LIFE CYCLE ENVIRONMENTAL ASSESSMENT AND KEY PROCESS PARAMETERS IDENTIFICATION FOR SEWAGE SLUDGE AND FOOD WASTE TREATMENT WITH BIOGAS UTILIZATION IN HONG KONG

ABSTRACT

Sewage sludge and food waste represent major contributions to organic waste in a city, and associated with adverse environmental performance if they are not well managed. This study aims to evaluate the environmental performance of different waste treatment strategies for sewage sludge and food waste in Hong Kong. The functional unit consists of 350 tonne per day (tpd) of sewage sludge generated from the proposed cavern sewage treatment works (STWs) and 105 tpd of food waste based on a 10:3 wet weight mixing ratio. In addition, this study compares the combined heat and power (CHP) system and the combined cycle gas turbine (CCGT) for biogas utilization with the use of anaerobic digestion and co-digestion treatments for the organic wastes. Life cycle assessment (LCA) is used to support the identification of a waste treatment strategy based on the environmental impacts. Key process parameters, which are considered to have the greatest contribution to the environmental impact, are identified based on a proposed selection approach in order to provide a better understanding of the variability in LCA. The results show that climate change is the key impact category among the most frequently evaluated midpoint impact categories of waste management studies. Anaerobic co-digestion treatment creates the greatest environmental benefits based on the above key impact category in Hong Kong. For the comparison of CHP and CCGT for biogas utilization, scenario 6 (i.e., anaerobic co-digestion with CCGT for biogas utilization) has -6.75×10^4 kg avoided CO_2e emissions while the second best scenario, which applies CHP for biogas utilization, only has -3.78×10^4 kg avoided CO_2e emissions. It indicates a significant advantage of CCGT over CHP in countries or cities with limited heat demand, like Hong Kong. Key process parameters are then identified and 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. It is suggested that extra attention should be paid to these parameters in future waste LCA studies in order to get a more realistic result. If scenario 6 (i.e., the best scenario obtained) is applied in the future, it can reduce approximately 1% of carbon emissions in the waste sector with reference to the year 2005. These findings underpin the significant contribution of proposed waste treatment strategy in reducing carbon emissions in order to meet the carbon reduction target in Hong Kong.

KEYWORDS

Anaerobic co-digestion; Climate change; Combined heat and power; Life cycle assessment; Organic waste; Sensitivity analysis

INTRODUCTION

The relentless generation of sewage sludge and food waste creates serious environmental concerns if they are not well managed. For instance, these types of waste contribute a large portion of organic waste in a city (Righi et al., 2013). In some European countries (e.g., Switzerland and Sweden), the banning of organic waste to landfills by legislation has been in effect since the early 2000s, aimed at reducing the environmental impacts from landfill disposal as well as promoting alternative treatment methods for resource recovery (Herczeg, 2013; Milios, 2013). As suggested by the European Environment Agency (EEA, 2013), the bioenergy generated from organic waste is accounted for more than half of the projected renewable energy output in Europe in 2020. Therefore, a sustainable waste treatment method is crucial for environmental sustainability and resource utilization.

Hong Kong has long been solely relying on the three strategic landfills for waste disposal. Both sewage sludge and food waste are disposed of at the landfills together with municipal solid waste and construction waste. The local government has 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 (OWTFs) for food waste treatment by anaerobic digestion (AD). In order to further raise the waste treatment capacity, the government proposes to apply 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 method for the sewage sludge generated from the proposed cavern STWs is not yet confirmed. Therefore, the evaluation of a sustainable waste treatment strategy is of paramount importance.

In addition, 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) unit for the biogas produced to generate both heat and electricity. The former can satisfy the head load demand by the digesters and the latter can be used as a fuel source (USEPA, 2011). Meanwhile, since the heat cannot be transported over a long distance efficiently (Irvine, 2012; Cromie et al., 2014) and the demand for heat in Hong Kong is limited, the heat generated from the CHP in existing STWs is used internally. If the heat is not utilized, the overall efficiency for CHP will consequently be 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; Williams et al., 2016). Fig. 1 shows the schematic diagrams of CHP system and CCGT system. For CCGT system, the heat is recovered to generate steam to drive a steam turbine and recirculates in the cycle instead of being served as heat supply source. To the best of the authors' knowledge, studies on CCGT are still scarce 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.

