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Solid digestate disposal strategies to reduce the environmental impact and energy consumption of food waste-based biogas systems

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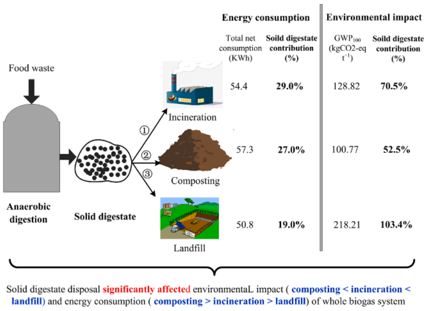
HIGHLIGHTS

- Solid digestate disposal significantly affected environmental and energy benefits.
- The most significant environmental impact among all scenarios was GWP_{100}.
- Digestate subunits in scenarios 1–3 showed large contributions to GWP_{100}.
- Composting and landfill had the most and least inputs of net energy, respectively.
- Scenario rank by environmental impact was: composting < incineration < landfill.

GRAPHICAL ABSTRACT



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ABSTRACT

This study examined the environmental impacts and energy consumption of three solid digestate treatment scenarios to quantify their impacts on the entire food waste (FW)-based biogas system: (1) incineration; (2) composting, and; (3) landfill. The results showed that composting had the largest net energy consumption, but least total environmental impact of 57.3 kWh and 8.75 E-03, respectively, whereas landfill showed the opposite pattern. Moreover, there were significant differences ($p < 0.05$) and relatively high contributions between the digestate treatment subunits among the three scenarios. The most significant contributions of digestate subunits in methods 1–3 to the 100-year global warming potential (GWP_{100}) were 70.5%, 52.5%, and 103.4%, respectively. The results indicated that solid digestate treatment had a significant impact, and reasonable disposal of solid digestate could significantly reduce the environmental impacts and energy consumption of the entire FW-based biogas system.

1. Introduction

Anaerobic digestion (AD) has become an increasingly popular method globally for the treatment of food waste (FW) due to its environmental benefits (Jin et al., 2015; Liikanen et al., 2018; Zhou et al., 2018). However, the use of AD alone is not able to completely stabilize

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FW, resulting in some nutrients remaining, which are discharged as a liquid or solid phase digestate (Ma and Liu, 2019; Peng et al., 2020). The widespread application of AD has resulted in a continuous growth in the amount of solid digestate requiring further disposal.

Solid digestate is a secondary product of the AD process and comprises residual indigestible material, process intermediaries, and dead microorganisms (Tiwary et al., 2015). There is a potential to use solid digestate as an agricultural fertilizer due to its high nutrient contents, such as nitrogen, phosphorus, and potassium (Cheong et al., 2020; Tiwary et al., 2015). However, in addition to nutrient contents, solid digestate also contains some heavy metals such as Zn and Cu as well as pathogenic bacteria, and therefore its use as a fertilizer poses a high environmental pollution risk (Logan and Visvanathan, 2019; Peng and Pivato, 2019; Tiwary et al., 2015). Therefore, a reasonable and effective method of treating solid digestate is required, and the effective treatment of solid digestate has become an important factor affecting the feasibility of AD engineering.

At present, the most commonly-used technologies for treating FW solid digestate in China include composting, incineration, and landfill disposal. Composting is considered a sustainable practice which contributes to improved agricultural and environmental conditions (Tiwary et al., 2015), and is widely implemented in Europe, the North America, and in other regions (Grigatti et al., 2020; Herbes et al., 2020; Möller and Müller, 2012). However, the disposal of solid digestate through composting often requires the addition of a certain amount of auxiliary materials or the implementation of a drying process due to a high moisture content and components resistant to biodegradation (Awiszus et al., 2018; Rehl and Müller, 2011). Moreover, this approach remains contentious due to its drawbacks, including emissions of greenhouse gases, odors, and heavy metals (Awiszus et al., 2018; Möller and Müller, 2012; Wojnowska-Baryła et al., 2018). Incineration treatment is based on the high organic matter content and high calorific value of solid digestate. Landfill is considered an economic and simple strategy for ensuring the final disposal of solid digestate. Among the three technologies, incineration and landfill disposal of solid digestate mainly rely on existing facilities within the municipal solid waste (MSW) treatment system (Ma et al., 2018). Although these two strategies do not consider the recycling of materials, they remain important technical options considered by most decision makers in China due to the convenience of using existing MSW facilities. However, whether such disposal methods are economical and environmentally friendly considering the entire FW treatment system remains unclear.

