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Life-cycle Cost-benefit Analysis on Sustainable Food Waste Management: the Case of Hong Kong International Airport

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Abstract

Food waste is responsible for a significant portion of solid waste generation in the international airports, where efficient on-site or off-site sorting and recycling may be feasible. The aim of this study is to develop a Life-Cycle Cost-Benefit Analysis (LC-CBA) framework, through the integration of the life-cycle assessment (LCA) and cost-benefit analysis (CBA), to guide decision-making in sustainable food waste management. The analysis tool assesses the environmental and economic performance of different food waste management options, as demonstrated in a case study of the Hong Kong International Airport with six food waste handling scenarios consisting of different combinations of treatment technologies. Both centralized (i.e., off-site) and on-site treatment options were evaluated. The on-site incineration scenario was found to be the most sustainable option with the lowest life-cycle net costs of

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HKD 461.73/tonne. The scenario achieved the highest energy recovery of 707 kWh/tonne, which led to an economic savings of HKD 697.81/tonne and an environmental savings of HKD 470.96/tonne. The LC-CBA developed in this study is widely applicable to inform decision-making on sustainable food waste management worldwide.

Keywords: Organic waste, Incineration, Anaerobic digestion, Energy recovery, Organic resource recovery, On-site treatment.

Introduction

The global food waste generation amounts to 1.3 billion tonnes per annum, which embeds an immense carbon footprint of 3.3 billion tonnes of CO_2 equivalent (FAO, 2013). The food waste problem is particularly significant in developed and densely-populated municipalities, for example, accounting for 60% and 86% of the putrescible waste in the United States and Hong Kong, respectively (Buzby et al., 2014; HK EPD, 2016a). In the Hong Kong International Airport (HKIA), which serves more than 60 million passengers annually, food waste accounts for 35% of the waste collected for recycling (Airport Authority Hong Kong, 2014). Therefore, food waste management offers high potential for achieving sustainability if properly managed, or otherwise causes significant environmental burdens if improperly handled. Although the direct landfill disposal of food waste has been restricted or prohibited in some jurisdictions, such as Massachusetts in the United States and Republic of Korea (Behera et al., 2010; Spencer, 2016), it remains as a common treatment option around the world, which is non-sustainable considering the pronounced greenhouse gas (GHG) emissions (Levis and Barlaz, 2011). To achieve food waste reduction, recycling, and energy recovery, alternative on-site and/or off-site treatments, such as anaerobic digestion (AD), composting and incineration, should be introduced to divert the food waste from landfills (European Union, 2016; HK EPD, 2017a; OSWER US EPA, 2015).

The environmental feasibility of the available food waste treatment alternatives including AD, composting, and incineration varies with the practices and infrastructure capacity. Life-cycle assessment (LCA) is a widely-recognized decision-supporting technique (Curran, 2006) that has been adopted to evaluate waste management strategies on municipal solid waste (MSW) (Song et al., 2013; Woon and Lo, 2014), food waste (FW) (Kim and Kim, 2010; Saer et al., 2013), sewage sludge (Lam et al., 2016), and other wastes (Rocchetti et al., 2013; Simion et al., 2013). In a food waste composting system, the emissions from the decomposition process contributed the most to the overall environmental impacts (Saer et al., 2013). Khoo et al. (2010) evaluated composting, AD, incineration, and the proposed new aerobic composting plant in Singapore via LCA, among which the AD facility with an expanded capacity would be the most environmentally favorable. Although LCA is an appropriate tool for evaluating the environmental performance of the different food waste management scenarios, it excludes the economic and the social impacts of the scenarios, which are also essential elements of sustainability (ISO 14040, 2006; Manfredi et al., 2011).

Economic instruments provide incentives for the decision makers to prioritize the utilization of resources in the society such that the social welfare could be maximized (Dunlop and Radaelli, 2016). Cost-benefit analysis (CBA) is an analytical approach that evaluates the favorability of investment decisions on social welfare. Via the quantification of the internal and external costs and benefits caused by the investment decisions, a single aggregated welfare function could be provided to guide decision-making (European Commission, 2014; US EPA, 2014). Such decision tools facilitate a rational thinking and avoid bias by the consideration of the total social utility (Mourato et al., 2006). Options with different attributes, effects on human well-being, and efficiencies on resource utilization could be analyzed and compared by the CBA tool (Kopp et al., 1997; Morrissey and Browne, 2004). Karmperis et al. (2013) identified several benefits of the CBA application in the waste management sector, such as the capability of comparing the economic consequences of different technical options, as demonstrated in the comparison between incineration with and without energy recovery. The CBA also allows the inclusion of external environmental impacts and the associated social benefits or costs upon valuation to inform the sustainable waste management. Considering the complementary strengths of the LCA and CBA approaches, a holistic life-cycle cost-benefit analysis (LC-CBA) framework by the integration of such approaches is considered necessary for evaluating the food waste treatment technologies in a comprehensive manner.

The first purpose of this study is to develop an LC-CBA framework for sustainable food waste management by (1) evaluating the environmental impacts of different food waste treatment options using the LCA approach, (2) linking the environmental results to the CBA through the economic valuation of emissions, and (3) assessing the sustainability and providing single final indicator for each food waste management option under evaluation in this study. The second purpose of this study is to guide sustainable decision-making in the selection of the food waste treatment technologies. Various factors, such as the distances between treatment facilities, the scale of facilities and the technologies adopted, that could influence the favorability of the options (Lundie and Peters, 2005; Lundin et al., 2000) are included in the LC-CBA framework. The framework is demonstrated in a case study of food waste management in the Hong Kong International Airport (HKIA), where efficient waste sorting, recycling, and treatment could be feasible on-site or off-site.

Methodology

Background of case study

The HKIA is located 40 kilometers away from the city center and is considered to be one of the busiest airports in the world (Airport Authority Hong Kong, 2014; ACI, 2017). To achieve sustainability, the Airport Authority has established strategies for reducing food waste disposal at landfills. The strategies include the target of attaining a recycling rate of 50% of the total waste generation in the terminal by 2021. In 2016, approximately 46% of the total waste generated in the HKIA was composed of recyclable wastes, which are mainly food and paper wastes (Airport Authority Hong Kong, 2016a, 2016b). Therefore, proper food waste management presents notable potential on the facilitation of sustainable operation of the HKIA. Numerous strategies for handling the annual amount of 1,150 tonnes of food waste were analyzed and compared in this study to guide the selection of the most sustainable option.

Sustainable food waste management is a possible solution to alleviate the food waste problem and the landfilling overcapacity in Hong Kong.

Life-cycle cost-benefit analysis framework

Figure 1 illustrates the integrated LC-CBA framework. The system boundary defines which processes are included in the LCA. To ensure the consistency between the environmental and economic analysis, the same system boundary and time scope are defined for both decision-supporting tools (Figure 1). The environmental performance of different food waste management options would be assessed by the LCA approach. The principles and methodological framework of LCA have been standardized by the International Organization for Standardization (ISO) in ISO 14040 and 14044 (ISO 14040, 2006; ISO 14044, 2006). A standard LCA includes four main phases: goal and scope definition, life-cycle inventory (LCI) analysis, life-cycle impact assessment (LCIA), and data interpretation. The overall sustainability of the options would take three essential aspects, namely the environmental, economic and social performance, into consideration using the CBA approach. The LCA results, which are the environmental impacts, were monetarized through economic valuation and included as the external environmental costs in the LC-CBA. The final results would be the net costs of scenarios given in monetary terms which could be easily understood and effectively guide the decision-making process.

