



# Life cycle environmental performance of two restaurant food waste management strategies at Shenzhen, China

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## Abstract

Restaurant food waste (RFW) can be separated from other municipal solid waste (MSW) for individual treatment or treated together with other MSW, and it is disputed which option is the optimal strategy for MSW management in the practice of Shenzhen, China. To weigh pros and cons of RFW separation, a hybrid life cycle assessment is conducted to compare (S1) all MSW incineration and (S2) individual anaerobic digestion of RFW and other MSW incineration referring to the real situation. The results show that S2 reduces 10.6% carbon emission than S1, mainly owing to higher heat value of incineration feedstock and higher yield of electricity. In addition, the cumulative energy demands of S1 and S2 are –6290 and –6544 MJ/t MSW, and their energy efficiencies are 67.4 and 70.3%, respectively. Moreover, RFW separation reduces acidic gases emission due to the substitution effect of more energy products. Overall, source sorting of RFW is a sustainable model of MSW management at Shenzhen, and the result provides quantitative support for the strategy of RFW separation from MSW.

**Keywords** Anaerobic digestion · Incineration · Municipal solid waste · Food waste · Life cycle assessment

## Introduction

A great quantity of food is wasted annually all over the world, triggered by the increasing demand for food quantity and quality and the consumption culture of wastefulness along with rapid urbanization and industrialization. Food waste, which has high contents of water, organics, and nutrients and high risk of polluting environment, has become a global issue not only in developed countries but also in many developing countries, especially in those with rapid economic development. For example, food waste reached approximately 11–16 Mt in Thailand in 2015 [1], and the proportions of food waste in municipal solid waste (MSW) were estimated at 39% in Malaysia and 23% in Indonesia in 2016 [2].

Food waste is usually treated together with other MSW in landfill sites or incinerators in many cities in developing countries. However, it is suspected that food waste is

incompatible to landfill and incineration and has negative impact on the performance of terminal MSW treatment facilities due to its physical properties (high content of water, oil, and salts) [3–5]. In China's landfill sites, food waste would produce a quantity of leachate that is difficult to clean, and release a vast volume of biogas that is difficult to collect completely, accordingly increasing the environmental burden and operational expenditure of landfilling [6]. In MSW incineration plants, food waste could decrease the calorific value of feedstock due to high water content, and hence reduce the energy recovery from MSW and the economic benefits from heat or electricity output [7]. To avoid these shortcomings, many efforts have been put into separate collection and treatment of food waste in China, particularly restaurant food waste (RFW). It is easier to collect RFW separately with the assistance of regulatory system than other food waste, and RFW is also the focus of food waste management. For instance, in more than 100 big cities in China, MSW separate collection system has been put into practice since 2010, and RFW is partly collected from restaurants and canteens [8].

RFW can be treated through anaerobic digestion, composting, and feeding insects for protein recovery. Anaerobic digestion is a promising technology for RFW treatment because it can recover energy from organic matter and the

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residue can be used for land utilization [9, 10]. Furthermore, two-phase anaerobic digestion (TPAD) is more popular with high stability and efficiency in comparison with single-phase anaerobic digestion (SPAD) [11]. In Singapore, TPAD had the best performance when the oil content in RFW was lower than 5%, and waste oil recovery for biodiesel production was preferred when the oil content higher than 5% [3]. It was demonstrated that anaerobic digestion had the lowest environmental impact and the highest carbon reduction. However, there are controversy on technical options. Life cycle assessment (LCA) is often used to compare different RFW treatment technologies [12]. Saleem et al. concluded that composting was better than incineration and anaerobic digestion using a hybrid input–output-based LCA method, because composting obtained the best scores in seven environmental impacts including photochemical oxidant formation, marine eutrophication, etc. [13]. Padeyanda et al. evaluated the environmental burden of different food waste management options and found that wet feed had the lowest impact on global warming potential (GWP) and acidification potential (AP) [14]. A research on Hong Kong reported that decentralized composting should be an effective option to deal with the increasing RFW generation in comparison to landfilling and centralized anaerobic digestion [15]. Three types of energy use from RFW valorizing, including electricity and heat, city gas, and biogas fuel for vehicle use, were ever assessed in the context of Hong Kong, and biogas fuel as a petrol substitute for vehicle use was recognized to be advantageous over other types of energy use in regard to human health and ecosystem [16]. Zhang et al. compared the environment impacts of different RFW treatment techniques, and thought that anaerobic digestion followed by aerobic composting was preferable choice than landfill and incineration in Lanzhou City since the former performed better in AP, GWP, and photochemical ozone creation potential [17].

