Front. Environ. Sci. Eng. 2021, 15(2): 33
https://doi.org/10.1007/s11783-020-1325-y

RESEARCH ARTICLE

Economics analysis of food waste treatment in China and its influencing factors

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HIGHLIGHTS

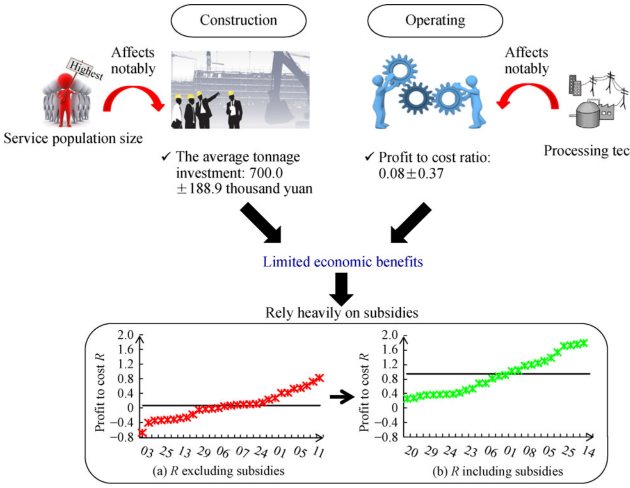
- Economics of food waste treatment projects at 29 pilot cities in China was examined.
- Roles of location, population size, processing technique, and income were studied.
- Economic benefits were limited with a profit to cost ratio of 0.08±0.37.
- Service population size affects construction economics significantly ($P = 0.016$).
- Choice of food waste processing technique affects operating economics notably.

ARTICLE INFO

Article history:
Received 13 May 2020
Revised 25 July 2020
Accepted 29 July 2020
Available online 8 September 2020

Keywords:
Recycling economics
Cost-benefit
Food waste treatment
Subsidy
Food waste economy
Circular economy

GRAPHIC ABSTRACT



ABSTRACT

This study examines the economic benefits of food waste treatment projects in China and factors affecting them. National-level pilot projects for food waste treatment located in 29 cities were selected as samples. The economics of food waste recycling from the investors' perspective, in terms of investment during the construction phase and cost and benefit during the operation phase, was assessed. Results indicate that the average tonnage investment of food waste treatment projects was RMB 700.0±188.9 thousand yuan, with a profit to cost ratio of 0.08±0.37. This ratio increased to 0.95±0.57 following the application of government subsidies. It highlights the limited economic benefits of food waste treatment facilities, which rely on government subsidies to maintain their operations in China. Further analysis using a multi-factor analysis model revealed that regional location, service population size, processing technique, and urban income exerted varying impacts on the economy of food waste treatment. Population size exerted the highest impact ($P = 0.016$) during the construction stage, and processing techniques notably influenced the project economy during the operation stage. The study highlights the need to prioritize service population size and processing techniques during economic decision-making and management of food waste recycling projects. The results of this study can serve as a valuable practical reference for guiding future policies regarding food waste treatment and related planning.

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1 Introduction

Food waste (FW) refers to biodegradable waste materials generated during food processing and food residues

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discarded after consumption (Stancu et al., 2016). It comprises an important part of municipal solid waste (Zhao and Deng, 2014). FW has to be treated properly as it can pollute urban sanitation systems, enter the human food chain, threaten food security, and compromise sustainable urban development and stability (Salemdeeb et al., 2017; Ribeiro et al., 2019; Septianto et al., 2020). With the rapid increase in China's food consumption, the government has prioritized the proper treatment of FW through several measures (De Clercq et al., 2017; Li et al., 2019). In June 2019, the State Council executive meeting adopted the "(Revised Draft) Solid Waste Pollution Prevention Law of People's Republic of China". The draft highlighted the need to accelerate the establishment of a system for classification, delivery, collection, transportation, and treatment of domestic waste. Between 2011 and 2015, China developed a "food waste recycling and safe disposal of urban construction pilot" implementation program. The program proposed 100 cities (districts) across the country to treat FW (Li et al., 2019). Currently, 148 FW disposal projects are operational, and FW disposal facilities are under construction in 219 cities in China. Reasonable and efficient disposal of FW has also been strengthened globally, for example in Belgium, Sweden, and China (Zhao and Deng, 2014; Wen et al., 2016; Malamis et al., 2017). With increasing production and the environmental, economic, and social impacts of FW (Malamis et al., 2017), the FW resource processing industry is rapidly expanding worldwide.

FW disposal constitutes a non-exclusive and non-competitive macro-environment and delivers valuable social performance. Further, its traditional simple feed and high yield approach offers high economic scope, which has prompted significant investment in the FW treatment market, based on the build-operate-transfer (BOT) operating model. The relevant literature on the economics of FW disposal is limited, and it has mainly focused on the evaluation of resource-based technologies. For example, Slorach et al. (2019) used the life cycle assessment to evaluate the economics of four FW treatment technologies including anaerobic digestion, reactor composting, incineration, and landfill in the UK, and found that the cost of incineration was the lowest at 71 GBP per ton. Chen et al. (2017) analyzed the cost and benefit of anaerobic digestion and FW treatment using an input generation method. Kim et al. (2011) noted that the economic cost of wet feed processing technology for FW in Korea was lower than that of dry feed, landfill, composting, and anaerobic digestion technologies. Martinez-Sanchez et al. (2016) suggested that the economic advantages of incineration of Denmark's FW were higher than anaerobic digestion and feed conversion. Guo and Yang (2019) included collection, transportation, and product treatment in the scope of their study and conducted an economic analysis of anaerobic digestion technology used for FW treatment in Beijing. Although these studies have contributed to a better understanding of the economics of FW treatment from the viewpoint of technologies, the impact of other factors has not been properly assessed.