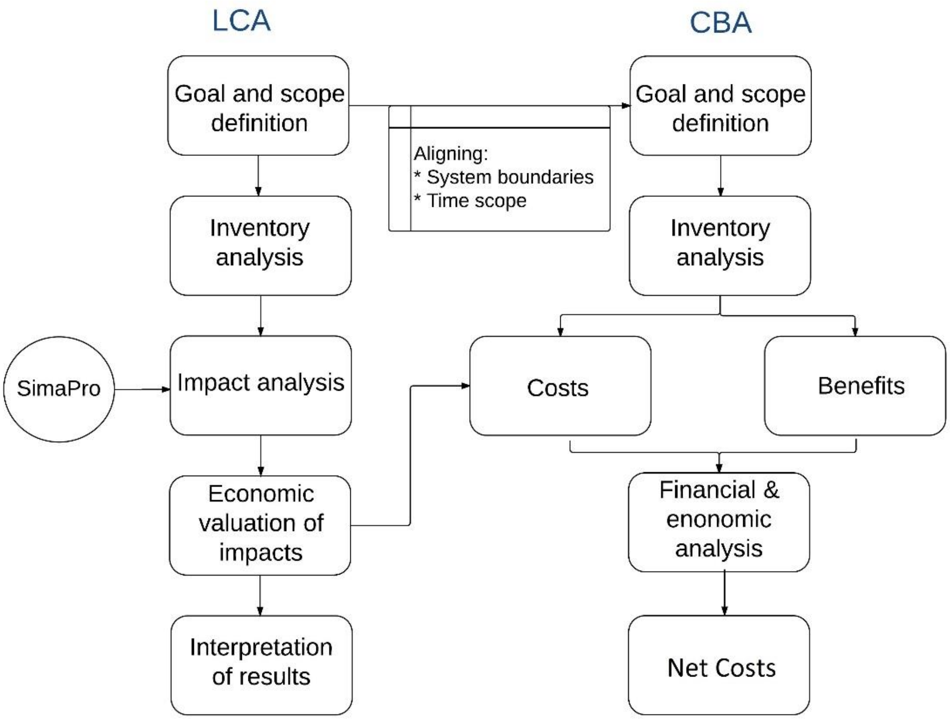

Figure 1 Integrated LC-CBA framework

Life-cycle assessment

Goal and scope definition

The goal of the LCA part of this study is to evaluate the environmental performance of the different food waste treatment options. The functional unit (FU) in an LCA defines the primary function of the product or the system being analyzed. The quantitatively defined FU provides a common unit for the analysis, thus a convenient comparison between entities could be made (de Bruijn et al., 2002; Rebitzer et al., 2004). As the scenarios in this study include different food waste treatment and disposal options which serve the same purpose of handling the food waste, the FU is defined as the management of 1 tonne of food waste (Chaya and Gheewala, 2007). The system boundary of the LCA covers the transportation, treatment, and disposal of the food waste generated from the HKIA and the lifetime of the operation of facilities was defined to be 15 years, which is consistent with the designed lifetime of the waste handling facilities (HK LegCo, 2014a; World Bank, 1999).

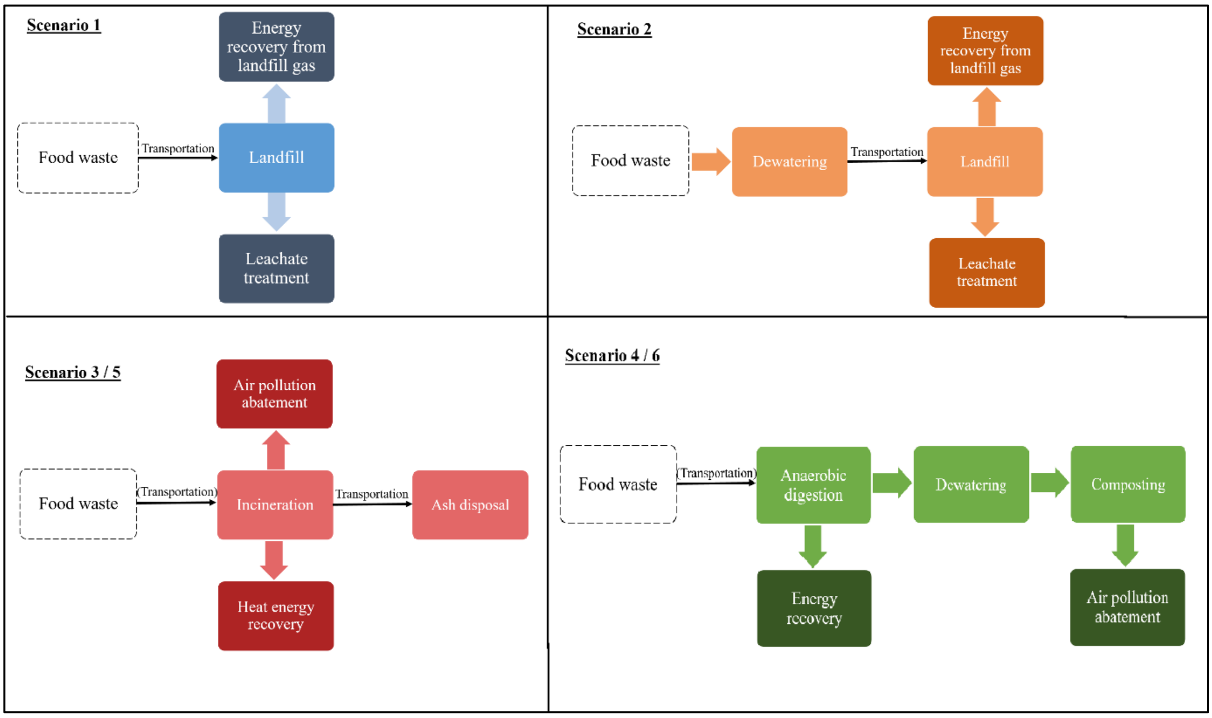

Figure 2 Food waste treatment scenarios

Six food waste management scenarios (Figure 2) are defined based on the existing treatment practice (Scenario 1 to 4) and the proposed treatment methods (Scenario 5 and 6) in Hong Kong. Scenario 1 (S1) is the direct landfill disposal of food waste, while Scenario 2 (S2) includes the dewatering of food waste before landfill disposal. Scenario 3 (S3) adopts the centralized incineration of wastes with energy recovery, and the ash is disposed of at the landfill. Scenario 4 (S4) adopts centralized organic waste treatment processes including AD, dewatering and composting. Scenario 5 and 6 (S5 and S6) apply the same treatment processes as in S3 and

S4, respectively, yet the food waste is treated by on-site infrastructure. Transportation of food waste is required between the HKIA and the treatment facilities (except for S5 and S6 which are on-site treatment scenarios) and from the treatment facilities to the disposal sites.

Life-cycle inventory analysis

A process-based LCA approach was adopted in this study in which the LCI was established based on the information of the inputs and outputs involved in the specific processes in each scenario. Some general components reckoned for the scenarios include the direct emissions, indirect emissions, and the emissions avoided from energy recovery. Table 1 lists the items included in the LCI for each scenario.

Table 1 LCI items for the six scenarios

Inventory items	**S1**	**S2**	**S3 / S5**	**S4 / S6**
Transportation	▪ From HKIA to landfill	▪ From HKIA to landfill	▪ From HKIA to incinerator* ▪ From incinerator to landfill	▪ From HKIA to organic waste treatment facility*
Treatment / disposal process	▪ Organic waste degradation in landfill	▪ FW dewatering ▪ Organic waste degradation in landfill	▪ Incineration	▪ AD ▪ Dewatering ▪ Composting
Energy recovery	▪ Energy from landfill gas (LFG)	▪ Energy from LFG	▪ Energy from FW incineration	▪ Energy from biogas in AD
Air pollution control	N.A.	N.A.	▪ Activated carbon, selective non-catalytic reduction (SNCR) and scrubber	▪ Odour treatment unit ▪ Air pollution control unit
Destination of by-product	▪ Leachate treatment ▪ LFG flaring	▪ Leachate treatment ▪ LFG flaring	N.A.	▪ Biogas flaring
Destination of end-product	N.A.	N.A.	▪ Solidification of fly ash	▪ Compost application on

			▪ Ash disposal in landfill	landscaping in facilities

*The transportation processes are excluded for on-site scenarios (S5 and S6)

In S1, the food waste is transported by the refuse collection vehicles (RCVs) from the HKIA to the North Lantau Transfer Station (NLTS) (12.3 km) and then transferred to the West New Territories (WENT) landfill by marine vessels (20.5 km) for final disposal (HK ACE, 1998). The emissions from the RCVs and vessels were accounted in the LCA. Food waste is an organic waste that contains a high content of carbon, which will be converted into carbon dioxide (CO_2) and methane (CH_4) during the degradation in a landfill. The landfill gas collection efficiency of the landfills is 95%, while the remaining landfill gas is leaked to the atmosphere (US EPA, 2011); for the landfill gas collected, about 80% is used for energy production and the remaining 20% is flared (HK EPD, 2016b). The indirect emissions from the electricity and resource consumption for leachate treatment were included.

