Environmental impact analysis of food waste anaerobic digestion and products utilization process

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Abstract. Anaerobic digestion technology is a widely used technology for food waste treatment. It can produce clean fuel gas and realize harmless treatment of waste. Different ways of utilizing the digestion products vary depending on the market demand and production technology. In this paper, life cycle assessment (LCA) was conducted to analyse the environmental impacts of different processes in food waste anaerobic digestion treatment and compare different utilization strategies of digestion products especially the digestate. The results of this study indicated that the incineration of digestate had advantages in most environmental impacts except global warming potential (GWP), compared with composting as fertilizers. Besides that, incineration had the lower energy efficiency due to drying heat demand. The high energy conversion efficiency of internal combustion engine contributed much to reducing environmental impacts. It's worth mentioning that the sufficient combustion performance of micro-turbine resulted in smaller global warming potential (GWP) and eutrophication potential (EP).

1 Introduction

Tremendous amount of food waste (FW) is generated annually worldwide. The mass production of food waste has been a burden to environment[1]. Food waste needs to be taken for proper and ecologically disposal. There are already several technologies for the food waste treatment being developed, such as landfill, aerobic compost and anaerobic digestion. The FW emits greenhouse gases and highly charged leachate. For these reasons, Many cities have implemented policies to limit the landfill disposal of FW and promote biological treatment[2]. The food waste composting has less environmental impact to waste-to-energy incineration[3]. Ammonia, methane and VOC emissions happened in the composting process still lead to severe environmental impacts[4]. Anaerobic digestion treatment utilizes food waste under anaerobic conditions to produce biogas, and the digested food waste can be converted into fertilizer for agriculture. Due to its mature technology and high energy conversion efficiency, anaerobic digestion is currently the mainstream technology for food waste processing. For the products after digestion, the utilization methods are also various. Biogas can be purified for use as biofuel, or combusted in internal combustion engine generator for electricity generation. Recently, micro-turbines by using bio-energy is being considered as a promising solution and putting into industrial practice across the world[5]. Digestate from food waste can be composting to produce fertilizer or sent to incineration plant for zero-harm disposal. These ways of utilization have their own advantages and

drawbacks. Energy consumption and environmental impact of different utilization should be compared.

Life cycle assessment (LCA) is an effective methodology for systematically evaluating and identifying the environmental inventory, impact, key factors, decisions, optimization, and improvement opportunities associated with all stages of a selected product, process, or activity[6]. LCA of anaerobic digestion system is frequently performed. Jin et al assessed the energy consumption and environmental impact an integrated food waste-based biogas system and its subsystems and found that primary treatment consumed majority of energy[7]. Kenji et al studied a regional-scale food-waste biogas plant and concluded that greenhouse gas emissions from biogas production is less than one third that of the other biofuels[8]. Chiew et al compared environmental impacts of recycling digestate as fertilizer and using chemical fertilizer, they indicated that use of digested food waste as fertilizer proved to have larger negative results than use of chemical fertilizer especially in terms of acidification and eutrophication[9]. Nam et al investigated the greenhouse gas emissions from livestock and food waste co-digestion system[10]. The existing studies are focused mainly on the specific anaerobic digestion process, while few of them examine the downstream use of biogas and digestate in detail.

The paper aims to conduct a life cycle assessment (LCA) of overall anaerobic digestion treatment for food waste, and quantify the environmental impact of each production process, then compare and analyse different utilization strategies of main digestion products: biogas and digestate.

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2 Methodology

2.1 Goal and scope

The study was based on a food waste anaerobic digestion treatment plant, which is located Zhejiang province of China. The goal of the study was to determine the environmental impact and energy consumption of all aspects of the overall treatment of anaerobic digestion technology. Different utilization ways of two main products (biogas and digestate) from anaerobic digestion was compared. Furthermore, optimization suggestions were proposed.

2.2 System boundary and functional unit

Fig. 1. System boundaries of the study

The system boundaries of the study attained at the moment when food waste was collected, stopped at the moment when food waste becomes inert materials, available energy, or environmental emissions, as is shown in Fig.1. Five processes of overall anaerobic digestion treatment were included: (1) food waste collection, (2) pretreatment, (3) biogas utilization, (4) digestate utilization, (5) solids-liquids separation and wastewater treatment (abbreviated as S-L treatment). The route with solid arrows (a) is the baseline case, while the dotted arrows (b) points to the alternative product utilization options. In the baseline case, environmental impacts of different processes in anaerobic digestion treatment were compared. For biogas and digestate utilization, environmental impacts of alternative options were compared separately.