Studies on integrated FW-based biogas systems based on the concept of the circular economy have become increasingly popular (de Sadeleer et al., 2020; Li et al., 2020; Nordahl et al., 2020). Some studies have demonstrated the important impact of digestate treatment on the environmental impact of the entire treatment system, with the different disposal methods showing different effects. Nordahl et al. (2020) demonstrated that a sole dependency on landfilling to treat solid digestate in the dry AD system could result in the 100-year global warming potential (GWP_{100}) footprint reaching 40 kg CO_2 per ton of organic waste. Tiwary et al. (2015) reported that composting of digestate could enhance acidification and eutrophication potentials. In addition, several studies have investigated the environmental or economic impacts of different biogas digestate processing technologies (Herbes et al., 2020; Rehl and Müller, 2011). However, these studies did not analyze the contributions of different digestate treatments to the entire FW biogas system.

Moreover, most past studies have focused on biogas digestate, which is composed of solid and liquid phase components, and relatively few studies have focused on solid digestate. Therefore, the study aimed to analyze and assess the impact of three solid digestate treatment methods on the energy consumption and environmental impacts of an extended integrated FW-based biogas system: (1) incineration; (2) composting, and; (3) landfill. The primary objectives were to: (1) quantify the impacts of different solid digestate treatment methods on the energy consumption and environmental impacts of the entire AD system; (2) quantify the contribution of the digestate treatment subsystem and identify a feasible strategy for the improvement of an extended FW biogas system. The results of the present study can provide a theoretical reference for further research and management of solid digestate, and the establishment of a sustainable low-consumption and environmentally friendly FW-based biogas system.

2. Materials and methods

2.1. The food waste-based biogas system and evaluation boundary

The present study selected a food waste-based biogas project from the city of Suzhou situated on the east coast of China with an urban population of over 4 million (Chen et al., 2017). The selected treatment plant is a pilot plant established in China for the treatment and utilization of FW, with a treatment capacity of 250 $t\ d^{-1}$. The main technologies employed by the plant are heat-moisture treatment (1 h at 120 °C to 180 °C) combined with a wet AD process. Chen et al. (2017) describes the specific FW process condition used.

Suzhou also hosts a MSW landfill site with a total storage capacity of 4.7 million m^3 and a MSW incineration plant with a processing capacity of 6,850 $t\ d^{-1}$. The MSW landfill site incorporates height expansion through vertical stacking based on the original valley-type landfill. The control of horizontal and vertical seepage has been adopted at the site to prevent groundwater and surface water pollution by leachate. The gas produced by the landfill is utilized within a biogas power generation device, which has generated electricity since July 2006. The MSW incineration plant has adopted grate furnace technology, and each incineration line in the plant has a treatment capacity of 350 $t\ d^{-1}$ or 500 $t\ d^{-1}$. The plant features advanced waste incineration adjustment, flue gas treatment, generator settings, automatic control, online monitoring, and other core technologies.

Moreover, since the landfill and incineration plants are situated in close proximity to the FW treatment plant, and the amount of solid residue that needs to be transported per ton of FW is relatively small, the transportation of solid digestate was not considered in the present study. Fig. 1 shows a conceptual representation of the evaluation system.

The FW treatment process illustrated in Fig. 1 regards FW, including waste vegetable oil, as material input, electricity as energy input, and renewable energy and recycled products as material outputs. The functional unit of the system was 1 ton of FW. In addition, the evaluation model was mainly built according to the following assumptions:

(1) The evaluation model used in the present study was mainly based on a comparison between treatment technologies, and excluded the waste collection and transportation processes. Previous studies have shown that the transportation of FW has certain or even significant environmental impacts and energy consumptions, depending on specific conditions (Li et al., 2018; Peng et al., 2020; Rehl and Müller, 2011). However, the present study excluded the impacts of non-technical aspects of treatment of solid digestate as much as possible as the focus of the study was on the impact of technical aspects. In addition, the layout of the treatment facilities in the city of Suzhou is common among various eco-industrial parks in China, as this layout reduces the distance between treatment facilities and thereby reduces the cost of transporting FW and MSW.

(2) FW-based biogas systems in China could obtain some resource-based products, such as waste oil. This is due to the typical three-phase, oil–water-solid characteristics of FW in China (Li et al., 2019). The present study estimated the energy and environmental benefits of these products by substituting them with traditional biological products, such as biodiesel.