Upon the introduction of Waste Charging Scheme, food waste is dewatered on-site in the HKIA before transportation to the landfill for disposal in S2. The dewatering process could reduce the weight and the volume of food waste by 78.5% and 58.8% respectively (Sotiropoulos et al., 2016). A screw press system with appropriate treatment capacity at 140 to 450 kg per hour was chosen for dewatering the food waste from the HKIA (Vincent Corporation, n.d.). The major emissions from the dewatering process are the indirect emissions associated with the electricity consumption. The other processes included in the LCI of S2 are similar to those in S1.

The food waste is assumed to be incinerated in the future Integrated Waste Management Facilities (IWMF) in Shek Kwu Chau, Hong Kong, in S3. The food waste is transported to the NLTS by RCVs (12.3 km), and then to the IWMF by marine vessel (32 km) (HK EPD, 2008). Advanced incineration technology is adopted in the IWMF to reduce the waste volume by more than 90% before the landfill disposal of waste (HK EPD, 2015). The energy stored in the waste will be recovered in forms of heat and electricity through the boiler and steam turbines in the facility. The exhaust gas from the boiler will be treated by the scrubbers, activated carbon, bag house filter, and selective non-catalytic reduction before releasing into the atmosphere (HK EPD, 2015). The bottom ash will be disposed of at landfill, and the fly ash will be solidified by cement before disposal (HK EPD, 2015). The final product, which is the incineration ash, will be transported to the WENT landfill for disposal by marine vessel (52.3 km).

In S4, the food waste is assumed to be transported by RCVs to the Organic Waste Treatment Facilities (OWTF) (12 km), which is located at Siu Ho Wan in the North Lantau, for AD, dewatering and composting. During the AD process, biogas containing about 60% of CH_4 will be collected for electricity generation. Thus, the energy content of the food waste is recovered. The digestate is then dewatered using a screw press dewatering system before composting. The compost is assumed to be used for the landscaping within the facilities. The direct atmospheric emissions from the composting process are controlled by an air pollution control unit (APC) which uses biofilter technique (Lui, 2011).

S4 and S6 are on-site treatment scenarios which adopt the same treatment technologies as S3 and S5, respectively. The transportation from the HKIA to the treatment facilities is omitted for S4 and S6. In S4, an on-site incineration is assumed to be built in the HKIA for treatment the total solid wastes generated from the airport. An on-site organic waste treatment facility with AD, dewatering, and composting installations is assumed to be constructed in the HKIA for handling food waste and other organic wastes, such as paper waste, from the airport.

Life-cycle impact assessment

Based on the LCI of the six food waste management scenarios, the associated emissions were estimated. The LCIA was conducted using the ReCipe Endpoint method and the LCA software used was SimaPro 8.3 (PRé Sustainability, 2017).

For the estimation of transportation emissions, the distances of transportation were estimated by the measurement on the map. The EMission FACtors (EMFAC) model version 3.3 (HK EPD, 2017b) is used to estimate the emissions from the RCVs in this study. The EMFAC model was developed by the Hong Kong Environmental Protection Department (EPD) based on the modifications on the California Air Resources Board (CARB) EMFAC model to fit the local climate conditions in Hong Kong. The model covers the emission rates of all types of motor vehicles operating on roads and highways in Hong Kong. The traffic data from the Transport Department (TD) is adopted in the model to allow location-specific information to be obtained. The general principal for the estimation of vehicle emissions using EMFAC version 3.3 model could be expressed as (HK EPD, 2017b):

$$\text{Emissions (tonnes per day)} = \text{Emission factor (tonnes per km)} \times \text{Correction factor} \times \text{Travel activity (km per day)} \quad \text{Eq.(1)}$$

The vehicle emissions, in tonnes per day, are estimated based on the emission factor and the travel activities. The emission factors, in tonnes per kilometer travelled, of different primary pollutants were measured using the portable emission measurement systems. The primary pollutants relevant to vehicle activities, including hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), carbon dioxide (CO_2) and particulate matter (PM), are included in the model estimation (HK EPD, 2017b). Speed meters were installed on vehicles to measure the speed and the travel activities in kilometers travelled per day. The EMFAC modeling results were compared to the dataset in Hong Kong to yield the correction factor. It was assumed that RCVs with a body volume of 16 m^3 is used to transfer the waste to the NLTS every day. The estimation of emissions from vessel transportation was based on the associated fuel consumption and the diesel fuel consumption for container vessels is 25.65 L/km according to Halford (2015). The transportation emissions originated from the food waste were estimated based on the proportion of food waste to the volume of the RCV or the vessel.

The First Order Decay (FOD) model for solid waste disposal sites (SWDS) developed by the Intergovernmental Panel on Climate Change (IPCC) was used for estimation of landfill gas

(LFG) produced by the landfilling of food waste (IPCC, 2006). The model accounts for the conversion of the degradable organic carbon (DOC) content of the waste into CH_4, which is the main component of LFG. The FOD model estimates the methane generation potential of the decomposable portion of the waste disposed of at the SWDS in a certain year, and such potential will decrease over time. This indicates that methane will be released from the decomposing waste disposed in a specific year and the emission will be at the highest level during the first few years after disposal. As the complete decomposition may take decades, the total LFG emissions associated with an annual amount of 1,150 tonnes of FW for the lifetime of 15 years were calculated. The average value of LFG emissions (m^3 per tonne of FW) over the 15-year time period was then taken to represent the emissions from 1 tonne of FW (i.e., the FU defined in this study). The calculation starts from the estimation of the mass of the degradable organic carbon deposited (DDOCm) in the SWDS using Equation 2:

$$DDOCm = W \times DOC \times DOC_f \times MCF \qquad \text{Eq.(2)}$$

where DDOCm is the degradable organic carbon deposited (Gg), W is the waste deposited (Gg), DOC is the fraction of the degradable organic carbon, DOC_f is the decomposable fraction of waste, and MCF is the CH_4 correction factor. The DOC content in the food waste is assumed to be 15% by wet weight (IPCC, 2006). As the complete degradation takes numerous years, the remaining waste from one year would be accumulated in the SWDS and continue to decompose in the following years. The degradable organic carbon accumulated at a specific year could be estimated by Equation 3.

$$DDOCma_T = DDOCmd_T + (DDOCma_{T-1} \times e^{-k}) \qquad \text{Eq.(3)}$$

where $DDOCma_T$ is the DDOCm accumulated at the end of year T (Gg), $DDOCmd_T$ is the DDOCm deposited in the SWDS in year T (Gg), $DDOCma_{T-1}$ is the DDOCm accumulated at the end of the year (T-1), and k is the reaction constant. A decay rate (k) of 0.4 is used in the moist tropical climate in Hong Kong for food waste as it is a rapidly degradable material (IPCC, 2006). Then the mass of the DDOCm decomposed (DDOCm $decomp_T$) in the SWDS for an inventory year could be estimated by Equation 4.

$$DDOCm\ decomp_T = DDOCma_{T-1} \times (1 - e^{-k}) \qquad \text{Eq.(4)}$$

With known DDOCm $decomp_T$, the fraction by volume of CH_4 in LFG (F) and the ratio between the molecular weight of CH_4 and carbon (16/12), the methane generated in the year T (CH_4 $generated_T$) could be computed using Equation 5.

$$CH_4\ generated_T = DDOCm\ decomp_T \times F \times 16/12 \qquad \text{Eq.(5)}$$

With the assumption that the fractions for both the CH_4 and CO_2 in the LFG are 0.5, the CO_2 generation of landfill disposal of FW could be estimated using the above method. The parameters used for calculating the CH_4 emissions from landfill disposal of food waste are listed in Table 2.

The environmental impacts originated from the FW dewatering process were considered to be the indirect emissions from the electricity consumption of the dewatering machines. The power and the operating duration of the dewatering machine were used to estimate the electricity consumption (Table 3).

