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Environmental Sustainability Assessment of Zero-Waste System for Wastewater Recycling and Food Waste Management in Building

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Towards sustainable urbanization, food waste and wastewater from buildings need the appropriate infrastructure systems for management. The zero-waste concept is gaining interest as a promising option for the sustainable development of society. The study aims to assess the cumulative energy demand and GHG emissions of a prototype zero-waste system for building wastewater recycling and food waste management. The system is the combination of the Moving Bed Biofilm Reaction-Membrane Bioreactor (MBBR-MBR) for wastewater treatment and the anaerobic digester with energy recovery for food waste management. The functional unit is set as the management of 60 kg of food waste along with 2 m^3 of building wastewater. The results revealed that the prototype zero-waste system could bring the negative fossil energy use (-96 MJ-eq) and the negative life-cycle GHG emissions (-4.4 kg CO_2-eq/functional unit). The main credit came from the avoided fossil energy use and GHG emissions due to the substitution of LPG with biogas. The biogas generation was 0.00013 Nm^3/mg COD removal (based on the hydraulic retention time (HRT) about 30 d). For anaerobic digestion system, pig slurry transport from the pig farm to the university as seed sludge and electricity consumption for the stirrer in the digester and the food waste shredder are the major sources of energy use and GHG emission. For the MBBR-MBR system, the primary source for both energy use and GHG emission is the electricity consumption for the air pump. The study shows the initial stage of the implementation of the prototype zero-waste, which there still has the potential to improve operational efficiency.

1. Introduction

The urbanization leads to increased concerns about environmental impacts caused by resource use and wastes generation. Food waste and wastewater from buildings require the appropriate infrastructure systems for management. The zero-waste concept is gaining interest as a promising option for the sustainable development of society. The zero-waste management is a concept with the principle that “waste has an economic value, and it can be recycled” (Romano et al., 2019). The target of zero-waste management is that waste should be minimized as much as possible by using existing management technologies or effective technologies (Song et al., 2015). Techniques for food waste and wastewater management and recycle are essential to fulfilling the target of zero waste management of buildings. This is especially for the bioenergy production which is expected by the government to help improve the environmental and socio-economic impacts of the country (Silalertruksa and Gheewala, 2011).

Anaerobic digestion of organic waste is one of the techniques that is gaining attraction as the measure to reduce and manage the organic wastes by converting organic waste into renewable energy, i.e., biogas (Digman and Kim, 2008). The obtained biogas can be used as fuel for cooking; the by-product from the system can be considered as the compost. The compost can be used for agriculture or other relevant purposes. There have been several previous studies on using anaerobic co-digestion technology to produce biogas from food waste and sludge (Ratanatamskul et al., 2014; Islas-Espinoza et al., 2017). Likewise, the organic waste, wastewater from buildings that generally contains organic matters can also be treated and recycled for use in other

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purposes. Nevertheless, the new systems for energy recovery as well as wastewater recycling will also require the material, chemical as well as energy for operations which in turn their impacts need to be traded off with the environmental benefits gained from the system. For instance, some studies have revealed that the treatment and reuse of wastewater could result in higher GHGs emissions as compared to the conventional wastewater treatment system (Benetto et al., 2009). Besides, sludge generated from the settling tank and sedimentation of a traditional wastewater treatment system generally becomes the environmental burden and cost to the wastewater treatment plant. However, the organic content of sludge also has the potential to be utilized for producing biogas by the anaerobic digestion process (Dinh and Le, 2020). The life cycle environmental performance of an anaerobic digester has been studied so far (Pérez-Camacho et al., 2018); however, the environmental impacts of the zero-waste system has not yet been considered.
The study aims to assess the cumulative energy demand and GHG emissions of a zero-waste system prototype for building wastewater recycling and food waste management using the life cycle assessment (LCA). The zero-waste system proposed in the study is the integrated system of the Moving Bed Biofilm Reaction-Membrane Bioreactor (MBBR-MBR) and the single-stage anaerobic digester for wastewater treatment and food waste management with energy recovery.

