value.

$$\omega'_i = \frac{1}{3}(l_i + m_i + u_i)$$

where ω'_i refers to the nonfuzzy synthetic extent of the i th criterion.

$$\omega_i = \frac{\omega'_i}{\sum_{i=1}^{n} \omega'_i}$$

ω_i is the final weight of criterion i obtained by fuzzy AHP.

Figure 3 The calculation steps for fuzzy AHP (modified from Hsieh at al. (2004) and Sun (2010))

2.3 Life cycle composite footprint index

Based on the analysis of different types of footprints and the corresponding weights, a composite footprint index can be generated. A normalization step is first conducted to process the calculated results. The different types of footprints can be regarded as assessed criteria, which can be classified into beneficial criteria and cost criteria. Beneficial criterion means that higher value of the criterion is preferred, like energy recovery. On the contrary, cost criterion refers to the indicator that lower value is preferred. In this context, cost criteria include carbon emissions, water consumptions, and the emissions of oxynitride and oxysulfide. The score on beneficial criterion and cost criterion can be calculated by Eq. (6) and Eq. (7), respectively.

$$s_{benefit}^{i} = \omega_{benefit} \cdot \frac{b_i - b_{\min}}{b_{\max} - b_{\min}} \tag{6}$$

$$s_{c'}^{i} = \omega_{c'} \cdot \frac{c'_{\max} - c'_{i}}{c'_{\max} - c'_{\min}} \tag{7}$$

where $s_{benefit}^{i}$ refers to the score of the i th assessed alternative on the beneficial criterion, that is energy recovery in this work. $s_{c'}^{i}$ means the score of the i th assessed alternative on the cost criterion, which can be carbon emissions, water consumptions, oxynitride emissions and oxysulfide emissions. Accordingly, $\omega_{benefit}$ and $\omega_{c'}$ represent the weight of beneficial criterion and cost indicator, respectively. Weights assignment can be adjusted according to the preference of stakeholders and practical situation. $b_{\max}$ and $b_{\min}$ mean the maximum and minimum value of the beneficial criterion. b_i is the performance value of the i th alternative on the beneficial criterion.

Similarly, $c'_{\max}$ and $c'_{\min}$ refer to the extremum in the cost criterion, while c'_i is the performance value of the i th scenario on the corresponding cost indicator. Then, the score of composite footprint index for alternative *i* can be expressed as Eq. (8).

$$s_i = \sum s^i_{benefit} + \sum s^i_{c'} \tag{8}$$

where s_i is the overall score of i th alternative.

3 Case Study: Life Cycle Composite Energy-Carbon-Water Index of Six Sludge-to-Energy Alternatives

Life cycle composite energy-carbon-water index was applied to analyze and evaluate the performances of six sewage sludge treatment scenarios aiming to guide the future development of research and management on sludge treatment. The process of each selected treatment is shown in Figure 4. In the basic scenario (T), there are three treatment steps including thickening, anaerobic digestion, and dewatering. A composting step is added after the dewatering as the Scenario TC. Drying the dewatered sludge is the last step of Scenario TD. Scenario TI is the Scenario T with incineration as the final stage. Melting is added after the incineration as the Scenario TIM. Scenario T added by a single melting process is marked as Scenario TM.

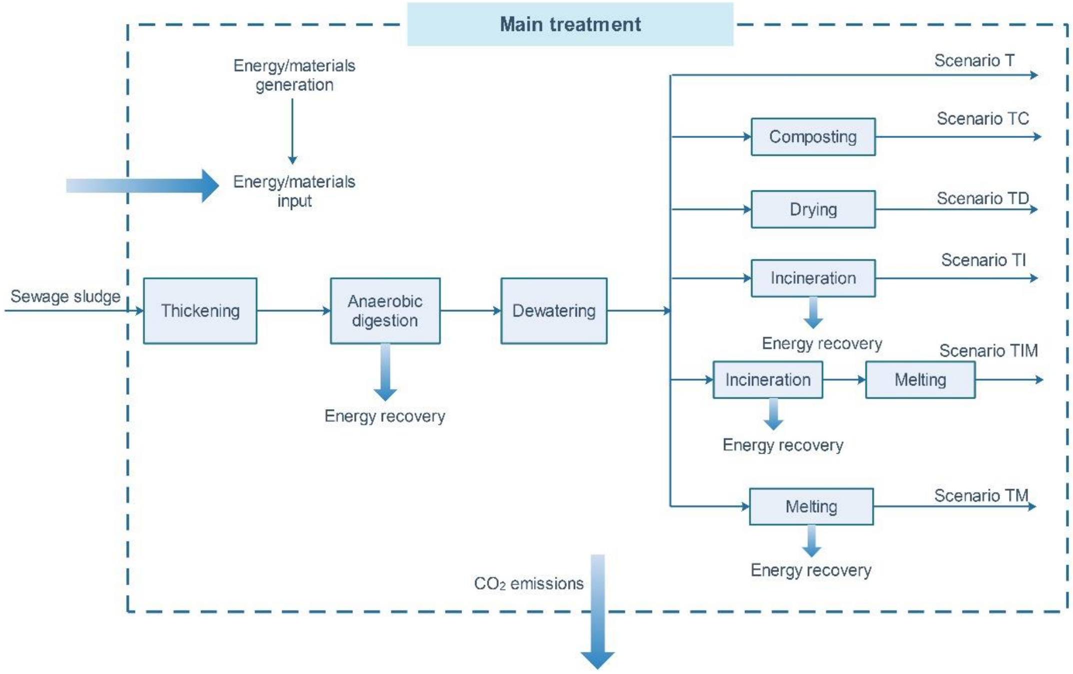


Figure 4 System boundary and procedures for each option in this work (adapted from (Hong et al., 2009))

The analysis is conducted for the main-treatment considering the production process of energy and materials input, while the post-treatment, and transportation for post-treatment is excluded, that is a gate-to-gate research. Energy and materials inputs, CO_2 emissions, energy recovery, and the equivalent consumption and flows of water were included in this work. Indirect CO_2 emissions and water consumptions, majorly referring to the emissions and consumptions from electricity and natural gas production, were considered in this study. According to the statistics data (Agency, 2009; BP, 2018), although the ratio of electricity generation from renewable resources has gradually increased, coal is still the dominate material for electricity production. Hence, electricity was assumed to be generated from coal combustion (Jaramillo et al., 2007) and steam was regarded as the heating medium in incineration with a high conversion rate of 90% from coal combustion. The major features of different kinds of treated sludge applied in this study were collected in Table S.1 in the Supplementary information (Hong et al., 2009). Life time of building, electric facility and equipment were supposed to be 30, 15, 7 years, respectively. The functional unit was selected to be the treatment of one ton of dry sludge (DS) of sludge. All the energy and materials input, CO_2 emissions and water consumptions were calculated based on this functional unit. Life cycle inventory list includes all the factors which can be used to analyze the energy, carbon, and water flows. Inventory indicators considered in this study consist of all the materials and energy consumed in the sludge treatment process, covering the consumption of electricity, heat, and natural gas. Relevant data were listed in Table S.2.

3.1 Energy recovery analysis

Energy consumptions were calculated based on the energy and materials input within the entire process provided in the reference (Hong et al., 2009) and their corresponding lower heating values. Detailed data sources of calculation for energy flows were listed in the Supplementary information.

Based on the inventory list and collected data, corresponding energy flows for each scenario were calculated, which were shown in Figure 5. Major data regarding different forms of energy input, energy recovery and loss were listed in Table 1. The energy from sludge takes the overwhelming majority of the total energy input, but the energy recovery from the treatment process is unsatisfactory with the highest amount of electricity generation from Scenario TM of 4941.72 MJ/t-DS. The amount of energy recovered from Scenario TI and Scenario TIM are perfectly equivalent because there is no energy recovery from the melting process after incineration. This also reveals that energy recovery can be mainly conducted through AD, incineration, and fluidized-bed gasification and melting, where the latter two methods contribute the main part of the total quantity of energy recovery. Other treatment methods such as drying and composting mainly aim to reduce the volume of sludge and apply it as a fertilizer, but the benefits from them are insignificant due to the increasing total energy input and less energy recovery.

