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Life cycle cost–benefit efficiency of food waste treatment technologies in China

Ziyao Fan[1] · Huijuan Dong[1,2] · Yong Geng[1,2,3,4] · Minoru Fujii[5]

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Abstract

Food waste treatment and utilization is important in sustainable waste management. Unlike most existing studies on environmental impact analysis of food waste treatment technologies, this study conducted both environmental impacts and economic cost analysis of food waste treatment technologies using life cycle assessment and life cycle cost methods. Five promising technologies in China are compared, including anaerobic digestion (AD), aerobic composting combined digestion (AC + AD), aerobic composting (AC), biochemical processor (BP), and anaerobic digestion combined feed processing technology (AD + FP). Results show that the rank of environmental impact is AD + FP > AD > BP > AC + AD > AC, while the rank of LCC is AC + AD > AD + FP > BP > AC > AD. Aerobic technology usually has a lower environmental impact, but slightly higher economic cost compared with anaerobic technology, about 188 CNY/t and 249 CNY/t, respectively. AD + FP has the best environmental performance (4.5E−11/t), and AC + AD has the best economic performance (5.3 CNY/t) due to profits from soil amendment selling. Mixed technologies AC + AD and AD + FP exhibit obvious better cost–benefit efficiency than single treatment technology AC or AD and thus are suggested to be set priority in food waste treatment. BP has relatively good performance and is worthy of consideration for regions with small treatment demand.

Keywords Food waste · Anaerobic digestion · Aerobic composting · Life cycle assessment · Life cycle cost

✉ Huijuan Dong
donghj@sjtu.edu.cn

1 School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

2 Shanghai Engineering Research Center of Solid Waste Treatment and Resource Recovery, Shanghai Jiao Tong University, Shanghai 200240, China

3 School of International and Public Affairs, Shanghai Jiao Tong University, Shanghai 200030, China

4 China Institute for Urban Governance, Shanghai Jiao Tong University, Shanghai 200030, China

5 Center for Social and Environmental Systems Research, National Institute for Environmental Studies, Tsukuba 305-8506, Japan

1 Introduction

Food waste is generated from both households and catering industry. It is a major component of municipal solid waste in China, accounting for about more than 50% in most Chinese provinces (Cheng & Dong, 2017; Bernstad and Jansen, 2011; Righi et al., 2013; Salemdeeb & Al-Tabbaa, 2015; Slorach et al., 2019, Zhu, 2014). Due to its high oil and water contents, it will cause unexpected environmental pollution if it is not efficiently collected and disposed of. In particular, if such waste is mixed with other municipal solid wastes for incineration or landfilling, the impacts will be further enhanced (Tong et al., 2018). In addition, with improved living standards, the Chinese people are consuming more food items, indicating that such waste will further increase. Therefore, it is critical to effectively treat and utilize such waste in China.

In order to increase the efficiency and recycling of municipal solid waste treatment, the Chinese government launched the MSW classification pilot city program in 46 cities in 2016 (Xiao et al., 2018). As one of the pilot cities, Shanghai played an important role in practicing MSW sorting and implemented China's first urban-level MSW sorting regulation on July 1st, 2019. It legally required that MSW be classified into four categories, including food waste, recyclable waste, residue waste, and hazardous waste. After implementing the MSW sorting regulation, much more food waste has been separated. According to official statistics, the amount of collected food waste in Shanghai reached 9504 tons per day in 2020. To meet the growing demand for food waste treatment, the daily capacity for food waste treatment increased from 5550 tons per day in 2019 to 6795 tons in 2020. However, there is still a huge demand for food waste treatment facilities. The question is what kind of treatment facility should be promoted for future food waste treatment.

There are many different treatment methods for food waste, such as landfill, incineration, composting, biochemical treatment, etc. The majority of food waste are treated by incineration or landfill in China, with a small percentage of biological treatment (Li et al., 2021), while in Europe, 47% of food waste is recycled into compost and digestate, and 28% is incinerated (Albizzati et al., 2021). Traditional methods like incineration and landfill are easier and cheaper options, but the disadvantages are also obvious, for example, the difficulty of incineration due to high water content, methane emission from landfill (Yong et al., 2015), and serious secondary pollution and human disease. Biological treatment options such as aerobic composting, anaerobic digestion, and feed processing are regarded to be better solutions for food waste treatment. These biological treatment technologies can turn food waste into resources like soil amendment, biogas and animal feed (Syafrudin et al., 2020), which can not only reduce environmental pollution, but also generate some economic profits for the treatment plant. However, not all biological treatment methods are good in environmental aspect. They also have some drawbacks and weaknesses. For instance, biological treatment facilities are usually more complex, high cost, and strict with operation conditions (Gao et al., 2017). Considering the life cycle environmental impacts and circular economy, biological treatment methods are still more promising than traditional treatment methods for food waste management to respond to MSW sorting policy in the future.

Academically, many studies have been conducted on the life cycle environmental impacts of different biological treatment techniques for food waste treatment, with results being varied over time and places. From the technical perspective, aerobic composting, anaerobic digestion, and feed processing technology are the main biological treatment methods for food waste disposal. Slorach et al. (2019) compared technologies of aerobic composting, anaerobic digestion, landfill and incineration using LCA, finding that they all met the same conclusion that anaerobic digestion was more environmental-friendly in terms of energy recovery and environmental impacts. However, Lundie and Peters (2005) also conducted life cycle assessment on food waste disposal but had opposite conclusion with Slorach. As for feed processing, Mondello et al. (2017) used LCA to compare the environmental impacts of anaerobic digestion and feed processing, finding that feed processing technology had the lowest impact in acidification, eutrophication, and ozone depletion categories and the other nine impact categories except for global warming potential. In addition to single biological technology, mixed biological technologies have become a preferred option for food waste treatment in some countries. Righi et al. (2013) compared single technologies with mixed technologies and found that anaerobic digestion combined aerobic composting technology performed better than single aerobic composting or landfilling in the environmental impact categories of global warming potential, acidification potential and eutrophication potential. More studies on LCA analysis of food waste treatment methods are presented in Table 1. We can notice that most of the studies choose global warming potential, acidification potential, eutrophication potential, and human toxicity potential to assess the environmental impacts of different food waste treatment technologies, probably because these impact categories can clearly reflect pollution and damage to air, water and human. As for treatment technologies, environmental benefits of different biological treatment technologies such as AC (aerobic composting), AD (anaerobic digestion), FP (feed processing), and AC + AD (aerobic composting combined anaerobic digestion) have been compared with traditional treatment methods INC (incineration) and LF (landfilling). Biological technologies are found to be better than traditional treatment methods. However, there are limited studies concentrating on mixed technologies. Therefore, we choose five biological treatment methods, including not only single technologies but also mixed technologies to compare their environmental and economic performance.