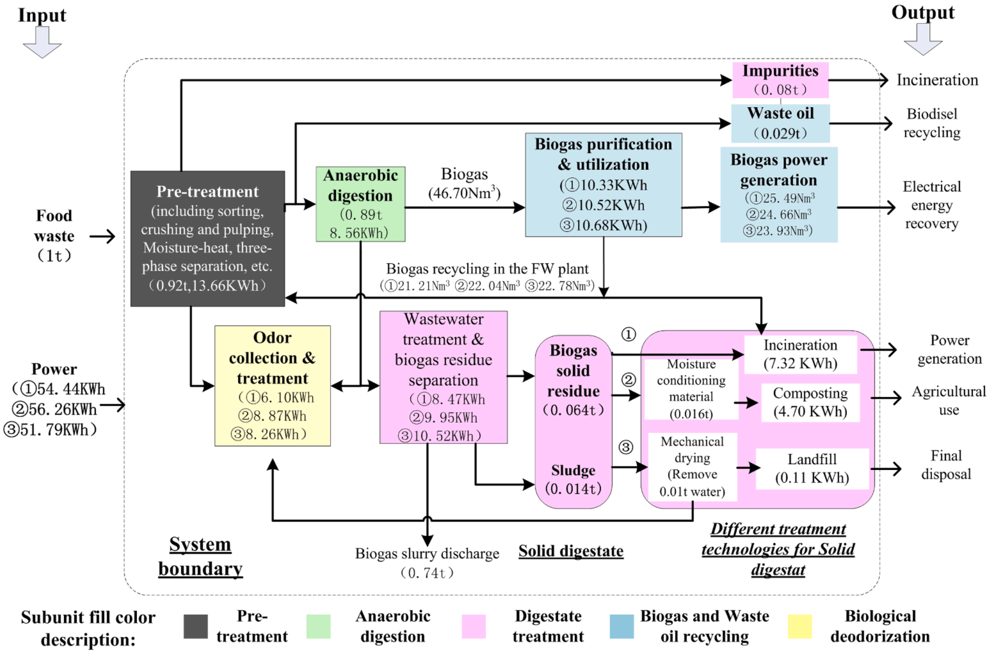

Fig. 1. Conceptual representation of a food waste (FW) treatment process in the city of Suzhou, China, showing the boundary of the evaluated system. The numbers represent different methods of processing solid digestate: (1) incineration; (2) composting; (3) landfill.

(3) Since FW in China contains a certain proportion of impurities, ~8% of total FW was extracted during the pretreatment process for evaluation by incineration.

(4) Since landfill or incineration of MSW is used for treatment of mixed waste and since no MSW incineration plants or landfill sites in China accept only FW and FW residues, the energy consumption and environmental impact of solid digestate incineration or landfill were estimated from MSW data (Wei et al., 2009), including pollution emissions, energy consumption of treatment, and resource recovery for power generation, namely biogas in landfill and heat in incineration.

2.2. Evaluation scenarios

The present study assessed three different solid digestate (including biogas, solid residue, and sludge) treatment scenarios: (1) incineration; (2) composting and; (3) landfill. Other processes such as the pretreatment of FW and AD, and the treatment of odor, were basically the same among the three scenarios, and were mainly included in the FW treatment plant, as shown in Fig. 1. In addition, the solid digestate composting scenario was operated in the same FW plant since the plant contains digestate residue composting facilities (Wen et al., 2016), and the solid digestate was mixed with wood chips and other moisture regulating materials to make its moisture content drops to ~55% before composting (Guo et al. 2018). However, solid digestate was transported to the MSW landfill and incineration plants for disposal under scenarios 1 and 3, respectively, and these two scenarios required different pretreatments in the FW plant due to their specific requirements. For detail, the solid digestate was directly transported to incineration after mechanical pressing, while the moisture content of solid digestate needed to be reduced to less than 60% before transportation to landfill (MEP, 2008), resulting in differences in the amount of recycled biogas and in the generation of odor in the above systems (Fig. 1) and in final energy consumption. Fig. 1 shows the inputs and outputs of material and energy within the three scenarios.

As shown in Fig. 1, the evaluation system was divided into five subprocessing units for further study of the impact of solid digestate treatment: (1) pre-treatment; (2) AD; (3) biogas and biodiesel recycling; (4) digestate treatment, and; (5) biological deodorization. Pretreatment mainly included sorting, crushing and pulping, moisture-heat, and three-phase separation. AD comprised the anaerobic fermentation unit, including the conditioning tank. Biogas and biodiesel recycling involved the reuse of biogas, power generation by residual biogas, and the recovery of waste oil. Digestate treatment mainly included incineration of impurities, treatment of biogas slurry, and treatment of solid digestate. Biological deodorization mainly involved the treatment of odors emitted by each processing unit within the system boundary and biological deodorization treatment. In addition, the contribution to environmental impact by each subunit was calculated as:

$$Subunit\ contribution(\%) = \frac{EB_i}{|TEB_i|} \times 100\% \qquad (1)$$

In Eq. (1), EB_i is the i-th environmental impact value of the subunit and TEB_i is the total environmental impact of the entire system. ANOVA was used to carry out statistical analysis of significance among variables, and $P < 0.05$ was set as the standard for statistical significance.

2.3. Evaluation methodology

As per the defined system boundary illustrated in Fig. 1, the present study mainly evaluated the energy consumption and environmental impacts of the above scenarios using the CML2001 life cycle assessment (LCA) method (Guinée et al., 2002). The assessment of energy consumption was used to compare and analyze seven energy indicators: (1) net energy input; (2) net energy output; (3) total energy output; (4) recycling energy; (5) total energy consumption; (6) energy input ratio and; (7) energy recycling ratio. A description of the calculation method can be found in Jin et al. (2015).