Some studies have indicated that the economics of urban waste treatment is also affected by population size, local economy, geographic location, and project size (Juul et al., 2013; Wang et al., 2013; Thyberg and Tonjes, 2016; Liao et al., 2018; Zhang et al., 2019). The population served determined the output of waste (Wang et al., 2013), thereby affecting the project scale and related costs. The composition and quantity of waste and the location of treatment facilities also affect the economics of treatment (Slorach et al., 2019). For example, Zhang et al. (2019) found that service population size was strongly associated with the economic performance of waste treatment. However, when these factors are analyzed on the same benchmark, it is unclear what effect they have on the economics of the FW project.

Under the current scenario of government promotion and BOT operation, investors are substantially investing in the market for FW disposal in China and are bearing the costs of project construction and operation management. The investments continue to increase to meet stringent constraints. However, the economic benefits of FW disposal have been significantly limited by the government's increasingly strict supervision and partial subsidy measures based on different benchmarks. Further, only 41 of 56 pilot cities passed the mid-term evaluation conducted between 2017 and 2019; 15 projects were canceled, indicating a cancellation rate of nearly 26.8%. If government subsidies are inefficient in balancing the two factors, the scope for making a profit to recover cost is limited; the economic interests of investors eventually diminish and affect the macro-environment and economy of FW disposal. Consequently, the interest of investors pursuing maximum profit has wanes. Thus, an overview of the economics of FW disposal from the investors' perspective is critical to ensure the successful environmental and social performance of FW disposal. Although some studies have examined the economics and factors influencing FW disposal from the investors' perspective (Chen et al., 2017; De Clercq et al., 2017; Guo and Yang, 2019; Slorach et al., 2019), they have failed to consider the relationship between various factors or to provide objective support for related investment decisions and subsidy support through policy formulation. Therefore, this study attempts to analyze actual operational waste treatment projects to understand the economics and factors that influence the FW treatment. This can help ameliorate economic benefits at both construction and operation stages of FW treatment projects and thereby improve project management efficiency and profitability.

2 Materials and methods

2.1 Data collection

The pilot cities selected from the Chinese “recycling and harmless treatment of food waste” program include provincial capitals and autonomous cities in China. Based on data availability, this study surveyed 29 pilot project cities in 2017, which included 19 provincial administrative regions and 8 economic regions, across China (highlighted in Table 1). Data collected include: 1) documents and technical information regarding the project profile, technical plan, construction investment, and operating costs; 2) costs of the project during construction and operating periods, such as annual average per ton (tonnage) investment, daily average tonnage cost, and daily average tonnage income; and 3) relevant influencing factor index data, including technical factors such as processing techniques, and non-technical factors such as service population size, regional location, and urban income (in terms of GDP per capita).

2.2 Economic analysis: Indicators and factors

Economic indicators (measured on per ton of FW basis) were employed to comprehensively evaluate the economic benefits of the projects. These indicators were categorized into construction and operation period indicators. The construction period indicators included construction period investment (such as construction cost, equipment purchase cost, installation cost, related construction costs, and preparation fee), construction period interest, and bottom floor working capital. To eliminate the difference in the treatment scale, the construction investment is calculated by dividing the total investment by the daily treatment scale (i.e., the construction investment for each ton of FW, Chen et al., 2017), which is consistent with the usual expression method of managers and investors in actual engineering practice.

Operating period indicators included operating cost, operating income, and cost-profit margin. Operating costs mainly included outsourced raw materials, fuel and power costs, wages and welfare fees, maintenance and repair costs, and residuals disposal fee. Operating income (measured on per ton of FW basis) represented the sale income of resourced products, such as waste oil and compost. These bio-products were sold by operators and could receive some income. Another important income source for Chinese FW projects was government subsidies, which were financial subsidies given by the government based on waste treatment capacity. Two scenarios excluding and including government subsidies were analyzed separately in this study. It should be noted that the economic survey of this study is limited to the range of FW treatment plants. After the wastewater is discharged into the sewage plant or the residues are transported to

Table 1 Survey sample cities and their numbers

No.	City	Affiliation	GL [a)]	ER [b)]	No.	City	Affiliation	GL [a)]	ER [b)]
1	Chifeng	Inner Mongolia	North-west	MYCEZ	16	Mianyang	Sichuan	Southern	GSEZ
2	Dali	Yunnan	Southern	GSEZ	17	Shanghai	Shanghai	Southern	ECEZ
3	Daqing	Heilongjiang	Northern	NEZ	18	Qiqihar	Heilongjiang	Northern	NEZ
4	Dongguan	Guangdong	Southern	SCEZ	19	Chongqing Qijiang	Chongqing	Southern	GSEZ
5	Ganzhou	Jiangxi	Southern	MYREZ	20	Shizuishan	Ningxia	North-west	GNEZ
6	Handan	Hebei	Northern	NCEZ	21	Wuzhong	Ningxia	North-west	GNEZ
7	Hangzhou	Zhejiang	Southern	ECEZ	22	Xi’an	Shanxi	Northern	MYCEZ
8	Hulun Buir	Inner Mongolia	North-west	MYCEZ	23	Xiangyang	Hubei	Southern	MYREZ
9	Huaibei	Anhui	Northern	MYREZ	24	Xuzhou	Jiangsu	Southern	ECEZ
10	Huangshi	Hubei	Southern	MYREZ	25	Zhenjiang	Jiangsu	Southern	ECEZ
11	Jilin	Jilin	Northern	NEZ	26	Yingchang	Hubei	Southern	MYREZ
12	Jinan	Shandong	Northern	NCEZ	27	Qingdao	Shandong	Northern	NCEZ
13	Jinzhong	Shanxi	North-west	MYCEZ	28	Quzhou	Zhejiang	Southern	ECEZ
14	Liaocheng	Shandong	Northern	NCEZ	29	Suzhou	Jiangsu	Southern	ECEZ
15	Luoyang	Henan	Northern	MYCEZ					