Some researchers also conducted economic analysis of food waste treatment technologies to investigate suitable treatment solutions for food waste by combing both environmental benefit and economic cost. For example, due to the huge amount of food waste in the Finger Lakes region of New York, Chan et al. (2013) analyzed the opportunity to produce sustainable energy from food waste by three primary pathways, including anaerobic digestion to produce methane, fermentation to produce alcohols, and transesterification to produce diesel, finding that biochemical treatment option is more applicable for food waste management from point view of economy. To be more specific, Babalola (2020) used an analytic hierarchy process (AHP) benefit–cost analysis technique to compare anaerobic digestion, aerobic composting, landfill, and incineration for food waste treatment, finding that anaerobic digestion was the most suitable treatment alternative in terms of cost–benefit ratio, and suggesting combining composting with anaerobic digestion as an optimal food waste management option in Oita City. Also, Ahamed et al. (2016) conducted both life cycle environmental impact assessment and cost–benefit analysis on food waste management technologies of incineration, anaerobic digestion, and waste-to-energy bio-diesel system in Singapore, finding that anaerobic digestion was the best choice for acidification potential, eutrophication potential, global warming potential, cumulative energy demand and economic sustainability. In the perspective of life cycle cost, Li et al. (2021) calculated the recovery rate, carbon emission and LCC of food waste incineration, anaerobic digestion, aerobic composting, and feed processing technology in China, finding that feed processing technology had the best environmental effect but incineration was the most cost-effective method.

Table 1 Literature review on LCA analysis of food waste treatment

References	Regions	LCA Software LCA method	Food waste treatment methods	Number of impact category	Critical findings
Gao et al. (2017)	Qingdao, China	SimaPro Eco-indicator	AC/AD/INC/LF	4	AD has more environmental benefits than other methods. It can be the first choice when treatment food waste
Xu et al. (2015)	China	Not specified ReCipe	AD/LF	18	LF is not suitable for disposing food waste. The environmental impact of AD is the lowest. Increasing biogas power generation capacity, improving electricity generation efficiency, and reducing electricity consumption in the anaerobic digestion stage are effective ways to reduce the negative impact for AD
Ahamed et al. (2016)	Singapore	Not specified CML	AD/INC	4	The environmental impact of INC is the highest. AD is more effective and uses less resource compared with INC
Brancoli et al. (2017)	Sweden	Not specified ILCD	AD/FP/INC	8	Turning food waste into animal feed and recycling the packaging bags can significantly reduce environmental impact than AD and INC
Lee et al. (2007)	Seoul, South Korea	SimaPro CML	AC/AD/FP/LF	5	LF has the largest contribution to human toxicity and global warming. FP greatly exacerbates the impact of eutrophication potential
Kim and Kim (2010)	Seoul, South Korea	Total 3.0 Not specified	AC/FP/LF	1	AC and FP are common methods in food waste disposal and more environmental-friendly than LF when their products being used properly
Bernstad and Jansen (2011)	Sweden	EASEWASTE Not specified	AC/AD/INC	5	Compared with INC, AC and AD can avoid greenhouse gas emission and cause less environmental impact
Eriksson et al. (2015)	Sweden	Not specified Not specified	AC/AD/FP/INC/LF	1	Since this study only concentrates on global warming, AD is the best choice
Morris et al. (2017)	the USA	Not specified Not specified	AC/AD/LF	6	Considering total environmental impact, AD is more preferred than AC and LF
Edwards et al. (2018)	Australia	SimaPro CML-IA	AC/AD/LF	8	If food waste is effectively sorted from other wastes and be treated by AD, the global warming potential of AD might be negative

Table 1 (continued)

References	Regions	LCA Software LCA method	Food waste treatment methods	Number of impact category	Critical findings
Lam et al. (2018)	Hong Kong	SimaPro ReCipe	AC/INC/LF	18	LF is the worst choice for food waste disposal. Dehydration before LF can reduce the impact but is still not enough environmental
Jorge et al. (2016)	Europe	EASETECH EC PEF	AC/AD/AC + AD/INC/LF	12	In all environmental impact categories, no one management option simultaneously performed better than the others. AC, AD, and AC + AD are relatively better than INC and LF
Righi et al. (2013)	Italy	GaBi CML	AC/AD/AC + AD/LF	5	AC + AD can significantly reduce environmental impact of food waste disposal. The impact of transportation and LF is high
Baky and Eriksson (2003)	Denmark	ORWARE Not specified	AC/AD/INC	4	The environmental impact of AC is higher than AD except for photochemical ozone creation potential
Blengini (2008)	Italy	SimaPro Not specified	AC/AD/LF	6	AC consumes more resource than LF. AD can recycle energy from food waste
Sonesson et al. (2000)	Sweden	ORWARE Not specified	AC/AD/INC	8	The environmental impact of AD is the lowest, but it causes more money. INC causes less but has higher impact than AC
Diggelman and Ham (2003)	the USA	Not specified Not specified	AC/INC/LF	3	LF cause more impact for environment. Recycling energy by INC can reduce environmental damage
Andersen et al. (2012)	Denmark	EASEWASTE EDIP	AC/INC/LF	9	AC has lower environmental impact compared with INC and LF especially in eutrophication potential, acidification potential, and water ecotoxicity potential
W et al. (2011)	the USA	SimaPro Eco-indicator	AC/AD	10	AD is more environmental-friendly for carcinogens, respirable organics, respirable inorganics, minerals, and fossil fuels