The midpoint method of life cycle assessment was adopted for the assessment of environmental impact, as described in Chen et al. (2017). The predicted environmental impacts were classified and characterized into five impact categories as follows: (1) 100-year global warming potential (GWP_{100}; kg CO_2 eq kg^{-1}); (2) human toxicity potential [HTPinf; kg 1,4-dichlorobenzene (1,4-DCB) eq kg^{-1})]; (3) fresh water ecotoxicity potential (FAETPinf; kg 1,4-DCB eq kg^{-1}); (4) acidification potential (AP; kg SO_2 eq kg^{-1}), and; (5) eutrophication potential (EP; kg

PO43- eq kg^{-1}). An endpoint methodology was applied based individual environmental impacts to calculate the total environmental impact using CML-IA. The weights of the five impact categories used to calculate the total environmental impact were determined using the analytic hierarchy process (AHP) method (Deng et al., 2014). The weights multiplied by each impact category represented the environmental impact of the individual impact category, and the sum of all the categories was considered as the total environmental impact, as described in Chen et al. (2017).

3. Results and discussion

3.1. Assessment of energy consumption and production

3.1.1. Assessment of energy consumed and produced within the entire FW treatment system under different solid residue treatment scenarios

Table 1 shows the energy input and output of the system under the three solid digestate treatment scenarios. The method of solid digestate treatment had a greater impact on the energy consumption of the entire system compared to that of the energy output, with a net energy consumption ranging between 50.8 kWh and 57.3 kWh and a maximum fluctuation of 12.8%. The net energy output ranged between 1,100.8 MJ–1,186.5 MJ with relatively lower fluctuation of 7.8%.

The net energy consumption was highest under Scenario 2 (composting), with a total energy consumption of 685.7 MJ, exceeding those of scenarios 1 and 3 by 4.3% and 1.1%, respectively, and Scenario 2 had a net energy input of 57.3 kWh, exceeding those of scenarios 1 and 3 by 5.3% and 15.3%, respectively. This result can be attributed mainly to the wide-spread use of small reactors for *in-situ* disposal of solid digestate in China. Such equipment integrates thermal insulation, stirring, and other technology, and utilizes an extended decay process that results in high energy consumption during operation (Guo et al., 2018). The total energy consumption of Scenario 3 was significantly higher than that of Scenario 1 at 678.5 MJ and 657.5 MJ, respectively, which could mainly be attributed to the high moisture content of solid digestate (63.58%) generated after the AD of FW. This high moisture content of FW required reduction to below 60% through mechanical drying (i.e., 58% in Fig. 1) before being transported to landfill (MEP, 2008). The energy consumption of mechanical dehydration was large due to the energy input requirements of drying equipment (Herbes et al., 2020; Rehl and Müller, 2011). Thus, it was evident that the method of solid digestate disposal chosen determined the moisture content of waste discharge for the FW treatment plant, and this moisture content had a certain impact on the energy consumption of the entire FW treatment system. The landfill disposal process was associated with lower energy requirements due to the use of less equipment. In contrast, the series of mechanical equipment used in the incineration of MSW, such as incinerators and equipment for the negative pressure collection of incineration odors, resulted in this process requiring a relatively high net energy input (Wei et al., 2009; Zhou et al., 2019). This explained the higher net energy input of Scenario 1 compared to that of Scenario 3 of 54.4 kWh and 50.8 kWh, respectively, which was consistent with the rank of the three scenarios according to the energy input ratio: Scenario 2 (30.1%) > Scenario 1 (29.8%) > Scenario 3 (26.9%). It was evident that the net energy consumptions and energy input ratios of the three treatment methods were mainly related to the complexity of the process equipment used and their energy consumption.

Table 1

Energy consumption and production under three solid digestate residue treatment scenarios within the anaerobic digestion (AD) treatment of food waste (FW) in China, focusing on the treatment facilities within the city of Suzhou.

Items	Units	Scenario 1	Scenario 2	Scenario 3
Net energy input	kWh	54.4	57.3	50.8
Net energy output	MJ	1,186.5	1,100.8	1,106.0
Electricity production of biogas*	kWh	43.2 (13.1%)	41.8 (13.7%)	43.2 (14.1%)
Electricity production of incineration*	kWh	45.3 (13.8%)	23.0 (7.5%)	23.0 (7.5%)
Energy production of waste oil*#	L	21.8 (73.1%)	21.8 (78.8%)	21.8 (78.5%)
Total energy output	MJ	1,648.0	1,580.4	1,601.6
Recycling energy	MJ	461.5	479.6	495.6
Total energy consumption	MJ	657.5	685.7	678.5
Energy input ratio	%	29.8	30.1	26.9
Energy recycling ratio	%	28.0	30.3	30.9

Note: * Values in brackets indicate the percentage of total production capacity energy; $^{\#}$1 ton waste oil and fat can produce 0.85 tons of biodiesel (Wen et al., 2016). The calorific value of biodiesel is 39.8 MJ L^{-1} (Eiman, 2018). Scenario 1: incineration; Scenario 2: composting; Scenario 3: landfill.