Notes: a) GL: geographical location, according to the characteristics of geographical location, natural geography and human geography, China is divided into four geographical regions: northern, southern, north-west, and Qinghai-Tibet regions; b) ER: economic regions, according to the “Strategy and Policy for Coordinated Regional Development” issued by the Development Center of Chinese State Council, China is divided into eight economic zones: the North-east Economic Zone (NEZ), the North Coast Economic Zone (NCEZ), the East Coast Economic Zone (ECEZ), the South Coast Economic Zone (SCEZ), and the Middle Yellow River Economic Zone (MYCEZ), Middle Yangtze River Economic Zone (MYREZ), Greater South-west Economic Zone (GSEZ), and Greater North-west Economic Zone (GNEZ).

incineration plants or landfills, the economics of their disposal is not included. However, the processing fee paid to these facilities by the FW treatment plant is included in the operating cost.

The above indicators were used to calculate the profit to cost ratio (*R*), which is the ratio of the total profit (operating income–operating cost) and operating cost of the project in one year (Chen et al., 2017). A higher *R* index value indicates better economic benefit. The formula to calculate *R* can be expressed as:

$$R = \frac{I - C}{C} = \frac{B}{C}, \tag{1}$$

where, *I* represents the annual operating income, *C* represents the annual operating cost, and *B* represents the total annual profit (Chen et al., 2017).

Based on economic evaluation, technical and non-technical factors that influenced the economics of FW treatment were analyzed.

2.2.1 Technical factor: Processing techniques

Processing techniques refer to the main treatment processes employed in the plant. The survey revealed that anaerobic biogas and aerobic fermentation were the predominant processing techniques in the pilot projects assessed in the study (Table A1, see Appendix). Further, only two projects employed aerobic fermentation, accounting for 6.9% of the samples investigated. The compost produced by the two projects is “humic acid biological bacterial fertilizer”, which is mainly used for local soil improvement, fertile soil engineering, and high value-added crops, such as wolfberry, watermelon, and other agricultural production. Li et al. (2019) suggested that, among other reasons, fewer projects employed aerobic fermentation for FW in China due to poor quality of fertilizer and concerns about its use. Only 5.2% of FW facilities employed aerobic fermentation techniques. This did not include rapid aerobic fermentation treatment, which was considered similar to rapid biological drying. Moreover, projects where only the digestate or solid FW used aerobic composting, such as Chifeng (No. 1) and Dali (No. 2), were excluded from the aerobic fermentation category, as the processing technique category applied in the study was based on the main treatment process.

2.2.2 Non-technical factor: Regional location

This study divides the country into four regions: northern, southern, north-west, and Tibetan regions based on the regional nature of food production and consumption. However, this study is limited by the scope of data collection, and the pilot survey did not involve Tibet. The regional distribution of the sample cities surveyed is listed in Table A2 (See Appendix).

2.2.3 Non-technical factor: Urban income

The proportional N-value division method proposed by Zhang (2017) was used to analyze spatial differentiation in urban income levels. The economic levels of cities were classified as low-income areas ($N < 0.7$), middle-income areas ($0.7 \leqslant N < 1$), and high-income areas ($1 \leqslant \mathrm{N}$) where *N* represents the ratio of GDP per capita to average GDP per capita of the specific city. Based on the per capita GDP of the cities in 2017, the urban income groups and details of the cities in each group are listed in Appendix Table A3.

2.2.4 Non-technical factor: Service population size

A proportional *P*-value was introduced to compare the service population size with the average level, as applied for urban income classification in Section 2.2.3. Accordingly, the pilot sites were divided into three classes: small area ($P \leqslant 0.8$), medium area ($0.8 < P \leqslant 1.8$), and large area ($1.8 < P$). The classification of areas based on the service population size is listed in Appendix Table A4.

2.3 Statistical analysis

A multi-factor analysis method was employed to analyze the effects of processing techniques, regional location, urban income, and service population size on the economic indicators of FW disposal projects. Variance was used to assess if an independent variable was affected by one or more factors or variables. This methodology has been used in environmental quality evaluation (Baksh et al., 2017), technical parameter optimization (Wen et al., 2020), and several other fields. In this study, the SPSS 19.0 statistical software (SPSS, Inc., Chicago, IL, USA) was used to test the inter-dependence effect based on the GLM model, where $P < 0.05$ was considered statistically significant.

3 Results and discussion

3.1 Economic analysis

The economic parameters of the pilot cities assessed in the study are illustrated in Fig. 1.

Figure 1 highlights that the economic indicators of the surveyed projects did not change significantly during the construction and operation periods. During the construction phase, the annual average tonnage investment of most projects fluctuated around 699950 yuan, within a fluctuation range of 50%. Shanghai Pudong New District (No. 17) recorded the largest tonnage investment, at 1.2243 million yuan (Table 2). This can be attributed to higher land acquisition and demolition fees for the project, which exceeded 150 million yuan , accounting for 41.1% of the total investment.