Table 2 Inputs for estimation of CH_4 from FW landfilling

W (Gg FW/year)	1.15
DOC (Gg carbon/Gg FW)[d]	0.15
DOC_f [d]	0.5
MCF [d]	1
DDOCm (Gg carbon/year)	0.08625
k [d]	0.4

Table 3 Inputs for LCIA on FW dewatering

Treatment capacity[e] (kg/hr)	294.84
Motor power[g] (kW)	2.61
Amount of food waste (kg/day)	3150.68
Operating hour (hr/day)	10.69
Electricity consumption (kWh/year)	10180.08
Electricity consumption (kWh/tonne FW)	8.85

The stack emissions, fuel consumption and ash production from incineration were based on the data inventory in the LCA study on food waste and sewage sludge treatment in Macau (Chiu et al., 2016). Information on most of the air emissions, fuel consumption, and ash production was based the field survey in Macau (Song et al., 2013). The GHG emission data were based on the Intergovernmental Panel on Climate Change (IPCC) model, while emissions

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[d] (IPCC, 2006).

[e] (Vincent Corporation, n.d.)

including volatile organic compounds (VOCs) and respirable suspended particulate (RSP) were based on the estimation in the previous literature (IPCC, 2006; Woon and Lo, 2014). The amount of electricity consumption and material requirements for the ash treatment using cement solidification and the air pollution control technologies, including activated carbon injection, SNCR and scrubber were also covered in the LCI (Møller et al., 2011; Song et al., 2013).

Table 4 Inputs for LCIA of FW incineration (per tonne FW)

SO_2 (kg)[f]	$1.00x10^{-2}$	Bottom ash (tonne)[f]	$1.80x10^{-1}$
HCl (kg)[f]	$8.90x10^{-3}$	Diesel consumption (MJ)[f]	$1.57x10^{1}$
NO_x (kg)[f]	$2.40x10^{-1}$	Gasoline consumption (MJ)[f]	$1.86x10^{1}$
NH_3 (kg)[f]	$1.10x10^{-2}$	Electricity consumption (kWh)[g]	$8.65x10^{1}$
CO (kg)[f]	$3.00x10^{-2}$	Iron (kg)[i]	$2.60x10^{-1}$
VOCs (kg)[f]	$1.32x10^{-1}$	Wastewater (m^3)[i]	$8.50x10^{-2}$
HF (kg)[f]	$2.65x10^{-2}$	Activated carbon (kg)[i]	$2.10x10^{-1}$
Dioxin and furans (kg)[f]	$6.60x10^{-10}$	Aqueous ammonia (kg)[i]	$7.30x10^{-1}$
PM_{10} (kg)[f]	$1.98x10^{-1}$	Slaked lime (kg)[i]	7.86
CH_4 (kg)[f]	$2.00x10^{-4}$	Cement (kg)[i]	1.51
N_2O (kg)[f]	$5.00x10^{-2}$	Electricity consumption for SNCR (kWh)[h]	$1.80x10^{-1}$
Fly ash (tonne)[f]	$3.60x10^{-2}$	Electricity recovered (kWh)[i]	$7.07x10^{2}$

The emissions from the AD process, the combined heat and power (CHP) system, flaring

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[f] (Chiu et al., 2016).

[g] (Song et al., 2013).

[h] (Møller et al., 2011).

[i] Calculated based on the heating value of FW (21MJ/dry kg FW), a moisture content of 79.8% of the FW in Hong Kong and the average combined heat and power (CHP) system efficiency of 60% (Chiu et al., 2016; OAR US EPA, 2015).

system and the odour treatment unit were estimated mainly based on the Environmental Impact Assessment report for the OWTF in Hong Kong (HK EPD, 2013). The leakage of CH_4 and CO_2, which are the major constituents of the biogas, from the anaerobic digestor was also considered, and the fraction of leakage was assumed to be 5% (IPCC, 2006). The energy recovery from AD was estimated based on the energy content of CH_4 and the generator efficiency (Chiu et al., 2016). The environmental impacts originated from dewatering were evaluated using the method introduced above. The GHG emissions from composting, such as CH_4 and N_2O, were included in the LCI. The environmental impacts from the air pollution control technique using biofilter were considered (Bindra et al., 2015; HK EPD, 2013).

Table 5 Inputs for LCIA of organic waste treatment processes for FW (per tonne FW)

AD	
SO_2 (kg)[j]	1.85E-02
HCl (kg)[j]	3.71E-03
NO_x (kg)[j]	1.11E-01
CO (kg)[j]	2.41E-01
VOCs (kg)[j]	3.05E-01
HF (kg)[j]	3.71E-04
PM_{10} (kg)[j]	8.85E-02
N_2O (kg)[j]	1.38E-02
CH_4 leakage (kg)	2.45E+00
CO_2 leakage (kg)	4.50E+00
Electricity recovery (kWh)	2.78E+02
Heat recovery (MJ)	1.23E+03
Dewatering	
Electricity consumption (kWh)[k]	4.43

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[j] (Chiu et al., 2016; HK EPD, 2013).

[k] (Vincent Corporation, n.d.)

Composting	
CH_4 (kg)[1]	1.83E+00
N_2O (kg)[n]	7.50E-02
NH_3 (kg)[n]	4.06E-01

Life-cycle cost-benefit analysis

To assess the sustainability of the FW management options, the three essential components of sustainability, namely the economic, environmental, and social aspects, should be considered. The economic costs and benefits, which are already in monetary terms, could be included in the CBA directly, while a valuation process should be conducted to convert the environmental and social performance into external costs and benefits for the inclusion in the CBA. The total cost and the total benefit in the CBA consist of three components, as shown in Equation 6 and Equation 7.

$$TC = C_{econ} + C_{env} + C_{soc} \qquad \text{Eq.(6)}$$

$$TB = B_{econ} + B_{env} + B_{soc} \qquad \text{Eq.(7)}$$

where TC represents the total cost, C_{econ} is the economic costs, C_{env} is the environmental costs and C_{soc} is the social costs, and; TB represents the total benefits, B_{econ} is the economic benefits, B_{env} is the environmental benefits, and B_{soc} is the social benefits. All the costs and benefits of this study were presented in present values (PVs) of the year 2016 using a discount rate of 4%, which is commonly adopted by the Hong Kong government in evaluating infrastructure

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[1] (Saer et al., 2013).

projects (HK EPD, 2013). For consistency between the LCA and CBA, the same FU and lifetime, which is 1 tonne of food waste and a 15-year project lifetime respectively, were defined for the CBA. The final results of the LC-CBA are the net costs of the scenarios, which are presented in the unit of HKD per tonne of food waste.

Economic costs and benefits

The economic costs and benefits assessed include the capital, the operation, and the transportation costs. The capital and the operation and maintenance (O&M) costs of the waste treatment and disposal facilities, including the WENT landfill, incinerator at the IWMF and the OWTF, were referred to government documents and previous literature (HK LegCo, 2014b, 2014c, 2013; Woon and Zhou, 2015). The capital costs were annualized using Equation 8.

$$Cap_{annualized} = Cap \times \frac{i}{1-(1+i)^{-n}} \qquad \text{Eq.(8)}$$

where $Cap_{annualized}$ is the annualized capital cost, Cap is the capital cost, i is the discount rate (4%) and n is the number of years of the lifetime (15 years). The operation costs of the dewatering facilities were estimated based on the labour and the electricity costs (CLP, 2016; HK LD, 2017). The economic benefit from energy recovery was estimated as the avoided costs for electricity. The economic benefit of the compost produced from the OWTF was taken as HKD 516.94/tonne based on a case in a Taiwanese study in which there is no market for the compost so the compost is used by the parties that involved in the waste recycling (Chen, 2016). The transportation costs were estimated based on the travelling distances, diesel consumption and the diesel price (Shell, 2016). The major inputs for analyzing the economic costs and benefits are a list in Table 6.