Food waste is transported by truck from urban district to the treatment plant. Pretreatment mainly refers to an upgrading process of sorting, crushing, pressure filtration, three-phase separation. After that, food waste is sent to digestion. During the digestion process, biogas was collected and stored. After purification, the biogas could be combusted in an internal combustion engine (IC-engine) or a micro-turbine for electricity generation. Digested mixture is separated into digestate and wastewater, the digestate is sent to composting for producing fertilizer in the baseline case. The wastewater is sent to subsequent wastewater treatment facility.

One ton of food waste as received at the plant is defined as functional unit. The quantitative results mentioned later are all based on functional unit. Upstream production of fuels and materials including

diesel, electricity, Fe_2O_3 , etc. is considered as the ‘cradle to grave’ type of calculation, data from the Gabi database are used. The electricity and heat generated by biogas combustion, digestate incineration avoid a same quantity of emissions, which should be subtracted from the system. The recovered electricity is assumed to substitute that provided by the “energy mix” of China average is selected. The produced heat displaces an equal amount of heat generated by “heat mix”, of which the heat production data based on China average is again used. Infrastructure construction and materials are not included due to the long operating life.

2.3 Data acquisition and assumption

2.3.1 Materials data

The quantity of materials used in the whole process such as biogas yield, digestate yield, steam consumption was obtained from design data which guides the plant operation. As a prototype of the plant's construction and operations, these data could be used because of their considerable accuracy. Every ton of food waste was assumed to produce 60 Nm^3 biogas which consists of 64% CH_4 and 36% CO_2 [16].

Before the biogas is sent to the power generation unit, it needs to be desulfurized. The main component of the desulfurizer is Fe_2O_3 , its consumption was calculated by the stoichiometric relationship and the adsorption capacity. The degree of desulfurization required for biogas to be used in IC-engine and micro-turbine is different. In general, micro-turbine is more tolerant to H_2S and therefore require less desulfurization agents before power generation. The operation of gas-fired internal combustion engine generator sets requires periodic replacement of lubricating oil. The lubricating oil consumption of gas generators generally sold was set at 1.5 g/kwh.

Table 1. Diesel consumption emission factors

exhaust emissions	factor: g/ L diesel
CO_2	2632.8
CO	32.311
SO_2	0.3486
NO_x	5.7602
HC	19.588
CH_4	0.415
VOC	6.9388
HCHO	0.5561
N_2O	0.4731
Pb	0.4067

The food waste collection distance was 80 km as planned, and the transport vehicle was a 5-t closed truck. The fuel consumption was assumed to be 20 L/100km according to typical vehicle in the market. The spreading distance of digestate fertilizer was set at 25 km, and the transport vehicle was a 2-t closed truck with a fuel consumption of 12 L/100km. Emissions while driving was calculated by emission factor per unit of fuel , as is given in Table 1[11].

2.3.2 Energy data

The electricity consumed by equipment in the overall process of anaerobic digestion was estimated by the daily processing scale and processing capability. For example, the pretreatment equipment can handle 15 t food waste per hour, then the operation time was set 10 hours under a 150 t/d scale. Operation time multiplied by power could get the consumed electricity.

The biogas can be burned in an internal combustion engine or a micro-turbine. The power generation efficiency for internal combustion engine was set at 30% and meanwhile the recovery heat efficiency was set at 30%[12][13] (including cylinder liner heat and flue gas recovery heat). For plants with small capacities, micro-turbine, which have less restrictive fuel requirements than IC-engine, appear to be suitable for biogas use[14]. Due to high temperature of exhaust gas, electricity efficiency was lower for micro-turbine cogeneration system (set at 20%), a higher recovery heat efficiency was obtained (set at 35%), if the unit is running at full load[15].

2.3.3 Emissions data

The emissions from IC-engine electricity generation process was based on the historic source test results[16], the emissions from micro-turbine generator was based on[15]. When food waste is exposed to the air, it will produce toxic gases such as NH_3 and H_2S [17,18]. The data of gas emissions happened in pretreatment and S-L treatment were from the environmental impact announcement of referenced food waste treatment project which was released by Zhejiang Industrial Environmental Design Institute Co. Ltd.