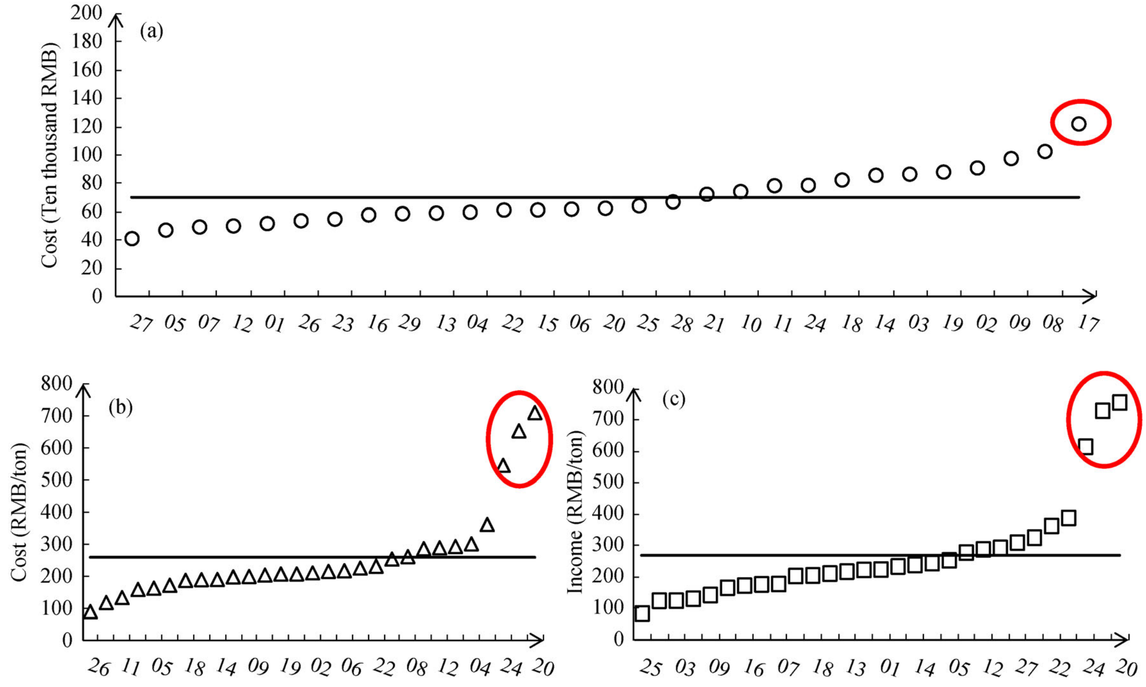

Fig. 1 Economic parameters of the pilot projects (the red circle means that the value deviation exceeds 50% of the average): (a) Investment cost per ton food waste, (b) Operating cost per ton food waste, (c) Operating income per ton food waste.

Table 2 Statistical analysis of economic data of the pilot projects

Items	Tonnage investment (ten thousand yuan/ton)	Tonnage cost (yuan/ton)	Tonnage income (yuan/ton)	Profit to cost ratio
Minimum	41.39	88.34	78.40	−0.67
Maximum	122.43	709.30	749.93	0.83
Average	70.00	256.26	266.62	0.08
Standard Deviation	18.89	144.78	165.35	0.37

In the operation stage, most of the projects fluctuated within±50% of the average tonnage cost of 256.26 yuan and an average tonnage income of 266.62 yuan. This may be related to the main process of anaerobic digestion used in most projects. Among the operating costs of these projects, wastewater treatment is an important component. FW in China has high moisture content at 80% (Li et al., 2019), which results in abundant wastewater to be treated. Given the improvement in environmental protection standards, wastewater treatment fees are an important part of the operating cost. For example, 16.7% of the operating expenses in Guangzhou are used to pay for the commissioned wastewater treatment fee. Meanwhile, it is as high as 38.1% in Hangzhou. Therefore, optimizing wastewater treatment and its final discharge method is an important entry point to reduce operating costs.

Regarding operating cost and income, projects located in Shizuishan (No. 20), Xuzhou (No. 24), and Quzhou (No. 28) had a deviation that exceeded 100%. Further analysis revealed that the main processes adopted by Shizuishan and Quzhou were aerobic fermentation, implying that the operating cost and income of the aerobic fermentation process were significantly higher than that of the anaerobic fermentation process. This can be ascribed to the higher moisture content of FW in China, with an average content of 80% (Li et al., 2019). The aerobic fermentation process removes a greater amount of water content and consumes additional energy and auxiliary materials, which increases energy consumption and cost. Although its operating cost was high (Guo et al., 2018), the resultant organic fertilizer produced offered better efficiency. It can be used for soil improvement, fertile soil engineering, and high value-added crops, such as wolfberry, watermelon, and other agricultural production. Economic income can be considerable if the output is channeled to the downstream industrial chain (Awasthi et al., 2020). Further, the large deviation of the Xuzhou (No. 24) project was due to the costs of a sub-project, which processed 30 tons of sewage oil to regenerate biodiesel. The project's main material is waste cooking oil. It takes nearly 24.9 million yuan per year to purchase 9900 tons of waste oil, which accounted for 62.6% of the entire operating cost. This is because the economic incentive is one of the dominant factors determining the quantity of recycling waste oil (Liu et al., 2018). However, the project also generated an annual output of 6600 tons of biodiesel and 495 tons of glycerin products, which offered good market value and delivered higher income. Although Xuzhou (No. 24) comprised a biodiesel refining subunit, the Xuzhou project's tonnage investment was only 789700 yuan, which was not significantly higher than the average value of 699950 yuan. This was mainly due to lower construction and equipment purchase costs. Additionally, the anaerobic biogas residue treatment process was simple mechanical dehydration to 60% moisture content, which was subsequently transported to a landfill for disposal.