Table 6 Inputs for economic costs and benefits of different processes

Facilities	Items	Costs (HKD)
WENT landfill extension	Capital cost[m]	10.53 billion
	O&M per tonne of wastes[n]	237.4
	Waste charge[o]	400.0
Dewatering	Labour wage per hour[p]	32.5
	Electricity cost per kWh[q]	0.987
Incineration	Capital cost[r]	12.27 billion
	Annual O&M[u]	434.80 million
Organic waste treatment facilities	Capital cost[s]	1.25 billion
	Annual O&M[v]	78.31 million
	Compost value per tonne[t]	516.94
Transportation	Diesel price per liter[u]	10.96

The net economic costs of the scenarios could be computed using Equation 9:

$$Net\ C_{econ} = Cap_{annualized} + OC_{annual} + T_{annual} - OB_{annual} \qquad \text{Eq.(9)}$$

where Net C_{econ} denotes the net economic cost, $Cap_{annualized}$ is the annualized capital cost, OC_{annual} is the annual operation cost, T_{annual} is the annual transportation cost, and OB_{annual} is the

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[m] (HK LegCo, 2013)

[n] (Woon and Zhou, 2015)

[o] (HK ACE, 2015)

[p] (HK LD, 2017)

[q] (CLP, 2016)

[r] (HK LegCo, 2014c)

[s] (HK LegCo, 2014b)

[t] (Chen, 2016)

[u] (Shell, 2016)

annual operation benefits.

Environmental costs and benefits

Monetary values are used as the principal evaluation unit in the CBA, while a number of environmental emissions, either with or without weighting, are measured in an LCA. The results of the two assessment results could be integrated only if the environmental impacts could be converted into monetary terms. Thus, it was proposed that the linkage between the LCA and the CBA is the monetary valuation of the environmental impacts (Powell et al., 1995).

An economic valuation of the environmental emissions was conducted to convert the emissions evaluated in the LCA into monetary terms so that the LCA results could be integrated into the CBA. Only the certain species of air emissions, which have been identified to have the most significant environmental impacts as reported in previous LCA studies in Hong Kong, were included (Woon and Lo, 2016, 2014). The information on the included emissions with their economic costs listed in Table 7 was extracted from previous local LCA studies on waste treatment strategies (Woon and Lo, 2016). The avoided emissions from energy recovery in forms of electricity and heat were included as the environmental benefits which brought external economic savings to the scenarios. The net environmental costs equal the summation of the external environmental emission costs minus the summation of the environmental benefits from the avoided emissions (Equation 10).

$$Net\ C_{env} = \left(\sum_i EM_i - \sum_i EMv_i\right) \times EV_i \qquad \text{Eq.(10)}$$

Table 7 External environmental costs of air emissions (Woon and Lo, 2016)

Category	Air pollutant compound	HKD/kg emission compound[w]	HKD/kg emission compound (Present value in 2016)[x]
Waste transport	CO_2	0.10	0.11
	NO_x	38.51	41.65
	SO_2	61.95	67.00
	Respirable suspended particulate (RSP)	2,040.00	2,206.46
Urban pollution	CO_2	0.10	0.11
	NO_x	18.19	19.67
	SO_2	31.105	33.64
	RSP	397.37	429.79
	Total of 9 heavy metals[v]	3,370.00	3,644.99
	Mercury	118,000.00	127,628.80
	Total cadmium & thallium	576.78	623.85
	Dioxins and furans	273,600,000.00	295,925,760,000.00

where EM_i denotes the quantity of air emission i, EMv_i denotes the avoided quantity of emission i and EV_i denotes the economic value of the emission i as given in Table 7.

Social costs and benefits

There are two major external social costs generated by the MSW facilities in Hong Kong,

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[v] The heavy metals include As, Co, Cr, Cu, Mn, Ni, Pb, Sb and V.

[w] Adopted from Woon and Lo (2016). Base year for the values is 2014.

[x] Converted to present values in year 2016, using formula $F=P(1+i)^n$, where F denotes future value, P denotes present value, i denotes discount rate (4%), and n denotes number of years.

namely the opportunity cost of land and the disamenity cost (Woon and Zhou, 2015). To account for the significant opportunity cost of land utilization in densely populated cities, such as Hong Kong, the local premium cost of sub-urban land for recreational purposes was used in the estimation (HKLegCo, 2005; Woon and Lo, 2016). The disamenity cost was represented by the reduction of housing prices in the surrounding areas near the MSW management facilities (Woon and Lo, 2016). The social disamenity costs are sensitive to the distance between the housings and the facilities, the population of residential apartments in the defined area and the housing prices in the area. Based on the study conducted by Brisson and Pearce (1996), a 5.2% price reduction was applied for a distance between 3.2 and 4.8 kilometers and 1.4% for a distance between 4.8 and 5.5 kilometers. The local price information was used for the housing prices in the surrounding areas of the facilities.

Results and discussions

Life-cycle assessment

The environmental emissions originated from the FW treatment processes were characterized, normalized and weighted using the ReCipe Endpoint method to give the overall environmental impacts of the six FW management scenarios. Figure 3 shows the single score LCA results of the six scenarios.

The overall environmental impacts and the contribution of individual processes to the overall impacts (presented in % to overall impacts) were analyzed. The LCA results revealed that the scenarios of landfill disposal (S1 and S2) impose the highest environmental impact, with leachate treatment (S1: 138%; S2: 268%), landfill operation with energy recovery (S1: -39%; S2: -185%), and dewatering in S2 (16%) as the most significant contributors (Supplementary Information (SI) Fig. S1 and Fig. S2). However, S2 performed better than S1, suggesting that dewatering of FW before landfilling could significantly alleviate the environmental impacts. This was because only about 40% by weight of the raw FW generated was required to be transported to the landfill for disposal after dewatering, reducing the consumption of 114 kWh electricity, 24 kg HCl, 41 kg NaOH and 677 L water in leachate treatment (Yang et al., 2013).

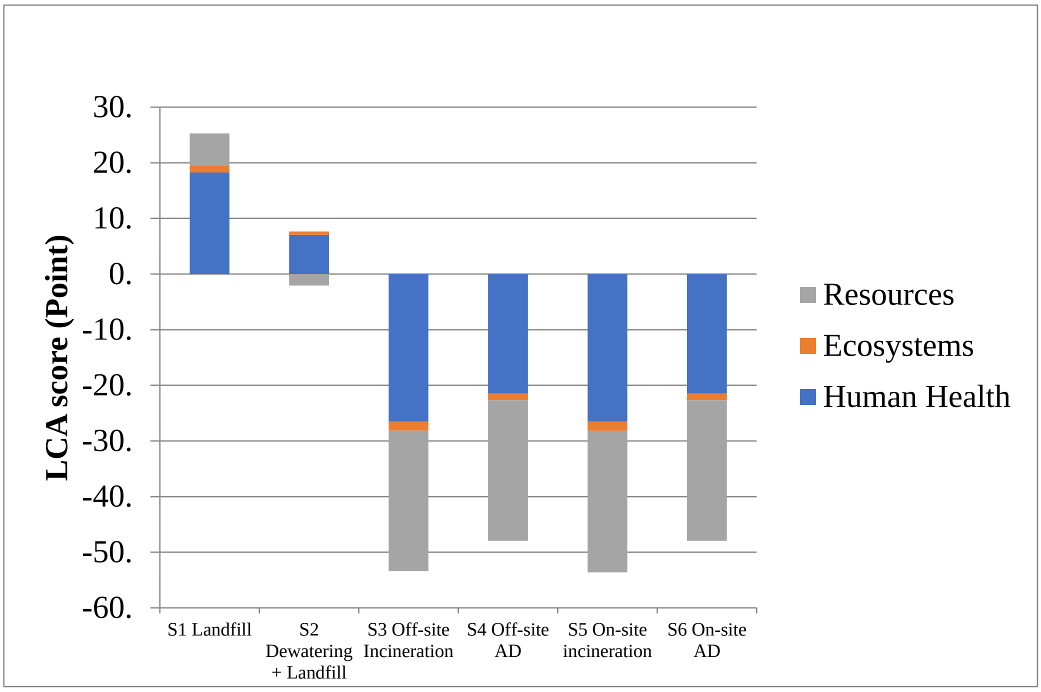

Figure 3 Life-cycle assessment results: environmental impact of different food waste management scenarios (Pt/tonne)

The incineration scenarios (S3 and S5) and AD scenarios (S4 and S6) had significant environmental merits due to the energy recovery. Incinerator operation with energy recovery presented -101% contribution, with electricity generation contributing to -107%, to S3 and S5 (SI Fig. S3 and Fig. S5). AD operation with energy recovery presented -111% contribution, with electricity generation contributing to -117%, to S4 and S6 (SI Fig. S4 and Fig. S6). The incineration scenarios presented the most favorable option, which recovered 82.13 kWh/tonne more energy than the AD scenarios. In addition, the incinerator was equipped with an air pollution control unit comprising activated carbon, scrubber, and SNCR, which presented lower environmental impacts than biofilters in the AD system (SI Table S1 and Fig. S7).