2. Methodology

2.1 Description of the prototype zero-waste system

Chulachakabonse building is the 4^{th}-floor building (around 6,400 m^2) located in the Chulalongkorn University of Thailand. The building consists of several faculty clubs and the main canteen. The amount of wastewater and food waste generated is around 2 m^3/d and 60 kg/d. The characteristics of wastewater include COD = 120-300 mg/L, TKN = 35-120 mg/L, TP = 3.8-10 mg/L and pH = 7.0-7.8 (Ratanatamskul and Kongwong, 2017). The characteristics of food waste based on the measurement results are as follows: the average COD = 162,000 mg/L, TS = 129,000 mg/L, TVS = 97,900 mg/L and pH = 4.7. The prototype zero-waste system has been installed and operated for wastewater and food waste treatment with aims to treat and utilize the benefits of the treated wastes. The zero-waste system consists of three major processes, i.e. (1) the Moving Bed Biofilm Reaction– Membrane Bioreactor (MBBR-MBR) process for wastewater treatment and reuse; (2) the shredder and screw conveyor unit to convey the food waste into the anaerobic digester; and (3) the anaerobic digester for treating the shredded food waste along with the biogas production.
Figure 1 shows the simplified zero-waste system operating at the Chulachakrabongse building, Chulalongkorn University. For wastewater treatment, MBBR is the biofilm wastewater treatment technology that combining biological contact oxidation and biological fluidized bed in order to improve wastewater treatment efficiency (Di Trapani et al. 2014). The moving bed biofilm reactor media (round shape type) used in the system is made from polyethylene, and the active surface area is around 3,000 m^2/m^3. The outlet water from the MBBR unit will go to the membrane bioreactor process (MBR) process. The MBR is gaining interest as the wastewater treatment technology that can help reduce the footprint required. The treated water after the MBR process is sent to the treated water tank and further use for watering the plants.
For food waste management, the anaerobic digester system in which the capacity about 2,500 L is installed to produce biogas. Firstly, the food waste is prepared to be the substrates (size between 5-10 mm) by the shredder and screw conveyor to feed the substrate into the digester. Electricity is used for a shredder, screw conveyor, and the stirrer in the digester. Due to the integrated system with the wastewater treatment, the sludge generated from wastewater treatment can be sent to the anaerobic digester to use the benefits from organic contents of it for biogas production.

2.2 Goal and scope of the assessment

Life cycle assessment (LCA), one of the recognized environmental sustainability assessment tools, has been used in the study for compilation and evaluation of the environmental impacts of the waste treatment system (Xu et al., 2015). The study goal is to evaluate life-cycle energy use and GHG emissions of the operating zero-waste system at the Chulachakrabongse building for reusing wastewater and producing the biogas from food waste by comparing to the conventional food waste and wastewater treatment techniques i.e., landfill of organic waste and the treatment of wastewater using the activated sludge system. The functional unit is set as the treatment of about 60 kg of food waste and 2 m^3 of wastewater, which is the average daily waste input into the system. Figure 1 also shows the simplified system boundary of the zero-waste system for conducting the life cycle analysis. The scope of assessment covers the “cradle-to-grave” which can be separated into four main life-cycle stages i.e. (1) production of materials/fuel/energy/electricity used; (2) wastewater treatment and recycling; (3) food waste treatment; and (4) Use of biogas and treated water reuse as well as their environmental credits. The environmental credits from the biogas and treated water reuse are accounted as the substitution of LPG used for cooking in the canteen and the replacement of tap water used for watering the plants. The key environmental interventions considered are the resources used, materials, and chemicals used for the operation of the zero-waste system.

