Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Comprehensive evaluation of environ-economic benefits of anaerobic digestion technology in an integrated food waste-based methane plant using a fuzzy mathematical model

Ting Chen[a,b,*], Dongsheng Shen[a,b], Yiying Jin[c], Hailong Li[d], Zhixin Yu[e], Huajun Feng[a,b], Yuyang Long[a,b], Jun Yin[a,b]

[a] *School of Environment Science & Engineering, Zhejiang Gongshang University, Hangzhou 310012, China*
[b] *Zhejiang Provincial Key Laboratory of Solid Waste Treatment and Recycling, Hangzhou 310012, China*
[c] *School of Environment, Tsinghua University, Beijing 100084, China*
[d] *Mälardalen University, School of Sustainable Development of Society and Technology, SE-721 23 Västerås, Sweden*
[e] *Department of Petroleum Engineering, University of Stavanger, N-4036 Stavanger, Norway*

HIGHLIGHTS

- Proposed fuzzy model realizes comprehensive evaluation of environ-economic benefits.
- Total environmental impact load of case study was low with value of 6.65 E-03.
- AD was effective in energy production as net energy output was higher than input.
- Overall environ-economic benefits scored good grade with value of 3.39.
- Economic benefit is the restrictive factor in integrated environ-economic benefits.

ARTICLE INFO

Keywords:
Fuzzy model
Anaerobic fermentation
Food waste
Environmental benefits
Economic benefits

ABSTRACT

In this study, a quantitative and comprehensive evaluation of environ-economic benefits of anaerobic digestion (AD) of food waste was conducted on an operational project in China. Fuzzy evaluation method based on life cycle assessment and cost-benefit analysis was employed. Single-factor evaluation of environmental impacts and energy consumption indicated that AD was a green and clean energy producing technology. The study indicated that the total environmental impact was not significant at 6.65 E-03, and the net energy output (186.01 MJ) was slightly higher than the net energy input (167.47 MJ), when only methane production was considered. However, economic benefits were not ideal, recording loss of 64.99 RMB for each ton of food waste. Additionally, results of comprehensive evaluation conducted using fuzzy mathematical model were consistent with above results. Environmental benefits, energy consumption, and economic benefits of AD technology were 4.75, 3.58, and 1.36, corresponding to grades I, II, and IV, respectively. Single benefits decreased in the order of environmental impact > energy consumption > economic benefit, indicating that economic benefit is the restrictive factor in integrated environ-economic benefits of AD technology in practice. Thus, increasing economic benefit should be the focus of research and management processes. Additionally, overall environ-economic benefit of AD rated good (Grade II), with a value of 3.39. Further sensitivity analysis results confirmed the stability of the comprehensive evaluation model. The established fuzzy mathematical evaluation model can realize comprehensive and quantitative evaluation of environ-economic benefits of AD technology; serve as valuable reference for perfecting evaluation systems, and assist in rational choice of renewable energy recovery technology from food waste.

1. Introduction

Renewable energy recovery from waste has attracted increasing attention as a consequence of primary energy crisis [1]. Anaerobic digestion (AD) is currently considered as one of the most successful technologies for renewable energy recovery especially during

* Corresponding author at: School of Environment Science & Engineering, Zhejiang Gongshang University, Hangzhou 310012, China.
E-mail address: chenting_2013@tsinghua.org.cn (T. Chen).

http://dx.doi.org/10.1016/j.apenergy.2017.09.082
Received 12 June 2017; Received in revised form 25 August 2017; Accepted 12 September 2017
0306-2619/ © 2017 Published by Elsevier Ltd.

biodegradable waste digestion [2–4] and is by far one of the most rational solutions to manage this waste [5–7]. With population and economic growth, food waste is one of the largest components of municipal solid waste (MSW) [8]. It has rapidly increased and accounts for one-third of the MSW, especially in China and South Korea [9,10]. Hence, methane production from food waste using AD has been investigated widely by research and engineering applications [11-15]. For example, over 21 500 t of food waste is processed daily in China, with more than 80% of the projects employing anaerobic fermentation technology to produce methane. Further technology improvement has been explored in the AD of food waste, including pretreatment [8,12,16], co-digestion [10,17], reactor [1,18], and others. Therefore, AD technology choice and evaluation is of urgent concern to managers and researchers at present.

Food waste is mainly produced by hotels, restaurants, families, canteens, and companies. The TS and VS contents of food waste are in the ranges of 18.1–30.9% and 17.1–26.35%, respectively [19]. Therefore, the moisture content is high, accelerating degradation of food waste, pathogen proliferation, and significant environmental pollution. Thus, as an energy recycling technology, the AD of food waste stresses upon the actual effectiveness and environmental benefits and inevitably entails cost inputs [2,14,15]. It is necessary to refocus the evaluation of this technology from a solely economic perspective to environ-economic comprehensive benefits to assess its sustainability.