Further, the profit to cost ratio was examined to assess the annual economic benefits of the project during the operation phase (Fig. 2(a)). The results indicate that the average ratio of the projects is 0.08±0.37, which is not high, but the standard deviation is relatively large (Table 2). Thus, it is evident that the profit margin of FW treatment is not high, but the difference between projects is large. This also confirms that the current market value of recycling FW in China is not outstanding (De Clercq et al., 2017), although there are significant environmental benefits of recycling FW, such as carbon dioxide emission reduction in China (Kim et al., 2011; Chen et al., 2017; Guo and Yang, 2019). A government subsidy mechanism was introduced in China wherein government and enterprises jointly agreed on a subsidy price, based on specific regional conditions. At present, the average price of FW disposal subsidies in China is 110 yuan/ton (Guo and Yang, 2019).

When government subsidies were included in the assessment, the profit to cost ratio of the projects increased significantly, with an average level of 0.95±0.57, recording an increase of 1088%. All projects achieved profit recovery ($R>0$, Fig. 2(b)). Thus, government subsidies are necessary to maintain the normal and stable operation of existing processing enterprises in the market economy. The vital role of subsidies identified in this work is consistent with Li et al. (2015). Further, the industrial chain of China's FW treatment techniques is not complete, and the treatment rate and market value of products are not high (Li et al., 2019). Moreover, increasingly stringent secondary pollutant discharge requirements have increased the overall investment and operating costs (Zhang et al., 2019). Additional problem in the resource-based product trading market, such as single channels, poor value, low profitability, uneconomical end-use, small market size, and inadequate management, contribute to lower product sales revenue (Wen et al., 2016; De Clercq et al., 2017; Li et al., 2019). In recent years, to obtain value-added bio-products from FW, solid-state fermentation has become a research hotspot, and it has yielded results (Cerda et al., 2018; Awasthi et al., 2020). Although it is still at the laboratory-scale stage, it could be cited as a future option, complementary to anaerobic digestion or composting. Overall, reduced engineering investment and operating costs and improved market value of resourced products are significant requirements to enhance the market competitiveness of FW recycling projects and complete the FW recycling industry chain.

Figure 2 illustrates that the profit to cost ratio is generally scattered irrespective of the application of government subsidies. For example, without government subsidies, the R deviation of most projects exceeded 100%, the highest of which reached 938%. This indicates that the economic volatility of the survey samples was large, and the role of influencing factors needed to be investigated further.

Statistical analysis of economic data in Table 2 indicates that during the construction phase, the samples registered a tonnage investment range of 413900 to 1224300 yuan, with an average level of 699950±188881 yuan. Fluctuations were moderate; the standard deviation was 188881 yuan, accounting for 27.0% of the average level of 699950 yuan, and the fluctuation range did not exceed 50%. The results in Fig. 1 are consistent with this. However, the tonnage cost during the operation phase ranged between 88.34 yuan and 709.30 yuan, with an average of 256.26±144.78 yuan, and tonnage income ranged between 78.40 yuan and 749.93 yuan, with an average of

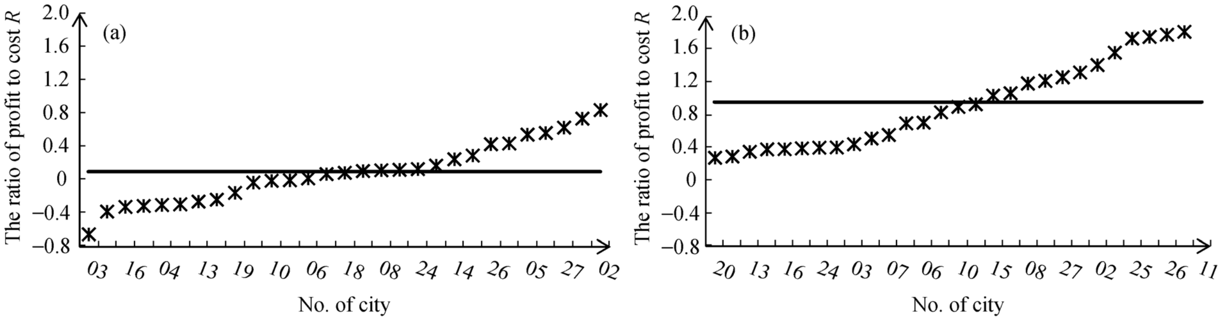

Fig. 2 The profit to cost ratio of pilot projects: (a) R excluding government subsidies, (b) R including government subsidies

266.62±165.35 yuan. The economic indicators of the cost and income of the FW recycling projects during the operation phase differed notably; the fluctuation range was large, and their standard deviations exceeded 50%. Thus, the economics of the project at different stages exhibits different trends, implying that the factors that affect the economics of the project are stage-specific. Therefore, the factors influencing project economics during the construction stage and operation stage were investigated.

3.2 Analysis of influencing factors

3.2.1 Analysis of factors influencing the construction economy

The average tonnage investment based on each influencing factor (Fig. 3(a)) was analyzed.

The four factors surveyed exhibited varying degrees of impact on the economy of the projects during the construction phase. Regional variation was negligible; however, different processing techniques, urban income, and service population size exhibited greater differences.