Table 1 (continued)

References	Regions	LCA Software LCA method	Food waste treatment methods	Number of impact category	Critical findings
Edwards et al. (2017)	Australia	SimaPro Not specified	AC/AD/LF	8	No method performs the best in all impact categories. LF has the higher impact in global warming potential. AC and AD have the lowest impact in more than two impact categories
Zhu (2014)	the U.S	Not specified Not specified	AC/AD/LF	3	From the environmental perspective, AD is the best choice for food waste disposal. But LF is the most economic choice
Slorach et al. (2019)	England	GaBi ReCiPe	AC/AD/INC/LF	19	AD has the lowest impact in 13 impact categories
Oldfield et al. (2016)	Ireland	GaBi CML	AC/AD/INC/LF	3	AD has the lowest environmental impact compared with AC, INC, and LF

In summary of existing studies, there are three research gaps. First, more studies were concerned with food waste treatment in European countries, with only a few studies related to China. With the compulsory implementation of the four-category garbage sorting policy in China (Xiao et al., 2020), proper food waste treatment will become a tricky challenge. In addition, biological treatment options such as aerobic composting, anaerobic digestion technology, and feed processing technology are more mature and popular than before to treat food waste. It is therefore necessary to investigate environmental impacts of food waste treatment technologies for China and other developing countries. Second, most of existing studies concentrate on environmental impacts of landfill, incineration, aerobic composting, and anaerobic, while only a limited number of studies focused on the economic cost/benefit of food waste treatment. However, economic cost/benefit is an important factor that affects the selection of treatment technologies, hence needs to be evaluated. Third, more treatment technologies, such as combined technologies that are suitable for local regions, have been developed in China with economic development. It is useful to investigate and compare their environmental benefit and cost efficiency of emerging technologies. Under such circumstances, this study considered not only life cycle assessment of environmental impacts, but also the life cycle economic cost of promising food waste treatment technologies in China. It is anticipated that not only existing research gaps can be filled, but also comprehensive technology comparison and identification of appropriate food waste treatment solutions for local government can be done by taking into consideration of both environmental benefit and economic cost.

The remainder of the article is structured as follows. Section 2 explains the LCA models established to evaluate the environmental impacts and economic costs of food waste treatment technologies. Section 3 depicts the results in detail, and Sect. 4 focuses on discussions the policy remarks. Finally, conclusions are drawn in Sect. 5.

2 Methods and data sources

2.1 Introduction of food waste treatment cases

Five emerging food waste treatment technologies are selected to be compared by taking different treatment plants located in cities of Shanghai, Shaoxing, Hohhot, and Baotou of China. More information about each case is listed in Table 2. These food waste treatment plants have already been in successful operation for a few years except the aerobic composting technology (AC) and the anaerobic digestion technology (AD) that are located in Hohhot. Feasibility reports for both the AD and AC technology in Hohhot have been finished, and the construction of the AD case is even finished for putting into operation. Further considering that AD and AC technologies are mature food waste treatment technologies worldwide, the two technologies are also selected for life cycle cost–benefit analysis in this study. The detailed data of each treatment plant/technology are obtained mainly through onsite survey, project reports, or communication with local experts. The following sections introduce more details about the treatment processes and life cycle input output data for the five food waste treatment technologies.

Table 2 Information about five food waste treatment cases

Abbre	Treatment technology	Location	Disposal capacity	Source of food waste	Operation year
AD	Anaerobic digestion	Hohhot	300 t/d	Catering food waste	Under construction
AC	Aerobic composting	Hohhot	300 t/d	Catering food waste	Feasibility analysis done
AC + AD	Aerobic composting combined digestion	Shanghai	200 t/d	Catering food and household food waste	2017
BP	Biochemical processor	Shaoxing	10 t/d	Food market waste	2018
AD + FP	Feed processing combined digestion	Baotou	300 t/d	Catering food waste	2018

2.2 Life cycle environmental impact assessment

The study is conducted according to the LCA methods defined by ISO 14040, which often includes four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation. As an effective tool, LCA can help to assess and compare the environmental impacts of human activities (Khoo et al., 2010). It was first used by Midwest Resources Institute (MRI) resource requirements, emission loads, and waste flows of different beverage containers for the Coca-Cola Company in 1969 (Dong et al., 2016).

2.2.1 Definition of goals and scope

In this study, five commonly used food waste treatment technologies are assessed, including anaerobic digestion technology (AD), aerobic composting combined digestion technology (AC + AD), aerobic composting technology (AC), biochemical processor (BP), and anaerobic digestion combined with feed processing technology (AD + FP). The functional unit refers to one ton treated food waste, which is the base for life cycle impacts comparisons Xu et al. (2015). The life cycle of food waste includes the following stages, including pretreatment of food waste, biological treatment process, incineration of impurities and wastewater processing. The detail treatment processes and system boundary of the five food waste treatment technologies are presented in Fig. 1. The biochemical processor is not included because of its simple treatment process. Considering that delivery of food waste to biological treatment plant can be regarded as the same with the transportation to other treatment facilities, this delivery is not included in the LCA boundary.

The treatment processes of the five case studies are described below.

AD technology: After being sent to the treatment facility, the food waste is sent to discharge hopper with heat tracing and draining device. The oil–water in the food waste is discharged into the oil extraction device. The rest residue is sent to the sorting machine and steamer for heating, then to the press dehydrator so that the organic matters can be removed from the debris like plastics. Through oil extraction and homogenization, the organic matter is sent to the digestion system for anaerobic digestion under medium temperature. The biogas slurry and residues from the digestion device are dewatered, and the biogas is sent into the boiler after purification.