Although many efforts have been put into the comparison of different treatment technologies, the management strategies of RFW have rarely quantitatively considered for most big cities of developing countries. Shenzhen is a young megacity with more than 21 million populations. Meanwhile, it is also the polit city of MSW classification which plays an exemplary role for other cities in China. According to our investigation, RFW accounts for approximately 14% of MSW at Shenzhen. When RFW is separated from MSW, the characteristics of the residual MSW would be different, and the whole performance of MSW management system would change significantly. Hence, there is always the debate on which strategy is the best for RFW management. Separate collection and utilization could prompt the direct environmental benefits from RFW, but mixed collection and treatment could save the fuel consumption of collection and transportation. Moreover, incineration can burn almost all the organic matter in MSW to generate heat, while anaerobic

digestion can convert only a part of organic matter to biogas. In the current practice of Shenzhen, some RFW is collected separately and treated using anaerobic digestion, and other RFW is treated together with other MSW using incineration. To help scientific decision, it should be carefully considered which option should be the optimal for MSW management at Shenzhen as well as other cities with the same problem.

In this study, this issue is discussed adequately using real industrial data. We aim to quantify and compare two MSW management strategies based on our survey data at Shenzhen: RFW is collected and treated together with other MSW, and RFW is collected and treated individually. Their environmental performance is investigated thoroughly using tiered hybrid LCA [18], which combined the advantages of process LCA (PLCA) and Economic Input–Output LCA (EIO-LCA) [19]. Food waste treatment processes and downstream processes (e.g. use and end-of-life) were analyzed using PLCA, and upstream processes (e.g. chemicals and energy production) were assessed using EIO-LCA due to the lack of local life cycle database for chemicals and energies. Carbon and energy flow analysis are used to explain the performance of different management options. In addition, economic performance is analyzed for the comprehensive comparison between different management options. The results provide valuable information to assist the future decision for RFW management strategies at Shenzhen and other similar big cities.

## Materials and methods

### The goal and scope

The goal and scope of LCA determine the boundary and functional unit of the target system. The system frameworks are shown in Fig. 1. The functional unit was set as treatment of 1 t MSW, including 0.148 t RFW and 0.852 t other remaining wastes (RW) according to our investigation (RW is 16357 t/d and RFW is 2847 t/d in Shenzhen). The composition, moisture, and lower heating value (LHV) of RW, RFW, and their mixture are shown in Table 1. Two scenarios are considered: (S1) RFW and RW are collected together (MSW) using the same collection system with transfer stations, and then fed into incinerators; (S2) RFW is collected separately and then treated using TPAD, while RW is incinerated as the same as S1. In the TPAD plant, RFW is first pretreated with waste oil recovery for biodiesel processing and then anaerobically digested with biogas utilization. The digestion effluent is mechanically dewatered and then becomes sludge cake and wastewater. The sludge cake is incinerated together with RW, while the wastewater is conveyed to a wastewater treatment plant.