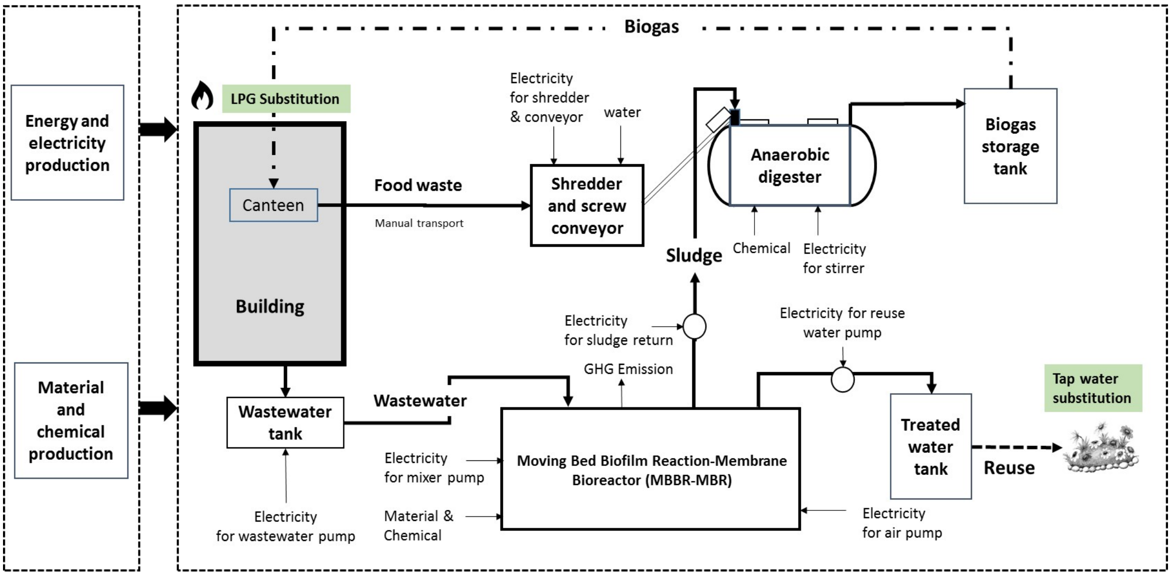

Figure 1: System boundary of the studied zero-waste system

2.3 Life-cycle energy use and GHG emissions assessment method

The life-cycle energy use of the zero-waste system is evaluated based on the cumulative energy demand (CED) assessment method of Frischknecht et.al. (2007). This CED indicator is widely used to indicate the primary energy consumption of the process or product system. The study evaluates the total primary energy input of the zero-waste system and comparing its results with total energy outputs or energy credits obtained from the products i.e. biogas and treated wastewater reuse. To determine the CED indicator, the inventory data on the input material, energy, and chemical during the operation of the waste treatment system are multiplied with their primary energy consumption. The background data for the productions of material and chemical used are referred from the Ecoinvent database (Ecoinvent 3.0, 2012). The grid electricity data of Thailand is referred from the Thai National LCI database. The results of the total cumulative energy demand of the waste treatment system are shown in the unit of MJ-eq/Functional unit.

Life-cycle GHG emissions of the studied waste treatment system are assessed by focusing on the major GHG substances i.e. CO_2, CH_4 and N_2O related to wastewater and food waste treatment processes. Eq(1) shows the scope of life cycle GHG emissions of the waste treatment system ($E_{waste\ treatment\ system}$), which can be classified into three categories i.e. (1) direct GHG emissions, (2) indirect GHG emissions, and (3) the GHG credits (that obtained from the reuse or recycle of the treated wastes of the system).

$$E_{waste\ treatment\ system} = E_{Direct} + E_{Indirect} - E_{Credit} \quad (1)$$

Where $E_{waste\ treatment\ system}$, in the study, represents the life-cycle GHG emissions of the combination system of the anaerobic digester and MBBR-MBR for food waste and wastewater treatment (kg CO_2-eq/Functional unit). E_{Direct} represents the direct GHG emissions e.g. GHG emissions combustion of fuel, fugitive methane emission at the anaerobic digestion system, fugitive N_2O emissions at the wastewater treatment system. $E_{Indirect}$ represents indirect GHG emissions due to the material, chemical, energy use e.g. the electricity consumption for system operation, the material used for media of MBBR system, the chemical used for the process of anaerobic digestion, membrane as well as the membrane cleaning at the MBBR-MBR system. (3) GHG credits obtained from the substation of LPG and tap water. For the direct GHG emissions, since the system does not use fuel in operation, only the GHG emissions from the fugitive methane and the GHG emissions from the fugitive N_2O emissions are investigated using Eq(2) and Eq(3).

$$E_{Direct,CH4\ fugitive} = 2\ \% \times Biogas\ produced\ \times \%\ CH_4\ in\ biogas\ \times 0.66\ \times GWP\ factor \quad (2)$$

$$E_{Direct,N2O\ fugitive} = TKN_{influent}\ \times EF_{N2O}\ \times GWP\ factor \quad (3)$$