AC + AD technology: After being sent to the treatment facility, the food waste is sorted and compressed to be separated into solid waste and leachate in the pretreatment system. The solid waste is then sent to the aerobic composting system, and the leachate is sent to the oil–water separation system before anaerobic digestion.

AC technology: After being sent to the treatment facility, the food waste is separated from other municipal solid waste by sorting machine. Three kinds of components, namely oil, water, and solid waste, are separated after the pretreatment process. The water content is sent to wastewater processing system for treatment. The oil content is further transformed into grease. The solid content is sent to the aerobic composting system.

BP technology: Food waste from the grocery/vegetable/food market is usually collected and treated using BP technology. After simple sorting, it is composted in the BP machine for 5–7 days. Then such compost is delivered to the local farms for free application.

AD + FP technology: After being sent to the treatment facility, the food waste is separated from other municipal solid waste by sorting machine. Then it is crashed and turned into seriflux for hydrothermal hydrolysis. Then after the three-phase separation

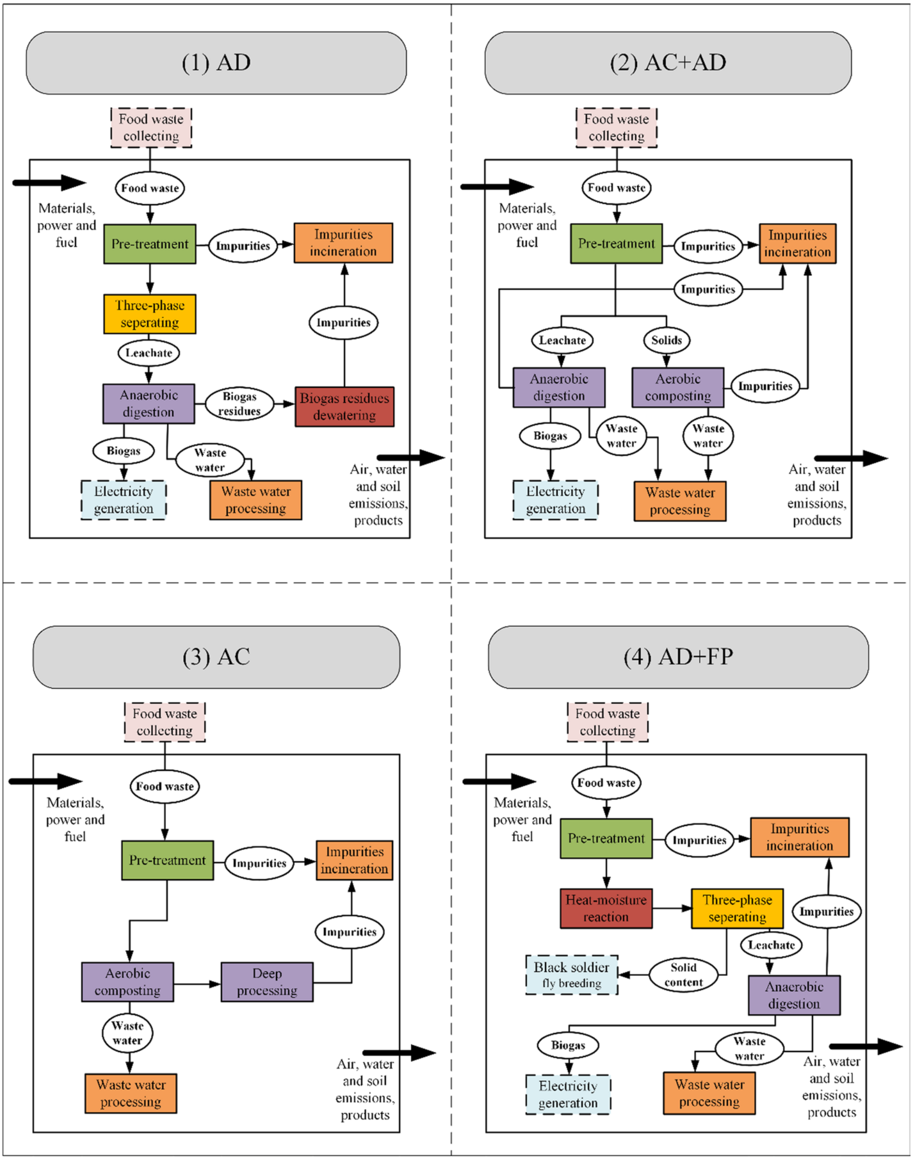

Fig. 1 System boundary of food waste treatment technologies

stage, oil, water and solid waste are obtained. The oil is further purified and sold in the markets. The wastewater is sent to the anaerobic digestion system to generate biogas. Solid waste is used to breed Black Soldier Fly larvae, which can be made into a high-protein fertilizer for sale.

Table 3 Life cycle inventory data for food waste treatment technologies (all data are for 1 ton of food waste)

Input/output	Category	Materials	Unit/t	AD	AC + AD	AC	BP	AD + FP
Input	Material	Food waste	kg	1000	1000	1000	1000	1000
		Sawdust	kg	–	230.55	250	36	–
		Water	kg	333.33	421.33	210	190	160
		HA transforming agents	kg	–	0.068	–	–	–
	Energy	Electricity	kWh	40	87.39	88.47	27.4	83.3
Output	Products/by-products	Biogas	Nm3	110	36.26	–	–	75
		Food waste oil	kg	20	5.28	10	–	30
		Soil amendment	kg	–	427.58	320	260	–
	Water pollutant emissions	NH_3-N	kg	–	0.16	0.009	–	–
		NO_X	kg	–	0.021	0.022	0.039	–
		HCl	kg	–	2.4E−6	2.4E−6	4.38E−6	–
		HF	kg	–	2.4E−7	2.4E−7	4.38E−7	–
		BOD	kg	2.7E−3	0.30	0.0068	–	0.0023
		COD	kg	6.32E−3	57.11	0.015	104	0.0057
		SS	kg	1.4E−3	0.16	0.0112	–	–
		Arsenic	kg	5E−6	–	–	–	4.20E−6
		Cadmium	kg	1.25E−6	–	–	–	1.055E−6
		Phosphate	kg	2.74E−3	–	–	–	0.0023
		Sulfate	kg	0.065	–	–	–	0.055

