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Multi-criteria sustainability assessment of urban sludge treatment technologies: Method and case study

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ABSTRACT

This study aims at developing a sustainability assessment framework for assessing the technologies for the treatment of urban sewage sludge based on the logarithmic fuzzy preference programming based fuzzy analytic hierarchy process (LFPPFAHP) and extension theory. LFPPFAHP was employed to determine the weights of the criteria for sustainability assessment, and extension theory was used to prioritize the alternative technologies for the treatment of urban sewage sludge and grade their sustainability performances. An illustrative case including three technologies (compositing, incineration, and resource utilization) was studied by the proposed method, and compositing, incineration, and resource utilization are recognized as "Moderately Sustainable", "Not Sustainable", and "Highly Sustainable", respectively. The sustainability sequence in the descending order is resource utilization, compositing and incineration, and the result is consistent to that determined by the sum weighted method.

1. Introduction

Urban sludge contains various harmful materials, and the inappropriate treatment of urban sludge may cause serious problems on environment and public health (Houillon and Jolliet, 2005; Trably et al., 2003). Accordingly, the treatment of urban sludge has become a hot spot recently (Bernal-Martinez et al., 2005). Many technologies have been developed for the treatment of urban sludge (Semiyaga et al., 2015), i.e. anaerobic digestion, thermal process (Hospido et al., 2005), electrocoagulation and flotation (Pouet and Grasmick, 1995), and resource utilization (Chen et al., 2012), etc. Among these, the utilization of urban sludge has been recognized as a promising pathway for the treatment of urban sludge for transforming sludge into resources, i.e. sludge utilization for electricity (Björklund et al., 2001), sludge utilization for biodiesel (Pokoo-Aikins et al., 2010), and sludge utilization for ceramsite (Xu et al., 2008). However, the sustainability of these pathway even resource utilization methods for the treatment of urban sewage sludge is in debate, because these pathways cannot perform well simultaneously in economic, environmental, and social aspects which are the three pillars of sustainability (Bertanza et al., 2016). Therefore, the investigation of the sustainability of these technologies for the treatment of urban sewage sludge is of vital importance for the stakeholders to select the most sustainable scenario for handling urban sludge.

Sustainability assessment of the technologies for the treatment of urban sewage sludge is a typical multi-criteria decision-making problem, and the decision-makers need to measure the sustainability and determine the sustainability sequence of multiple alternative technologies with the considerations of multiple criteria for sustainability assessment. As to the MCDM problems, there are two main tasks: one is to determine the weights of the criteria, and another is to rank the alternatives. There are usually various methods for determining the weights of the criteria, including subjective weighting method, objective weighting method, and the combined method. The subjective weighting method is to determine the weights of the criteria based on the opinions of

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the decision-makers/stakeholders which can represent the preferences and willingness, and the Analytic Hierarchy Process (AHP) (Saaty, 1980) is the most popular method. The objective weighting method is to determine the weights of the criteria based on the differences among the data of the alternatives with respect to the criteria, there are several objective methods, i.e. Entropy weighting method (Shemshadi et al., 2011), and CRiteria Importance Through Intercriteria Correlation (CRITIC) (Diakoulaki et al., 1995). The combined method is to combine both subjective method and the objective method. Among these methods, AHP is the most widely used method, because the weights determined by this method can reflect the preferences and willingness of the decision-makers/stakeholders. However, it is usually difficult for the users to establish consistent comparison matrix by using the numbers from 1 to 9 and their reciprocals due to the vagueness, subjectivity and ambiguity existed in human's judgements (Ren and Sovacool, 2014). Accordingly, the fuzzy AHP methods as the modified AHP methods have been widely used (An et al., 2016; Ren et al., 2015a; Ren et al., 2016). Among these fuzzy AHP methods, the logarithmic fuzzy preference programming based fuzzy analytic hierarchy process (LFPPFAHP) developed by Wang and Chin (2011) can overcome the weak points of the extent analysis method on fuzzy AHP (Chang, 1996). Therefore, LFPPFAHP was applied to determine the weights of the criteria.