Table 1 Main results of energy flow for each scenario

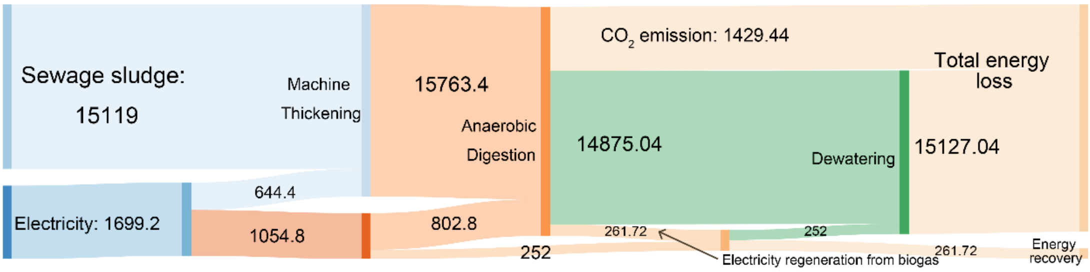
	T	TC	TD	TI	TIM	TM
Energy input						
Electricity	1699.2	1951.2	2124.00	2796.48	3139.2	3041.64
Heat			5760			
Gas consumption				1652.80	1652.80	
Sewage sludge[a]	15119	15119	15119	15119	15119	15119
Total input	16818.20	17070.20	23003.00	19568.28	19911	18160.64
Energy recovery						
Electricity generation	261.72	261.72	261.72	3604.32	3604.32	4941.72
Energy loss						
Energy carried by CO_2	1429.44	1429.44	1429.44	2604.75	2604.75	1429.44
Total energy loss	16556.48	16808.48	22741.28	15963.96	16303.68	13218.92

Unit: MJ/t-DS

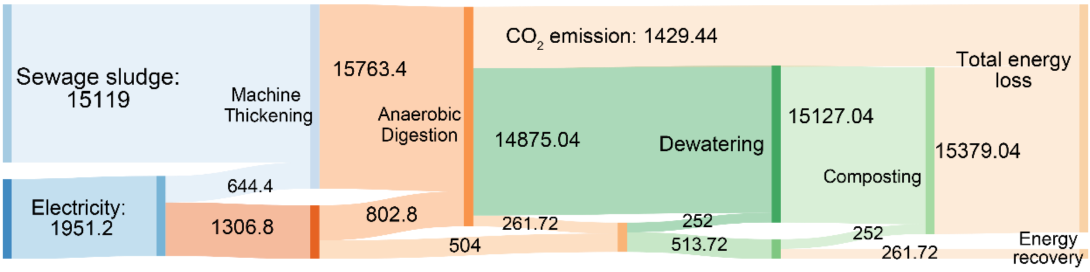
1 kWh=3600 kJ

a: LHV of sewage sludge was estimated as 6500 Btu/lb (Cooper et al., 1999).

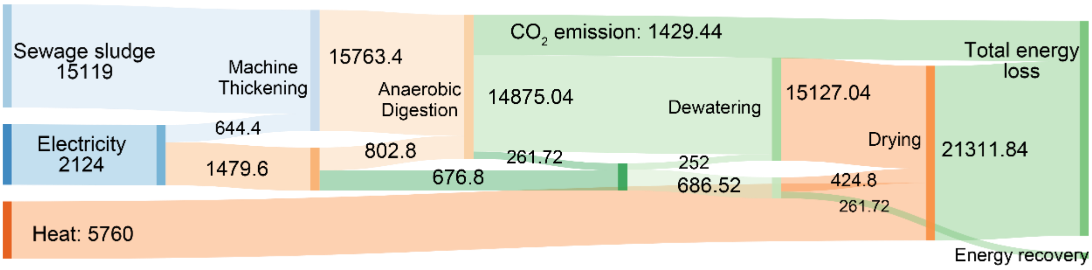
1 Btu/lb=2326 J/kg



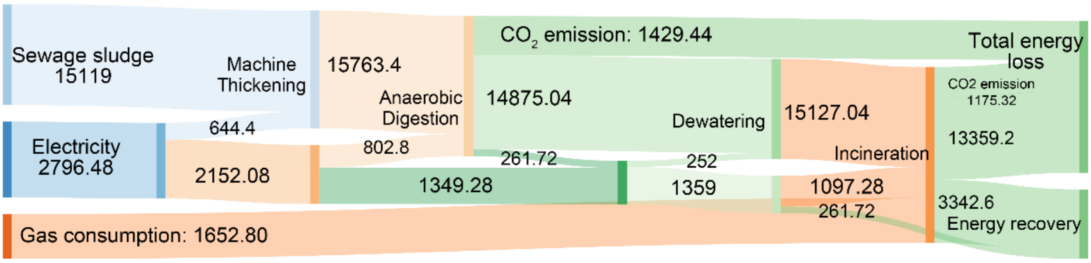
(a) Scenario T



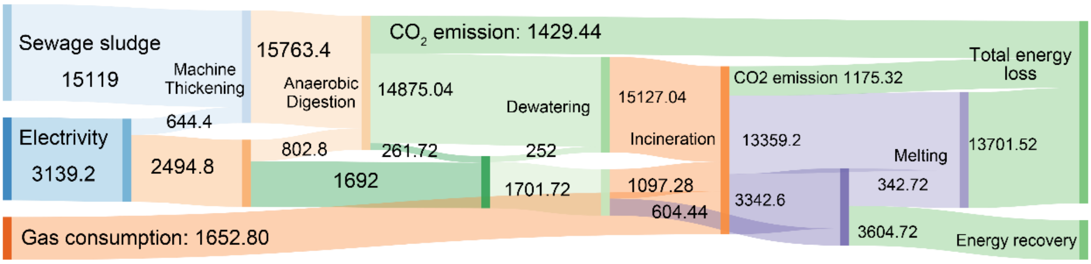
(b) Scenario TC



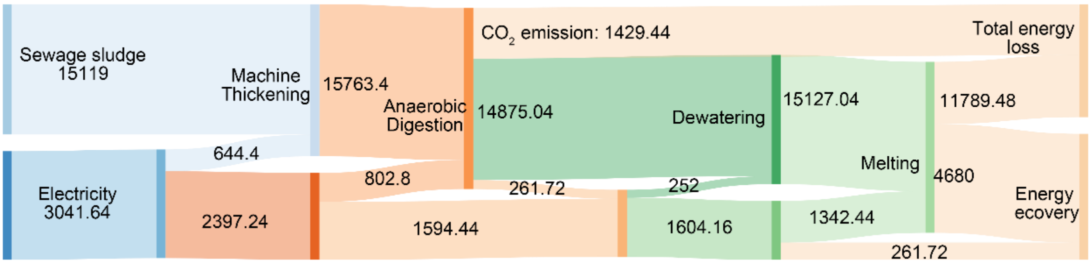
(c) Scenario TD



(d) Scenario TI



(e) Scenario TIM



(f) Scenario TM

Figure 5 Energy flows for the six alternatives. Data were presented by MJ per functional unit.

Energy contribution of each procedure for the selected technologies was shown in Table 2. Except the energy from sludge, electricity and heat consumption in drying are also considerable with over 25% contribution. Energy consumed in incineration for Scenario TI and TIM share the similar proportion for around 14%. Energy recovery from the former three alternatives is almost negligible (less than 2%) compared with the total energy consumed. Although energy recovery from Scenario T and TIM are the same value, total energy loss in the latter one is a bit higher than that of the former one due to the adding process of melting. Melting process does not increase the energy recovery amount but may improve the extent of sludge treatment. Compared with Scenario TI and TIM, the total amount of energy recovery from Scenario TM increases with a certain degree, which can cancel the entire energy consumed for over 25%. It indicates the obvious advantages of energy recovery of the gasification and melting technology.

Table 2 Contribution ratio of energy inputs from each process

	T (%)	TC (%)	TD (%)	TI (%)	TIM (%)	TM (%)
Energy input						
Machine thickening	3.83	3.77	2.80	3.29	3.24	3.55
AD	4.77	4.70	3.49	4.10	4.03	4.42
Dewatering	1.50	1.48	1.10	1.29	1.27	1.39
Composting		1.48				
Drying			26.89			
Incineration				14.05	13.81	
Melting					1.72	
Gasification and melting						7.39
Sewage sludge	89.90	88.57	66.73	77.26	75.93	83.25
Energy recovery	1.56	1.53	1.14	18.42	18.10	27.21

3.2 Carbon emissions analysis

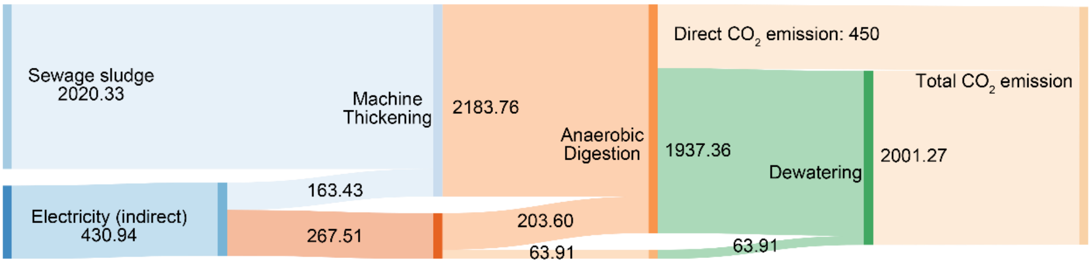
Major data about carbon flows analysis were listed in Table 3 and corresponding carbon flows for each scenario are described in Figure 6. The highest total amount of carbon emissions belongs to Scenario TD with 3138.53 kg/t-DS, closely followed by TIM and TI, then the Scenario TM. Scenario TM and TIM own the same amount of direct CO_2 emissions because of the shared processes of AD and incineration, but the total input of Scenario TIM is higher than that of TI, which means that the left amount of carbon is discharged in other forms. Scenario T and TC own relatively less amount of CO_2 input, but the entire treatment for sewage sludge is inadequate because not only the valuable matters are not recycled but also the harmful substances are not completely disposed during the process. Although drying may promote the complete treatment of sewage sludge, energy recovery is not included throughout the whole process leading to the lack of commercial competitiveness.