Table 3 (continued)

Input/output	Category	Materials	Unit/t	AD	AC + AD	AC	BP	AD + FP
	Air pollutant emissions	NH_3	kg	–	0.14	0.63	0.197	–
		NO_X	kg	0.057	0.017	0.17	–	0.048
		CO	kg	0.011	0.025	0.0065	0.012	0.0094
		CO_2	kg	26.35	118.95	135.60	183	22.23
		CH_4	kg	0.029	2.53	–	3.29	0.024
		SO_2	kg	0.17	0.0031	0.0015	0.0032	0.15
		SO_X	kg	–	0.0029	0.0018	–	–
		H_2S	kg	5.04E−5	0.0095	0.0134	0.0132	4.24E−5
		VOC	kg	2.98E−4	0.015	–	–	0.00025

2.2.2 Life cycle inventory

The inventory data for the five technologies are presented in Table 3. And the data sources are diverse. Life cycle inventory data of technologies AC + AD, BP, and AD + FP were mainly obtained through onsite survey on theses food waste treatment plants and the Gabi database. The data of AC and AD were mainly from the project feasibility analysis report due to the project was still under or consider for construction. During the food waste disposal, it is assumed that the impurities and biogas residues in the pretreatment system, aerobic composting system and anaerobic digestion system are sent to the incineration plant without heat recycling. Wastewater can meet the emission discharge standard, no matter it is treated on site or sent to the wastewater treatment plant. Biogas produced by the anaerobic digestion system is recycled and purified as supplementary energy of the treatment plant.

2.2.3 Environmental impact assessment

GaBi 9.0 software and the well-established midpoint impact method CML-2001 developed by the Centre for Environmental Science of Leiden University in Netherlands were used to evaluate the life cycle environmental impact. Different environmental impacts can be divided into two categories, namely, consumption of material and energy sources, and environmental pollution and damage, which can be further classified into 10 subcategories as follows.

Global warming potential (GWP, unit: kg CO_2 eq);
Acidification potential (AP, unit: kg SO_2 eq.);
Eutrophication potential (EP, unit: kg phosphate eq.);
Ozone layer depletion potential (ODP, unit: kg R11 eq.);
Photochem ozone creation potential (POCP, unit: kg ethane eq.);
Freshwater aquatic ecotoxicity potential (FAETP, unit: kg DCB eq.);
Terrestrial ecotoxicity potential (TETP, unit: kg DCB eq.);
Human toxicity potential (HTP, unit: kg DCB eq.);
Abiotic depletion potential (ADP elements, unit: kg Sb eq.);
Fossil fuel depletion (ADP fossil, unit: MJ).

Different impact categories reflect different environmental problems. GWP is of great importance for quantifying greenhouse gases (GHG) that contribute to climate change. Also, the storage and stacking of food waste and the generation of its leachate will generate acid air or water emissions, leading to the increase of AP impact, thus causing a wide range of impacts to surface water bodies, soil, building, etc. Meanwhile, EP represents environmental impacts caused by excess nutrients in the ecosystem, especially water bodies. The ODP is mainly influenced by electricity consumption. Methane, nitrogen oxides, carbon monoxides, and VOC are the main contributors of POCP, so these compounds released after the combustion of fuels will cause higher environmental impact. The ecological toxicities can be influenced by the types and amount of different heavy metals. Finally, ADP elements refer to the avoided use of nonrenewable resources excluding fossil fuels; ADP fossil refers to the use of nonrenewable fossil fuels.

To better compare different environmental impacts of different technologies, the CML2001 normalization method is further used after life cycle assessment.

2.3 Cost–benefit analysis

Economic cost is usually more important compared to environmental impacts when enterprises selecting appropriate technologies. Therefore, cost–benefit analysis is applied in this study to assess not only the environmental impacts, but also the economic cost of different food waste treatment methods. The life cycle cost (LCC) of one treatment technology can be calculated according to Eq. (1).

$$\mathrm{LCC} = C_c + C_O - R \tag{1}$$

where C_c: capital costs including cost for construction, facility and equipment, etc. C_O: operation costs such as facility maintenance, labor cost, electricity fee, and daily material consumption (Chinese yuan (CNY)/t food waste). R: revenues from food waste treatment, including benefit from product sale (CNY/t food waste).

In this study, the biogas generated from the application of AD, AC + AD, and AD + FP is recycled and used to produce electricity for the operation of plants. The source of profits for each plant depends on the technology they used. For example, the main income for AC + AD and AC is the sale of soil amendment products. As for AD + FP, selling dry worms is the dominant profit. Except BP, the oil separated from food waste is also an important part of profits although the output of each plant differs significantly.

Formula (2) is defined here to better compare the comprehensive benefits of the five treatment technologies by combining both the environmental impact and economic aspects. The larger the value is, the better the overall benefit of this technology is.

$$\mathrm{CB\,efficiency} = \frac{1}{\mathrm{LCC} \times \mathrm{lifecycleenvironmentalimpact}} \tag{2}$$

3 Results

3.1 Life cycle environmental impact

Comparison results of the life cycle environmental impact for the five food waste treatment technologies are presented in Fig. 2. It can be found that anaerobic technologies AD, AD + FP, and BP have better environmental performance than aerobic technologies AC + AD and AC. To be more specific, technology AD has the lowest environmental impact in AP, ADP fossil, ODP, POCP, and HTP, while BP performed better in toxicity impact (FAETP and TETP) and impact of ADP elements. AD + FP has the lowest impact in GWP and EP. The reason for the good environmental performance of AD and AD + FP is in part due to the benefits for the electricity recovered from biogas generation, in part due to less pollution produced by its treatment process. As for BP, the small treatment capacity and simple technological process also reduce the corresponding pollution and energy consumption.