With respect to the treatment process utilized, the tonnage investment of projects employing anaerobic technique (700000 yuan) was relatively large and was higher than the investment for aerobic technology (650000 yuan). This conclusion is consistent with Slorach et al. (2019) and can be ascribed to material and process characteristics. Compared with the aerobic process, the anaerobic process has higher requirements for the reaction slurry, resulting in a longer process flow. Moreover, the anaerobic process often requires subsequent treatment of secondary pollutants such as biogas slurry and biogas residue, necessitating secondary pollution control equipment and facilities (Guo et al., 2018; Ryue et al., 2020). However, most solids in the aerobic process are converted to resource products in the form of organic fertilizer (Cerda et al., 2018; Li et al., 2019; Awasthi et al., 2020). Further, the moisture in the raw materials of FW is effectively neutralized following the addition of a moisture regulator,

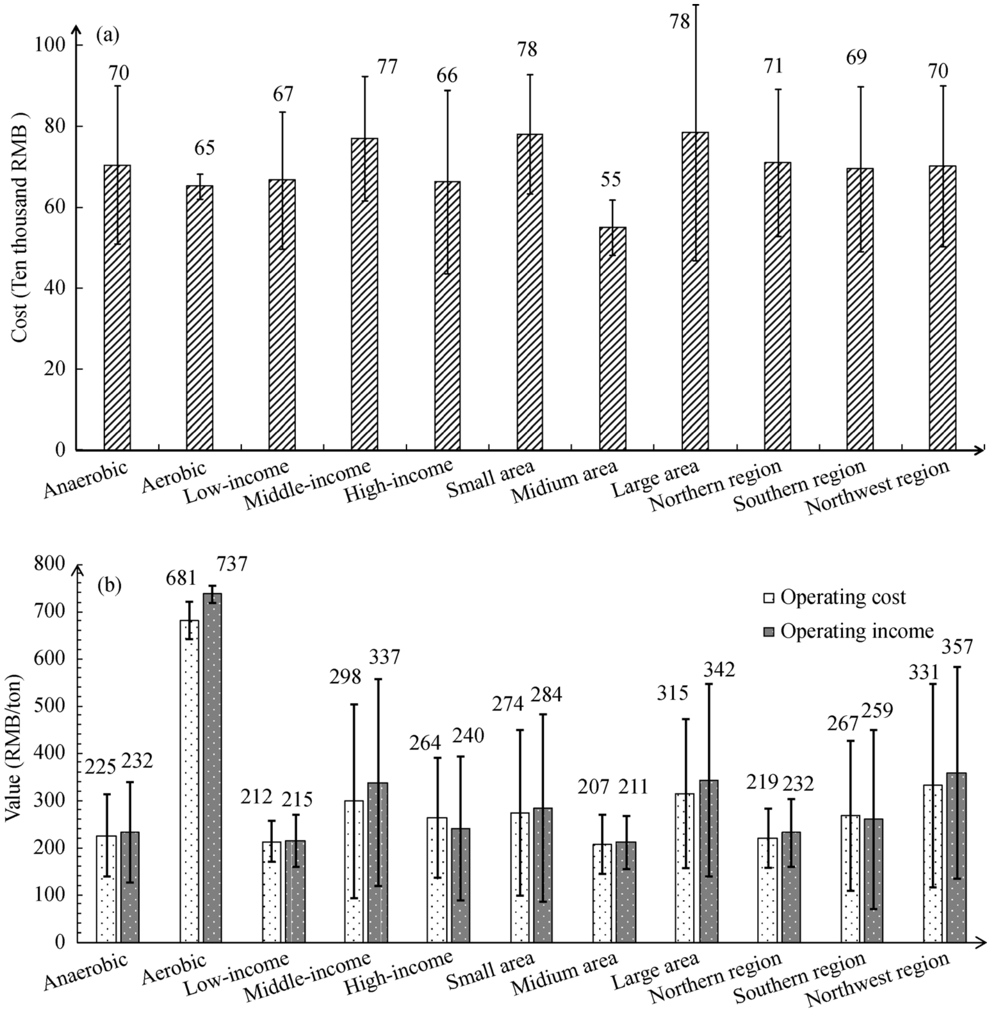

Fig. 3 Factor-wise assessment of FW treatment projects: (a) the average tonnage investment during the construction phase; and (b) average tonnage cost and tonnage income during the operation phase

and less sewage is generated. The secondary pollution treatment facilities to be established are relatively small. Therefore, construction engineering and equipment purchase costs for the aerobic process are lower.

In terms of urban income, the tonnage investment of projects in the middle-income area (770000 yuan) was significantly higher than in other income areas. This can be attributed to a lack of evident advantages in labor costs and related equipment in the middle-income areas, resulting in higher equipment purchase costs, installation costs, and engineering costs.

In terms of service population size, small and large regional projects registered relatively high tonnage investment. Generally, smaller service population size suggests a smaller processing scale, which is inversely proportional to the investment of public municipal projects. This is in agreement with the general trend as tonnage investment in small areas is higher. Simultaneously, the tonnage investment in large areas is relatively high. This can be because when the service population exceeds a certain scale, a single processing line can no longer meet the processing needs. Moreover, it is often necessary to increase investment to increase the processing capacity. Furthermore, the urban area tends to be relatively large for more service populations, as seen in the Shanghai Pudong New District. Larger cities incur higher equipment installation fees and land requisition and relocation fees related to labor, resulting in higher construction investment.