Table 3 Data of carbon flows analysis for each alternative

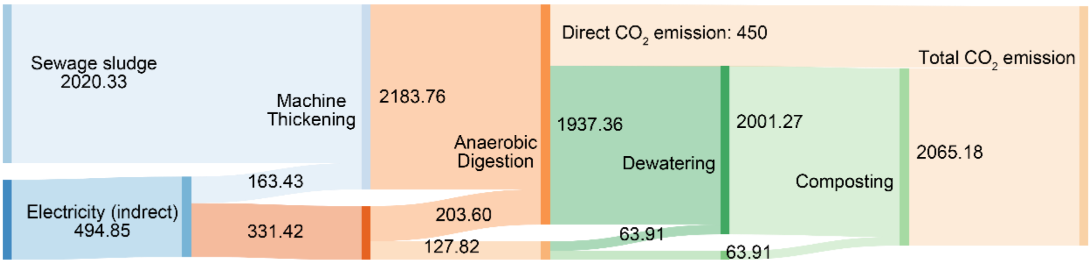
	T	TC	TD	TI	TIM	TM
Carbon input						
Electricity (indirect)	430.94	494.85	538.67	709.22	796.14	771.39
Heat (indirect)			579.52			
Natural gas (indirect/direct)				2.15/150.74	2.15/150.74	
Sewage sludge[a]	2020.33	2020.33	2020.33	2020.33	2020.33	2020.33
Total CO_2 input	2451.27	2515.18	3138.53	2882.44	2969.36	2791.73
Direct CO_2 emission	450	450	450	820	820	450

Unit: kg/t-DS

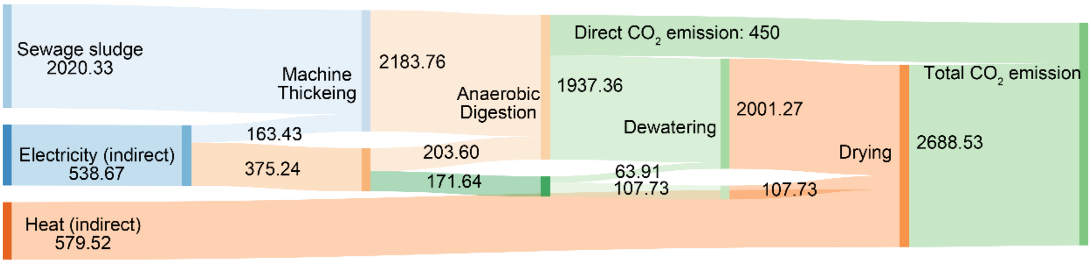
a: The amount of carbon dioxide carried by sewage sludge was estimated according to the C content of 55.1 wt.% (Cooper et al., 1999) based on the assumption of full combustion.



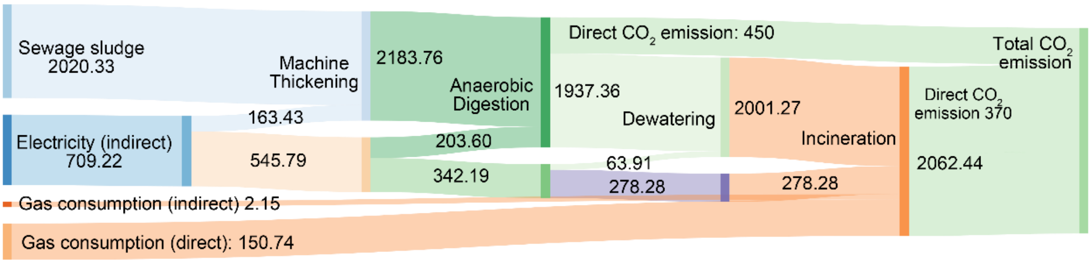
(a) Scenario T



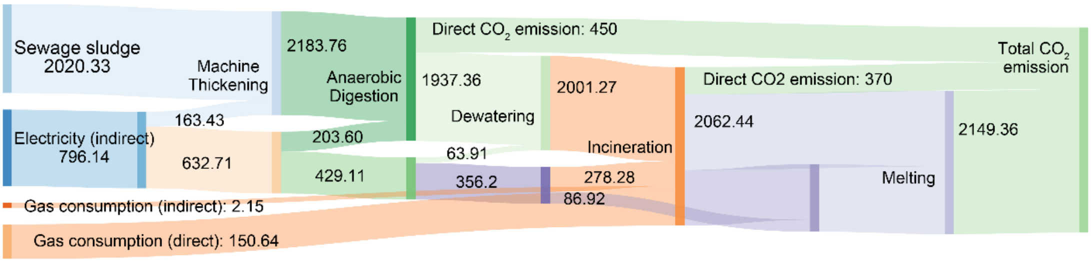
(b) Scenario TC



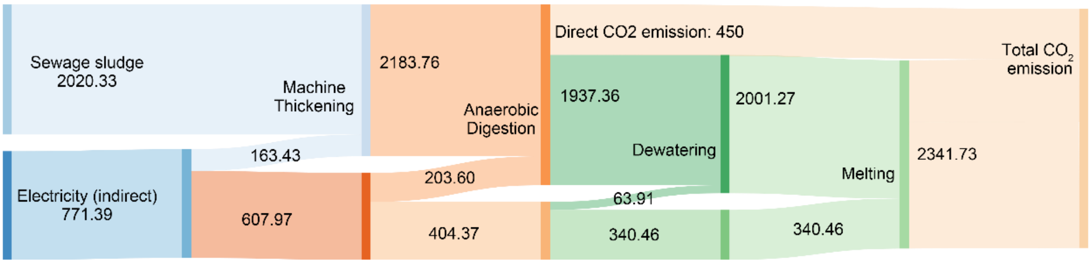
(c) Scenario TD



(d) Scenario TI



(e) Scenario TIM



(f) Scenario TM

Figure 6 Carbon flows for the selected alternatives. Data were presented by kg per functional unit.

Contribution of each life stage for CO_2 emissions of the selected options is shown in Table 4. Sludge is still the major source of carbon emissions. The carbon input for drying from heating and electricity is also significant which contributes about 20% of the total emission in Scenario TD. Direct CO_2 emissions from Scenario TI and Scenario TIM are obvious, both occupying around 30%. Similar to the situation of energy flows, the carbon emission contribution of Scenario TI and TIM are almost the same, except the part of input electricity for melting. Carbon emissions from both AD and machine thickening are in charge of about 7% for the first two alternatives while the percentages of these two processes are a bit less than 7% for other four options. In addition, the part of gasification and melting contributes over 10% for Scenario TM. Direct carbon emissions majorly come from AD and the incineration of sludge, which take up ranging from about 15% to 30%, where the highest ratios belong to the Scenario TI and TIM. Results also show that the process with energy recovery usually accompanied by a certain amount of carbon input.

Table 4 Contribution ratio of carbon inputs from each process

	T (%)	TC (%)	TD (%)	TI (%)	TIM (%)	TM (%)
Carbon input						
Machine thickening	6.67	6.50	5.16	5.62	5.45	5.80
AD	8.31	8.09	7.28	7.93	7.70	8.18
Dewatering	2.61	2.54	2.02	2.20	2.13	2.27
Composting		2.54				
Drying			21.71			
Incineration				14.82	14.39	
Melting					2.90	
Gasification and melting						12.08
Sewage sludge	82.42	80.33	63.82	69.44	67.43	71.68
Direct CO_2 emissions	18.36	17.89	14.22	28.18	27.37	15.96

3.3 Water consumption analysis

Major results for water flows analysis of each scenario were collected in Table 5 and the corresponding diagrams of water flow for the analyzed options were shown in Figure 7. Moisture content in sewage sludge is still the most important source of water input for the entire system. Although the data of total water loss listed in Table 5 are not as considerable comparing with the amount of total water input, it is still worthy to discuss due to the daily large amount of sewage sludge treatment and the unsatisfactory water recycled in the practice.