The fugitive loss of methane is estimated to be about 2 % (WaCCliM, 2018). The amount of biogas produced from the system is 9.3 Nm^3; % methane in biogas is about 65 % and 0.66 kg methane/Nm^3. For the N_2O emission from the wastewater treatment plant, the primary data about wastewater influent i.e. $TKN_{influence}$ = 40 mg/L and the N_2O emission factor = 0.003 kg N_2O/kg $TKNi_{nfluent}$ (GWRC, 2011) are used. The global warming potential (GWP) factors are referred from the ReCiPe method v.1.10 (Huijbregts et al., 2014) i.e. the GWP factors of CO_2, methane, biogenic methane, and dinitrogen monoxide (N_2O) are 1, 25, 22.3 and 298 kg CO_2-eq/kg substance. The construction of the zero-waste system is excluded from the system boundary due to the assumption that its impact would be not significant after distributed to the 20 y lifetime of the equiement. Table 1 shows the inventory data that primarily collected from the operating prototype zero-waste system at the Chulachakabonse building based on the functional unit. Table 2 shows the LCI data sources used in the study.

Table 1: Life cycle inventory of the studied zero-waste system as per functional unit (Waste input: 60 kg food waste and 2 m^3 wastewater)

Life cycle stage	Inventory	Unit	Value
Food waste treatment	Food waste input	kg	60
	Electricity (shredder, screw conveyor and stirrer)	kWh	1.95
	Water (during shredding)	L	6
	Lime	kg	0.6
	Pig slurry	m^3	0.01
	Transport distance for pig slurry	km	100
	Biogas produced	Nm^3	5.6
Wastewater treatment	Inlet wastewater	m^3	2
	Electricity (inlet wastewater pump)	kWh	0.32
	Electricity (MBBR-MBR e.g. mixer, air pump and sludge return)	kWh	1.76
	Polyethylene (media material)	kg	0.003
	Tap water (membrane cleaning)	L	3.4
	Sodium hypochlorite (membrane cleaning)	kg	0.34
Use of biogas	LPG substitution[1]	kg LPG	0.03
Use of treated wastewater for watering plants	Electricity (water pump)	kWh	0.24
	Tap water substitution	m^3	1.9

[1]Calculated based on the heating value of LPG =49 MJ/kg and the heating value of biogas = 23 MJ/Nm^3

Table 2: LCI data sources

Life cycle stage	Inventory	Sources
Material and chemical production	Lime, Polyethylene, Tap water, Sodium hypochlorite, LPG	Ecoinvent 3.0 (2012)
Utility	Grid-mixed electricity Tap water	Thailand National LCI database (MTEC, 2014) Ecoinvent 3.0 (2012)
Transport of pig slurry	Municipal waste collection service by lorry	Ecoinvent 3.0 (2012)

3. Results and discussion

Table 3 shows the cumulative energy demand and the life-cycle GHG emissions of the zero-waste system based on the management of 60 kg of food waste and 2 m^3 wastewater/d. The results revealed that the zero-waste system could bring about the reduction of fossil energy use by around 96 MJ-eq, the main credit came from the fossil energy use reduction due to the substitution of LPG with biogas. The total life-cycle GHG emissions would also be negative value i.e. -4.4 kg CO_2-eq/functional unit. The credits mainly originated from the biogas as well. The main contributor to the energy use and GHG emissions of the anaerobic digestion system with energy recovery is the diesel consumption for pig slurry transport from pig farm outside Bangkok to the university as the seed sludge. The other contributors are followed by the electricity consumption for the stirrer in the digester and the food waste shredder, consecutively. For the MBBR-MBR system, the primary fossil energy use is the electricity consumption for the air pump, which contributes around 52 % and 51 % of the total fossil energy use and GHG emission. Based on the analytical results of the anaerobic digester, the influent COD of the feeding substrates (food waste) was about 162,000 mg/L, and the effluent COD was 54,900 mg/L; the COD removal of the system was about 107,100 mg/L and the biogas generation was 0.00013 Nm^3/mg COD removal. This is based on the hydraulic retention time (HRT) about 30 d. Nevertheless, it must be noted that the biogas production rate could be significantly varied by the HRT i.e. the longer HRT would have less amount of total biogas production; the percentage of methane in biogas would be higher (Ratanatamskul et al., 2014).