Apart from environmental impacts EP, ADP elements, POCP, and FAETP, other impacts of AC technology are much higher than the other four technologies. POCP and

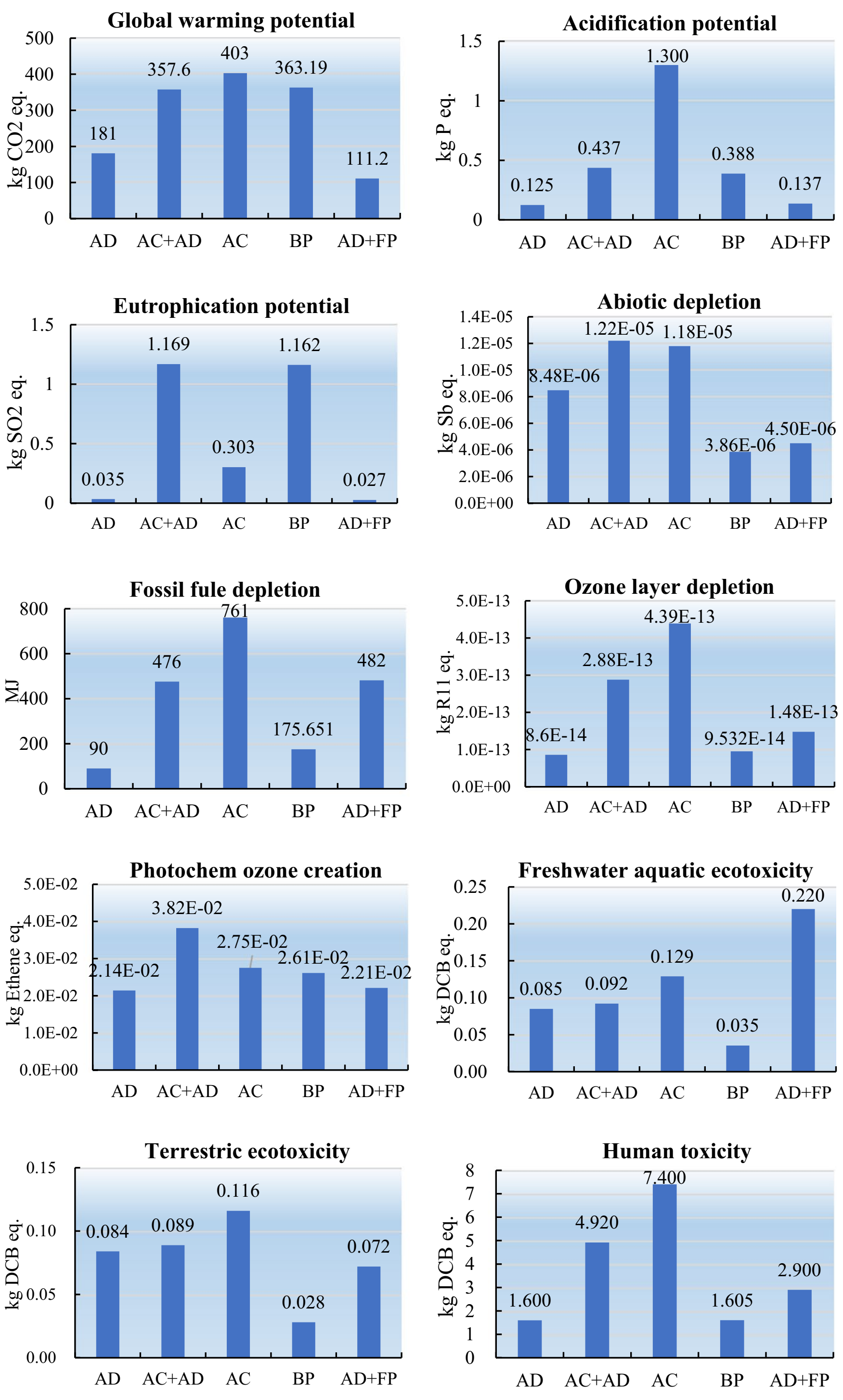

Fig. 2 Environmental impacts of the five technologies (per functional unit)

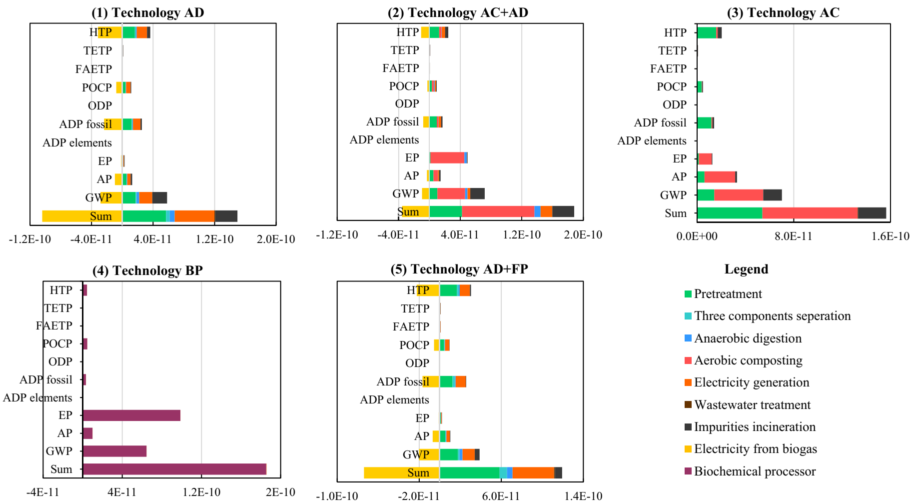

Fig. 3 Normalized environmental impacts of key processes for five technologies

ADP elements of AC also ranked the second among the five technologies. This is mainly because aerobic bacteria will generate fugitive air emission when food waste is fermented. It should be noted that the eutrophication potential of AC + AD and BP is higher (1.169 kg SO_2 eq. and 1.162 kg SO_2 eq., respectively) than other treatment technologies. AC + AD has the highest impact of fossil ADP and POCP, while AD + FP has the highest impact of FAETP.