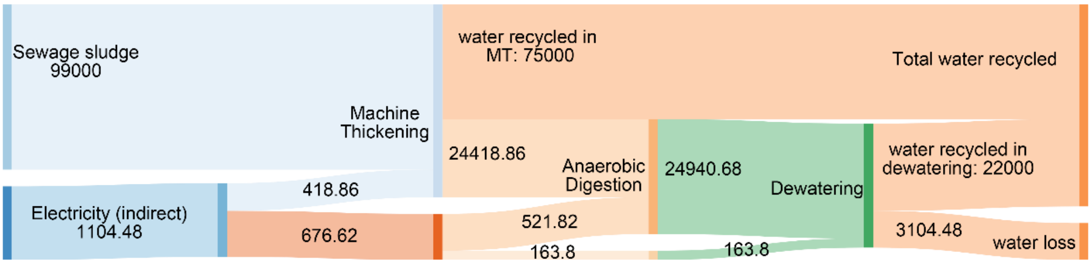
All the alternatives share the same quantity of recycled water because all the treatment process have the common steps for water recycling, that is machine thickening and dewatering. Meanwhile, the water content in injected sludge is also the same for all the options. Hence, the slight differences in total water loss were resulted from the different method applied for sludge treatment and energy recovery. The least water loss belongs to Scenario T with the least number of disposal steps. As the amount of thermochemical treatment steps increases, the total water loss also rises, where the Scenario TIM owns the highest value, closely followed by Scenario TM, then the Scenario TI. Apart from the input from sludge, water indirectly coming from electricity generation is also significant while the part of natural gas is negligible.

Table 5 Data of water flows analysis for each alternative

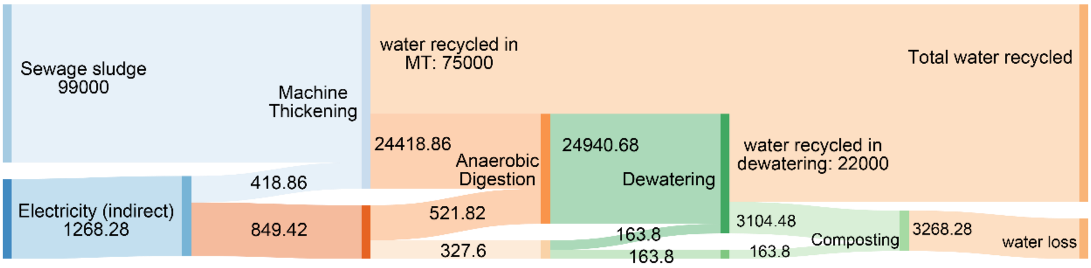
	T	TC	TD	TI	TIM	TM
Water input						
Electricity (indirect)	1104.48	1268.28	1380.60	1817.712	2040.48	1977.07
Heat (indirect)			177.74			
Natural gas (indirect/direct)				14.88/29.67	14.88/29.67	
Sewage sludge (direct)[a]	99000	99000	99000	99000	99000	99000
Total water input	100104.48	100268.28	100558.34	100862.26	101085.03	100977.07
Water recycled from thickening and dewatering	97000	97000	97000	97000	97000	97000
Total water loss	3104.48	3268.28	3558.34	3862.26	4085.03	3977.07

Unit: kg/t-DS

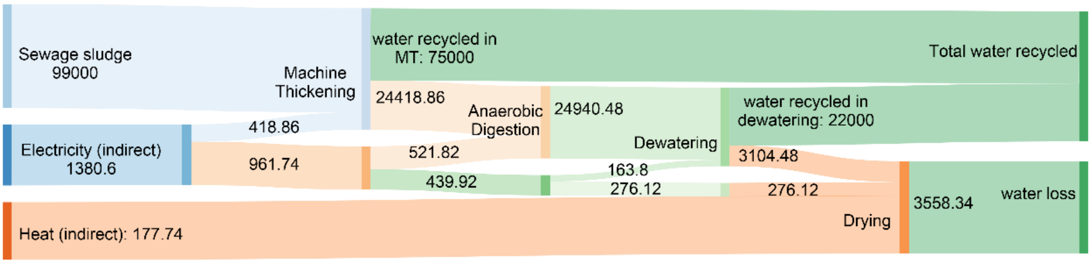
a: Water brought by sewage sludge was calculated by the data in Table S.1 (in Supplementary Information). Since the water content is 99 wt%, to obtain 1 t of dry solids needs to treat 100 t sewage sludge.



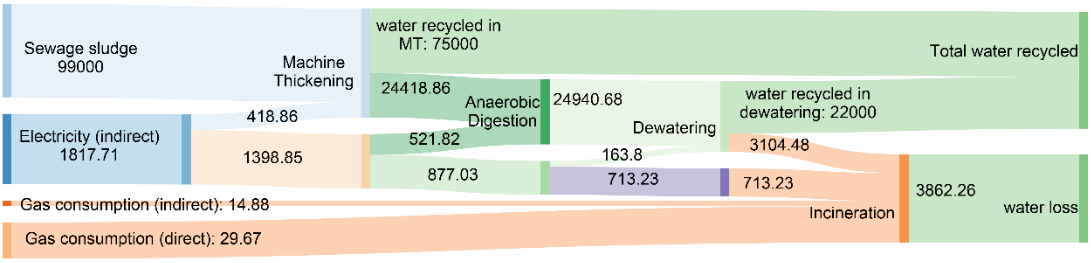
(a) Scenario T



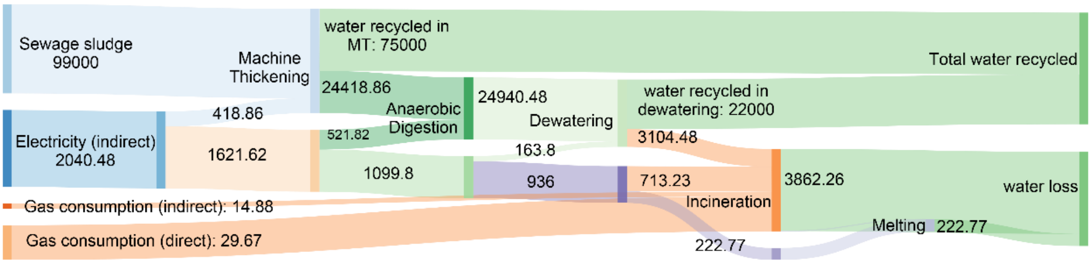
(b) Scenario TC



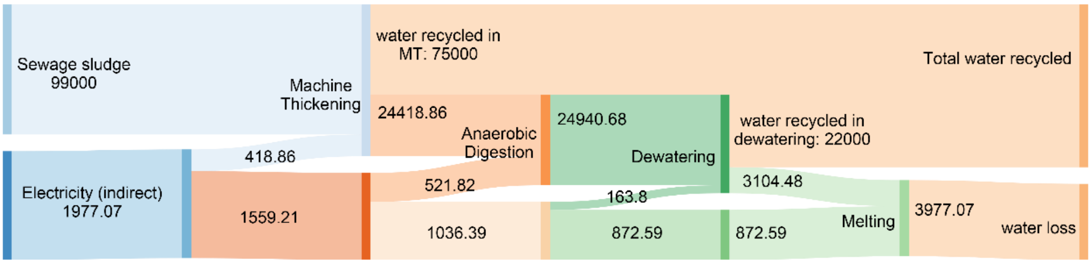
(c) Scenario TD



(d) Scenario TI



(e) Scenario TIM



(f) Scenario TM

Figure 7 Water flows for the selected alternatives. Data were presented by kg per functional unit.

Detailed data of the contribution ratio of each process was provided in Table 6. For all the alternatives, the sum of water input proportion from the operation processes (excluding the part from sludge) is less than 3%. Meanwhile, the contribution rates from the operation process almost remain the same among all the alternatives. The ratios actually change, but the variations are too tiny relative to the whole system which causes them can be ignored. The percentages of total water loss for each alternative keep the same ranking with that of water loss because of the nearly same amount of total water consumption. The amount of water loss in the Scenario TI, TIM and TM, are similar and much higher than that of Scenario TD considering the quantity. There also exists more water loss in Scenario TD compared with T and TC due to the process of drying.

Table 6 Contribution ratio of water inputs from each process

	T (%)	TC (%)	TD (%)	TI (%)	TIM (%)	TM (%)
Water input						
Machine thickening	0.42	0.42	0.42	0.42	0.41	0.41
AD	0.52	0.52	0.52	0.52	0.52	0.52
Dewatering	0.16	0.16	0.16	0.16	0.16	0.16
Composting		0.16				
Drying			0.45			
Incineration				0.75	0.75	
Melting					0.22	
Gasification and melting						0.86
Sewage sludge	98.90	98.74	98.45	98.15	97.94	98.04
Total water loss	3.10	3.26	3.54	3.83	4.04	3.94
Total water recycled	96.90	96.74	96.46	96.17	95.96	96.06

3.4 Aggregated energy-carbon-water index for sustainability evaluation

A combined evaluation can be obtained by scoring the option from 1 to 6 and 6 is the optimal case among all the options based on the above analysis, which were shown in Table 7.