Digestate is abundant in organic matter and nutrients, could be used as a soil amendment or a substitute for fertilizer[8]. When digestate is used as a fertilizer through composting, the main emissions in the process are gas emissions and heavy metal emissions[19]. The application of digestate fertilizer to the soil may also cause the release of heavy metals, with the highest levels of pollution caused by Cu, Zn and Hg emissions. The emissions data were based on the measurement by Yan[20].

the slag produced by digestate incineration accounts for 10%-15% of unit mass, while the fly ash accounts for 1%-2% of unit mass. That slag is currently used in a comprehensive way to produce building materials; waste incineration fly ash should be treated as hazardous waste, but it can be identified as meeting the relevant standards for sanitary landfills. The paper assumes that after production into building materials The slag is stable in nature, and the fly ash does not produce landfill gas, and its environmental impacts are neglected here.

The digestate blending domestic waste needs to be dehydrated before incineration, the water content is reduced from 80% to 30%, and the mass of digestate is reduced to 0.0297 t per functional unit. Based on Li's data[21], the energy consumed by dehydration and the energy released by incineration are calculated.

The amount of digestate is 3.5% of the processing capacity of the incineration plant. Therefore, it is assumed that the blending behaviour has little effect on the composition of the flue gas. The incineration flue gas data is derived from the Zhejiang Province self-monitoring information disclosure platform and the Taizhou Environmental Protection Bureau. The main pollutant in the gas is NO_x , and the digestate incineration also mainly produces nitrogen oxide pollution. Emission concentration of other pollutions such as HCl , SO_2 is very low, and the weight of the digestate incineration release is very low, so only the pollution quantity of NO_x is calculated. The CO_2 emissions from the digestate incineration are calculated from the elemental analysis data ($\omega(\text{C})=0.21$) of the sampled digestate by mass conservation.

2.4 Life cycle inventory

2.4.1 Baseline case

The baseline case includes a complete process of food waste treatment. As for the product utilization, biogas is sent to the internal combustion engine for power generation, and the digestate is used to make fertilizer though composting, and then spread it out. Table 2 shows the main inputs and outputs per functional unit.

Table 2. Main input and output flows per functional unit

FW collection		Digestate utilization	
diesel, L	3.2	NH_3 , kg	0.021
		CH_4 , kg	0.128
Pretreatment		N_2O , kg	0.003
steam, t	0.12	Cu to soil, kg	0.042
NaOH , kg	1.13	Zn to soil, kg	0.14
electricity, $\text{kW}\cdot\text{h}$	25.05	Hg to soil, kg	0.0042
NH_3 , kg	0.11	As to soil, kg	0.0073
H_2S , kg	0.005	Cr to soil, kg	0.0052
		Ni to soil, kg	0.0063
Biogas utilization		fertilizer, t	0.104
Fe_2O_3 , kg	0.032	diesel, L	0.156
NO_x , kg	0.083	S-L treatment	
CO , kg	0.25	electricity, $\text{kW}\cdot\text{h}$	25.87
CH_4 , kg	0.447	NH_3 , kg	0.048
SO_2 , kg	0.012	H_2S , kg	0.002
CO_2 , kg	147.9	SS, kg	0.40
lubricating oil, kg	0.184	$\text{COD}_{(\text{Cr})}$, kg	0.50
electricity-out, $\text{kW}\cdot\text{h}$	105.0	BOD_5 , kg	0.30
heat-out, $\text{kW}\cdot\text{h}$	105.0	N-total, kg	0.074

2.4.2 Digestate

The digestate can be composted as fertilizer or sent to an incineration facility for incineration. The incineration ash can be stabilized to effectively fix heavy metals, and

the relatively high calorific value of the dry digestate can be incinerated without external heat addition.

Table 3. Inventory data for digestate utilization

Consumption and emission	Fertilizer	Incineration
NH ₃ , kg	0.021	-
CH ₄ , kg	0.128	-
N ₂ O, kg	0.003	-
CO ₂ , kg	-	16.0
NO _x , kg	-	0.027
Cu to soil, kg	0.0416	-
Zn to soil, kg	0.1352	-
Hg to soil, kg	0.0042	-
As to soil, kg	0.0073	-
Cr to soil, kg	0.0052	-
Ni to soil, kg	0.0062	-
Heat-output, MJ	-	137.0
Heat-demand, MJ	-	75.79
Transport-weight, t	0.04	0.0059
diesel for transportation, L	0.156	0.0178

2.4.3 Biogas

Nowadays, IC-engine is the mainstream biogas power generation equipment due to its low price and stable performance. However, with the advancement of technology and the increasingly stringent environmental standards, the application of micro-turbine in the field of biogas power generation is also very promising. Table.3 lists the power generation performance, air pollutant emissions, and materials consumption of this two alternative utilization strategies.