The three scenarios showed relatively small differences in energy output. The net energy outputs of the three scenarios were in the forms of power generated by biogas, impurities and/or incineration of solid digestate residue, and the recovery of waste oil. The use of recycled energy in the FW plant was excluded in this calculation. The energy output (21.8 L) of waste oil accounted for a large proportion of total energy output, exceeding 73.1%. This can be attributed to FW in China containing high proportions of oil and fat (Jin et al., 2015; Li et al., 2019). Waste oil in FW has a relatively high resource value and can be used within biodiesel production (Eiman, 2018). The energy produced through the production of biodiesel from waste oil can be equated to that produced by biodiesel generated from crops. Therefore, the effective recovery of waste oil is important for increasing the energy efficiency and economic benefits of the entire circular economy (Jin et al., 2015; Wen et al., 2016). Biogas power generation under scenarios 2 and 3 accounted for the second largest energy output of the system at 13.7% and 14.1%, respectively, whereas power generation through incineration (13.8%) slightly exceeded that through biogas (13.1%) in Scenario 1. This is because 0.078 t of solid digestate could be incinerated for power generation in Scenario 1. Although biogas is the main product of AD treatment of FW, it has a relatively lower energy output. In particular, the energy output of incineration of 0.078 t of solid digestate residue under Scenario 1 acted to offset the recovered biogas under Scenario 2. This result can be attributed to the low efficiency of current biogas power generation technology of only 36.3% (Wu et al., 2016). Therefore, an improvement of the biogas energy recovery efficiency for FW recycling is required, such as cogeneration of biogas.

The differences among the solid digestate treatment methods resulted in the ranking of scenarios in terms of energy reused by the FW plant being: Scenario 3 (495.6 MJ) > Scenario 2 (479.6 MJ) > Scenario 1 (461.5 MJ). This resulted in differences between the treatment scenarios in the amount of remaining biogas, and the treatment scenarios had the same rank in terms of the biogas energy recycling ratio. However, the biogas generated during landfill treatment in Scenario 3 could be used for power generation. Ultimately, the ranking of treatment scenarios in terms of the output of biogas power generation was slightly different: Scenario 3 (43.2 kWh) ≈ Scenario 1 (43.2 kWh) > Scenario 2 (41.8 kWh). Scenario 3 required the removal of 0.01 t of water per ton FW through mechanical drying in addition to energy consumption requirements of hydrothermal treatment; therefore, Scenario 3 was associated with higher consumption of energy during recycling. Scenario 2 had higher energy consumption requirements compared to Scenario 1 due to insulation of composting equipment. In addition, impurities comprise 10%–15% of FW in China (Li et al., 2019), mainly including plastic, large pieces of wood, and cloth. These impurities were separated through pretreatment and were transported to the incineration plant for power generation, which generated 23.0 kWh of electric energy.

Total energy output is the sum of net energy output and recycled energy. The rank of the treatment scenarios in terms of their total energy output was: Scenario 1 (1,648.0 MJ) > Scenario 3 (1,601.6 MJ) > Scenario 2 (1,580.4 MJ). The treatment scenarios showed the same ranking in terms of net energy output. These results showed that the energy outputs of the three treatment scenarios exceeded 1,500 MJ per ton of FW; however, the AD of the project had a low biogas energy recycling ratio of 28.0%–30.9%. Complex processes were responsible for this result, and included the stability of biogas yield and the applicability of a small biogas generator. Interestingly, even under existing levels of technology, the reuse of all generated power by biogas within the treatment of FW would reduce the net energy input of scenarios 1–3 by 79.4%, 72.9%, and 85.0% respectively. This result indicates that the further improvement of the recycling of produced biogas to power the treatment of FW is an important energy-saving strategy in the AD treatment of FW.

In summary, the differences among the treatment scenarios resulted in differences in the compositions of the respective process equipment used, resulting in large differences in energy consumption. For example, composting of solid digestate requires small-scale *in-situ* composting facilities, whereas incineration requires complex MSW incineration processing facilities. Therefore, further study on the contributions of digestate treatment processes to overall energy consumption is important. In addition, the remaining biogas generated limited power, accounted for only 13.1%–14.1% of the total energy output, which is consistent with the findings of Wu et al. (2016).