Table 7 Performances on energy recovery, carbon emissions, and water loss and combined ranking of the selected scenarios

	Unit	T	TC	TD	TI	TIM	TM
Energy							
Energy recovery rate	%	1.56	1.53	1.14	18.42	18.10	27.21
Ranking	-	3	2	1	5	4	6
Carbon emissions							
Total carbon emissions	kg-CO_2 eq	2451.27	2515.18	3165.52	2909.44	2996.36	2818.73
Ranking	-	6	5	1	3	2	4
Water consumption							
Water loss rate	%	3.10	3.26	3.54	3.83	4.04	3.94
Ranking	-	6	5	4	3	1	2

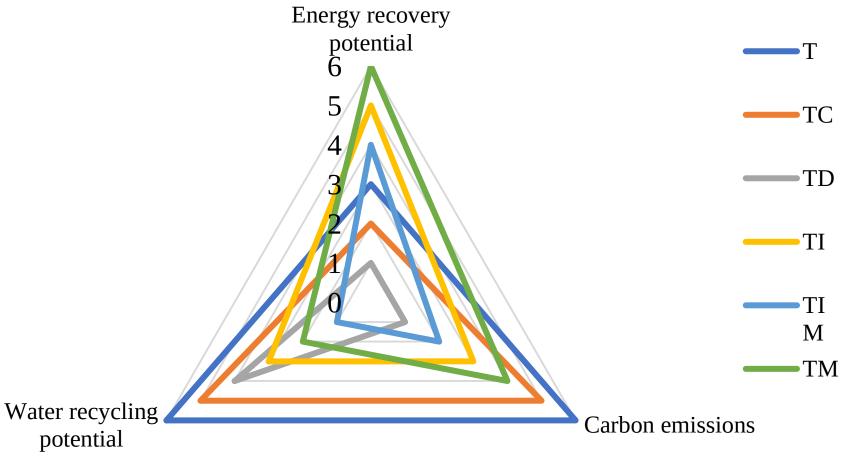


Figure 8 Radar map for the performances of the six scenarios on three dimensions

Data in Table 7 reflected that the former three scenarios show more advantages on carbon emissions and water consumptions and the latter three options perform well in energy recovery, which can be directly described by a radar map (Figure 8). The values in Figure 8 correspond to the ranking results in Table 7. The features of different technologies are more intuitive in Figure 8. Scenario T and TC perform more prominently on the carbon emissions and water consumption aspects, while alternative TI, TIM and TM show more superiority on energy recovery and lack of competitiveness on the other two perspectives. As for Scenario TD, it performs badly especially on the energy recycling and carbon emissions. Figure 8 also clearly indicates the future improvement direction for the sludge treatment technologies combined with energy recovery, which was discussed in detail in Section 4.

Fuzzy BWM and fuzzy AHP were applied to obtain the overall scores for the performance evaluation of these six alternatives. Table 8 collected the normalization results based on the above analysis. It provides more precise information on the merits and shortcomings of each energy recovery technology. According to Eq. (6) and Eq. (7), the alternative shows more superiority on the specific aspect if the value is closer to 1. Thus, Scenario T has the best performance on carbon emissions and water consumptions, although the energy recovery is poor. Scenario TC has similar performances with Scenario T on the three aspects. Alternative TD performs badly on both energy recovery and carbon emissions. Scenario TI, TIM and TM have remarkable outcomes on energy recovery, but all of them present disadvantage on carbon emissions and water consumptions, especially the Scenario TIM with the worst case on water consumptions.

Table 8 The scenarios' performances on the three aspects

	T	TC	TD	TI	TIM	TM
$\frac{e_i - e_{\min}}{e_{\max} - e_{\min}}$	0.0161	0.0150	0	0.6628	0.6506	1
$\frac{c_{\max} - c_i}{c_{\max} - c_{\min}}$	1	0.9105	0	0.3585	0.2368	0.4855
$\frac{w_{\max} - w_i}{w_{\max} - w_{\min}}$	1	0.8330	0.5371	0.2272	0	0.1101

3.4.1 Aggregated results by fuzzy BWM

According to the fuzzy BWM (Guo and Zhao, 2017), the weights of energy recovery, carbon emissions and water consumptions were calculated to assess the combined performances of the six scenarios (Step 1 in Figure 2). In this study, energy recovery is the major focus. Therefore, the criterion energy recovery is selected to be the best criterion. Since the total amount of recycled water are the same for the six scenarios, water consumption is chosen to be the worst criterion (Step 2). The fuzzy reference comparison of the best criterion to the other criteria and the other criteria to the worst criterion were listed in Table S.3 and Table S.4. Then the corresponding fuzzy best-to-others vector and others-to-worst vector can be expressed as Eq. (9) (Step 3) and Eq. (10) (Step 4).

$$\tilde{A}_B = [(1,1,1), (3/2,2,5/2), (5/2,3,7/2)] \tag{9}$$

$$\tilde{A}_W = [(5/2,3,7/2), (2/3,1,3/2), (1,1,1)]^T \tag{10}$$

The nonlinearly constrained optimization problem can be built according to the method (Guo and Zhao, 2017) and above analysis, which was shown by Eq. (11).

$$\min \ \tilde{\xi}^*$$
$$s.t. \begin{cases} \left| \dfrac{(l_1^w, m_1^w, u_1^w)}{(l_1^w, m_1^w, u_1^w)} - (l_{11}, m_{11}, u_{11}) \right| \le (k^*, k^*, k^*) \\ \left| \dfrac{(l_1^w, m_1^w, u_1^w)}{(l_2^w, m_2^w, u_2^w)} - (l_{12}, m_{12}, u_{12}) \right| \le (k^*, k^*, k^*) \\ \left| \dfrac{(l_1^w, m_1^w, u_1^w)}{(l_3^w, m_3^w, u_3^w)} - (l_{13}, m_{13}, u_{13}) \right| \le (k^*, k^*, k^*) \\ \left| \dfrac{(l_1^w, m_1^w, u_1^w)}{(l_3^w, m_3^w, u_3^w)} - (l_{13}, m_{13}, u_{13}) \right| \le (k^*, k^*, k^*) \\ \left| \dfrac{(l_2^w, m_2^w, u_2^w)}{(l_3^w, m_3^w, u_3^w)} - (l_{23}, m_{23}, u_{23}) \right| \le (k^*, k^*, k^*) \\ \left| \dfrac{(l_3^w, m_3^w, u_3^w)}{(l_3^w, m_3^w, u_3^w)} - (l_{33}, m_{33}, u_{33}) \right| \le (k^*, k^*, k^*) \\ \sum_{j=1}^{3} R(\tilde{w}_j) = 1 \\ l_j^w \le m_j^w \le u_j^w, \ j = 1,2,3 \\ l_j^w \ge 0, \ j = 1,2,3 \end{cases} \tag{11}$$

The optimization problem can be rewritten as Eq. (12) by substituting the concrete numbers.

$$\min \quad k^*$$
$$s.t. \begin{cases} l_1 - 1.5u_2 \le ku_2; l_1 - 1.5u_2 \ge -ku_2; \\ m_1 - 2m_2 \le km_2; m_1 - 2m_2 \ge -km_2; \\ u_1 - 2.5l_2 \le kl_2; u_1 - 2.5l_2 \ge -kl_2; \\ l_1 - 2.5u_3 \le ku_3; l_1 - 2.5u_3 \ge -ku_3; \\ m_1 - 3m_3 \le km_3; m_1 - 3m_3 \ge -km_3; \\ u_1 - 3.5l_3 \le kl_3; u_1 - 3.5l_3 \ge -kl_3; \\ l_2 - 1.5u_3 \le ku_3; l_2 - 1.5u_3 \ge -ku_3; \\ m_2 - m_3 \le km_3; m_1 - m_3 \ge -km_3; \\ u_2 - 0.67l_3 \le kl_3; u_2 - 0.67l_3 \ge -kl_3; \\ \frac{1}{6}l_1 + \frac{2}{3}m_1 + \frac{1}{6}u_1 + \frac{1}{6}l_2 + \frac{2}{3}m_2 + \frac{1}{6}u_2 + \frac{1}{6}l_3 + \frac{2}{3}m_3 + \frac{1}{6}u_3 = 1; \\ l_1 \le m_1 \le u_1; \\ l_2 \le m_2 \le u_2; \\ l_3 \le m_3 \le u_3; \\ l_1 \ge 0; l_2 \ge 0; l_3 \ge 0; \\ k \ge 0 \end{cases} \tag{12}$$

The label *j* (*j*=1,2,3) represents the criteria energy recovery, carbon emissions, and water consumptions, respectively. The fuzzy weight for each criterion can be obtained by solving the optimization problem (12). The solutions were listed in Table 9.

Table 9 The optimal fuzzy weights for the three criteria

Variable	Value
$\tilde{\xi}$	(0.4168,0.4168,0.4168)
$\tilde{\omega}_e$ a	(0.4420,0.5573,0.6726)
$\tilde{\omega}_c$ b	(0.2306,0.2306,0.2306)

$\tilde{\omega}_w$ c	(0.2122,0.2122,0.2122)

a: fuzzy weights of energy recovery;
b: fuzzy weights of carbon emissions;
c: fuzzy weights of water consumptions.

Then the crisp weight of each aspect can be corresponding calculated which were shown as

$$\omega_e = 0.5573, \omega_c = 0.2306, \omega_w = 0.2122.$$

The value of objective function *k* is 0.4168. The consistency index for this situation is 6.64. Hence the consistency ratio is 0.4168/6.64=0.0628, which is close to zero leading to the high reliability of this result. By using the obtained weights, the total scores for each scenario were obtained, which were listed in Table 10.