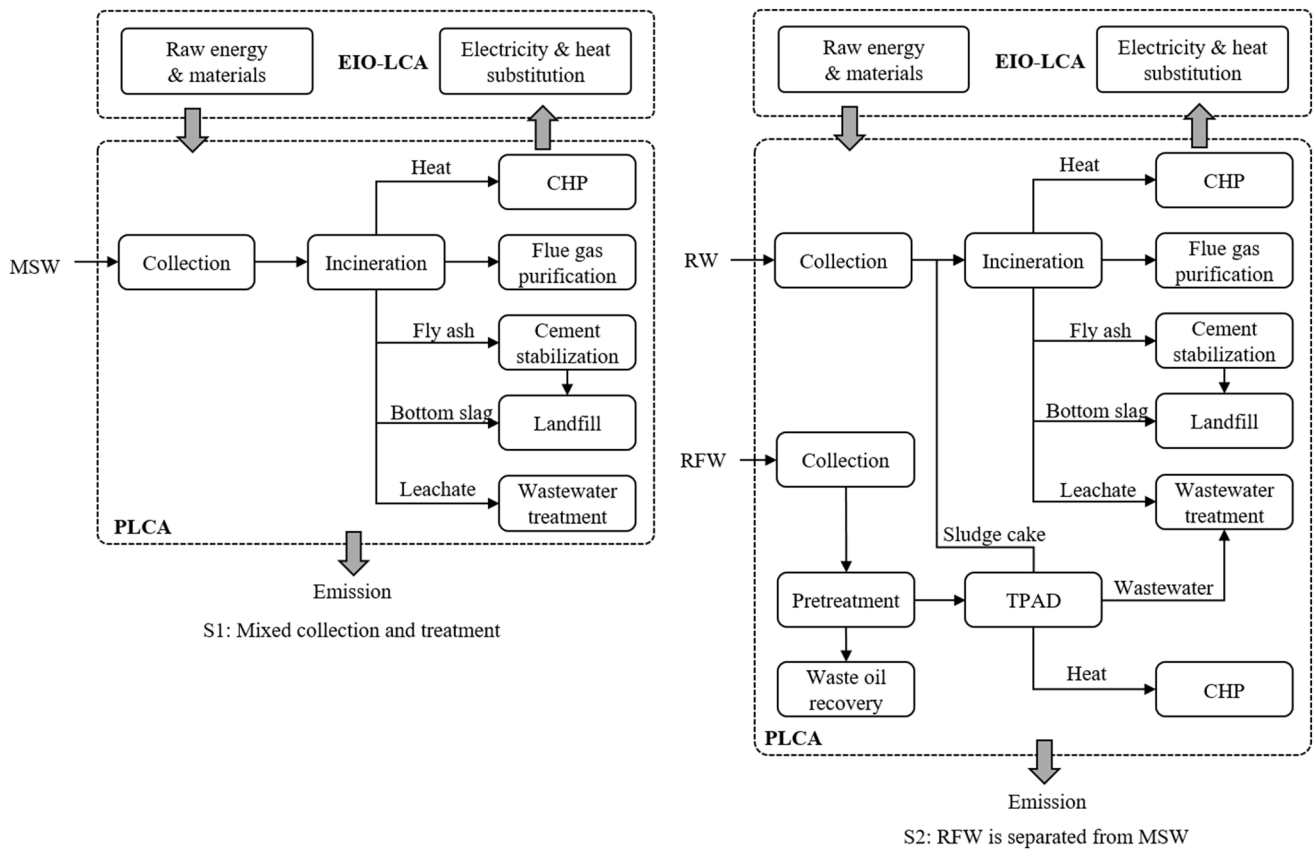


Fig. 1 Flow charts and system boundaries of two restaurant food waste (RWF) management scenarios (S1: Mixed mode; S2: Separation mode)

Table 1 Physicochemical properties of restaurant food waste (RWF) and other remaining waste (RW)

Type	Composition (wt.%, wet basis)	LHV (MJ/t, dry basis)	BSC (% wet basis)	FSC (% wet basis)	Before storage in pits		After storage in pits	
					Water content (%)	LHV (MJ/t, wet basis)	Water content (%)	LHV (MJ/t, wet basis)
<b>RW</b>								
Household kitchen waste	50.39	15,000	7.0	0	80	730	70	2370
Garden waste	0.98	15,690	19.6	0	60	4285	60	4285
Textile	3.30	20,591	26.8	6.7	33	11,999	33	11,999
Rubber and plastic	22.36	41,946	0.0	56.3	25	29,680	25	29,680
Paper	15.53	16,931	27.1	0	41	8201	41	8201
Metal	1.11	0	0	0	0	666	0	666
Glass	4.45	0	0	0	0	132	0	132
Others	1.88	0	0	0	0	0	0	0
Total	100	22,768	8.9	12.9	54	8769	45	11,302
RFW	100	15,000	7	0	80	730	70	2370
MSW (RW and RFW)		23,360	8.6	11.0	58	7577	49	10,198

**Assessment methods**

The OpenLCA software is used to construct the model. Direct energy demand, material requirement, and pollutant emission are calculated using PLCA referring to ISO