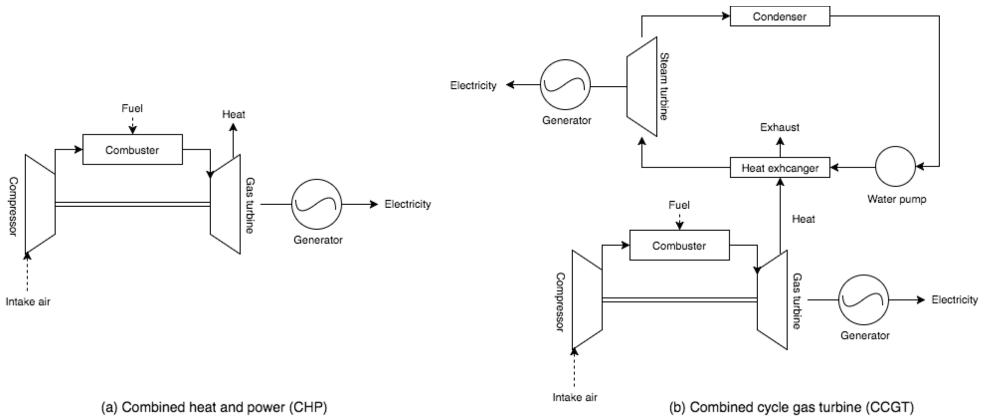


Fig. 1 Schematic diagrams of (a) CHP system and (b) CCGT system

In order to identify a waste treatment strategy for the good of environmental sustainability and resource utilization, life cycle assessment (LCA) is widely used to evaluate the environmental performance of different waste treatment systems as it can quantify their environmental impacts in a scientific manner (Humbert et al., 2009). In LCA studies, the key process parameters are those having the greatest contribution to the environmental impact and hence provide a better understanding of the variability in the LCA result (Ning et al., 2013). It is important to identify the key process parameters for possible improvement of current treatment systems, and in the determination of the significances of the parameters for future study. Wolf et al. (2016) also suggested that less data collection efforts should be put for those parameters of minor importance in future studies. However, the selection of key process parameters in LCA is usually based on expert judgment and there could be considerable variation across LCA studies (Laurent et al., 2014). In three LCA studies for food waste treatment, which included anaerobic digestion (AD) as a treatment option (Evangelisti et al., 2014; Kirkeby et al., 2006; Zhao and Deng, 2014), key process parameters were selected by expert judgment. Evangelisti et al. (2014) and Kirkeby et al. (2006) applied sensitivity analysis in their LCA studies to evaluate the environmental performance of different waste treatment technologies. In these two studies, four key parameters with potentially large impacts on the results were selected based on expert judgment, while only one parameter, the fugitive emissions of methane in the AD process, was identical. On the other hand, Zhao and Deng (2014) only investigated the parameter of energy mix without considering other process parameters to determine their sensitivities to the result. It was revealed that the expert judgment based selection approach for the key process parameters may lead to overestimation or underestimation of the parameter importance, leading to a wrong conclusion. In order to identify the key process parameters with consideration of all the process parameters involved in a LCA study, a proposed selection approach by accumulating the sensitivity ratio from sensitivity analysis can be used to evaluate the influence of process parameters on the result.

Based on the above considerations, this study aims to (i) determine the key environmental impact and analyze the process contributions of the waste treatment system for sewage sludge and food waste by LCA, (ii) to determine whether CHP or CCGT is more environmentally friendly for biogas utilization in Hong Kong, and (iii) to identify the key process parameters for sewage sludge and food waste treatment.

MATERIALS AND METHODS

System boundary and description

This LCA study applies ISO 14040 and 14044 (ISO, 2006a,b). Six scenarios (i.e., scenarios 1, 2, 3, 4, 5, and 6) are proposed for sewage sludge and food waste treatment, and they represent all possible treatment scenarios for sewage sludge and food waste in Hong Kong. A schematic diagram of the scenarios' system boundary is shown in Fig. 2 and a detailed description of different waste treatment processes is shown in Table 1. As seen in Table 1, a 10:3 mixing ratio is adopted for coAD treatment. For fair comparison, the same ratio for sewage sludge and food waste is applied in each treatment scenario. The functional unit is defined as 350 tonne per day (tpd) of sewage sludge produced from the proposed cavern STWs (DSD, 2015; Lam et al., 2016) and 105 tpd of food waste based on a 10:3 wet weight mixing ratio considering the amount of sewage sludge generated from the cavern STWs. In addition, it is assumed that only the environmental impacts from the operational phase of the waste treatment facilities are considered, since they are regarded as the major environmental burdens (Gentil et al., 2010), while the environmental impacts of the construction and capital equipment are not included in this study. As mentioned in Cleary, (2009), these are considered as secondary environmental burdens and are relatively insignificant compared to the primary environmental emissions from the waste treatment process. Moreover, the environmental impact due to waste hauling is assumed to be negligible due to its low contribution in the authors' previous waste LCA study in Hong Kong (Woon et al., 2016). The GHG and air pollutant emission factors for substituted electricity are collected from China Light & Power Hong Kong Company Limited (CLP) and those for substituted heat are collected from Hong Kong and China Gas Company Limited (Towngas).

