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Research article

Fuzzy multi-objective optimization case study based on an anaerobic co-digestion process of food waste leachate and piggery wastewater

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ABSTRACT

This paper presents the development and evaluation of fuzzy multi-objective optimization for decision-making that includes the process optimization of anaerobic digestion (AD) process. The operating cost criteria which is a fundamental research gap in previous AD analysis was integrated for the case study in this research. In this study, the mixing ratio of food waste leachate (FWL) and piggery wastewater (PWW), calcium carbonate ($CaCO_3$) and sodium chloride (NaCl) concentrations were optimized to enhance methane production while minimizing operating cost. The results indicated a maximum of 63.3% satisfaction for both methane production and operating cost under the following optimal conditions: mixing ratio (FWL: PWW) – 1.4, $CaCO_3$ – 2970.5 mg/L and NaCl – 2.7 g/L. In multi-objective optimization, the specific methane yield (SMY) was 239.0 mL CH_4/g VS_{added}, while 41.2% volatile solids reduction (VSR) was obtained at an operating cost of 56.9 US$/ton. In comparison with the previous optimization study that utilized the response surface methodology, the SMY, VSR and operating cost of the AD process were 310 mL/g, 54% and 83.2 US$/ton, respectively. The results from multi-objective fuzzy optimization proves to show the potential application of this technique for practical decision-making in the process optimization of AD process.

1. Introduction

Population growth and higher living standards causes an increase in food waste (FW) generation in industrial, residential, commercial and institutional establishments (Dai et al., 2013). In South Korea, 13,000 ton/day of FW are produced that accounts for 27% of the total municipal solid waste generated (Lee et al., 2009). To enhance the FW recycling, several recycling facilities have been installed to produce animal feedstocks and fertilizer for agricultural use. However, these FW recycling facilities convert 70–90% of the FW to food waste leachate (FWL) (Lee et al., 2009). The previous traditional legal disposal method for FWL is through ocean dumping (Lee et al., 2009). However, FWL has problems of being a malodorous liquid organic waste with high organic and biological oxygen demand (BOD) contents (Park et al., 2015). The FWL can have detrimental effects in the marine environment due to contamination that could cause a drop in the oxygen level for aquatic life due to a high BOD (Lee et al., 2009). As the society became more environmentally sensitive through the years, Korea prohibited ocean dumping in 2012 to comply with the London dumping convention and inter-governmental treaties (Ohm et al., 2009).

Concerning the problems of energy depletion and climate change, the biogas digesters have been revitalized in several developing countries like India (Chanakya et al., 2005) and China (Wang et al., 2016). The anaerobic digestion (AD) process has traditionally been used as a cost-effective treatment process due to attaining appreciable energy production from rich organic wastes that effectively addresses the concerns of high energy demand and global climate change (Lee et al., 2009). Despite its advantages, the AD process could still fail if process conditions such as carbon to nitrogen (C/N) ratio, pH, hydraulic retention time, solids retention time, and the type of substrate used are not properly optimized (Demirel and Scherer, 2008). Although the digesters can be utilized at a small to medium-scale (household and rural area) or large-scale (city), much attention has been given to the study of small-scale digesters rather than large-scale digesters. Large-scale digesters would require intricate construction planning and high maintenance cost that can be applied only in large industries (Tilley et al., 2014). On the other hand, a small-scale digester would be easy to maintain, requires less process control and lower investment cost than a large-scale digester. In terms of energy production, large-scale digesters would attain higher conversion efficiency (White et al., 2011) and biogas production rate (Wang et al., 2018). However, this would consequently need higher operating time (Pantaleo et al., 2013) and a

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larger waste heat recovery unit (Wang et al., 2018) as compared to a small-scale digester. In a co-generation configuration setup, small-scale digesters have an advantage of effectively facilitating the use of excess heat generated towards matching with the local loads (Pantaleo et al., 2013).

In the case of piggery wastewater (PWW), low CH_4 production and high volatile fatty acid production have been reported during AD (Angelidaki and Ellegaard, 2003; Hansen et al., 1998). To improve the CH_4 production of PWW, a co-digestion process with other organic wastes (kitchen waste, food-processing waste or sewage sludge) can be introduced. The co-substrates will provide more biodegradable organic matter, essential micronutrients and reduce the concentrations of toxic compounds to efficiently produce CH_4 (Behera et al., 2010; Fernández et al., 2005; Murto et al., 2004). Furthermore, FWL in Korea has high salt concentration that can cause inhibition of methanogenesis or the formation of CH_4 through microbes. The FWL also lacked sufficient alkalinity levels as a single substrate in the AD that could be supplemented by the PWW as a co-substrate (Han et al., 2012). It is also vital to consider the optimization of CH_4 production that can appropriately alter the stimulation of methanogens through nitrogen consumption, alkalinity and salinity to improve its efficiency.