Table 10 Combined scores of the six scenarios obtained by fuzzy BWM

Scenario	T	TC	TD	TI	TIM	TM
Combined score	0.4517	0.3950	0.1140	0.5002	0.4171	0.6926

3.4.2 Aggregated results by fuzzy AHP

Fuzzy AHP (Hsieh et al., 2004; Sun, 2010) was also applied to calculate the weights of three footprint indices (Step 1 in Figure 3). The fuzzy pairwise comparisons between the three criteria were conducted according to the opinions collected from stakeholders, which are shown in Table 11 (Step 2). Then, according to the calculation principles in the research of Hsieh et al. (2004) and Sun (2010), the fuzzy value of $\tilde{r}_i$ and $\tilde{\omega}_i$ for each indicator can be obtained as follows:

$$\tilde{r}_1 = (1.5536, 1.8171, 2.0606),$$
$$\tilde{r}_2 = (0.6437, 0.7937, 1),$$
$$\tilde{r}_3 = (0.5754, 0.6934, 0.8434),$$

$$\tilde{\omega}_1 = (0.3979, 0.5499, 0.7432),$$
$$\tilde{\omega}_2 = (0.1649, 0.2402, 0.3607),$$
$$\tilde{\omega}_3 = (0.1474, 0.2098, 0.3042).$$

According to the calculation results above and the defuzzification step, corresponding weight of each index can be computed.

$$\omega'_e = 0.5637, \omega'_c = 0.2552, \omega'_w = 0.2205$$

By normalization, the final weights for the performance criteria can be calculated, which are shown as follows

$$\omega_e = 0.5423, \omega_c = 0.2456, \omega_w = 0.2121.$$

Table 11 The fuzzy pairwise comparison matrix of the selected criteria

	C1	C2	C3
C1	(1,1,1)	(3/2,2,5/2)	(5/2,3,7/2)
C2	(2/5,1/2,2/3)	(1,1,1)	(2/3,1,3/2)
C3	(2/7,1/3,2/5)	(2/3,1,3/2)	(1,1,1)

By using the obtained weights, the total scores for each scenario were calculated, which were listed in Table 12.

Table 12 Combined scores of the six scenarios obtained by fuzzy AHP

Scenario	T	TC	TD	TI	TIM	TM
Combined score	0.4664	0.4084	0.1139	0.4957	0.4110	0.6849

3.4.2 Aggregated results analysis

According to the aggregated results obtained from fuzzy BWM and fuzzy AHP, both methods indicated the same ranking order of the six scenarios: TM>TI>T>TIM>TC>TD. Scenario TM performs the best which is credited by the large amount of energy generation from gasification and melting process. Scenario TI also has impressive performance with a total score around 0.5. Although Scenario TI and TIM share the same amount of energy recovery, the aggregated performance of Scenario TIM is inferior to that of Scenario TI because of the extra energy consumptions, more carbon emissions and worse water consumptions. On the contrary, Scenario T is not remarkable on the energy recovery, but the advantages on the other two aspects leading to a better score than Scenario TIM. Scenario TD has the lowest score which is resulted from the unsatisfactory performances on all of the aspects, especially the former two. From the analysis above, it is found that scenarios with large amount of energy recovery are usually accompanied by considerable quantity of carbon emissions and water consumptions. These two drawbacks may influence the further promotion of sludge-to-energy technologies if there is no effective measure to ease or solve the problems.

In actual production practice, different weights may be assigned to the three aspects due to the different preference of stakeholders, which can directly influence the decision-making results. Therefore, different groups of weights were set to find out the specific impact on the assessment results.

3.5 Sensitivity analysis

Three groups of weights distribution were designed to investigate the changes in assessment results, called Group A, B, and C. Each group has eight weighting assignment alternatives. The detailed values were provided in Table S.5 – Table S.7 (in Supplementary information). For each group of weights assignment, the weight for the specific aspect gradually increases, while the weights for the other two aspects were set to be equal to see the influence of weights changing on the specific aspect.

3.5.1 Weight variation analysis for energy recovery

According to the results in Table 8 and Eq. (8), combined assessment scores for each scenario with the assigned weights distribution in Table S.5 were obtained and described by Figure 9. The scores of Scenario TI, TIM and TM present an increasing trend as the weight of energy recovery rises. On the whole, the performance of Scenario TM is better than TI and TIM because the entire line of TM is above the other two lines. On the other hand, the grades of Scenario T, TC and TD tend to decrease as the emphasis on energy recovery rises, while the former two have remarkable reduction and the latter one has a slight decline. The score of Scenario T and TM are close to each other. When the weight on energy recovery is larger than 0.4, Scenario TM shows more superiority on the assessment. Alternative TI and TIM also exhibit advantages over Scenario T when the weight of energy recovery is larger than 0.6. Scenario TD is the least preferred one almost all the time because of the bad performance on the three aspects.

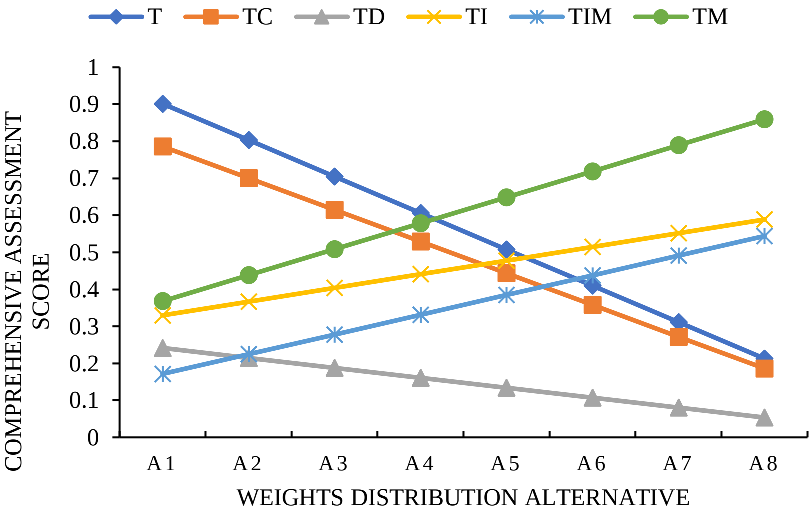


Figure 9 Combined scores for the six alternatives with the increasing weights of energy recovery

3.5.2 Weight variation analysis for carbon emissions

Combined scores for the six alternatives with the assigned weights distribution in Table S.6 can be calculated and the results are plotted in Figure 10. When the weights of carbon emissions are emphasized, the scores of Scenario T and TC have obvious increase while the grades of the other four options all decrease. Among the cases with declining scores, Scenario TD shows a more obvious downward trend and the scores of the other three alternatives keep relatively flat decline, with the scenario TM at around 0.5, TI at around 0.4, and TIM at about 0.3. It indicates that the weights on carbon emissions cannot put much influence on the scores of the scenarios with large amount of energy recovery due to their relatively average performances on carbon emissions compared with the other two aspects (see Table 8). As for the Scenario T and TC, increasing weights of carbon emissions can make these two scenarios more preferred. When the weight is set to be 0.8, the score of Scenario T is even over 0.9 which occupies the absolute advantage among the six options, closely followed by the Scenario TC with the highest score of about 0.8. Still, Scenario TD is the worst method with the lowest score of 0.05 when the weight of carbon emissions is set to be 0.8.

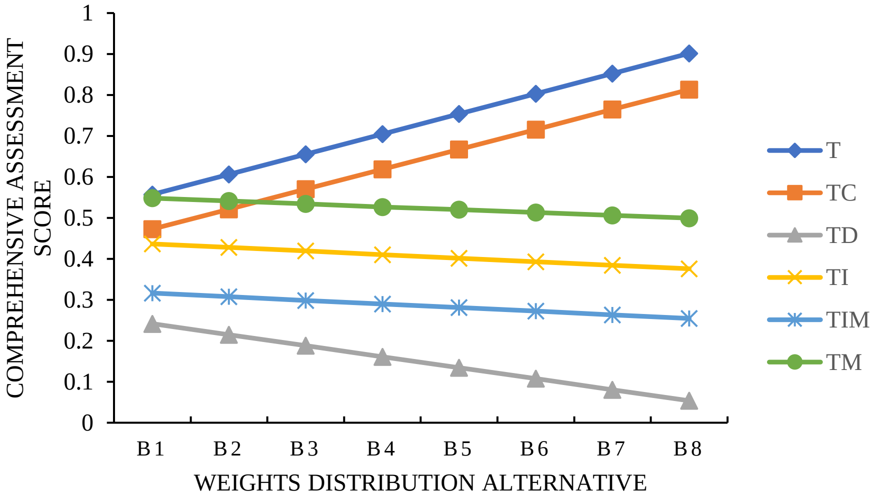


Figure 10 Combined scores for the six alternatives with the increasing weights of carbon emissions

3.5.3 Weight variation analysis for water consumptions

Using the similar calculation method, the assessment results with the assigned weights distribution in Table S.7 can be obtained and illustrated in Figure 11. According to Figure 11, the grades of Scenario T, TC and TD tend to increase, especially that of Scenario TD which significantly increases from 0.05 to above 0.4 as the weight of water consumptions rises. On the contrary, dramatical decline happens to the scores of Scenario TM, TI and TIM, where the most significant change occurs in the line of

Scenario TM decreasing from about 0.7 to 0.2. When the weight of water consumptions is larger than 0.7, alternative TI would have a better performance than alternative TM. Although Scenario TD performs badly under the weight assignment of Group A and Group B, the performance of Scenario TD is better than that of Scenario TIM when the weight of water consumptions is larger than 0.5 and can further exceeds Scenario TI and TM if the weight is or above 0.7. Considering the results in Table 8, the score of Scenario TD on water consumption is the only non-zero value among the three aspects for TD. As for the Scenario T and TC, their advantages are obvious in terms of carbon emissions and water consumptions based on above discussion. Thus, emphasizing the importance of saving water can improve the preference of Scenario T, TC, and TD.