However, the results revealed that the on- and off-site infrastructure had a similar environmental implication (S3 vs S5 for incineration and S4 vs S6 for AD) in the case of HKIA. The avoidance of transportation emissions for the on-site scenarios (S5 and S6) was trivial as only short transportation distances (mean distances of 12 km and 31 km for RCVs and marine vessels, respectively) were required for off-site scenarios in a compact city like Hong Kong (Woon and Lo, 2016). The off-site scenarios and their on-site counterparts were assumed to have the same emissions from the operation of the facilities as similar technologies were adopted.

Life-cycle cost-benefit analysis

The economic, environmental, and social costs and benefits of the six food waste management scenarios were quantified and expressed in HKD per tonne of food waste handled. The cost and benefit components were summed up to provide the final results of the net costs of the scenarios. The LC-CBA results are summarized in Table 8. The LC-CBA showed a different ranking of options from the LCA results, demonstrating the significance of the economic and social consideration. The on-site incineration scenario (S5) was the most sustainable food waste management approach in view of the lowest net cost of HKD 462/tonne FW, followed by landfill disposal after dewatering (S2; HKD 711/tonne FW), and then off-site incineration (S3).

Table 8 Life-cycle cost-benefit analysis results

HKD/tonne FW	S1	S2	S3	S4	S5	S6
Economic						
Capital cost	341.17	154.04	1,032.06	1,546.22	568.87	1,306.13
O&M cost	256.77	180.91	453.00	1,124.30	453.00	1,124.30
Transportation cost	48.92	20.17	17.60	40.30	0.00	0.00
Waste charge	400.00	85.92	87.11	0	87.11	0
Energy recovery	-195.72	-195.72	-697.81	-611.82	-697.81	-611.82
Compost	0.00	0.00	0.00	-51.69	0.00	-51.69
Environmental						
Env. cost	420.55	219.48	454.14	118.70	451.61	118.70
Env. benefit	-131.81	-131.34	-470.96	-412.92	-470.96	-412.92
Social						
Disamenity cost	254.80	254.80	48.88	566.80	0.00	0.00
Land cost	297.73	122.75	29.77	120.43	69.91	120.43
Net cost	**1,692.42**	**711.00**	**953.78**	**2,440.32**	**461.73**	**1,593.13**

Figure 4 presents the costs and the benefits of the scenarios. The capital cost, O&M cost, environmental costs/benefits were the most significant determinants of the scenario sustainability. The good performance of scenario S5 was attributed to the efficient energy recovery from FW incineration, avoidance of disamenity cost and the relatively low capital and O&M costs. S5 presented a total economic and environmental savings of HKD 1,170/tonne from energy recovery. Assuming the on-site incinerator to be built on the reclaimed area adjacent to the future third runway, the disamenity cost could be avoided as its distance to the nearest residential area in Tung Chung would be over 7 km. As for S2 (second most favorable

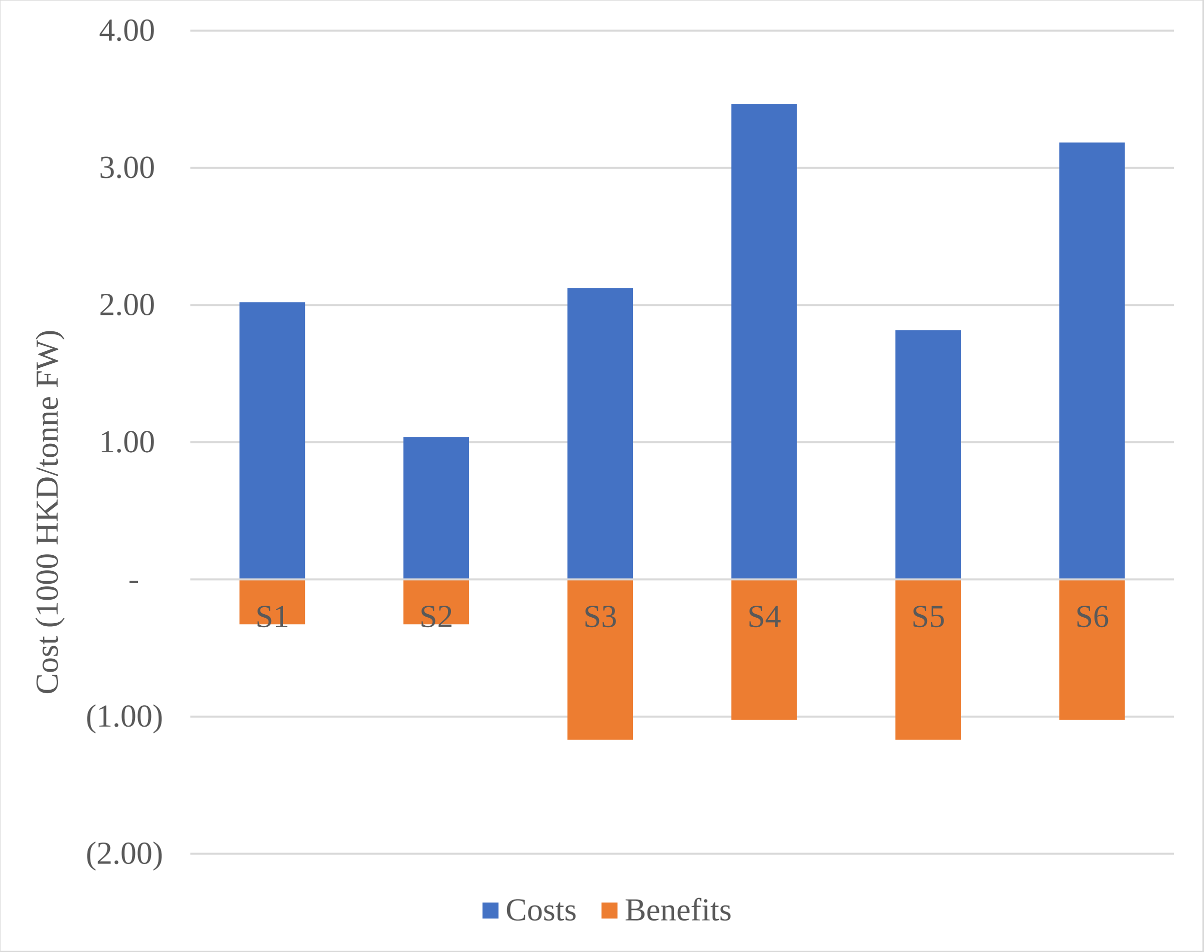

Figure 4 Life-cycle costs and benefits of the scenarios (HKD/tonne FW)

option), the capital and the O&M costs were the lowest among the studied scenarios, due to the volume reduction via dewatering and the low level of treatment respectively. This largely compensated for the shortcoming of S2, which was the marginal energy recovery because only 80% of the collected LFG was combusted at a relatively low electrical conversion efficiency of 35% (SI Table S2, Table S3 and Fig. S8) (HK EMSD, 2002).

The AD scenarios (S4 and S6) became the least favorable (HKD 1593-2440/tonne FW) upon the inclusion of economic and social considerations. It showed the highest capital cost and O&M cost per tonne of FW because of the expensive construction and/or equipment and the small capacity of the infrastructures, i.e., 200 and 32 tonne/d of organic waste for S4 and S6, respectively. In comparison to the landfilling scenarios (S1 and S2), food waste was discarded at the landfill as a category under MSW, of which the total volume was 81 million m^3 in the 15-year lifetime (HK LegCo, 2013). In such case, the capital costs would be borne by the 81 million m^3 of MSW, and per unit cost could be lowered. Similarly for the incineration scenarios, the high expenses on the construction of the off-site centralized incinerator (S3) and the reclamation works were shared by the 3,000 tonnes per day MSW, whereas the on-site incineration (S5) could treat 70 tonnes per day solid waste. These results demonstrated that the significance of the economy of scale and per unit cost of the food waste treatment options.