CHP is applied for biogas utilization in scenarios 2, 3, 4, and 5. The heat is assumed to be internally used in the treatment plant. In order to compare the environmental performance of CHP and CCGT for biogas utilization, in scenario 6, it is proposed to apply CCGT to evaluate the utilization of the biogas produced from the coAD treatment plant. It should be noted that all the key processes in scenario 6 are identical to scenario 5 except the use of CCGT replacing CHP. For scenario 5, the biogas produced is combusted to generate heat and electricity by the CHP unit. The electricity generated is utilized by internal consumption and the excess electricity is exported to the public grid. On the other hand, 25% of the heat generated is utilized for the internal heat demand by the anaerobic digesters (Woon et al., 2016). For scenario 6, the biogas is firstly upgraded to biomethane, with 90% methane content, for the application of CCGT to generate electricity (Cromie et al., 2014; León and Martín, 2016). The biogas is upgraded and purified by water scrubbing as it is the most suitable technology for biogas upgrading (Chiu and Lo, 2016; Lems and Dirkse, 2009). The sources of the life cycle inventory data on the substrate composition and waste treatment processes are presented in Table 2.

The major assumptions and limitations of this study include: (i) the data are mostly collected from local sources and they may not replicate global trends; (ii) only the environmental emissions from the operational phases are considered while the environmental emissions from construction and capital equipment are excluded as they are insignificant compared to the emissions from the operational phases (Cleary, 2009: Gentil et al., 2010; (iii) waste hauling is assumed to be negligible (Woon et al., 2016); (iv) heat produced from CHP is assumed to be used internally; and (v) the mixing ratio of sewage sludge and food waste in coAD is applied from a Korean plant data while additional experiments should be made to determine the suitable mixing ratio of substrates in Hong Kong.

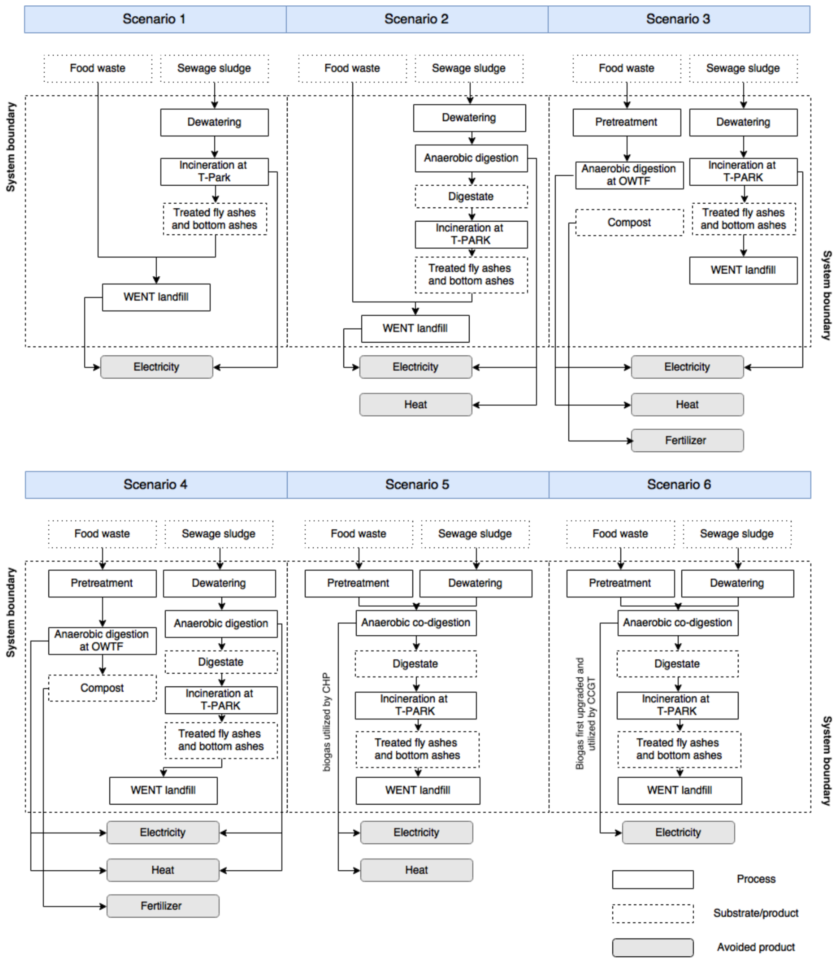


Fig. 2 System boundary of the treatment scenarios for treating 350 tpd of sewage sludge generated from the proposed cavern STWs and 105 tpd of food waste in Hong Kong

