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Identifying key process parameters for uncertainty propagation in environmental life cycle assessment for sewage sludge and food waste treatment

Sam L.H. Chiu, Irene M.C. Lo *

Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong, China

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A B S T R A C T

Life cycle assessment (LCA) results are often subject to uncertainty, which may lead to erroneous conclusions. This paper aims to tackle the parameter uncertainty involved in LCA. Hong Kong is selected as the reference city for the treatment of sewage sludge and food waste. A selection approach with sensitivity analysis is proposed to identify the key process parameters and Monte Carlo simulation is further conducted to propagate the uncertainty of the key process parameters identified. The results show that climate change is the major impact category among various impact categories that are generally considered in waste LCA studies. Scenarios 5 and 6, which consider anaerobic co-digestion (coAD) treatment, achieve the best performance in regard to the climate change impact. Scenario 6 which includes a combined cycle gas turbine system for biogas utilization has -6.75×10^4 kg avoided CO_2e emissions and it is equal to 44% more avoided emissions compared to scenario 5 which applies a combined heat and power system. For the key process parameters identified, it is found that the electricity generation efficiencies in different waste treatment facilities, such as the incineration plant and the anaerobic digestion plant, have the greatest sensitivity to the result. Uncertainty propagation is then conducted to obtain the probability distribution functions in environmental performance of different scenarios. Scenario 6 has a 95% probability of achieving at least -5.32×10^4 kg avoided CO_2e emissions, while the probability of scenario 5, which is the second best scenario, achieving the same avoid emissions is below 5%. It indicates a significant advantage of using combined cycle gas turbine over combined heat and power unit for biogas utilization in Hong Kong. The methodologies and results of this study provide comprehensive material that can be adapted for other areas planning sustainable sewage sludge and food waste treatment, as well as in tackling parameter uncertainty in general LCA studies.

1. Introduction

Organic waste management has long been a major challenge in urban areas. Improper management of organic waste could create negative environmental impacts such as generating unpleasant odors, spreading disease, and contributing to global warming (Singh et al., 2011). Since the early 21st century, the disposal of organic waste in landfills has been banned by legislation in some European countries, such as in Switzerland and Sweden (EEA, 2017). This legislation is aimed at reducing the negative environmental consequences from landfilling and in promoting resource recovery by using alternative treatment methods. For instance, the European Environment Agency (EEA, 2013) estimated that the energy produced from organic waste could reach more than 50% of the total renewable energy generated in Europe in 2020. Regarding the composition of organic waste, sewage sludge and food waste represent the greatest portion in urban areas (Righi et al., 2013). For example, in Hong Kong, such wastes accounted for 89% of the total organic waste generated in 2015 (HKEPD, 2017), so if these wastes can be properly treated, the environmental impacts created would be minimized and useful resources would also be recovered at the same time. Hence, the identification of a cleaner and sustainable treatment method for sewage sludge and food waste is vital.

In order to identify a waste treatment strategy for environmental sustainability, life cycle assessment (LCA) is widely used as it can quantify the environmental impacts of different treatment

* Corresponding author.
E-mail address: cemclo@ust.hk (I.M.C. Lo).

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scenarios in a scientific manner (Humbert et al., 2009). However, LCA results are often subject to uncertainty, and may lead to incorrect conclusions for the decision makers (Huijbregts et al., 2003). The International Organization for Standardization (2006) recommends that the uncertainty should be considered in order to improve the reliability of the LCA results. Regarding the types of uncertainty in LCA, Huijbregts (1998) categorized uncertainty into parameter uncertainty, model uncertainty, and scenario uncertainty while Assefa and Frostell (2004) categorized uncertainty into parameter uncertainty and model uncertainty, with both studies suggesting that parameter uncertainty is of the utmost importance. Sensitivity analysis and uncertainty propagation can be undertaken when investigating the parameter uncertainty involved in an LCA study (EC, 2010).