There are also various MCDM methods which have been widely used for ranking the alternatives, i.e. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981), VIKOR (An et al., 2015; Ren et al., 2015b; Vahabzadeh et al., 2015), ELimination and Choice Expressing Reality (ELECTRE) family methods (Roy, 1991), Extension theory method (Cai, 1983), Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) family methods (Brans and Vincke, 1985), Data Envelopment Analysis (DEA) (Ren et al., 2014), and Grey Rational Analysis (GRA) (Chan and Tong, 2007), etc. Among these methods, the extension theory cannot only prioritize the alternatives according to their relative priorities, but also determine their grades according to their priorities. As for sustainability assessment of the technologies for the treatment of urban sewage sludge, this method cannot only prioritize these technologies accordingly to their sustainability performances, but also grade their sustainability. Therefore, the extension has been employed as the MCDM method to assess the alternative technologies for the treatment of urban sewage sludge.

The remainder parts of this study have been organized as follows: Section 2 presents the method for sustainability assessment of the technologies for the treatment of urban sewage sludge, including both LFPPFAHP method for determining the weights of the criteria and extension theory for ranking and grading these alternative technologies. An illustrative case has been studied by the proposed method in Section 3, and the results have been verified by another MCDM method (sum weighted method) in this part. Finally, this study has been discussed and concluded in Section 4.

2. Methods

The MCDM method for sustainability assessment of the technologies for the treatment of urban sewage sludge was presented in this Section, the framework of multi-criteria decision making for sustainability assessment of the technologies for urban sludge treatment was presented in Fig. 1. Section 2.1 developed the criteria for sustainability assessment. Section 2.2 presented in logarithmic fuzzy preference programming based fuzzy analytic hierarchy process as the weighting method for determining the weights of the criteria for sustainability assessment, and Section 2.3 presented the extension theory to prioritize the alternative technologies for the treatment of urban sewage sludge and grade their sustainability.

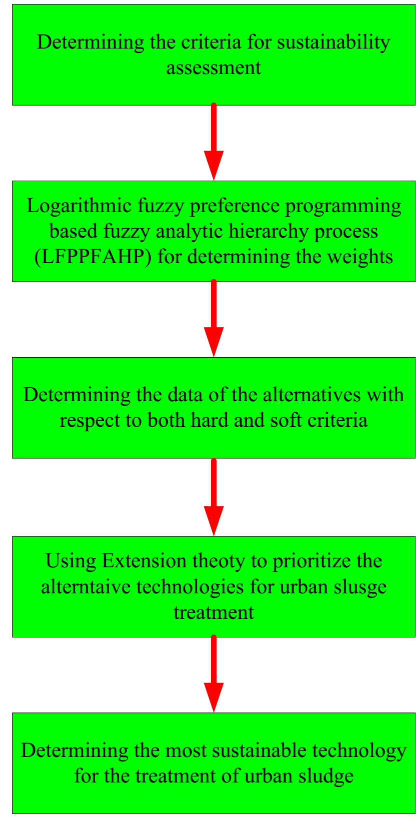

Fig. 1. Framework of multi-criteria decision making for sustainability assessment of the technologies for urban sludge treatment.

2.1. Criteria for sustainability assessment

Ten criteria including capital cost and running cost in economic aspect, occupied land, environmental risk, and resource utilization efficiency in environmental aspect, social acceptability in social aspect, operability, site selection, applicability, and management level requirement in technological aspect were used to measure the sustainability of the technologies for the treatment of urban sewage sludge in this study (Yang et al., 2007), they have been specified as follows:

(1) Economic aspect: there are two criteria in economic including capital cost and running cost. Capital cost is the total initial investment for the plant adopting a technology for treating the urban sewage sludge. Running cost is the cost during the operation of the plant adopting a technology for treating the urban sewage sludge;
(2) Environmental aspect: there are three criteria in environmental aspect. Occupied land is the total occupied land for building the plant for treating the urban sewage sludge. Environmental risk is the risk potential when adopting a technology for the treatment of the urban sewage sludge. Resource utilization efficiency is a measure of the utilization efficiency of urban sewage sludge when recognizing it as a kind of resource.
(3) Technological aspect: it consists of four criteria including operability, site selection, applicability, and management level requirement. Operability is a criterion to measure the complexity level of the technology for the treatment of the urban sewage sludge. Site selection is a measure of the difficulty in selecting the suitable site for building the plant for the treatment of