Table 1 Description of the feasible waste treatment methods in this study

Feasible treatment/ disposal method	**Waste**	**Description**
West New Territories (WENT) Landfill	Food waste, fly ashes and bottom ashes from T-PARK	Waste is transported to the WENT landfill whenever landfill disposal is required. The landfill gas recovery rate is with reference to Woon and Lo (2014). Uncollected landfill gas is combusted in a flaring system into the atmosphere. Complete combustion is assumed in this flaring process. Leachate is collected and pumped to a landfill leachate treatment plant. A generator fuelled by landfill gas is installed to provide heat and electricity for internal use.
T-PARK (Sludge incinerator)	Sewage sludge	T-PARK has been operated since 2016, and is located at Tuen Mun, Hong Kong, which is next to the WENT Landfill. The maximum treatment capacity of T-PARK is 2,000 tpd of sewage sludge (i.e., with 30% solid content). The heat energy generated from the incineration process is recovered and turned into electricity that can support the needs of the entire facility. Excess electricity is exported to the public grid (HKEPD, 2009a).
Organic waste treatment facility (OWTF)	Food waste	OWTF adopts biological technologies, which consist of AD and composting to stabilize the food waste and turn it into biogas for energy recovery and useful compost products. In OWTF, the biogas produced is combusted to produce heat and electricity by the combined heat and power (CHP) unit. The digestate is used to produce compost for land applications (HKEPD, 2009b). The compost produced avoids the application of artificial fertilizers.
Anaerobic digestion	Sewage sludge	An anaerobic digester is proposed to be built for treating the sewage sludge generated from the cavern STWs. The biogas generated during the AD process is combusted to produce heat and electricity by the CHP unit. The digestate is transported and treated in T-PARK.
Anaerobic co-digestion	Sewage sludge and food waste	The anaerobic digester, originally for sewage sludge AD in the cavern STWs, is used for coAD of sewage sludge and food. In this study, two biogas utilization methods for electricity generation are studied. The operational data of the anaerobic co-digestion process are collected from the Yongyeon Wastewater Treatment Plant in South Korea (Ejlertsson and Magnusson, 2013). The same data are used in the authors' previous study (Chiu et al., 2016) for the following reasons: (1) the plant is reconstructed for anaerobic co-digestion in 2010 in which the technology is compatible with current technology; and (2) Hong Kong and South Korea have a similar Asian diet and their food characteristics are similar. A mixing ratio of 10:3 by wet weight of sewage sludge and food waste is used in this study, based on the South Korean plant. On the one hand, the biogas generated during the coAD process is combusted to produce heat and electricity by the CHP unit in scenario 5. On the other hand, the biogas is utilized by the combined cycle gas turbine (CCGT) in scenario 6 to generate electricity. Biogas is first upgraded to 90% methane content (Woon et al., 2016) and then combusted by the CCGT system, with reference to Gutierrez et al. (2016). The remaining co-digestate is then transported to the T-PARK for combustion.

Table 2 Sources of life cycle inventory data on the substrate composition and waste treatment processes

Processes	Source
Substrate composition	Hoffman and Marmsjö, 2014; IPCC, 2006; Zhao and Deng, 2014
Sludge dewatering and food waste pre-treatment	Bernstad and la Cour Jansen, 2012; Righi et al., 2013
Incineration of sludge	HKEPD, 2009a; IPCC, 2006; Murphy and McKeogh, 2004; Woon and Lo, 2014
Anaerobic digestion /co-digestion	Ejlertsson and Magnusson, 2013; Evangelisti et al., 2014; HKEPD, 2009b; Krich et al., 2005; Pöschl et al., 2010; Swedish Gas Centre, 2012;
Landfill	HKEMSD, 2002; HKEPD, 2009c; IPCC, 2006; Lee et al., 2007; Swedish Gas Centre, 2012; Woon and Lo, 2014
Composting	HKEPD, 2009b; Weidema et al., 2013
Avoided electricity and heat	CLP, 2015; Towngas, 2015

Life cycle impact assessment

SimaPro 7.2.4 software with ReCiPe version 1.04 is applied for life cycle impact assessment (Goedkoop et al., 2009). Four environmental impact categories are chosen as they are most commonly studied with reference to waste LCA, namely climate change, particulate matter formation, photochemical oxidant formation and terrestrial acidification (Bernstad and la Cour Jansen, 2012; Evangelisti et al., 2014). According to the ReCiPe method, climate change, photochemical oxidant formation and particulate matter formation are categorized under the human health endpoint damage category by quantifying the midpoint impact to disability-adjusted life years. On the other hand, climate change and terrestrial acidification are classified under the ecosystems endpoint damage category by quantifying the midpoint impact to the loss of species during a year. Among the midpoint impact categories studied, the midpoint impact with the highest contribution to the endpoint damage is identified as the key impact category. The key impact category is then used as a baseline result for sensitivity analysis so as to identify the key process parameters.