14040 [20], while the pollution emission and energy consumption from upstream supply chain such as the manufacturing of chemicals are analyzed using EIO-LCA based on the input–output table of China in 2012, referring to our previous study [21]. EIO-LCA is also taken to evaluate

the avoided burdens and energy saving associated with the byproducts of electricity, steam, and biodiesel. The energy products are assumed to replace similar products on the market (grid power, steam, and diesel), and their offset effect is qualified by the average emission level of relevant sectors in China. PLCA is carried out using the CML method [22]. Two indexes are adopted including GWP and AP because they are the most concerning indicators by the public and local managers. All the direct and indirect emissions from the systems are grouped into the two categories. GWP is calculated using the carbon dioxide equivalence of greenhouse gases (GHG). AP comes from the emission of  $\text{SO}_2$ ,  $\text{NO}_x$ , and other acidic gases. Energy consumption and generation are assessed using cumulative energy demand (CED) as an indicator, and it is calculated using life-cycle energy input minus the energy saved. Carbon flow and energy flow analysis is also conducted [21]. The carbon emission from biological source carbon (BSC) in waste is regarded as carbon neutral, while the carbon emission from fossil source carbon (FSC) is carbon source. In TPAD, some BSC is transferred to wastewater and sludge cake, and finally converted to  $\text{CO}_2$  with the effect of carbon neutral. The carbon emission from fossil fuel is recognized as carbon source.

Economic performance is also important for technical selection. The two scenarios are economically evaluated based on their financial reports, which shows the capital expenditure is approximately 1,010,000 CNY/t for the incineration plant and 350,000 CNY/t for the TAPD plant. The capital expenditure of MSW incineration is averagely in the range of 500,000–600,000 CNY/t in China, whereas the investment in this study is higher because of the strict emission standard at Shenzhen. The investment is influenced by many factors like land price, financial cost, etc., and accordingly the direct operational expenditure including collection and treatment cost is considered with sale revenue and government subsidy in this study.

### Life cycle inventory

Most of the data used here were collected from our field survey on a treatment plant of RFW (Shenzhen Lisai Environmental Technology Co. Ltd.) and an incineration plant of MSW (Shenzhen Energy Environmental Co. Ltd.) in 2019. Carbon in RFW is belonging to BSC, accounting for 7% of total mass [23], and the BSC and FSC ratios of different components are obtained from IPCC (2006). In the incineration plant, waste is first stored in a pit for several days to remove some water, and then fed into incinerators. The water content of household kitchen waste is approximately 80%, which decreases to 70% after storage. Synchronously, the water content of RW decreases from 54 to 45% assuming other components would not lose their water. The leachate collected from the pit accounts for 20% of raw waste before

storage, which is also reported based on another investigation [24].

### Incineration

After storage in a pit, RW or MSW is fed into the incinerators. Combined heat and power generation (CHP) is utilized to recover energy embodied in waste. The heat recovery rate of incinerators is 25.6%, and the electricity yield is around 14%. The leachate is treated using on-site anoxic–oxic–membrane bioreactors followed by ultra-filtration. The material input and pollutant discharge of leachate treatment are collected from the public data of environmental facilities in Shenzhen, and some data are referring to a previous report [21]. The flue gas is treated using the craft combination of SNCR denitrification, semi-dry desulphurization, activated carbon injection, and bag filtering. After incineration, bottom slag and stabilized fly ash are sent to landfill sites 40 km away. The process of fly ash cement stabilization has been analyzed using PLCA [25]. The emission of landfill sites is referring to the literatures [26–28] and the regulation “GB16889-2008”. The key input and output of the incineration system are collected (Table 2), where it is assumed that the material input and pollutants emission keep constant when the feedstock shifts from MSW to RW.

### Anaerobic digestion

TPAD is applied to treat sourced separated restaurant food waste, and the process consists of pretreatment, acidogenesis, methanogenesis, biogas utilization, and sludge dewatering. The pretreatment unit has several steps including sorting, crushing, desilting, steam heating, and three-phase separation. After steam heating at 90 °C for 30 min, RFW was input to a three-phase separation centrifuge to obtain waste oil, liquid effluent, and solid residue. The separated waste oil accounts for 1.3 wt.% of total RFW, and the liquid effluent and solid residue are used for anaerobic digestion with biogas production. The digestion effluent is chemically conditioned and mechanically dewatered and finally becomes wastewater and sludge cake with water content of approximately 60% and LHV of 820 MJ/t. During this process, the BSC of RFW enters into different forms including biogas, waste oil, wastewater, and sludge cake with distribution ratios of 55.3, 8.8, 11.1, and 24.8%, respectively, and the distribution of bioenergy is assumed to follow the same rule. CHP is used to convert biogas to electricity, steam, and hot water (for heating digesters) with a little pollutant emission. The waste oil would be purified (remaining approximately 0.8 wt.% RFW) and then processed to biodiesel in external treatment plants. The inventory of biodiesel production process is modeled according to the reference [29]. Digested wastewater is treated using the same craft as used in the