To find the optimum operating condition for biogas production, conventional one-factor-at-a-time and response surface methodology (RSM) have been used in the literature (Monlau et al., 2013; Reungsang et al., 2016; Shahbaz et al., 2016). Han et al. (2012) reported the RSM optimization, an uni-model objective function, of CH_4 production with simultaneous volatile solids reduction (VSR) by utilizing the co-digestion of FWL and PWW. However, that study severely lacked the analysis with regards to the operating cost which is essential to evaluate possible implementation of a small-scale digester. Moreover, most previously published literatures related to AD also accounted only the optimization process of CH_4 production without the consideration of its cost (Naran et al., 2016; Zhang et al., 2011; Zou et al., 2016). There are only limited studies that reported the interdependency of operating cost and CH_4 production. The integration of an operating cost criteria is essential to determine the viability of the process in its environmental and technical applications. This research gap in past literatures is what the present study would address by applying an alternative optimization approach in which decision-makers could utilize for a multiple goal-oriented analysis. Therefore, the key novelties in this study are on the determination of a global optimal solution of CH_4 production and the integration of an operating cost analysis in its variable cost. Furthermore, the novelties of this research will highlight the use of a fuzzy optimization approach using a global optimizer software to comprehensively determine and analyze the best solution of CH_4 production in an anaerobic co-digestion of FWL and PWW that concurrently incorporates the consideration of the operating cost.

Fuzzy optimization is a modeling tool towards environmental and economic systems to strategically resolve conflicting goals resulting from decision-makers. Thus, this can be potentially used to determine the best possible solution for determining the highest CH_4 yield at the lowest cost in this study. This is based on the concept of fuzzy sets developed by Zadeh (1965). The theory of fuzzy optimization is able to express qualitative and uncertain subjective information to numerical language which is a suitable tool for a multi-criteria analysis (dos Santos et al., 2017; Santos et al., 2017). This has already been used in various applications such as groundwater quality assessment (Vadiati et al., 2016), flood management (Akter and Simonovic, 2005), flood-diversion planning (Wang and Huang, 2013) and integrated eco-system assessment (Vasslides and Jensen, 2016) to simultaneously design and optimize process systems that satisfy its respective constraints and demands. The fuzzy mathematical programming is utilized to solve problems which maximize the degree of satisfaction among various goals and constraints (dos Santos et al., 2017; Zimmermann, 1978). This, therefore, demonstrates a promising application in a multi-objective optimization of CH_4 production and its associated cost. Although past studies have utilized the fuzzy algorithm in the AD process in wastewater treatment plants, these only focused on its control parameters and have not integrated the operating cost criteria (Carlos-Hernandez et al., 2009; Murnleitner et al., 2002). This research paper aims to answer on how the global optimal results of integrating an operating cost analysis through the multi-objective fuzzy optimization approach differ from uni-objective local optimal results derived from previous studies along with its underlying practical implications.

High CH_4 production can theoretically incur high costs due to demand for raw material and chemicals. Therefore, the main objective of this research paper is to utilize a fuzzy optimization analysis to account for the variable costs such as the use of FWL, PWW, calcium carbonate ($CaCO_3$) and sodium chloride (NaCl) that produces CH_4 in an anaerobic co-digestion process in order to determine the global optimal solution. In this study, the anaerobic co-digestion of FWL and PWW and the corresponding operating cost for CH_4 production with simultaneous VSR in a small-scale digester was investigated. The specific objectives which is in line with the chronological order of the structural flow of discussion in the manuscript are as follows: (i) to study the effect of individual parameters of mixing ratio (FWL: PWW), $CaCO_3$ concentration and NaCl concentration with respect to CH_4 production and operating cost, (ii) to determine the Pareto set of specific methane yield (SMY), VSR and the corresponding operating costs with respect to the process parameters, (iii) to perform a fuzzy optimization approach to ascertain the best possible conditions for the highest SMY with VSR at the lowest operating cost, (iv) to compare with various results from past literatures and (v) to draw out the practical applications and future outlook of this study. The five indicated flow of discussion corresponds to the respective discussions in Sections 3.1–3.5.

2. Materials and methods

2.1. Materials

FWL and PWW were obtained from Sung-am food waste resource recovery plant and a pig farm located in Ulsan, Korea, respectively. The substrates were pre-screened using a metallic sieve (2 mm mesh) to remove coarse particles and stored at 4 °C. The inoculum was acquired from the anaerobic sludge digesters at Yongyeon sewage treatment plant in Ulsan, Korea. The characteristics of the two samples and the inoculum are listed in Table 1 (Han et al., 2012).

2.2. Experimental method

The current research paper is an expansion of the study of Han et al. (2012) by utilizing its generated model equations and additionally incorporating an operating cost analysis through fuzzy optimization. This addresses its underlying research gap on a basis of studying the cost criteria in a small-scale digester. The details of the methodology of utilizing FWL and PWW as co-substrates in the anaerobic co-digestion for CH_4 production was based on the study of Han et al. (2012). The FWL – PWW substrate mixture and inoculum were maintained at a 1:1 ratio on VS basis (*w/w*) for all the experimental runs. Serum bottles (500 mL capacity) capped with natural rubber sleeve stoppers were utilized for the batch experiments to assess the biochemical methane

Table 1
Material characteristics of food waste leachate (FWL), piggery wastewater (PWW) and inoculum.

Materials	pH	Volatile solids/total solids (VS/TS)	VS (%)	$CaCO_3$ (g/L)	NaCl (g/L)	C/N
FWL	3.99	0.88	12.1	0	–	10.81
PWW	7.71	0.49	0.62	1.05	–	0.3
Inoculum	7.14	0.6	1.97	895	4.9	