To compare the comprehensive performance and further analyze the distribution of environmental impacts in every life cycle stage for five treatment technologies, the ten different types of environmental impact categories are normalized to the same unit (Fig. 3). It is found that ODP is the lowest among the impact categories for every technology. For AD and AD + FP anaerobic technologies, pretreatment and biogas electricity generation stages are the main processes that cause environmental impact for most impact categories. The total environmental impact of the pretreatment process and biogas electricity generation process is 2.8E−10 and 2.31E−10 for AD, 5.84E−11, and 4.04E−11 for AD + FP, respectively. And electricity produced by recovered biogas can reduce environmental impact as much as possible. For AD, the reduction of GWP, ADP fossil, and HTP is 2.84E−11, 2.37E−11, and 3.61E−11. As for aerobic technologies AC + AD, the aerobic composting stage causes most of the environmental impacts, which is 1.46E−10. For AC technology, the amount of different environmental impact categories depends on different processes, such as aerobic composting is the major source for GWP (4.05E−11), AP (2.53E−11), and EP (1.07E−11). In addition, the environmental impacts of aerobic technology AC and AC + AD are about three times that of anaerobic technologies AD and AD + FP.

With regard to the comparison of comprehensive total environmental performance of five food waste treatment technologies, the rank is AC > AC + AD > BP > AD > AD + FP, with figures of 1.56E−10, 1.53E−10, 1.36E−10, 4.55E−11, and 4.53E−11, respectively. Moreover, it can also be found that GWP and HTP are usually dominant impact categories for all the five technologies, except technology BP that has higher EP impact.

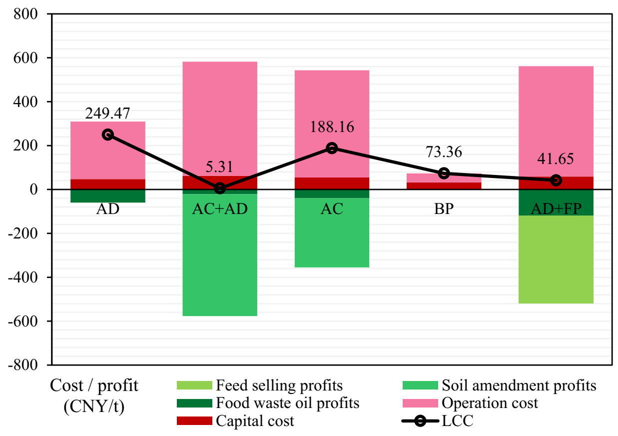

Fig. 4 LCC of the five food waste treatment technologies

Table 4 CB efficiency of five technologies

	LCC (CNY/t)	Rank	Environmental impact	Rank	CB efficiency	Rank
AD	249.47	5	4.55E−11	2	8.81E+7	4
AC + AD	5.31	1	1.53E−10	4	1.23E+9	1
AC	188.16	4	1.56E−10	5	3.41E+7	5
BP	73.36	3	1.36E−10	3	1.00E+8	3
AD + FP	41.65	2	4.53E−11	1	5.30E+8	2

3.2 Life cycle cost analysis

The life cycle costs (LCC) of treating one ton of food waste by five different treatment technologies are presented in Fig. 4. It shows that the total unit cost of BP is 73.06 CNY/t, which is the lowest among the five technologies, followed by AD with a value of 309.47 CNY/t. The total unit cost of AC + AD, AC are similar, with figures of 581.93 CNY/t and 543.16 CNY/t, respectively. The total unit cost of AD + FP is the highest, with a figure of 561.65 CNY/t. The profits of five technologies are also different. BP does not generate any profits because the compost product cannot meet the market standards for sale. The only product that can bring profit for AD is food waste oil, with a figure of 60 CNY/ton food waste. For technologies that include aerobic composting processes such as AC and AC + AD, the production of soil amendment that can meet the market requirements is another profitable source for food waste treatment, in addition to the sale of food waste oil. The profit of soil amendment for AC is about 315 CNY/t. AC + AD has the highest profit of 555.52 CNY/t due to its large amount of soil amendment production and high quality, indicating that AC + AD is a better option for treating food waste. AD + FP can bring the second highest profit, with a figure of 520 CNY/t. Although the economic profit of AD + FP is not the largest, it has the advantage of stable market and significant reduction of food waste. Therefore, AD + FP seems to be a preferable choice for food waste treatment factories.

3.3 CB efficiency

Table 4 depicts the life cycle costs, environmental impacts and CB efficiency of five treatment technologies. It is obvious that rank of LCC is AC + AD > AD + FP > BP > AC > AD, while the rank of environmental impact is AD + FP > AD > BP > AC + AD > AC. As for CB efficiency, the order is AC + AD > AD + FP > BP > AD > AC. Although the environmental benefits of AC + AD are not the largest, it performs best in CB efficiency with the lowest LCC. The environmental impacts of AD + FP and AD are close to each other and are the lowest among the five technologies. Thus, AD + FP and AD are better options from an environmental sustainability perspective, but may need more subsidy from local government. The rank of LCC and environmental impact for BP is in the medium level; its cost is not so high and has less environmental impact. It is more flexible and suitable to treat small amounts of food waste in sparsely populated regions, such as less developed areas.

4 Discussions and policy recommendations

4.1 Policy recommendations

Some researchers have also conducted studies regarding the comparison of different food waste treatment technologies and draw different conclusions. Several of them compared the food waste treatment technologies in developed countries, and drew similar conclusions that anaerobic digestion (AD) technology was much more environmentally friendly than aerobic composting (AC) technology although environmental values may vary in a reasonable range (Slorach et al. (2019); Edwards et al. (2017); Padeyanda et al. (2016)). Besides, feed processing technology was also found to have more advantages compared with AC and biochemical processor (Chen et al., 2011). Production of high-value animal feeding products reduced global warming potential and socioeconomic impacts compared to use of conventional feed products (Albizzati et al., 2021). Our findings are consistent with these literatures. To be more specific, we find that anaerobic digestion technology is more environmentally friendly and less costly. We also found that combined technologies AC + AD and AD + FP can lead to better cost–benefit efficiency than one single treatment technology AC or AD. And AD performs better than AC in terms of environmental impact. However, some researchers draw different conclusions that AC, AC + AD, and incineration showed better performance with regards to environmental impact (Cristóbal et al., 2016). These different environmental impacts and economic costs may be due to the characteristics of food waste between different countries, the use of different LCI database, different operating conditions and different processes (e.g., input materials, equipment type, and rates) in different food waste treatment plants, etc. (Padeyanda et al., 2016).