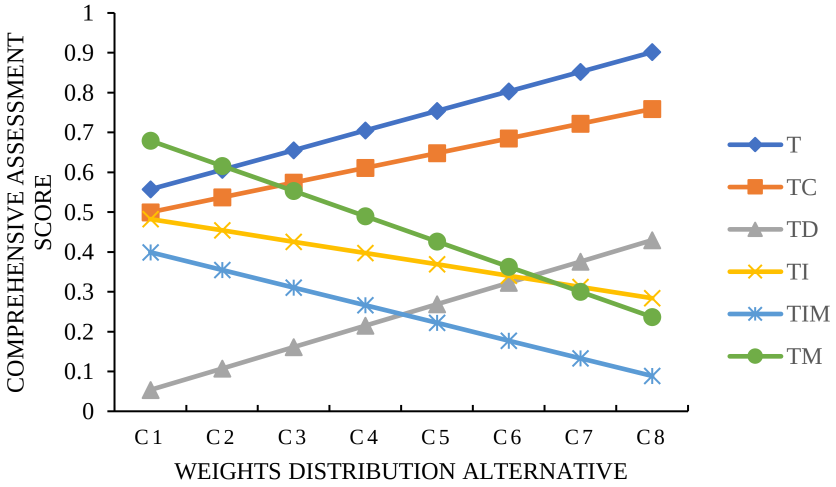


Figure 11 Combined scores for the six alternatives with the increasing weights of water consumptions

3.6 Uncertainty analysis

Several assumptions were specifically made in the case study to analyze the energy and materials flows, including the energy recovery among from different technologies (mainly refer to anaerobic digestion and incineration or melting in this study), the LHV of sewage sludge, and the carbon content in sewage sludge. These parameters may have significant influence on the evaluation results of the sludge-to-energy alternatives. Therefore, uncertainty analysis was conducted to analyze the influence of the variation of the parameters from the perspective of energy recovery amount in AD, LHV of sewage sludge, and the C content in sewage sludge.

3.6.1 Analysis of the variation on the energy regeneration from anaerobic digestion

The energy regeneration amount from AD usually varies with plenty of indicators, such as the investigated regions, the treated sewage sludge, and operating conditions, which leads to a wide variation of energy recovery amount from anaerobic digestion. In the case study, the electricity recovery from AD was only 261.72MJ/t-DS (Hong et al., 2009), while the value in another research was recorded as 2215.37MJ/t-DS (Xu et al., 2014), which indicates the large distinction between the related data in different research. Therefore, the energy recovery amount from AD was set to belong to the interval [196.29, 2159.19] to investigate the influence of the variation of this parameter, where 196.29 is the three quarters of the data applied in original case study (261.72), and 2149.19 is 4.5 times of the same data. Corresponding result was calculated and analyzed every 0.25 increase of the coefficient, that is, the situation when energy recovery amount was 0.75, 1, 1.25, …, .4, 4.25, 4.5 times of the original data, respectively. The energy recovery efficiency of each situation was shown in Table S.8 in Supplementary Information.

According to the data in Table S.8, the energy recovery efficiency of all the scenarios increased with the rise of coefficient, while the influence on the efficiency of difference alternatives were different. The increase of energy recovery efficiency on Scenario T, TC, TD kept consistent with the rise of coefficient. When the coefficient was set to be 0.75 of the initial data, the energy recovery efficiency of T, TC, and TD decreased by one quarter. When the coefficient was set to be 4.5, the energy recovery rate of these three alternatives increased by 3.5 times of the original data. This is because anaerobic digestion is the only process for energy recovery in the three alternatives. Therefore, the variation of energy recovery amount in AD was fully reflected in the final energy recovery efficiency of the three options. On the other hand, energy recovery efficiency of Scenario TI, TIM and TM was insensitive to the variation of energy recovery amount from AD. The changing of energy recovery efficiency on Scenario TI and TIM kept the same, both within the range of [-1.82%, 25.41%] since the energy recovery sources of these two alternatives were the same. The energy recovery rate of Scenario TM was even more insensitive than TI and TIM, whose changing was only within the range of [-1.32%, 18.54%]. This is because the energy recovered from AD was only a small part in the entire treatment process of Scenario TI, TIM and TM, but the improvement on energy recovery amount in AD can still contribute to the total recycling process.

The variation of the score on energy recovery for the six alternatives was also analyzed, which was shown in Table S.9. According to the analysis results, the changing on energy recovery among from AD put no influence on the final score on energy recovery aspect for Scenario TD and TM, both still in the last and first place, respectively. The scores of Scenario T and TC showed an increase trend with the rise of coefficient, while the scores of TI and TIM presented a slight downward trend. Similar with the variation trends presented by energy recovery efficiency of the alternatives, the changing of coefficient had considerable impact on the final energy recovery scores of Scenario T and TC, which kept the same variation percentage within the range of [-24.18%, 332.39%]. On the contrary, the scores of TI and TIM almost unaffected by the changing of coefficient, especially for Scenario TI, which at most decreased by 0.03%. The score variation range of TIM was a bit wider than that of TI within the interval of [-0.41%, 0.03%].

3.6.2 Analysis of the variation on the LHV of sewage sludge toward the assessment

The LHV of sewage sludge is influenced by many factors, such as the type, source, and treatment state of sewage sludge. According to the literature review (Fytili and Zabaniotou, 2008; Manara and Zabaniotou, 2012), the LHV of different types of sewage sludge can vary from 12000 MJ/t-DS to 29000 MJ/t-DS. Therefore, the uncertainty analysis for the variation of LHV of sewage sludge was conducted through setting the LHV within the range of [12095.2, 18142.8] (MJ/t-DS), which was 0.8 and

1.2 times of original data as the lower and upper bound, respectively. Corresponding result was calculated and analyzed every 0.05 increase of the coefficient, that is, the situation when energy recovery amount was 0.80, 0.85, 0.9, …, .1.1, 1.15, 1.2 times of the original data, respectively. The energy recovery efficiency of each situation and relevant variation between the initial results were shown in Table S.10.

According to the analysis results in Table S.10, the energy efficiencies of all the alternatives decreased as the LHV of sewage sludge increased. The energy recovery efficiency variation of T and TC were similar, both within the range around [-15%, 22%] as the LHV decreased. The changing trends of TI, TIM and TM were similar, which all increased by around 18% when LHV was four fifths and declined by about 13% when LHV was 1.2 times of initial data. The influence of changing LHV of sewage sludge was not as significant as that of changing energy recovery amount from AD on the final energy efficiency for the assessed alternatives. However, all the options were influenced by the LHV variation obviously, the variation of energy recovery efficiency ranging from approximately 10% to 20% in absolute value. The influence on the score of energy recovery under different assumption for LHV of sludge was also investigated and were shown in Table S.11.

The energy recovery performances of TD and TM always remained in the same ranking as where they were in the case study. Although the energy recovery efficiency showed a decrease trend with the rise of LHV in all the alternatives, the scores of different scenarios presented different variation trends. The energy recovery scores of

Scenario T and TC gradually fallen down by about 12% if the LHV of sludge was set to be 1.2 times of initial data. On the contrary, the scores of TI and TIM showed a slight upward trend. This may be resulted from the difference in energy recovery source. Since anaerobic digestion is the only source of energy recovery in Scenario T, TC, and TD, they were significantly influenced by the energy input to the total system and the output from anaerobic digestion. On the other hand, the energy efficiencies of Scenario TI, TIM and TM remain relatively stable under different situation because the energy recovery from thermochemical process (e.g. incineration and melting) contributed a main part in the total process.