Sensitivity analysis

Sensitivity analysis is conducted for all process parameters in different scenarios based on the key impact category identified. The one-at-a-time method is used for sensitivity analysis as it has been a commonly used method for scientific research due to the ease of implementation as well as being particularly useful in providing early approximation in identifying key parameters (Hemsath and Bandhosseini, 2015; Saltelli et al., 2006). The sensitivity analysis is undertaken by varying one parameter at a time, while keeping the other parameters constant in order to determine the sensitivity of the parameters to variation in the input data variables. The minimum and maximum parameter values, which are considered as the amplitude of sensitivity analysis to reflect the degree of influence of the parameters on the assessment result, are collected from literature. By varying the process parameters with both minimum and maximum values, two sensitivity ratio (SR) values can be calculated respectively and the higher SR value is chosen for the process parameter to reflect its sensitivity. To assess the influence of the process parameters on the result, the SR is calculated for each process parameter using Eq. 1 (Clavreul et al., 2012). Since the SR can be a negative value in the avoided environmental impact result, the absolute value is applied for SR with the aim of determining the sensitivity of the process parameter. A higher SR value indicates higher parameter sensitivity.

$$SR = \left| \frac{\left(\frac{\Delta Result}{Initial\ result}\right)}{\left(\frac{\Delta Process\ parameter}{Initial\ process\ parameter}\right)} \right| \quad (1)$$

Identification of key process parameters

Although SR reflects the sensitivity of the process parameter to the result, the selection of key process parameters cannot be solely determined by an exact value of SR, since there is no standard or reference for SR values. In addition, the SR value of individual process parameters can be different in each study due to the variation of the system boundaries. A more practical way to determine the key process parameters is by selecting parameters with high SR values. Therefore, the relative importance of the SR value should be found in order to determine the significance of the process parameters. In this study, a selection approach based on the relative importance of the SR value is used to identify the key process parameters. The relative importance of the SR can be calculated by dividing an individual SR value with the total SR value of all the process parameters. Afterwards, the cumulative relative importance of SR can be obtained by adding up the relative importance of SR starting from the highest SR value. Once the cumulative relative importance of SR exceeds 50%, those process parameters used for the summation are identified as key process parameters. 50% is used as it represents over half of the sensitivity being contributed by the key process parameters selected.

RESULTS AND DISCUSSION

Results in key impact category

As mentioned in the materials and methods section, four midpoint impact categories are evaluated in this study and their relative contribution to the endpoint damage categories are presented in Table 3. Detailed results regarding the midpoint impact categories are presented in Table 4. Regarding the endpoint damage categories for human health and ecosystems in Table 3, scenarios 4, 5, and 6 have an overall positive environmental performance on human health and ecosystems in general, due to the avoided emissions resulting. It indicates the substitution effect of avoiding direct emissions from energy production from fossil fuels. Scenario 6 performs the best in both endpoint categories, with 52.3% more avoided impacts in human health, and 43.9% more avoided impacts in ecosystems, compared with scenario 5, which is the second best scenario. Based on the contribution from the midpoint impact categories in Table 3, climate change has the highest impact in both endpoint damage categories and hence it is identified as the key impact category.

Fig. 3 illustrates the environmental impacts related to climate change. The positive values represent the emissions of waste treatment that are greater than the avoided impacts resulting from the resource utilization, and vice versa for negative values. Fig. 3 shows that scenarios 5 and 6 are the best two scenarios with -3.78×10^4 kg CO_2e and -6.75×10^4 kg CO_2e per functional unit, respectively. The avoided impacts are mainly contributed by the coAD process, bringing environmental benefits compared to those without using this process. Apart from the coAD process in scenarios 5 and 6, AD processes in scenarios 2, 3, and 4 also result in negative values, which indicates the avoided impacts are greater than the direct impacts of the process. In this study, a default value of 5% for the fugitive CH_4 emissions (IPCC, 2006) is applied for AD and coAD. The avoided impacts are contributed by the energy recovery system in generating heat and electricity, which considerably reduce the negative implications to the environment. Meanwhile, it is interesting to notice that the avoided impacts from scenario 4, which involve AD treatment for sewage sludge and food waste separately, exhibit similar reductions to scenario 5. This is because the compost produced from the food waste digestate can be used as artificial fertilizers which avoids the direct emissions from the production of artificial fertilizers. For direct impacts, both landfilling of food waste and incineration of sewage sludge or digestate at T-PARK create direct impacts on climate change. The landfill gas cannot be completely collected for the energy recovery system and flaring process. As a result, the uncollected landfill gas diffuses from the surface of the landfill and CH_4 is released as a GHG to the atmosphere, resulting in climate change impacts. Regarding the sludge incineration in T-PARK, the most significant contribution during the incineration process is the N_2O emission from the combustion of sewage sludge due to the high nitrogen content (Chiu et al., 2016). Since N_2O is a potent GHG with a global warming potential of 298 (Forster et al., 2007), the incineration of sewage sludge makes a large contribution to climate change. Last but not least, the environmental impacts brought by sludge dewatering and food waste pre-treatment are relatively insignificant compared to other major processes.