**Table 2** Key input and output of the incineration system

Processes	Units	MSW	RW	Reference
<b>Incineration</b>				
Water consumption	t/t	2.37	2.37	The enterprises
Electricity consumption	kwh/t	63.50	63.50	The enterprises
Ammonia	kg/t	5.00	5.00	The enterprises
Lime	kg/t	7.33	7.33	The enterprises
Activated carbon	kg/t	0.49	0.49	The enterprises
Diesel (auxiliary)	L/t	0.02	0.02	The enterprises
Bottom slag	t/t	0.17	0.20	The enterprises
Fly ash	t/t	0.022	0.026	The enterprises
NO <sub>x</sub>	kg/t	0.196	0.196	The enterprises
HCl	kg/t	0.011	0.011	The enterprises
CO	kg/t	0.010	0.010	The enterprises
Dust	kg/t	0.012	0.012	The enterprises
Dioxins	mg/t	9.72E–05	9.72E–05	The enterprises
SO <sub>2</sub>	kg/t	0.018	0.018	The enterprises
Steam	t/t	0.69	0.78	The enterprises
Electricity production	kwh/t	313.41	357.38	The enterprises
Leachate	t/t	0.20	0.17	The enterprises
CO <sub>2</sub> , fossil	t/t	0.40	0.47	The enterprises
CO <sub>2</sub> , biogenic	t/t	0.66	0.32	The enterprises
<b>Fly ash stabilization</b>				
Cement	t/t fly ash	1	1	[26]
Water consumption	t/t fly ash	141.13	141.13	[26]
Electricity consumption	kwh/t ash	50	50	[26]
<b>Wastewater treatment</b>				
Electricity consumption	kwh/t wastewater	1.93	1.93	[25]
Flocculants consumption	kg/t wastewater	0.712	0.712	[25]
Ca(OH) <sub>2</sub> consumption	kg/t wastewater	0.105	0.105	[25]
COD	g/t wastewater	14.2	14.2	The enterprises
TN	g/t wastewater	7.8	7.8	The enterprises
TP	g/t wastewater	0.4	0.4	The enterprises
<b>Landfill of slag and ash</b>				
Water consumption	t/t slag and ash	0.158	0.158	[27]
Electricity consumption	kwh/t slag and ash	0.173	0.173	[27]
Diesel	L/t slag and ash	0.158	0.158	[27]
COD	kg/t slag and ash	0.15	0.15	(GB16889-2008)
SS	kg/t slag and ash	0.045	0.045	(GB16889-2008)
TN	kg/t slag and ash	0.06	0.06	(GB16889-2008)
CO <sub>2</sub>	kg/t slag and ash	0.42	0.42	[27]
SO <sub>2</sub>	kg/t slag and ash	4.63E–04	4.63E–04	[27]
NO <sub>2</sub>	kg/t slag and ash	0.01	0.01	[27]
TP	kg/t slag and ash	4.50E–03	4.50E–03	(GB16889-2008)
Hg	kg/t slag and ash	1.50E–06	1.50E–06	(GB16889-2008)
Cd	kg/t slag and ash	1.50E–05	1.50E–05	(GB16889-2008)
Cr	kg/t slag and ash	1.50E–04	1.50E–04	(GB16889-2008)
<b>Leachate treatment at landfill sites</b>				
CO <sub>2</sub>	kg/t slag and ash	2.23	2.23	[28]
CO	kg/t slag and ash	0.0007	0.0007	[28]
CH <sub>4</sub>	kg/t slag and ash	0.0075	0.0075	[28]
NO <sub>x</sub>	kg/t slag and ash	0.003	0.003	[28]
SO <sub>2</sub>	kg/t slag and ash	0.0024	0.0024	[28]

incineration plant, and the inventory is established [30]. Sludge cake is finally transported to the incineration plant 50 km away, and it would not produce leachate any more in the pit of the incineration plant. During the incineration of sludge cake, the energy consumption and gaseous emission level except CO<sub>2</sub> are assumed to be the same as those of RW incineration. The inventory of TPAD is listed below (Table 3).