Table 3: Cumulative energy demand (Fossil energy) and Life-cycle GHG emissions of the zero-waste system (Waste input: 60 kg food waste and 2 m^3 wastewater)

Cumulative energy demand	Unit	Anaerobic digester	MBBR-MBR	Total system
Electricity	MJ-eq	16	20	36
Lime	MJ-eq	5		5
Transport (pig slurry)	MJ-eq	20		20
Polyethylene	MJ-eq		0.2	
Sodium hypochlorite	MJ-eq		4	4
LPG (substitution credit)	MJ-eq	-151		-151
Tap water (substitution credit)	MJ-eq		-10	-10
Total CED	MJ-eq	- 110	14	-96
GHG emissions				
Electricity	kg CO_2-eq	1.2	1.6	2.8
Lime	kg CO_2-eq	0.8		0.8
Transport (pig slurry)	kg CO_2-eq	1.4		1.4
Fugitive methane	kg CO_2-eq	1.1		1.1
Polyethylene	kg CO_2-eq		0.0	0.0
Sodium hypochlorite	kg CO_2-eq		0.4	0.4
Fugitive N_2O	kg CO_2-eq		0.2	0.2
LPG (substitution credit)	kg CO_2-eq	-10.0		-10.0
Tap water (substitution credit)	kg CO_2-eq		-0.5	-0.5
Total GHG emissions	kg CO_2-eq	- 5.6	1.2	-4.4

Although the total results of the zero-waste system indicated the negative values for both cumulative fossil energy consumption and life-cycle GHG emissions; however, the main benefit is mainly from the credit of biogas. Focusing on the MBBR-MBR, the life-cycle GHG emission value was about 0.6 kg CO_2-eq/m^3 of wastewater management. This value is higher than the GHG emission of the municipal wastewater treatment used for the carbon footprint of product calculation in Thailand, which is about 0.14 kg CO_2-eq/m^3 of wastewater (TGO, 2020). This comparison is just to look at the gap of the GHG emission result; however, it does not imply that the MBBR-MBR system is the lower performance in terms of GHG emissions because the functions of the two systems are different. The GHG emission factor of TGO is also lack of enough background information of the system to analyze. The zero-waste system aims at the wastewater reuse, sludge recovery, as well as the energy recovery; the conventional municipal wastewater treatment is only to treat the wastewater. There are several environmental advantages of MBBR-MBR e.g. low space requirement, high efficiency of wastewater treatment and recycling, resource depletion reduction that needs to be considered. It can be concluded that the prototype zero-waste developed in the study can deliver the biogas and treated wastewater reuse from food waste and wastewater management with the net fossil energy use and GHG emission credits. The study shows the initial stage of the implementation of the prototype zero-waste, which there still has the potential to improve operational efficiency. Nevertheless, there can also have the uncertainty of the environmental performance especially due to the variations of the amount and composition of food waste and wastewater throughput into the system.

4. Conclusions

The study assessed the cumulative energy demand and the life-cycle GHG emissions of the integrated system between the Moving Bed Biofilm Reaction–Membrane Bioreactor (MBBR-MBR) process and the anaerobic digester for treating food waste and wastewater management. The pilot system was developed and implemented under the zero-waste policy promotion at Chulalongkorn University, Thailand. The system was called as “Zero-waste system” because the wastewater from the building could be treated and resused; the food waste from the canteen and the sludge from the wastewater treatment plant could be returned to the anaerobic digester to produce biogas. The assessment results showed that the prototype zero-waste system could bring the net fossil energy reduction i.e. about -96 MJ-eq and GHG emissions reduction i.e. around -4.4 kg CO_2-eq as per the daily wastewater and food waste generation of the studied building. The main credit originated from the avoided fossil energy use and GHG emissions due to the substitution of LPG with biogas. Pig slurry transport from the pig farm as seed sludge, electricity consumption for the stirrer in the digester, and the air pump of the MBBR-MBR system are the significant sources of energy use and GHG emissions. The results were based on the initial stage of the system's implementation. There are opportunities to improve the system efficiency via either identification of the suitable condition of food and vegetable waste in operation and the enhancement of the benefits from treated wastewater and biogas by utilizing for the other purposes.

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