Table 3 Midpoint impact category contribution to endpoint damage category in each scenario

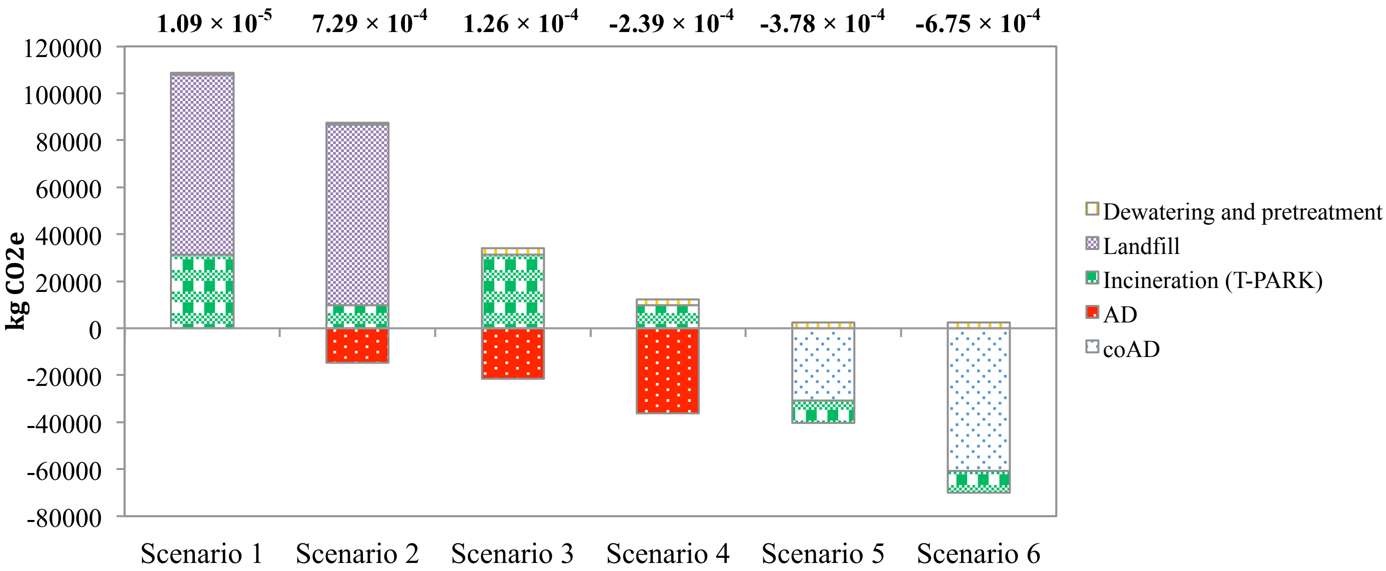
Impact category	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Climate change human health	DALY[a]	0.153	0.102	0.0176	-0.0334[b]	-0.0529	-0.0946
Photochemical oxidant formation	DALY	2.45×10^{-6}	1.70×10^{-6}	-1.23×10^{-7}	-8.65×10^{-7}	-1.75×10^{-6}	-3.77×10^{-6}
Particulate matter formation	DALY	3.58×10^{-3}	7.50×10^{-3}	-4.06×10^{-4}	3.50×10^{-3}	4.97×10^{-3}	3.88×10^{-4}
Human health*	**DALY**	**0.156**	**0.109**	**0.0172**	**-0.0299**	**-0.0479**	**-0.0942**
Climate change ecosystems	species-year	8.65×10^{-4}	5.77×10^{-4}	9.88×10^{-5}	-1.90×10^{-4}	-3.00×10^{-4}	-5.36×10^{-4}
Terrestrial acidification	species-year	-7.30×10^{-8}	-1.52×10^{-7}	-2.97×10^{-7}	-3.76×10^{-7}	-5.31×10^{-7}	-8.43×10^{-7}
Ecosystems*	**species-year**	$\mathbf{8.65 \times 10^{-4}}$	$\mathbf{5.77 \times 10^{-4}}$	$\mathbf{9.85 \times 10^{-5}}$	$\mathbf{-1.90 \times 10^{-4}}$	$\mathbf{-3.01 \times 10^{-4}}$	$\mathbf{-5.37 \times 10^{-4}}$