### Collection and transportation

The energy consumption of RFW collection is obtained through a survey on the employees of treatment plant. Based on the location of different RFW sources, optimal collection and transportation routines are planned and executed by truck drivers. According to the survey, the collection and transportation distance is averagely 13.1 km/t, and the diesel consumption is 2.88 L/t. The RW or mixed MSW collection system has a different structure with additional transfer stations. The diesel consumption of collection trucks and transfer stations is 1.6 and 0.4 L/t, respectively, with additional electricity consumption of 1 kWh/t on transferring station [31]. The transportation of waste (e.g. bottom slag, stabilized fly ash, and sludge cake) is also considered, and the diesel consumption is approximately 0.03 L/(t km) [32]. The emission from diesel combustion refers to “GB17691-2005”.

### Sensitive analysis

In real world, the operation and the corresponding performance are fluctuant. An analysis is conducted to quantify the impact of varied parameters to the two systems. A  $\pm 10\%$  change of some parameters is assessed using Monte Carlo method. It is assumed that each parameter obeys uniform distribution in an interval of 0.9–1.1 times of its average value. The deviation, maximum, and minimum of the results can show the degree to which the performance of the systems is sensitive to these parameters. After pre-analysis, six key parameters with considerable contribution to the whole performance are further evaluated, including electricity yield, heat yield, water content in RFW, water content in household kitchen waste, household kitchen waste content in MSW, and dehydration degree after storing in pits.

## Results and discussion

### Carbon emission

In the two scenarios, the carbon emission is derived from the systems and their upstream supply chains (Fig. 2a). The two scenarios show the reduction effect of GHG, and their net emission is  $-275.8$  (S1) and  $-305.0$  kg CO<sub>2</sub>-eq/t MSW

**Table 3** Key input and output of the two-phase anaerobic digestion (TPAD) plant

Processes	Unit	TPAD	Reference
<b>TPAD</b>			
<b>Input</b>			
Extracted oil	t/t RFW	0.039	The enterprises
Steam consumption	t/t RFW	0.09	The enterprises
Electricity consumption	kWh/t RFW	24.88	The enterprises
Water consumption	t/t RFW	0.65	The enterprises
Fe <sub>2</sub> O <sub>3</sub> or desulfurization	kg/t RFW	0.83	The enterprises
PAM for dewatering	kg/t RFW	0.03	The enterprises
FeCl <sub>3</sub> for dewatering	kg/t RFW	3.58	The enterprises
CaO consumption	kg/t RFW	1.56	The enterprises
<b>Output</b>			
Biogas production	m <sup>3</sup> /t RFW	72.3	The enterprises
Electricity production	kwh/t RFW	144.24	The enterprises
Steam production	t/t RFW	0.116	The enterprises
Sludge cake	t/t RFW	0.26	The enterprises
Wastewater	t/t RFW	0.92	The enterprises
CO <sub>2</sub> emission	kg/t RFW	142.02	Estimated
CO from CHP	mg/kWh	986	[31]
NO <sub>x</sub> from CHP	mg/kWh	821	[31]
SO <sub>2</sub> from CHP	mg/kWh	439	[31]
Dust from CHP	mg/kWh	164	[31]
<b>Wastewater treatment</b>			
Electricity consumption	kwh/t wastewater	1.93	[25]
Flocculants consumption	kg/t wastewater	0.712	[25]
Ca(OH) <sub>2</sub> consumption	kg/t wastewater	0.105	[25]
COD	g/t wastewater	100	GB 18918-2002
Suspended solids	g/t wastewater	3.3	[25]
NH <sub>3</sub> -N	g/t wastewater	10.2	[25]
TP	g/t wastewater	0.4	[25]
<b>Waste oil processing</b>			
Water consumption	t/t waste oil	1.8	[30]
Steam consumption	t/t waste oil	0.6	[30]
Electricity consumption	kWh/t waste oil	48	[30]
Methanol consumption	t/t waste oil	0.081	[30]
Biodiesel production	t/t waste oil	0.525	[30]
VOC emission	kg/t waste oil	0.36	[30]
CO emission	kg/t waste oil	0.032	[30]
SO <sub>2</sub> emission	kg/t waste oil	0.637	[30]
NO <sub>x</sub> emission	kg/t waste oil	0.097	[30]
CO <sub>2</sub> emission	kg/t waste oil	74.6	[30]

**Table 3** (continued)

Processes	Unit	TPAD	Reference
Incineration of sludge cake			
Steam	t/t Sludge cake	0.07	Estimated
Electricity production	kwh/t Sludge cake	31.10	Estimated
Electricity consumption	kwh/t Sludge cake	63.5	Estimated
Biogenic CO <sub>2</sub>	kg/t Sludge cake	86.06	Estimated