Table 4. Inventory data for power generation

Consumption and emission	IC-engine	Micro-turbine
Fe ₂ O ₃	0.0316	0.0025
lubricating oil, kg	0.18375	-
NO _x , kg	0.0831	0.0035
CO, kg	0.246	0.313
CH ₄ , kg	0.4474	0.0804
SO ₂ , kg	0.0118	0.0972
CO ₂ , kg	147.9	148.2
Electricity-out, kW·h	105.0	70.0
Heat-out, kW·h	105.0	122.5

2.5 Life cycle impact assessment

There are many impact assessment methodologies in compliance with ISO 14040 framework. In the paper, the methodology CML-2015 has been adopted. CML-2015 is an impact assessment method developed by Leiden University in Netherlands, which restricts quantitative modelling to early stages in the cause-effect chain to

limit uncertainties. Analysis Results are grouped in midpoint impact categories [3]. The paper selected seven impact categories as follows: global warming potential (GWP₁₀₀, in kg CO₂-eq), acidification potential (AP, in kg SO₂-eq), eutrophication potential (EP, in phosphate-eq), Human toxicity potential (HTP, in kg DCB-eq), fresh water eco-toxicity (FAETP, in kg DCB-eq), and abiotic depletion fossil (ADP fossil, in MJ -eq).

3 Results

3.1 Baseline case

Fig. 2. Analysis of five base process contribution to the system.

Fig.2 provides six environmental impacts (GWP₁₀₀, ADP fossil, AP, EP, HTP, FAETP) during the whole process of anaerobic digestion. The power consumption in pretreatment and wastewater treatment and the consumption of diesel in the collection process were the

primary contributions to GWP_{100} , which accounted for 37.1% and 34.3% respectively. Despite the avoided impact in the GWP caused by the displaced electricity production, large amount of CO_2 released by the combustion of biogas also made its GWP_{100} (5.96 kg CO_2 -eq) still a negative effect. The contribution from collection was fairly large (16.3%), hence it's significant to design the collection and transportation routing more reasonably and improve efficiency. The methane leakage during the compost process also made a negative effect of global warming (1.74 kg CO_2 -eq), though composting avoided using a portion of chemical nitrogen fertilizers. The fossil energy consumed in the anaerobic digestion process (592.53 MJ-eq) accounts for 38.5% of the energy generated by biogas power generation (1540 MJ-eq).

The overall acidification potential was fairly low (0.0037 kg SO_2 -eq) on account of biogas utilization, while the eutrophication potential (0.104 kg phosphate-eq) had considerable impact on environment. The NH_3 and H_2S leakage happened in the pretreatment and S-L treatment process were responsible for 96.9% of AP and 93.3% of EP. Thus, it's urgent to collect and control the odor permeated in workshop. The energy produced by the biogas power generation process greatly reduced AP and EP of whole system.

The HTP was estimated at net 275 kg DCB-eq, mostly (95.3%) owing to the digestate utilization. The toxic effect attributed to heavy metals such as Cu and Zn released into the soil. Similarly, digestate utilization was the dominant contribution (98.7%) to FAETP. The electricity power and district heat generation avoided a large amount of fossil energy consumption, making ADP fossil overall positive effect, which implicated food waste can be used to generate recycling energy. Avoided fossil resource consumption alleviates environmental burdens of acidification, eutrophication and toxicity.

3.2 Digestate utilization

Fig.3 provides the environmental impacts of GWP, ADP fossil, AP, and EP, in terms of digestate utilization. The effect of incineration on climate warming was 8.03 times greater than using as fertilizer, because the C element in the digestate is released in the form of CO_2 . The net impact on ADP for digestate incineration (-3.28 MJ-eq) was much tinier than that for digestate composting (-47.6 MJ-eq). Incineration can release the calorific value of the digestate, so it can avoid the use of a certain amount fossil energy. However, the sludge should be dewatered and thermal dried before incineration[22], which led to a lower energy efficiency. digestate fertilizer was superior to chemical nitrogen fertilizers at global warming, energy consumption[23]. The fertilizer produced by digestate composting can avoid the production of a part of chemical fertilizer, and the fossil energy consumption avoided was greater, so digestate composting to produce fertilizer is a more efficient and energy-saving utilization pattern.