3.2.2 Analysis of factors affecting the operating economy

Figure 3(b) illustrates the average tonnage cost and tonnage income of different types of pilot cities (districts). As evident in Fig. 3(b), processing techniques exhibited the most significant impact. The treatment cost of the aerobic process (681 yuan/ton) was significantly higher than that of the anaerobic process (225 yuan/ton). To meet the moisture content requirements of compost products, FW needs to remove a lot of water, which requires a higher ventilation rate of 0.2–0.6 L/min/kg during aerobic treatment (Cerda et al., 2018). Further, to achieve the maturity and stability of organic matter, a long duration is required to complete the composting process (Li et al., 2019), such as one or more months for a small-scale composting operation (Awasthi et al., 2014; Guo et al., 2018). This increases the energy consumption of the ventilation equipment and cost of subsequent odor treatment (Wang et al., 2018), contributing to higher treatment costs (Guo et al., 2018; Slorach et al., 2019).

In terms of urban income, the tonnage cost decreased in the order of middle-income area>high-income area>low-income area. In terms of the service population size, the tonnage cost marginally increased as the service population increased. However, the medium exhibited the lowest cost. In terms of regional location, the tonnage cost in the north-west region was significantly higher than the north and south regions, with relatively high deviation.

Tonnage income exhibited a trend consistent with the average daily tonnage cost; that is, high cost incurred resulted in higher income. For example, the tonnage income of the aerobic process (737 yuan) was significantly higher than that of the anaerobic process (232 yuan). This can be attributed to the introduction of suitable additives from external sources, such as high-efficiency microbial inoculants (Cerda et al., 2018; Awasthi et al., 2020), biochar (Jindo et al., 2016; Malinowski et al., 2019), and zeolite (Waqas et al., 2019), which improved the quality of organic fertilizer products (Cerda et al., 2018; Awasthi et al., 2020). Further, better economic income can be obtained when the end products are channeled through lower-end industrial chains such as cash crop cultivation and organic agriculture. Obviously, the quality of the compost product is closely related to the quality of FW raw materials (Cerda et al., 2018). Thus, the source separation of FW is vital. In recent years, the Chinese government has attached great importance to promoting garbage classification (Guo et al., 2018). Although it remains challenging, the garbage source-separation in small cities is relatively easier to promote than in big cities. Thus, the aerobic composting projects in this study are located in the small areas of Shizuishan and Quzhou. With a 120 t/d treatment capacity, the source quality of FW is relatively easy to control. Hence, the quality of compost products is better. However, the economic benefits of biogas, an anaerobic treatment resource, are poor, as it is mainly processed by torch burning in China. Moreover, limited amounts can be used for online power generation and on-board fuel.

3.2.3 Multi-factor analysis of the economics of FW treatment projects

The correlation between the four factors (processing techniques, regional location, urban income, and service population size) was examined using four test methods, namely Pillai's Trace, Wilks' Lambda, Hotelling's Trace, and Roy's Largest Root. The four methods consistently reported that the correlation probability between the factors was notably greater than 0.05, indicating that there was no interaction between the above factors and they can be considered as independent variables. Next, the correlation between the factors and economic indicators was assessed. The results are listed in Table 3.

During the construction period of the projects, the impact of the tonnage investment decreased in the order: service population size>processing techniques>urban income>regional location. The service population size exerted the highest impact (P = 0.016), which it can because the population size is the key factor in determining the output of FW (Wang et al., 2013; Zhang et al., 2019). According to the "technical code on food waste treatment"

Table 3 Correlation between economic indicators and influencing factors

Source		Dependent variable	Type III sum of squares	df	Mean square	F	Sig.
Construction period	Tonnage investment	Processing technique	994.291	1	994.291	4.125	0.065
		Regional location	30.058	2	15.029	0.062	0.940
		Urban income	567.051	2	283.525	1.176	0.342
		Population size*	2854.270	2	1427.135	5.921	0.016*
Operation period	Tonnage cost	Processing technique*	240807.169	1	240807.169	27.505	0.000*
		Regional location	14961.552	2	7480.776	0.854	0.450
		Urban income	4032.568	2	2016.284	0.230	0.798
		Population size	20628.465	2	10314.233	1.178	0.341
	Tonnage income	Processing techniques*	262776.387	1	262776.387	17.904	0.001*
		Regional location	4090.907	2	2045.453	0.139	0.871
		Urban income	5654.746	2	2827.373	0.193	0.827
		Population size	64233.263	2	32116.631	2.188	0.155

Notes: * is considered a significant effect ($P < 0.05$).

(MOHURD, 2012), different sizes of treatment facilities should be established based on different FW amounts, which inevitably affects the construction scale of elements such as the main technology, odor treatment, and wastewater and residue treatment. These elements significantly affect the project investment. Certainly, technological advancement could increase the treatment capacity to a certain extent. For example, many FW treatment facilities in good condition can achieve more than 20% overload operation in China. However, the effect is limited. For the new constructions of FW project, in particular, it is usually designed according to the normal operating load. The project capacity often determines the number of treatments lines directly, which inevitably affects the investment significantly. Thus, it can be concluded that the impact of the population size is the most critical during the project construction period, and is significantly greater than the technological factor. Population size exerted a greater impact on economic indicators compared with processing techniques, which is contrary to livestock waste treatment results of Zhang et al. (2019). This is mainly because the technique construction costs of FW treatment processes assessed in the current research do not differ much, as shown in Fig. 3(a). Further, the specific impact of service population size on tonnage investment was assessed by analyzing the interaction between small, medium, and large population areas (Appendix Table A5). A significant difference in tonnage investment can be noted between medium area and small areas (P = 0.003), as well as medium and large area (P = 0.025), while the difference between the large area and small area is not significant ($P \geqslant 0.05$). This result is consistent with Fig. 3(a). As the population increases, the tonnage investment declines significantly, but when the population size increases beyond a certain degree, tonnage investment gradually rises. Therefore, when investing in FW disposal projects, the appropriate service population size should be determined to optimize the investment cost.