However, very few researches have focused on the environ-economic benefits of AD technology. Most researches have focused on environmental or economic factors alone. For example, Woon et al. (2016) comparatively analyzed the environmental benefits of three forms of energy utilization when methane generated by AD technology was used for combined heat and power generation, natural gas, and in vehicles [20]. Xu et al. (2015) evaluated the environmental benefits of three methods of methane generation including co-digestion of food waste and sewage sludge, AD of food waste alone, and landfill of food waste [21]. Khoo et al. (2010) evaluated the environmental benefits (such as global warming, acidification, eutrophication, photochemical oxidation, and energy use) of a combination of four waste treatment processes (including incineration, composting, and AD) [22]. Only a small percentage of these researches pertained to environ-economic benefits of food waste recycling [23,24]. Moreover, environmental and economic benefits were discussed separately and not in conjunction with each other. For example, Franchetti (2013) used life cycle assessment (LCA) to independently evaluate the economic, energy, and environmental benefits of four types of AD technologies for food waste and compared these technologies with waste landfill technology [24]. Chen et al. (2015) analyzed the energy consumption and environmental benefits of an operational methanogenesis project based on AD of food waste [2].

Most researches above used LCA to evaluate different economic or environmental benefits (for example, global warming, internal rate of return, cost accounting based on social life cycle, and energy generation efficiency) of anaerobic fermentation of food waste [2,8,20–24]. Uncertainty analysis was conducted frequently to improve the reliability of evaluation results. However, the evaluation methods did not integrate the qualitative/quantitative environmental benefit indexes and were deficient in the comprehensive evaluation of environmental and economic benefits. Today, administrators of food waste recycling, enterprise operators, and research personnel are required to quantitatively analyze and evaluate environ-economic comprehensive benefits and provide useful reference for technology choices and research.

The aim of this study is twofold: firstly, to establish a quantitative evaluation method for comprehensive environ-economic benefits assessment of AD technology and secondly, to present the results of selected case studies to highlight the environ-economic benefits of currently practiced engineering in AD-based food waste technology and suggestions to improve it. This paper evaluates the environmental benefits, energy consumption, and economic impacts of AD technology individually using the case of an operational methane production facility in China. Additionally, a comprehensive evaluation model based on fuzzy mathematics theory was applied to evaluate AD technology comprehensively and quantitatively. This model can be employed to compare the advantages and disadvantages of AD technology with the principle of "minimization of system cost and environmental impact and maximization of economic benefits and energy utilization", and provide methodological and technical support for promoting reasonable evaluation and scientific selection of renewable energy recovery from food waste.

2. Materials and methods

2.1. Description of the food waste-based methane plant

The food waste-based methane plant evaluated in this paper has a waste processing capacity of 250 t/d and is located in Suzhou, China. The process employed in the plant is described below.

Food waste generated from catering establishments such as restaurants and hotels are collected and transferred to a workshop where they are successively subjected to sorting, impurity removal, heat-moisture treatment (1 h at 120 °C to 180 °C), and solid–liquid separation, thus generating three phases (namely grease, waste water, and solid matter). Subsequently, the grease is fed into an intensive-processing workshop for biodiesel production, while the waste water and solid matter are collectively fed into an adjusting tank, where they undergo wet AD to generate methane gas. Following purification and desulfurization, the biogas is used to generate electricity and heat through cogeneration systems (combined heat and power). Nearly 43% is generated as electricity and 57% is generated as heat. The electricity is supplied to the plant itself and the heat is reused to heat food waste in the hydrothermal pot.

The evaluation case of food waste based-AD technology utilized in this paper has been elaborated in an article published by the author [2].

2.2. System boundary and basic framework of the evaluation model

The evaluation model employed in this study focuses on the impacts of AD alone, without accounting for the generation, collection, and transportation of the food waste. In addition, the evaluation model is mainly built on the following hypotheses: (1) the environmental and economic benefits of the recycled products (mainly methane and waste grease) were considered as substitutes of traditional methane and biodiesel, but not as specific extensions of industrial chains or value-added processing such as waste oil recycling as biodiesel process (2) waste water, bad odor, and refractory impurities (including plastics and glass) were finally disposed using conventional methods. The odor generated from the treatment process was treated using bio-filters to attain B-grade standard of the "Emission Standard for Odorous Pollutants" [25]. Biogas slurry was treated using continuous loop reactor with anoxic/oxic (CLR + A3O3) processes at a sewage treatment station to meet B-grade standard of "Wastewater quality standards for discharge to municipal sewers" of China [26]. The slurry was discharged to a municipal sewage treatment plant via pipeline network for further treatment. The biogas residues produced by AD were transported to incineration plants following centrifugation. The functional unit was defined as 1 t of food waste.

The final system boundary, as illustrated in Fig. 2, consisted of the following units: pretreatment, main treatment, product production, and other pollutants disposal. The system boundary considers food waste as material input, electricity as energy input, and renewable energy and product as material outputs. Additionally, the system included a recycling system for other pollutants produced during the treatment process, which served as the "final" treatment and disposal system of secondary pollutants (including digestate). The "final" treatment and disposal system can be converted into a recycling system using the