The acidification potential (AP) was about $4.4e-4$ kg SO_2 -eq for digestate composting, while digestate

incineration avoided insignificant amounts ($-4.8e-3$ kg SO_2 -eq). As for eutrophication, digestate composting showed 8.38 times larger potential than digestate incineration. Gases pollutants such as NH_3 and N_2O released during the composting process cannot be disposed effectively, resulting in negative effects of AP and EP. In the aspect of co-incineration of digestate and domestic garbage, since the flue gas treatment equipment can be used for centralized disposal, the amount of gas pollutant released into the atmosphere is little.

Fig. 3. Comparison of environmental burdens of two digestate utilization strategies

After incineration, heavy metals are generally concentrated in the bottom slag and fly ash[24], both of which are stabilized with chelating agent and released to the environment in an extremely low amount with little toxic effects in this case. The process of digestate incineration presented a slightly positive effect to reduce toxicity. Conversely, the fertilizer produced by digestate composting will produce huge toxic effect from heavy metal, with 311 kg DCB-eq for human toxicity potential and 45.9 kg DCB-eq for freshwater aquatic eco-toxicity potential. The toxic effect comparison is too stark to be graphically illustrated in Fig 3. Thus, heavy metals from the fertilizer produced by digestate are essential to be removed before land application.

3.3 Biogas utilization

Fig. 4. Comparison of environmental burdens of two biogas utilization strategies

Fig.4 provides the environmental impacts of GWP, ADP fossil, AP, EP, HTP and FAETP, in terms of biogas utilization. Owing to its lower energy conversion efficiency, micro-turbine showed larger global warming potential (14.85 kg CO₂-eq) than IC-engine (5.96 kg CO₂-eq). On the part of the gas released by combustion, micro-turbine contributed less than IC-engine (150 kg CO₂-eq and 159 kg CO₂-eq respectively). The main reason is that the combustion of the micro-turbine is completer than IC-engine, hence CH₄ is thoroughly converted to CO₂. Moreover, The effect of CH₄ on global warming was 25 times that of CO₂ per mass in 100-year horizon[25], so full conversion of biogas fuel will effectively reduce the global warming potential.

The concentration of SO₂ emission from micro-turbine is too high, resulting in a larger acidification potential (0.118 kg SO₂-eq), than IC-engine (0.0557 kg SO₂-eq). Although the micro-turbine is more tolerant to H₂S, desulfurization is recommended due to the low environmental impact of consumed desulfurizer (Fe₂O₃). Main contributors to EP were the NH₃ and NO_x emissions. The low concentration of NO_x emitted by micro-turbine resulted in lower eutrophication potential (4.55e-4kg phosphate-eq), compared to IC-engine (0.0108 kg phosphate-eq). The avoided electricity power and heat production contributed -0.047 kg phosphate-eq for IC-engine and -0.042kg phosphate-eq for micro-turbine. In general, the biogas utilization via micro-turbine power unit can reduce more eutrophication potential (-0.0415kg phosphate-eq) than IC-engine power unit (-0.0365kg phosphate-eq).

Electricity power and heat generated in the biogas utilization process could lead to significant reduction in two toxic impacts (HTP and FAETP). The quantity of impacts avoided was proportional to how much energy they produced.

4 Conclusion

Contribution analysis of five production stages to whole anaerobic digestion system was made in this paper. Main factors causing GWP₁₀₀, AP and EP are pretreatment and S-L treatment. when the digestate is composted as fertilizers, the toxic impacts (HTP, FAETP) will occupy a large proportion in the whole process, largely owing to the heavy metal emissions.

When the digestate undergoes incineration, the toxic impacts are greatly reduced despite higher GWP. Due to the concentrated treatment of the flue gas, the AP and EP of incineration are also reduced compared to composting. The only disadvantage of incineration is that the energy consumed by the drying of the digestate takes a great toll. Developing an efficient digestate dewatering technology can remarkably improve the economics of operation.

Biogas is more energy efficient to generate electricity through IC-engine, which can avoid more environmental impacts. Nevertheless, insufficient combustion happened in IC-engine brings about the high concentration of CH₄ in the flue gas, which contributes a lot to GWP. The micro-turbine is a promising biogas power generation equipment with low NO_x and CH₄ emissions, resulting in a lower GWP and EP. Desulfurization of biogas is required despite the high H₂S tolerance of micro-turbine.

The present study can provide a scientific basis for decision makers regarding developing food-waste anaerobic digestion products utilization strategies in the future. Apart from environmental impact analysis, comprehensive economic analysis is supposed to carry out for further comparison.

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