* Endpoint damage categories
[a] DALY stands for Disability-adjusted life year
[b] Negative value represents a positive impact to the environment

Table 4 Midpoint impact categories results for the baseline case study

Impact category	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Midpoint category							
Climate change	kg CO_2e	1.09×10^{5}	7.29×10^{4}	1.26×10^{4}	-2.39×10^{4}[a]	-3.78×10^{4}	-6.75×10^{4}
Photochemical oxidant formation	kg NMVOC	62.6	43.5	-3.15	-22.2	-44.9	-96.6
Particulate matter formation	kg PM_{10}e	13.8	28.8	-1.56	13.5	19.1	1.49
Terrestrial acidification	kg SO_2e	-12.6	-26.2	-51.3	-64.9	-91.6	-145

[a] Negative value represents a positive impact to the environment



Note: The numbers on top of the figure represent the net environmental impacts/benefits of the scenarios (i.e., positive value represents environmental impact and negative value represents environmental benefit) in kg CO_2e.

Fig. 3 Process contribution by different scenarios to climate change impact category

Identification of key process parameters

Considering climate change impact as the key impact category, sensitivity analysis is then conducted for all the process parameters in order to calculate their respective SR values and relative importance. The values of SR of all the process parameters in each scenario are presented in Table 5. When the cumulative relative importance of the SR value exceeds 50%, those process parameters that are used for the summation are identified as key process parameters in Table 6. It can be summarized that six key process parameters are identified, including, the energy recovery efficiency in sewage sludge incineration plant, CHP (for AD/coAD) and CCGT (for coAD) efficiency, lower heating value of sewage sludge, lower heating value of methane, and percentage of methane in biogas.

The percentage of methane in biogas and the biogas production rate from food waste depend on the characteristics of the waste. These parameters can be improved by applying appropriate pre-treatment technologies to the organic wastes, such as mechanical and thermal pre-treatment (Chiu and Lo, 2016). In order to maintain a good performance of the energy recovery efficiency of the sewage sludge incineration plant, CHP, and CCGT efficiency for electricity, these energy generation facilities need to be frequently cleaned and maintained (Defra, 2013). Meanwhile, the lower heating value of methane cannot be controlled and is relatively a fixed value. The identification of the key process parameters is beneficial to future LCA studies of organic waste and it is suggested that extra efforts should be made to collect more reliable data for these key parameters in order to provide a more accurate result, based on the environmental performance.

Table 5 Sensitivity ratio (SR) for each process parameter in different scenarios

Process parameter	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
Electricity consumption for sludge thickening and dewatering	0.02	0.02	0.11	0.04	0.02	0.02
Electricity consumption for food waste pre-treatment	n.a.[a]	n.a.	0.14	0.07	0.04	0.02
Lower heating value of sewage sludge	0.25	0.11	2.11	0.34	n.a.	n.a.
Lower heating value of digestate	n.a.	n.a.	n.a.	n.a.	0.52	0.29
Energy recovery efficiency (sewage sludge incineration plant)	0.25	0.11	2.05	0.33	0.52	0.29
Bottom ash and treated fly ash production	0.00	0.00	0.00	0.00	0.00	0.00
Energy consumption for internal use (sewage sludge incineration plant)	0.09	0.05	0.88	0.14	0.22	0.12
Biogas production rate (food waste)	n.a.	n.a.	0.71	0.45	n.a.	n.a.
Biogas production rate (sewage sludge)	n.a.	0.19	n.a.	0.68	n.a.	n.a.
Biogas production rate (co-substrate)	n.a.	n.a.	n.a.	n.a.	0.87	0.92
Biogas leakage	n.a.	0.01	0.05	0.06	0.05	0.05
Heat consumption for internal use (AD/coAD plant)	n.a.	0.01	0.03	0.03	0.14	0.01
CHP efficiency (heat) (AD/coAD plant)	n.a.	0.07	0.23	0.33	0.23	0.00
CHP efficiency (electricity) (AD/coAD plant)	n.a.	0.34	1.36	1.76	1.34	0.00
Percentage of methane in biogas	n.a.	0.22	0.90	1.15	0.92	0.97
Lower heating value of methane	n.a.	0.34	1.24	1.83	1.41	1.06
Digestate produced	n.a.	0.14	0.00	0.42	0.25	0.14
Energy consumption for internal use (landfill)	0.06	0.05	0.00	0.00	0.00	0.00
Landfill Gas collection rate	0.04	0.05	0.00	0.00	0.00	0.00
Energy recovery efficiency (landfill)	0.05	0.05	0.00	0.00	0.00	0.00
CCGT efficiency	n.a.	n.a.	n.a.	n.a.	n.a.	1.08
Energy consumption for biogas upgrade	n.a.	n.a.	n.a.	n.a.	n.a.	0.10
Methane loss during biogas upgrade	n.a.	n.a.	n.a.	n.a.	n.a.	0.06