The on-site scenarios (S5 and S6) tended to be more sustainable than the off-site centralized treatments (S3 and S4) in the case of HKIA. Although the off-site incineration (S3) recovered a significant amount of energy, it incurred the high capital cost in building the artificial island in the adjacent area to Shek Kwu Chau in Hong Kong. The high costs of HKD 2,434.4 million for land reclamation and the related civil works could be avoided in the on-site scenario (S5) (HK LegCo, 2014c). For the on- and off-site AD scenario, the discrepancy was derived from the disamenity cost (i.e., social cost) in addition to the capital cost. The on-site AD (S6) could avoid the costs for the construction of auxiliary buildings for administration. In addition, the on-site options also eliminated the transportation cost. Despite its relatively small amount (HKD 17.6-40.3/tonne FW), the transportation cost remained critical from the view of the waste producer, i.e., the Airport Authority in this study, who was the actual payer for the logistics.

The waste charge is another important consideration to the waste producer in selecting an economical treatment option. In the incineration scenarios (S3 and S5), significant reduction in the weight of FW could be achieved so the waste charge decreased to 22% of the charge in the cases of landfill disposal. Yet, dewatering before landfilling (S2) could be adopted to lower the waste charge by 79%. For the AD scenarios (S4 and S6), the waste charge was completely avoided because composts generated as the by-product from the AD facilities could be used for landscaping application.

Considering the impacts on the community, the disamenity cost of the off-site centralized incineration (S3) was the lowest because the facilities would be constructed on an artificial island, which was distant from residents. The disamenity cost for the off-site centralized AD located at the North Lantau was the highest due to the high housing price and the density of the residential area adjacent to the facility. Both the on-site incinerator and AD system were assumed to be built in a remote reclaimed area in the northwest of HKIA, adjacent to the future third runway, to avoid the impacts on the neighborhood.

Sensitivity analysis

A sensitivity analysis was conducted to reveal the sensitivity of the scenarios to the changes in waste charge and electricity price. The waste charge was a critical consideration in the decision-making process of the waste producers, while the energy recovery made a significant contribution to the sustainability as revealed in the LC-CBA. While the actual waste charge has not been officially announced, the Business Environment Council estimated a charge of HKD 400 to 499 per tonne for the commercial and industrial wastes (Chai, 2014; Woods, 2017), thus the actual charge could be higher than the original assumption in the LC-CBA (i.e. HKD 400/tonne). The sensitivity analysis showed that increasing the waste charge by HKD 1.00/tonne induced the highest net cost increase in the direct landfilling scenario (S1: HKD 1.00/tonne), followed by landfilling after dewatering, off- and on-site incineration (S2: HKD 0.21/tonne; S3 and S5: HKD 0.22/tonne), whereas the AD scenarios (S4 and S6) maintained the same net cost as no disposal was needed (Figure 5). The results suggested that scenarios showing higher dependence on landfill disposal were more sensitive to the change in the waste charge. The enforcement of waste charging scheme could thus encourage the diversion of FW from the landfills to the organic waste treatment facilities, especially for AD option.

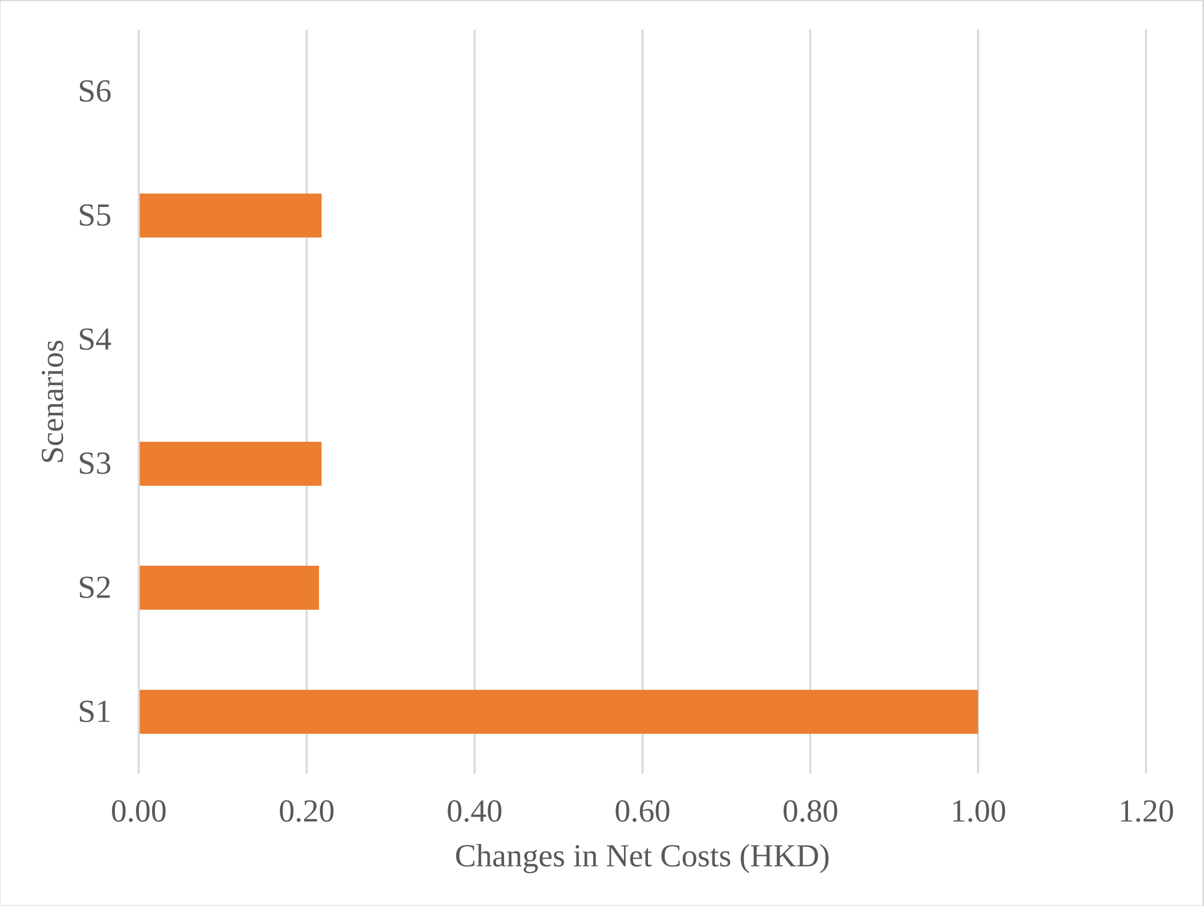

Figure 5 Sensitivity analysis results on the waste charge: changes in net costs induced by HKD 1.00/tonne increase in waste charge