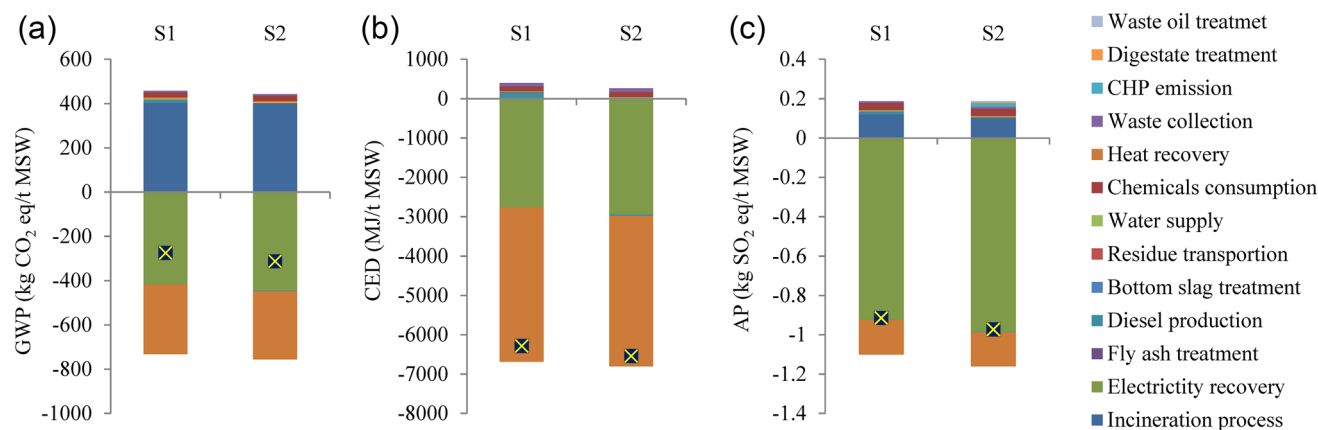
(S2), respectively. The substitution of raw fossil fuels by electricity and steam is the top contributor to the reduced GWP because a vast amount of upstream energy is saved. The direct GHG emission from incinerators and CHP is considerable and almost equal to the GHG reduction of electricity substitution. The CO<sub>2</sub> released from FSC burning in incinerators is the main source of GHG emission. In a previous report on MSW incineration in China [6], the net GHG emission was  $-124 \text{ kg CO}_2\text{-eq/t MSW}$ , which was also mainly contributed by FSC incineration (approximately  $180 \text{ kg CO}_2\text{-eq/t MSW}$ ) and electricity substitution ( $-304 \text{ kg CO}_2\text{-eq/t MSW}$ ). In S2, waste oil recovery and biodiesel processing are helpful for GHG reduction, but some diesel is consumed on RFW collection and treatment. Hence, the total contribution of diesel production to GHG emission reduction in scenario S2 is limited. Overall, the RFW separation mode reduces 12.1% GHG emission than the mixed incineration system, mainly owing to higher LHV of incineration feedstock and higher yield of electricity. Moreover, in the scenario S2, the internal energy in digestate (LHV: 7116 MJ/t, dry basis) is further recovered through incineration, and it would avoid methane leakage from landfill sites.

Carbon flow analysis can provide more details about the carbon reduction effect, which is illustrated in the Sankey