To the best of our knowledge, few studies have been conducted considering both environmental impacts and economic costs of food waste treatment technologies. Based on our economic cost and environmental benefit results, policy recommendations are proposed in the following sub sections.

First, a hierarchy of food waste treatment technology is proposed that considers both environmental benefit and economic cost (Fig. 5) for policy makers as a guideline for food waste management. No matter what kind of treatment technology is selected, the most important step is to guarantee the stable and enough food waste supply. Therefore, the key to a sustainable food waste treatment system is source separation. Strict MSW

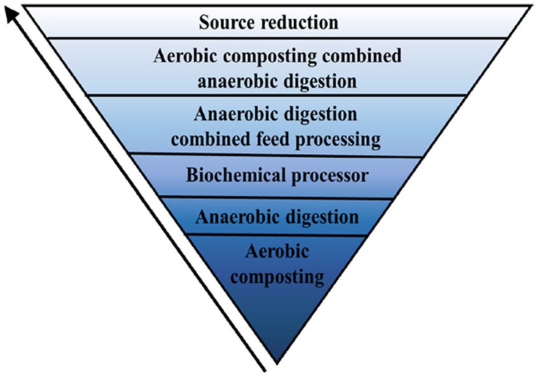

Fig. 5 Priority hierarchy for food waste management

separation policy should be implemented to ensure that food waste can be separated from other MSW. For most of the fast-developing countries, waste separation is still in its early stage. They lack effective regulatory frameworks and environmental consciousness. In this regard Shanghai is a leading city for waste separation. Its four waste separation system can ensure the separation and stable supply of food waste for subsequent bio-treatment. With regards to treatment technology, our results revealed that AC + AD was the most economical method with the highest CB efficiency although it was found to be less environmentally friendly compared with AD + FP, BP, and AD. Treatment technology AD + FP can minimize the total environmental impact and achieve the financial goal to ensure the continuous operation of treatment facilities and thus is recommended as the backup option. The LCC and environmental impact of biochemical processor are relatively low due to its small treatment capacity. Such biochemical processor can be applied in areas that has small amount of food waste generation, such as villages, business district or grocery/vegetable/food market, etc. Finally, those technologies with only aerobic composting or anaerobic digestion do not have significant economic and environmental benefits and should be abandoned.

Second, the combined technologies are recommended for newly established food waste treatment facilities. According to the environmental impact and economic cost results of the five biological treatment options, AC + AD and AD + FP have more potential to increase revenues and reduce environmental impacts compared to one single aerobic composting or anaerobic digestion technology. Furthermore, with the fast growth of food waste amount and implementation of waste separation, city managers should consider enhancing food waste treatment capacities and construct more food waste biological treatment facilities. It is recommended to apply AC + AD or AD + FP due to their higher economic and environmental benefits. Local government should support such application by preparing waste separation regulations, providing financial subsides, and organizing training activities.

Third, feed processor is suggested to be a backup and flexible treatment technology for areas which are far away from large treatment plants, such as rural areas, business districts, or grocery/vegetable/food markets. Although the financial benefits are modest compared to AC or FP, the effect of food waste reduction and environmental sustainability is apparent. On the other hand, it can greatly reduce the collection and transportation fees incurred by the producer. One problem is that the food waste in the grocery / vegetable / food market is high in fiber, which cannot be processed by ordinary feed processors with ordinary blades in the pretreatment process. Therefore, remedial measures such as changing blades or spare parts to adapt to the specific conditions should be adopted. Moreover, the operator of feed processors are always the market managers, who are lack of adequate device operation knowledge. It is imperative to remind them of the operating procedures and cautions that will ensure the lifespan of feed processors.

4.2 Limitations

Several research limitations exist in this study. First, some data of the treatment process are unavailable in database or project reports; thus, we use data from literatures or estimate such data by asking the relevant experts. Second, the database in GaBi is mainly based on western countries, which are different from the Chinese realities and may cause certain uncertainty. Third, the results of LCC may vary according to regions and the level of local development, particularly initial cost and the operating cost. Thus, the cost–benefit efficiency rank and priority hierarchy proposed may be different when applying in other international countries.

5 Conclusions

Food waste treatment and recovery becomes more and more important for sustainable municipal solid waste management, particularly with the implementation of waste separation policy in China. Unlike most existing studies that focused mainly on life cycle environmental impacts, this study conducted both life cycle environmental impact assessment and life cycle cost analysis for five promising food waste treatment technologies, namely anaerobic digestion (AD), aerobic composting (AC), combined aerobic composting combined digestion (AC + AD), biochemical processor (BP), and combined anaerobic digestion combined feed processing technology (AD + FP). The main findings are as follows. Anaerobic technologies have better environmental performance in GWP, AP, EP, ADP, and ODP, compared with aerobic technologies. Stages of pretreatment, biogas electricity generation, and composting are the main sources to cause environmental impact, while for life cycle cost, AC is slightly lower than AD. However, the LCC of the mixed technology AC + AD and AD + FP will become much lower due to the economic benefit from selling recycled products. The priority of selection for food waste treatment technology considering both environment and economic costs is AC + AD > AD + FP > BP > AD > AC. Combined technologies AC + AD and AD + FP can lead to better cost–benefit efficiency than one single treatment technology AC or AD. It is therefore suggested that combined technologies should be selected for the newly established food waste treatment facilities. Moreover, feed processor can be considered as a backup option for areas that have small food waste treatment demand.

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Declarations

Conflict of 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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