3.1.2. Energy analysis of the sub-processing units

An analysis of the net energy consumption values of the sub-processing units in the treatment system showed clear differences among the three scenarios ($P < 0.05$). The energy consumption of Scenario 3 was the lowest at 9.6 kWh, whereas those of Scenario 2 and Scenario 1 were similar at 15.7 kWh and 15.8 kWh, respectively. The rank of the scenarios in terms of the energy consumption contribution ratio in their respective systems was Scenario 3 (19.0%) < Scenario 2 (27.3%) < Scenario 1 (29.0%). It was evident that the range of energy consumption contribution of 19.0%–29.0% among different solid digestate disposal methods far exceeded the range of material proportion of 6%–10%, which had a greater impact on the energy consumption of the entire system. Among the three scenarios, the energy consumption of Scenario 3 was the lowest. Although the other sub-processing units involved in the treatment of FW in Scenario 1 had the smallest energy consumption, the energy consumed in the incineration of solid digestate far exceeded that of landfill, resulting in the energy consumption of Scenario 1 exceeding that of Scenario 3. The high energy consumption of Scenario 2 was mainly due to the small scale of solid digestate composting as well as the long-term decomposition process used of ≥ 20 d (Guo et al., 2018).

As shown in Fig. 2, in addition to differences in energy consumption of digestate subunits among the scenarios resulting directly by the different solid digestate treatment methods used, the biological deodorization subunit used in each treatment scenario also had a significant impact on energy consumption, accounting for 6.1 kWh, 8.9 kWh, and 8.3kWh in scenarios 1–3, respectively. The high energy consumption values of scenarios 2 and 3 were mainly due to the treatment of large quantities of odor generated by composting or mechanical drying of solid digestate in the FW treatment plant.

The above analysis also indicated that the energy consumption of different solid digestate treatment methods can be transferred among different stakeholders. For example, within the FW treatment plant, the energy consumption of solid digestate incineration was lower than that of landfill and *in-situ* composting which required pretreatment. However, by considering the energy consumption in the solid digestate incineration treatment stage, it is clear that the energy consumption of solid digestate incineration was relatively high, and in fact exceeded that of landfill. In other words, the selection of solid digestate incineration treatment involves the transfer of a portion of the energy consumption responsibility of the FW plant to the incineration plant. Therefore, it is reasonable to assign responsibility for some of the solid digestate disposal costs to the FW plant. An appropriate selection of solid digestate disposal technology requires consideration of the scope considered by the decision maker and site-specific conditions, such as whether the MSW landfill accepts solid digestate of a FW treatment plant.

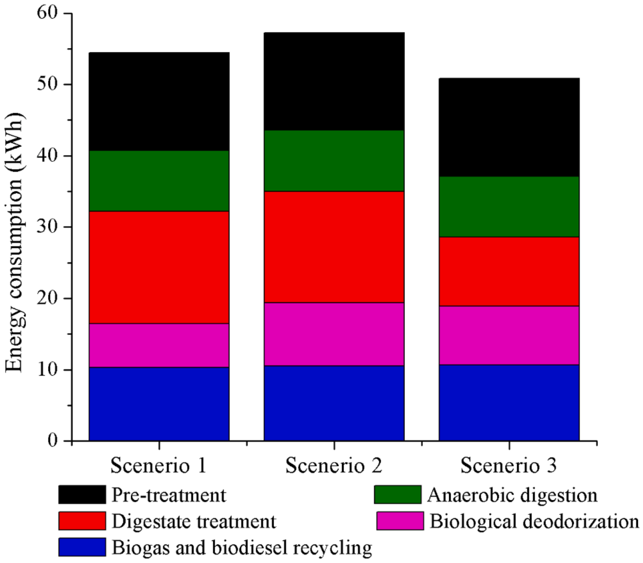

Fig. 2. The energy consumption of sub-processing units among three solid digestate treatment scenarios. Scenario 1: incineration; Scenario 2: composting; Scenario 3: landfill.

3.2. Evaluation of environmental impact

3.2.1. Environmental impacts of the different scenarios

As shown in Table 2 and Fig. 3, there were differences in the environmental impacts of the overall system and subunits among the three solid digestate treatment scenarios, and GWP_{100} constituted the largest environmental impact among all the treatment scenarios. Scenario 3 had greatest GWP_{100}, whereas the AP and EP load of Scenario 2 was significantly greater than those of scenarios 1 and 3. For example, the GWP_{100} of Scenario 3 was 218.21 CO_2 kg-eq t^{-1}, 1.7 and 2.2 higher than that of scenarios 1 and 3, respectively.. This result shows that the solid digestate processing method used had a significant impact on the environmental impacts of the entire system, and that Scenario 3 had poor environmental benefits. The poor environmental benefits of Scenario 3 were mainly due to the large emissions of methane, resulting in a higher GWP_{100} impact (Nordahl et al., 2020). Composting under Scenario 2 was

Table 2
Environmental impacts of the entire biogas system under three food waste solid digestate treatment scenarios.