As a number of process parameters are generally included in an LCA study, they may cause a large variation in the results due to the presence of individual parameter uncertainty. It is important to consider the parameter uncertainty involved in an LCA study in order to improve the reliability of the results. Those process parameters leading to the highest environmental gain or loss by only a small deviation are considered as key process parameters (Heijungs, 1996). The identification of the key process parameters is important as they suggest room for possible improvement of current treatment systems and the determination of the parameter significance for future study. In LCA studies, researchers generally study the influence of selected key process parameters that are regarded as sensitive or important to the results. Since the selection of the key process parameters is usually based on the knowledge or experience of the researcher (i.e., expert judgment), there could be considerable variation of the selected parameters across LCA studies (Laurent et al., 2014). For example, Kirkeby et al. (2006) and Evangelisti et al. (2014) evaluated the environmental performance of different food waste treatment technologies. In these two studies, four key parameters with potentially large impacts on the results were selected based on expert judgment, and only one parameter, the fugitive emissions of methane in the AD process, was identical in the two studies. Zhao and Deng (2014) only investigated the influence of the energy mix parameter without considering other process parameter in food waste LCA. It is generally agreed that the expert judgment based selection approach for the key process parameters may lead to overestimation or underestimation of the parameter importance, leading to wrong conclusions. In order to identify the key process parameters in consideration of all the process parameters involved in an LCA study, sensitivity analysis can be used to evaluate the influence of each process parameter to the result. The key process parameter indicates the greatest contribution to the environmental impact and hence provides a better understanding of the variability in the LCA result (Ning et al., 2013). Wolf et al. (2016) suggested that less data collection effort should be afforded for those parameters of minor importance in future studies. This approach was applied in LCA studies for wind power generation in order to identify the key process parameters when assessing the greenhouse gas (GHG) emissions (Padey et al., 2012). Regarding waste LCA studies, Eriksson and Baky (2010) identified the key process parameters for municipal solid waste management by using sensitivity analysis. Specifically for sewage sludge and food waste treatment, the key process parameters have not yet been identified in any published study.

Uncertainty propagation quantifies the uncertainty of model results due to various process parameter uncertainties and aims to improve the robustness and reliability of the results by providing ranges of possible outputs. To date, very few LCA studies have applied uncertainty propagation with only 6% of waste LCA studies considered uncertainty propagation in their assessments (Xu et al., 2015). The reasons can likely be attributed to the large effort required for the collection of uncertainty information on the parameters and the difficulty in determining uncertainty information for all process parameters in an LCA study (Wolf et al., 2016). Clavreul et al. (2012) proposed a general framework for uncertainty propagation by considering the key process parameters in waste LCA. Nevertheless, the selection process of key process parameters was not described in the study (i.e., how to determine the key process parameters). Determination of the key process parameters is important for possible improvement of treatment systems, as well as being used for uncertainty propagation.

In order to identify a sustainable treatment method for sewage sludge and food waste, as well as quantify the parameter uncertainty involved in the LCA study, Hong Kong is chosen as a reference city in this study. Hong Kong has long been solely relying on the three strategic landfills for sewage sludge and food waste disposal. The local government introduced a new waste management policy entitled “Hong Kong Blueprint for Sustainable Use of Resources 2013–2022” (HKEB, 2013). The directions of the policy are to reduce the waste at source, as well as utilize the waste for sustainable uses such as recovering energy from waste treatment. To tackle the latter objective, the government aims to commission a couple of waste-related infrastructures for turning waste to energy, such as building a sewage sludge incineration facility (T-PARK), and organic waste treatment facilities (OWTF) for food waste treatment by anaerobic digestion (AD). In order to further raise the waste treatment capacity, the government proposes to use sewage sludge and food waste anaerobic co-digestion (coAD) in the existing sewage treatment works (STWs) (HKCEO, 2016). In the meantime, the relocation of three existing STWs is suggested to be feasible, according to the cavern development strategy in Hong Kong (CEDD, 2011). However, the treatment methods for the sewage sludge generated from the proposed cavern STWs have not yet been established, therefore, the evaluation of a sustainable waste treatment strategy is of paramount importance.

With the use of AD and coAD in the future, a large amount of biogas will be produced in Hong Kong. It is a common practice to apply a combined heat and power (CHP) system for the biogas produced to generate both heat and electricity. The former can satisfy the heat load demand by the digesters and the latter can be used as a fuel source (USEPA, 2011). Meanwhile, since the heat cannot be efficiently transported over a long distance (Cromie et al., 2014) and the demand for heat in Hong Kong is limited, the heat generated from the CHP in existing STWs can only be used internally. If the heat is not fully utilized, the overall efficiency for the CHP is consequently greatly reduced (Cromie et al., 2014). As an alternative for biogas utilization, the use of a combined cycle gas turbine (CCGT) for upgraded biogas has gained more attention recently, achieving around 55% efficiency for electricity generation (Gutierrez et al., 2016). To the best of the authors' knowledge, studies on CCGT are still sparse in regard to biogas utilization. In particular, for countries or cities with low heat demand, evaluation of CCGT for biogas utilization in generating electricity is essential.

Based on the literature review, researches on identifying key process parameters and tackling the uncertainty in waste LCA are scarce while these are necessary for process improvement and to strengthen the result reliability. To fill these gaps, the major objective of this study is to identify the key process parameters and tackling the uncertainty for an LCA study for sewage sludge and food waste treatment in Hong Kong. To achieve this major objective, four specific objectives are included: (i) to determine the key environmental impact and analyze the process contributions of the various waste treatment scenarios for sewage sludge and food waste using LCA; (ii) to evaluate whether CHP or CCGT is more environmentally friendly for biogas utilization; (iii) to identify the