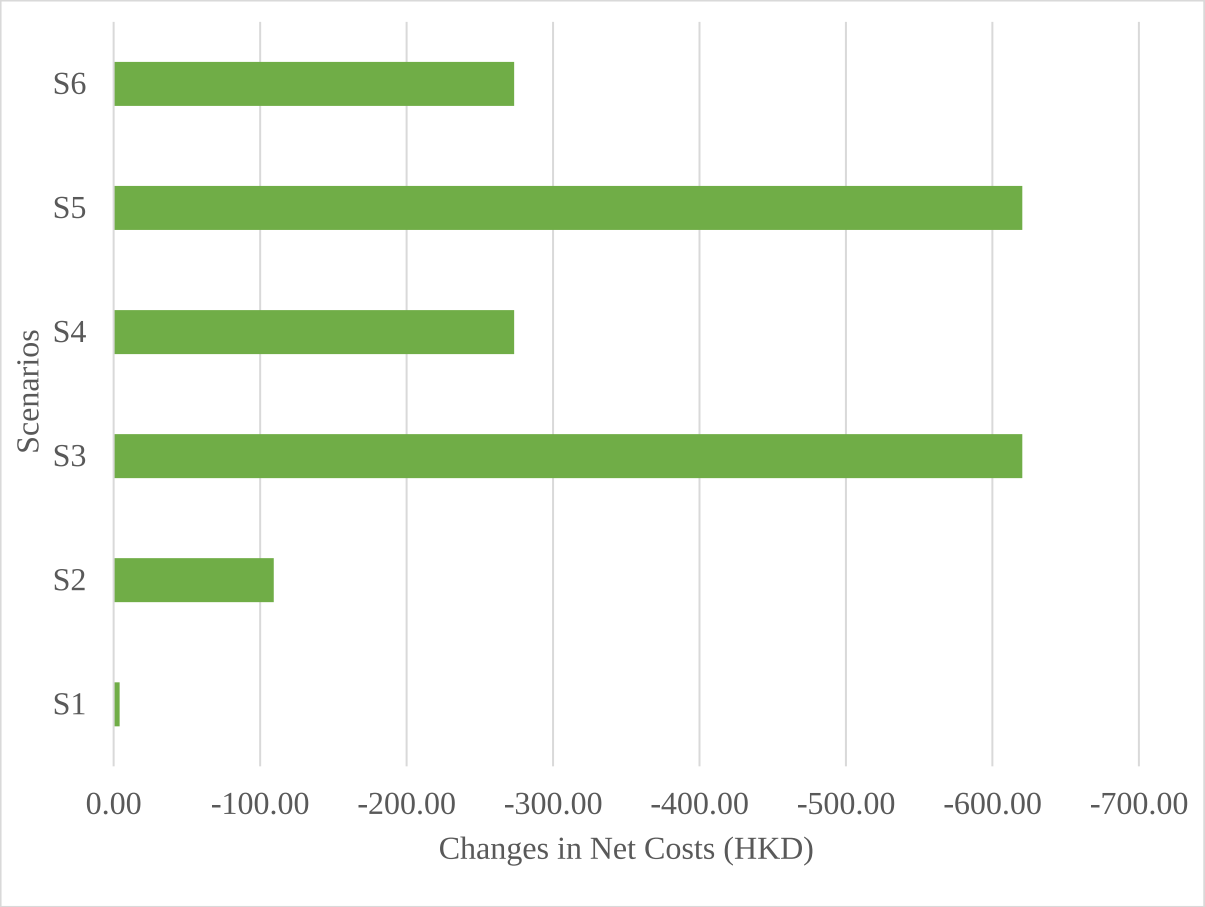

Figure 6 Sensitivity analysis results on the electricity price: changes in net costs induced by HKD 1.00/kwh increase in electricity price

The proposed future fuel mix for electricity generation in Hong Kong requires either an increased reliance on imported grid electricity or investments on new natural gas generation systems, both implying a doubled unit cost for electricity (HK Environment Bureau, 2014). Figure 6 presents the sensitivity of the scenario towards a HKD 1.00/kWh increase in the electricity price. The net cost in all of the scenarios was reduced as they were capable of recovering energy and generating surplus electricity during their operation. The incineration options (S3 and S5) that produced the greatest amount of energy showed the highest reduction of HKD 620/tonne in the net cost, whereas only HKD 4 and HKD 109 reduction per tonne were accomplished in the cases of landfill disposal without dewatering (S1) and with dewatering (S2), respectively, suggesting that the benefits from the rising electricity price were proportional to the magnitude of net energy generation.

Conclusions

In this study, an integrated LC-CBA framework to assist decision-making on sustainable food waste management was developed and demonstrated in a case study as a successful and suitable tool for achieving sustainability. The contributions of this study include the development of the LC-CBA tool, with the following innovative features: (1) the inclusive coverage of the economic, environmental, and social costs and benefits originated from food waste management; (2) the clear and easily-understood final indicator in monetary terms with the external environmental and social costs integrated, and; (3) the wide applicability of the LC-CBA tool for sustainable decision-making on food waste management worldwide.

The LC-CBA framework was demonstrated in the case study of sustainable food waste management at the HKIA. The on-site incineration with recovery (S5) was identified to be the most favorable option to be applied in the HKIA due to the significant energy recovery and the acceptable level of capital and other costs. The second-best option would be S2. Although the environmental benefits from S2 were not high when compared with other scenarios, low costs were required and only a low level of treatment (i.e., dewatering only) was adopted in this scenario. The sensitivity analysis on the effects of the variations in waste charge and electricity price supported the favorability of the on-site incineration option in the case of HKIA because the scenario could react fairly well to rising waste charge and present positive effects when facing a rise in electricity price.

A limitation of this LC-CBA study is the unknown uncertainties of the input data and results. The input values used in the calculations in this study were collected from government documents, international guidelines and published literature closely related to the waste management in Hong Kong, which are considered to be reasonable and appropriate for the estimations. Yet, the ranges and errors of most values are not available, thus uncertainty analysis, for example using Monte Carlo simulation, is hardly possible to be conducted. The LC-CBA demonstrated in the HKIA case only covered the food waste generated from a single facility, that is the airport. When more information on food waste generation is available, the LC-CBA could be extended to cover the food waste generated from the whole city. The disamenity effects and the transportation distance are expected to vary between different locations. Based on such differences, the LC-CBA results are expected to guide decisions to select different food waste management options for different locations. The inclusive LC-CBA framework developed in this study is expected to assist decision-making process on food waste management towards sustainability and enhance the selection of the most cost-effective treatment technologies.

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Abbreviations

ACI	Airports Council International
AD	Anaerobic digestion
APC	Air pollution control unit
CARB	California Air Resources Board
CBA	Cost-benefit analysis
CHP	Combined heat and power
CLP	China Light and Power Corporation Limited
DOC	Degradable organic carbon
EMFAC	EMission FACtors
FAO	Food and Agriculture Organization of the United Nations
FOD	First Order Decay
FU	Functional unit
FW	Food waste
GHG	Greenhouse gas
HC	Hydrocarbons
HK ACE	Hong Kong Advisory Council on the Environment
HK EMSD	Hong Kong Electrical and Mechanical Services Department
HK EPD	Hong Kong Environmental Protection Department
HK LD	Hong Kong Labour Department
HK LegCo	Hong Kong Legislative Council
HKD	Hong Kong dollar
HKIA	Hong Kong International Airport
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
IWMF	Integrated Waste Management Facilities
LCA	Life-cycle assessment
LC-CBA	Life-Cycle Cost-Benefit Analysis
LCI	Life-cycle inventory
LCIA	Life-cycle impact assessment

LFG	Landfill gas
MSW	Municipal solid waste
NLTS	North Lantau Transfer Station
O&M	Operation and maintenance
OSWER US EPA	Office of Solid Waste and Emergency Response, United States Environmental Protection Agency
OWTF	Organic Waste Treatment Facilities
PM	Particulate matter
PV	Present value
RCV	Refuse collection vehicle
RSP	Respirable suspended particulate
SNCR	Selective non-catalytic reduction
SWDS	Solid waste disposal sites
TD	Transport Department
US EPA	United States Environmental Protection Agency
VOC	Volatile organic compounds
WENT	West New Territories

Nomenclature

B_{econ}	Economic benefits ($)
B_{env}	Environmental benefits ($)
B_{soc}	Social benefits ($)
Cap	Capital cost ($)
$Cap_{annualized}$	Annualized capital cost ($/year)
C_{econ}	Economic costs ($)
C_{env}	Environmental costs ($)
$CH_4\ generated_T$	Methane generated in the year T (kgCH_4/kgFW)
C_{soc}	Social costs ($)
$DDOCm$	Degradable organic carbon deposited (Gg)
$DDOCm\ decomp_T$	Mass of the DDOCm decomposed (Gg)
$DDOCma_T$	DDOCm accumulated at the end of year T (Gg)
$DDOCma_{T-1}$	DDOCm accumulated at the end of the year (T-1) (Gg)
$DDOCmd_T$	DDOCm deposited in the SWDS in year T (Gg)
DOC	Fraction of the degradable organic carbon
DOC_f	Decomposable fraction of waste
EM_i	Quantity of air emission i (kg)
EMv_i	Avoided quantity of emission i (kg)
EV_i	Economic value of the emission i (HKD/kg)

F	Fraction by volume of CH_4 in LFG
i	Discount rate (%)
k	Reaction constant
MCF	CH_4 correction factor
n	Number of years of the lifetime
$Net\ C_{econ}$	Net economic cost ($)
OB_{annual}	Annual operation benefits ($)
OC_{annual}	Annual operation cost ($)
T_{annual}	Annual transportation cost ($)
TB	Total benefits ($)
TC	Total cost ($)
W	Waste deposited (Gg)

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