Indicators	Units	Scenario 1	Scenario 2	Scenario 3
		(Power generation with remaining biogas)		
GWP_{100}	kgCO2-eq t^{-1}	128.82	100.77	218.21
AP	kgSO2-eq t^{-1}	−0.17	0.33	−0.03
EP	kgPO4-eq t^{-1}	0.03	0.09	0.03
$FAETP_{inf}$	kg1,4DCB-eq t^{-1}	5.36	5.29	2.33
HTP_{inf}	kg1,4DCB-eq t^{-1}	−0.25	−0.14	−0.02
Total environmental impact	–	9.06E-03	8.75E-03	1.43E-02

Note: Scenario 1: incineration; Scenario 2: composting; Scenario 3: landfill; Positive values indicate a negative impact on the environment, whereas negative values indicate a positive impact (avoided impact) on the environment. Abbreviations: GPW_{100}: 100-year global warming potential; AP: acidification potential; EP: eutrophication potential; $FAETP_{inf}$: fresh water ecotoxicity potential; HTP_{inf}: human toxicity potential.

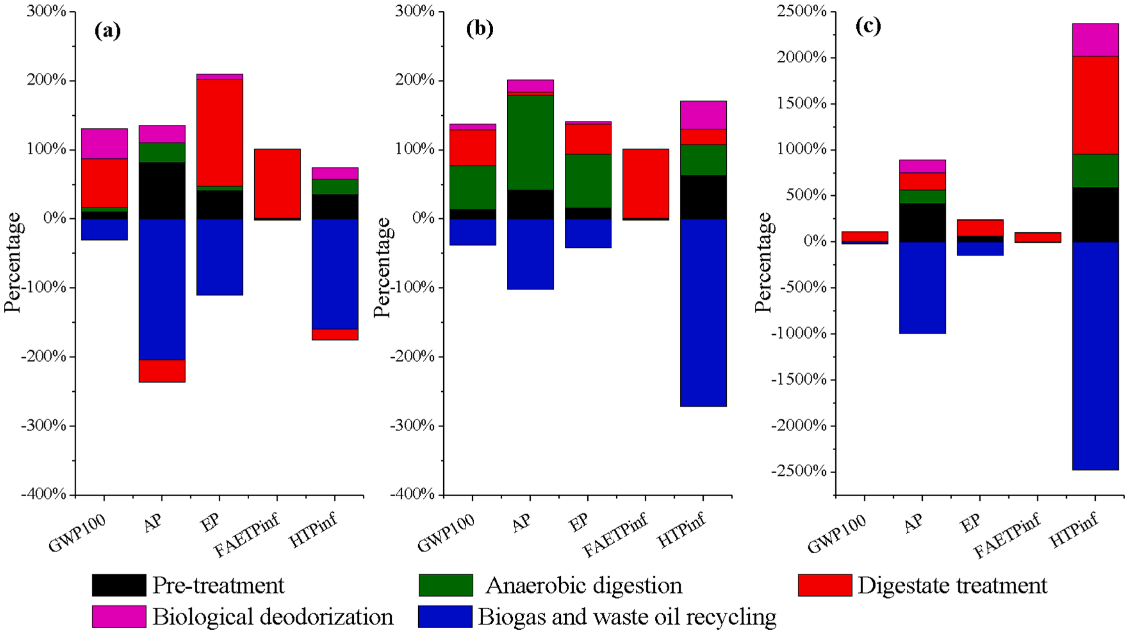

Fig. 3. Analysis of the contribution of subunit mid-point environmental impact categories (a: Scenario 1 - incineration; b: Scenario 2 - composting; c: Scenario 3 - landfill). GPW_{100}: 100-year global warming potential; AP: acidification potential; EP: eutrophication potential; $FAETP_{inf}$: fresh water ecotoxicity potential; HTP_{inf}: human toxicity potential.

associated with the highest net energy consumption, resulting in this scenario having the highest AP and EP impacts since coal-fired power remains the dominant source of power in China (IEA, 2017), thereby having a large impact on the environment and playing a major role in the release of greenhouse gases.

However, scenarios 1 and 3 did not result in an AP environmental load. AP is mainly related to atmospheric pollution by sulfur and nitrogen derived from human activities, such as NOx or ammonia, and is measured as kg SO_2. Fig. 3 shows that the AP impacts of scenarios 1 and 3 were mainly derived through pretreatment, AD, and biological deodorization subunits, which were mainly reduced by the biogas and waste oil recycling subunits. The resource products such as waste oil and biogas produced by these two subunits can replace the traditional fossil fuel sources of energy such as diesel and coal-fired power generation, thereby effectively avoiding the AP effects of fossil fuel mining and use (Jin et al., 2015). In addition, the AP effect of the digestate treatment subunit in Scenario 1 was negative, while that in Scenario 3 was positive (Fig. 3). This was mainly due to that fact that power generated by solid digestate incineration could replace power derived from traditional coal-fired plants, which could improve the AP effect to a certain extent; however, the concentrations of acid gases such as H_2S and SO_2 in the landfill released during the solid digestate landfill process are high (Wei et al., 2009), which leads to some AP impact.