3.6.3 Analysis of the variation on the carbon content in sewage sludge

Carbon content is also an important property of sewage sludge, which is associated with many factors. In the case study, the carbon content was assumed to be 55.1 wt% (Cooper et al., 1999). While the carbon content was measured within the range of [23.52, 46.48] (wt%) in another report (Phyllis2Database, 2020). In this section, the carbon content in sewage sludge was assumed to be within the range of [20%, 55%] and corresponding result was calculated and analyzed every 2.5 wt% increase of the C content. The total carbon emissions under each situation and the comparison with original results were collected in Table S.12.

Based on the data results in Table S.12, the total carbon emissions in all the alternatives decreased as the C content in sewage sludge decreases. The difference between investigated point and the initial result in the case study was only associated with the difference between C content. Therefore, the variation in value under the same C content situation of all the alternatives was the same. Scenarios T and TC presented similar variation trends within the range around [-52%, -0.15%] as the C content increased. The later three options showed alike tendency within the variation range about [-44%, -0.13%]. Scenario TD was less influenced by the changing of C content in sewage sludge compared to other alternatives, but still decreased by [-40.66%, -0.12%]. The score of carbon emissions under different C content situation was also analyzed and results revealed that the scores kept consistent with those in case study. This is because the normalization step canceled the influence caused by changing C content. Direct carbon emission rate under each situation was calculated and the corresponding difference with initial result in the case study was also obtained, which were shown in Table S.13.

The direction carbon emissions rate performed a significant decline trend as the C content in sewage sludge increased. Since the total amount of direct carbon emissions from the treatment process was assumed to be fixed, the improvement on C content of sewage sludge only contributed to the indirect forms of carbon emissions and the total amount of possible carbon emissions. This situation was particularly evident in the first two alternatives (T, TC) whose direct carbon emission rates could be around double when the C content was 20 wt%. The direct carbon emission rates of TI, TIM and TM could increase by about 75-85% at most. The rate of TD was relatively stable, and the increase was less than 70% when the C content was 20 wt%.

4 Discussion

4.1 Sensitivity analysis

The features of the six alternatives can be figured out according to the above analysis. Improving the weight of energy recovery efficiency can make the Scenario TI and TIM more preferred, closely followed by Scenario TIM. Variation on carbon emissions' weight has insignificant influence on the assessment results of Scenario TI, TIM and TM, which means that these scenarios show less competitiveness compared with Scenario T and TC when the importance of carbon emissions is emphasized. However, the weight of water consumptions has remarkable impact on the assessment results. Due to the extra input of energy and materials for sludge thermochemical process, water consumptions in the process of TI, TIM and TM are much more than that those of the other alternatives. Hence, these three scenarios present obvious interiority on the aspect of water loss. When stakeholders put emphasis on water consumptions, Scenario T and TC are more suitable for the sludge treatment; when the weight for energy recovery is higher, Scenario TI, TIM and TM are more in line with the decision-makers' expectations.

4.2 Uncertainty analysis

Based on the above analysis under different assumptions for energy recovery amount from AD, LHV, and C content in the sludge, more characteristics of the six investigated alternatives can be obtained. The major pointed can be summarized as follows.

Scenarios T, TC, and TD were easily influenced by the variation of the three parameters, especially the former two options. It can be evidently reflected by the results in Section 3.6.1 and Section 3.6.3. Scenario TD was also sensitive to the changing of energy recovery amount from AD, but it kept relatively stable in the analysis for the other two assumptions. This is because T and TC shared quite similar treatment route and the only difference was the added composting in TC, with relatively low additional energy and materials input. Drying in Scenario TD required plenty of extra energy and materials supply, which was regarded as the major energy consumption step in the technique route. Meanwhile, anaerobic digestion was the only source for energy recovery in the three alternatives, leading to the high sensitivity of T and TC on the energy recovery amount from AD and LHV of sewage sludge.

The variation trends of Scenarios TI, TIM and TM were similar, especially the first two alternatives, due to the alike treatment route and considerable amount of energy recovery from thermochemical process, i.e. incineration and melting. In total, the energy efficiencies and corresponding scores of these three alternatives were less influenced by the changing of energy recovery amount from AD and LHV of sewage sludge compared to the other three options, which is resulted from the considerable amount of energy regeneration from incineration or melting.

4.3 Implications

Corresponding suggestions can be put forward based on the features of these scenarios.

On the one hand, further developing current sludge treatment technologies in order to improve the energy recovery efficiency and reduce the investment is recommended. Since extra energy input is necessary and unavoidable for energy recovery process, which means that reducing the carbon emissions and water consumptions may not be feasible, it is essential to optimize the technology itself and make the sludge-to-energy technologies more attractive and competitive. Process design, facility design, and operating conditions improvement may all be the entry points for future optimization research aiming at improving energy recovery rates to balance the corresponding input. In addition, recycling and reusing the free water in sewage sludge is also important to reduce the water loss. On the other hand, it is suggested to detect the specific contents of the treated sludge to know the features before determining the treatment route as well as considering the local development status of different treatment technologies. According to the discussion on sensitivity analysis and uncertainty analysis, some important properties and parameters of treated sludge may have great influence on the treatment effectiveness. Hence, conducting an additional step for detection on the treated sludge in the region is suggested if it is possible. The determination of treatment technologies should also consider the diverse development status of sludge-to-energy technologies and features of different sources of sludge in different regions. The sludge in some regions may be more suitable for anaerobic digestion with a relatively mature technology to realize effective utilization. Some regions may be suitable to conduct incineration for more thorough treatment. It is acknowledged that incineration is the most thorough method for sludge treatment with considerable potential for energy recovery. Improving the energy recovery rates from incineration and anaerobic digestion as well as the energy exchange efficiency for utilization is also one of the directions for future research.

Apart from the efforts of research and industry, the government is also expected to make reasonable charge standards and provide incentive policy and sufficient financial support to guarantee the basic development of relevant research and encourage the industries to conduct sludge treatment with energy and resource recovery as thorough and complete as possible. A previous report recorded current situation on the related policy and measures on sludge manage in different cities in China (Asian Development Bank, 2012).

Therefore, it should be acknowledged that some energy recovery technologies are still not competitive enough compared with some basic treatment, especially when the advanced methods are limited by the technical maturity. Meanwhile, the advantages of applying sludge incineration mainly reflected by the contribution of reducing the environmental burden on some specific indicators, such as human and ecosystem toxicity, acidification and eutrophication, but the unsatisfactory energy recovery, possible air pollution, and external resource depletion may limit the wide application of incineration in developing countries (Lombardi et al., 2017). More efforts are still needed to figure out the potential of recycling energy and resources from digested sludge to decide whether it is necessary to conduct further treatment. This study also indicates that the assessment for sewage sludge treatment methods with energy recovery should be conducted in detail based on the specific conditions of the development of local technologies and legislation.

5 Conclusions

In this study, a life cycle composite footprints index was proposed and relevant assessment methodology framework was developed for sludge-to-energy technologies evaluation. Fuzzy BWM and fuzzy AHP were applied to obtain the weights of concerned aspects and overall scores of the composite footprint index. Life cycle composite energy-carbon-water index was applied to assess six scenarios for sewage sludge treatment combined with energy recovery, including dewatering, composting, drying, incineration, incinerated ash melting, gasification and melting. A gate-to-gate analysis was conducted to study the energy, carbon, and water flows for each alternative. Results showed that Scenario TM had a better performance, followed by Scenario TI and T, then the Scenario TIM and TC. Alternative TD took the last place with a total score of 0.1140. To analyze the influence of different weighting assignment on each aspect, sensitivity analysis was conducted which included three groups of weight distribution. Results showed that Scenario TM, TI and TIM were favored by the increasing weight of energy recovery. The weight of carbon emissions had no significant effect on the combined assessment of these three options while the scores of the other scenarios had obvious changes as the weight of carbon emissions rises. The scores of scenarios with large amount of energy exhibit a downward trend due to the undesirable performances on water consumptions. On the contrary, Scenario T, TC and TD all showed an increasing trend when the importance of water consumptions was emphasized. Uncertainty analysis was also carried out to examine the influence of assumptions on energy recovery amount from AD, LHV and C content in sewage sludge. Results revealed that the variation of the former two parameters have significant influence on Scenario T and TC. Other options were less affected than the first two alternatives, especially Scenario TD. Future research may also consider analyzing the compound effect of different parameter on the evaluation.

The study also found that the major barrier of current energy recovery technologies from sewage sludge is the low energy recovery rate, leading to the less advantage in balancing energy and materials input. The focus of future work should be improving the entire performance of sludge treatment technologies, especially the energy production yields. Water recycling during the process of mechanical dewatering is also critical because of the existence of large amount of free water in sewage sludge. Considering the carbon tax, sludge treatment plants may need to add extra disposal for carbon capture, which also contributes to a higher investment for the entire system. Hence, local government should provide suitable financial support as incentives to maintain the operations and promote the development of waste management plants. Life cycle assessment is a powerful tool to evaluate the performances of selected alternative. Nevertheless, the assessment work should be conducted according to the specific situation of the specific region because the evaluation results are deeply influenced by the assumptions on the features of sewage sludge and technologies.

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