[a] n.a. stands for not applicable

Table 6 Process parameters required to obtain a cumulative relative importance SR value of over 50%

Key process parameters	**Relative importance of SR value (%)**	**Cumulative relative importance of SR (%)**
Scenario 1		
Lower heating value of sewage sludge	33.8	67.6
Energy recovery efficiency (sewage sludge incineration plant)	33.8	
Scenario 2		
CHP efficiency (electricity) (AD/coAD plant)	19.3	
Lower heating value of methane	19.3	50.3
Percentage of methane in biogas	12.5	
Scenario 3		
Lower heating value of sewage sludge	21.5	
Energy recovery efficiency (sewage sludge incineration plant)	20.9	56.0
CHP efficiency (electricity) (AD/coAD plant)	13.6	
Scenario 4		
Lower heating value of methane	24.0	
CHP efficiency (electricity) (AD/coAD plant)	23.1	62.2
Percentage of methane in biogas	15.1	
Scenario 5		
Lower heating value of methane	21.6	
CHP efficiency (electricity) (AD/coAD plant)	20.5	56.2
Energy recovery efficiency (sewage sludge incineration plant)	14.1	
Scenario 6		
CCGT efficiency	21.1	
Lower heating value of methane	20.7	60.7
Percentage of methane in biogas	18.9	

Evaluation of carbon reduction in the waste sector with the best scenario

With the best scenario obtained, an evaluation of carbon reduction in the waste sector is conducted in order to determine the contribution of the proposed waste treatment scenario for the carbon reduction target in Hong Kong. In Hong Kong, a carbon reduction target was set in 2010, to reduce the carbon intensity (i.e., carbon emissions per unit of GDP) by 50-60% from the 2005 level by 2020. However, the carbon emissions produced from the waste sector contradictorily increased by around 9% compared to the reference year 2005 in 2014 (HKEPD, 2016). If scenario 6 (i.e., the best scenario obtained) is applied in the future, a carbon reduction of -5.32×10^4 kg CO_2e per day can be achieved. It is approximately equal to a 1% reduction of carbon emissions in the waste sector with reference to the year 2005. These findings underpin the significant contribution of proposed waste treatment strategy in reducing carbon emissions in order to meet the carbon reduction target in Hong Kong.

CONCLUSIONS

This study applies LCA to evaluate the environmental performance of different treatment systems for sewage sludge and food waste with reference to the Hong Kong situation. The endpoint damage results indicate that scenarios 5 and 6, which involve coAD as the major treatment method, are more advantageous over other possible treatment methods for these wastes. Among the midpoint impact categories studied, climate change impact is the key impact category with the highest contribution to environmental performance. By studying the key midpoint impact, it is found that coAD treatment contributes the greatest environmental benefits while landfilling brings the greatest environmental burdens to the waste treatment scenarios. Regarding the use of CHP and CCGT for biogas utilization, scenario 6 (i.e., coAD with CCGT) has -6.75×10^4 kg CO_2e avoided emissions while scenario 5 (i.e., coAD with CHP) has only -3.78×10^4 kg CO_2e avoided emissions, indicating a significant advantage of CCGT over CHP. The key impact category then serves as a baseline category for sensitivity analysis in the proposed selection approach for the identification of the key process parameters. With respect to the key process parameters identified, the electricity generation efficiency in waste treatment plants is commonly regarded as having the greatest sensitivity in each scenario. It suggests more attention should be paid to these processes in future waste LCA studies in order to evaluate the environmental performance. If scenario 6 (i.e., the best scenario obtained) is applied in the future to treat 350 tpd of sewage sludge produced from the proposed cavern STWs and 105 tpd of food waste, it approximately reduces 1% of the carbon emissions in the waste sector with reference to the year 2005 in Hong Kong. It underpins the significant contribution of reducing carbon emissions in order to meet the carbon reduction target in Hong Kong. It is concluded that coAD treatment is more advantageous than other treatment methods for sewage sludge and food waste treatment, and CCGT is particularly suitable for biogas utilization for electricity generation in countries or cities with limited heat demand, like Hong Kong.

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