The present study mainly considered the impact of toxic substances produced by the system on aquatic ecology and human health, represented as $FAETP_{inf}$ and HTP_{inf}, respectively. Table 2 shows that there were some positive $FAETP_{inf}$ impacts as well as some negative HTP_{inf} impacts among the three solid digestate treatment scenarios, and that there were fewer differences among the three scenarios. Scenario 1 had the largest $FAETP_{inf}$ among the three scenarios due to the greater net energy consumption.

Overall, the impact of emissions on GWP_{100} was the most significant for the entire system (Chen et al., 2017; Jin et al., 2015), and the order of scenarios in terms of the GWP_{100} impact of solid digestate treatment technologies was: Scenario 3 > Scenario 2 > Scenario 1, resulting in a ranking in the treatment scenarios in terms of the total environmental impact of: Scenario 3 (1.43 E-02) > Scenario 1 (9.06 E-03) > Scenario 2 (8.75 E-03), as shown in Table 2. The total environmental impact of solid digestate composting was 3.4% and 38.8% less than those of incineration and landfill, respectively, which illustrates that solid digestate treatment technology had a significant impact on the total environmental impact of the entire system. Among the three treatment scenarios examined in the current study, composting had the lowest environmental impact. There has been an increasing focus on the development of environmentally friendly FW treatment technologies by developers and practitioners globally (Peng et al., 2020). Therefore, a reasonable solid digestate disposal strategy for reducing the environmental impact of FW treatment should be considered carefully.

3.2.2. *Contribution of the digestate processing subunit to environmental impacts*

As shown in Fig. 3, the contribution of digestate processing subunits, including the treatment of solid digestate, to different environmental impact categories ranged from −32.4% to 1,062.7%. This result indicated that the digestate processing subunits made a large contribution to environmental impacts, and environmental impacts varied considerably among the three treatment scenarios ($P < 0.05$). The digestate processing subunits in scenarios 2 and 3 made positive contributions to environmental impacts (Fig. 3b), producing 7.5%–100.3% and 100.7%–1,062.7% of the five EI categories, respectively. The higher contribution ratios were mainly due to the high energy consumption of the digestate processing subunit (Fig. 2) in Scenario 2 and the high emission concentrations of pollutants in Scenario 3 (Wei et al., 2009). In contrast, the digestate processing subunit in Scenario 1 only made positive contributions to the EIs of GWP_{100}, EP, and $FAETP_{inf}$, whereas its contributions to AP and HTP_{inf} were negative. As mentioned above, the negative contribution of Scenario 1 was mainly due to the effect of modern MSW incineration in reducing AP and HTP_{inf}, such as efficient flue gas purification, energy recycling, and the power generation system (Wei et al., 2009). In other words, the benefit of avoiding the impact of solid digestate and the incineration of impurities on AP and HTP_{inf} exceeded the negative impact of net energy consumption. In addition, due to the small energy consumption of landfill in Scenario 3 (Fig. 2), this scenario had a small HTP_{inf} impact (Table 2), resulting in a greater contribution of digestate processing subunits to HTP_{inf}, reaching 1,062.7%.

Fig. 3 shows that the digestate processing subunits of the three solid digestate treatment technologies had a greater influence on the environmental impacts of the system, particularly in scenarios 2 and 3. The contributions of the digestate processing subunits in scenarios 1–3 to GWP_{100} reached 70.5%, 52.5%, and 103.4%, respectively. However, the impacts of digestate processing subunits to AP were not obvious compared with those of other subunits, such as biological deodorization, biogas, and waste oil recycling. This shows that the digestate processing subunits had various impacts on different environment categories and technologies. Within the present study, the impacts of digestate processing subunits on the main environmental impact category, i.e. GWP_{100}, were very significant. Therefore, reasonable solid digestate residue treatment would be beneficial to reducing the environmental impact of the entire FW treatment system.

4. Conclusions

The three treatment scenarios showed significant differences in environmental impacts and energy consumption. Although *in-situ* composting of solid digestate had the greatest energy consumption (57.3 kWh), it showed the least environmental impact (total environmental impact of 8.75 E-03). In contrast, co-processing using MSW landfill or incineration plants was found to be an acceptable technical option in terms of energy consumption. Further research is needed to improving the rate of recycling of biogas to reduce the energy consumption of composting, reduce the greenhouse gas emissions of landfills or incineration, and to establish a low-consumption and environmentally friendly FW-based biogas system.

CRediT authorship contribution statement

Ting Chen: Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Xiaopeng Qiu:** Data curation, Investigation. **Huajun Feng:** Validation, Software. **Jun Yin:** Visualization, Writing - review & editing. **Dongsheng Shen:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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