As listed in Table 3, during the project operation period, the impact of influencing factors on tonnage cost decreased in the order: processing technique>service population size>regional location>urban income. The treatment process was the key constraint ($P < 0.05$), while all other factors exceeded 0.05, and their impact on the tonnage cost was not significant. For tonnage income, the impact of influencing factors decreased in the order: processing technique>service population size>urban income> regional location. Similarly, a process technique is a key constraint (P = 0.001). The other factors exceeded 0.2 and their impact on tonnage income was not significant. Therefore, the project economics during the operation period was mainly influenced by technical factors. In the anaerobic biogas and aerobic fermentation process assessed in this study, the tonnage cost and income varied significantly. Material characteristics, process units, secondary pollution control, resource products obtained, and the backend industrial chain of the two processes also exhibited notable differences. The operation economy may be significantly affected by the above technical factors. For instance, the deviations in operating costs and revenues of projects with the same anaerobic process reached 87 yuan and 106 yuan per ton, respectively (Fig. 3(b)). This is because these projects have large differences in specific treatment subunits, such as anaerobic process conditions, wastewater treatment methods, and sale of resourced products. Research on the economic impact and contribution of these subunits to the overall project is not considered in this study, which gives scope for in-depth future research considerations. Therefore, the appropriate FW treatment process should be adapted to local conditions and quality for an economical process.

Further, the impact of the service population size on tonnage income was significantly greater than the tonnage cost. This can be ascribed to the change in the quantity of waste to be disposed of due to the service population size (Wang et al., 2013; Zhang et al., 2019). As indicated in Table A4, most of the cities were categorized as small and medium-sized, comprising 86.21% of the total. Small-sized projects have higher operating costs and incomes (Fig. 3(b)). This is mainly because within such projects are two high-cost and high-income aerobic projects. If these two projects are not considered, the average operating costs and incomes of small-sized projects are 211 yuan and 214 yuan per ton FW, respectively, which is slightly higher than the medium-sized processing project. The FW operation cost per ton decreases with the increase in waste treatment capacity, which is mainly determined by the increased utilization rate of the treatment facility. Notably, under the premise of a certain amount of waste, the improvement of the process and the optimization of operating conditions can increase the amount of waste disposal, thereby reducing the unit operating cost.

However, the tonnage income was different. The material balance of the process highlights that the amount of products generated following the treatment exhibited a significant positive correlation with the amount of FW treated (Martinez-Sanchez et al., 2016; Chen et al., 2017; Guo and Yang, 2019). A larger population size generates higher waste volume to be processed; consequently, higher amounts of end products are produced and tonnage income increases. Further, urban income exerted less impact on tonnage cost and tonnage income. In this study, urban income was divided according to per capita GDP, which reflects the regional tax level and the economic endurance of FW disposal projects. Based on the surveyed samples, this study concludes that urban income levels did not affect the FW recycling economy significantly. For national pilot projects, the central government provides special funds for the development of a circular economy at rates ranging from 20% to 50%. Furthermore, local governments are required to provide financial support to ensure smooth operation of the projects. Therefore, the samples analyzed in this study are different from other public municipal projects (Juul et al., 2013; Chu et al., 2016; Zou et al., 2019; Liu et al., 2020) and their economic impact is less affected by urban income.

In summary, the service population size significantly affects the investment of the FW project, and the operation economy is more susceptible to the impact of processing techniques. It should be noted that the factors influencing the economy of the construction and operation stages in the FW project are no indication that there is a causal or positive correlation between these factors and the FW project economy. Rather, it is indicative of how much these factors affect the economics of the project to provide a reference for managers or investors to make economic decisions or optimizations for FW projects.

4 Conclusions

FW is a municipal solid waste; but unlike daily household waste, it has some economic value. This study found that the economic benefits of the current FW management and treatment system are not high; the average R was 0.08 ± 0.37, which is consistent with the conclusions of other researchers. Therefore, the normal operation of China's FW treatment projects is still largely dependent on the government's financial incentives, such as tax reductions, loan concessions, and operating subsidies.

During the construction stage, the overall tonnage investment of existing FW treatment projects fluctuated moderately. The key influencing factor was the service population size. The impact of technological factors was less than that of the population size. Therefore, the identification of an appropriate service population size is vital for controlling tonnage investment during the construction of FW projects. The key to addressing economic fluctuations during operations lies in the choice of processing technique, as it affects the operation phase of the FW significantly. Therefore, improving the economics of the process technique should be the focus of the research and application of FW technique, such as developing high-value supplementary products by solid-state fermentation to complement aerobic digestion. Further, choosing or developing low-cost and high-income treatment techniques can serve as an alternative option for improving the economics of FW treatment projects.

Economic influencing factors are multi-level and need comprehensive consideration. The study found that technical factors such as processing techniques are important, but the impact of non-technical factors such as the service population size cannot be ignored. Therefore, service population size and processing techniques should be carefully identified during the economic decision-making or optimization process for FW management. However, the specific pattern or extent of the impact of population size and processing technique on the economics remains unclear (e.g., process subunits, such as wastewater treatment methods, bio-production sale). Components of the whole FW project economy and their contribution values remain unclear and need clarification. Moreover, the economic influencing factors investigated in this work need to be examined further. Other influencing factors such as transportation distance, consumption habits, and attitudes of relevant stakeholders are yet to be analyzed.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 51878611), and the State Scholarship Found by the China Scholarship Council (201908330103).

Electronic Supplementary Material Supplementary material is available in the online version of this article at https://doi.org/10.1007/s11783-020-1325-y and is accessible for authorized users.

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