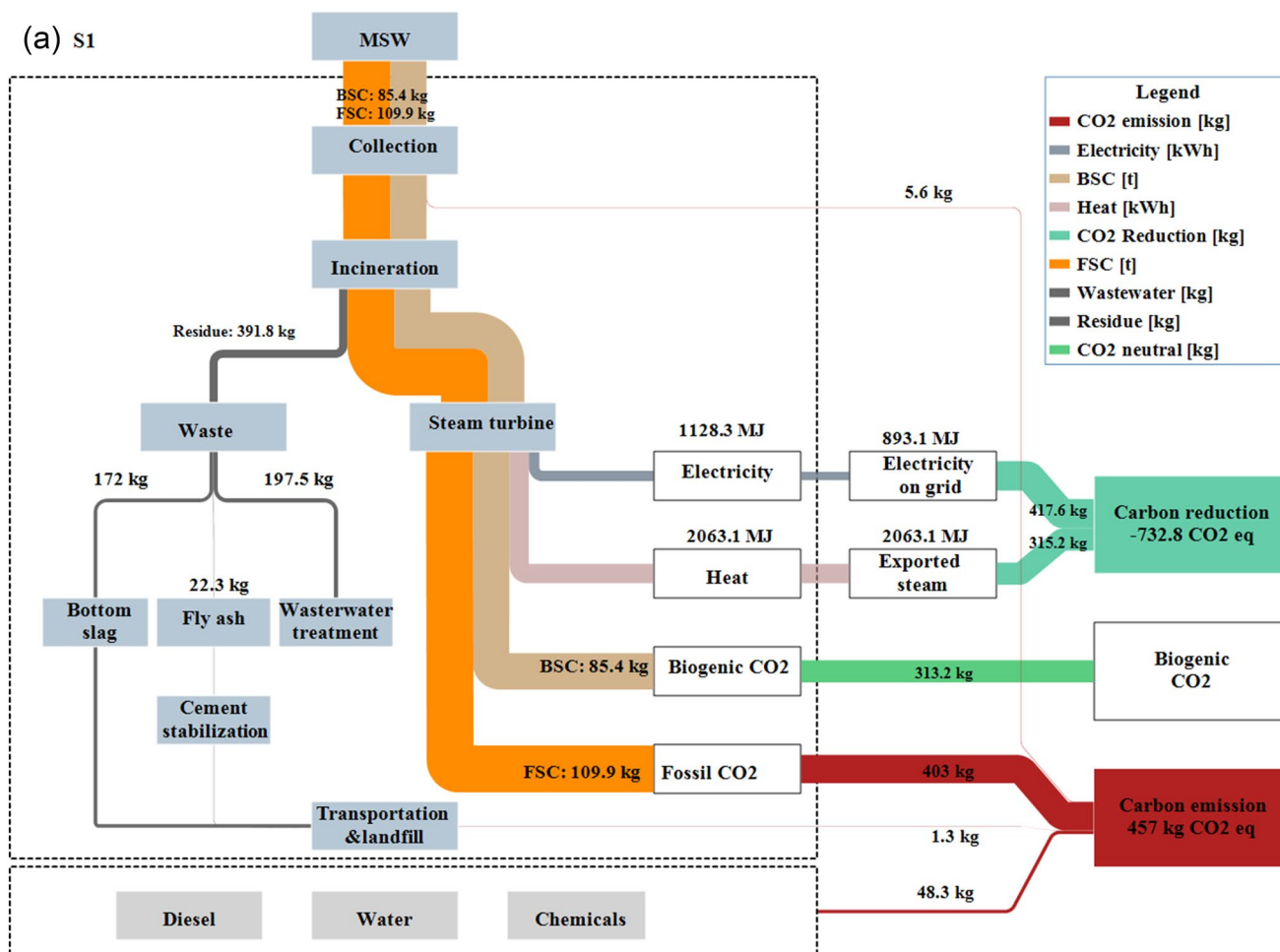
charts (Fig. 3). The BSC content is approximately  $85.4 \text{ kg/t MSW}$ , 12.2% of which is sourced from RFW, and FSC content is  $109.9 \text{ kg/t MSW}$ , which is fully sourced from RW. The FSC in RW is burned to CO<sub>2</sub>, resulting in a carbon emission of 403 kg, and it is the biggest contributor of GHG in the two management scenarios. The indirect GHG emission derived from upstream chain is  $48.3 \text{ kg CO}_2\text{-eq/t FU}$  for S1 and  $49.4 \text{ kg CO}_2\text{-eq/t FU}$  for S2, which account for approximately 10% of the total carbon emission. The other sources of carbon emission are indeed neglected (1%), such as collection, transportation, and landfill. Energy products (electricity, heat, and biodiesel) are recovered, and a part of energy is used inside the plants (the energy flow is not shown in Fig. 3) and the excess energy is exported. The latter can replace raw fuels and reduce the corresponding carbon emission. Hence, a considerable amount of carbon sink is achieved in the two scenarios. The RFW separation system (S2) has an additional biodiesel recovery and more carbon reduction is observed as much as  $20.6 \text{ kg CO}_2\text{-eq}$ . Although RFW-biogas-energy is an inefficient energy production process compared with incineration, the RFW separation system (S2) has a better performance than the current practice (S1) from the point of view of carbon reduction. The result is attributed to higher LHV of feedstock to incineration and the corresponding more substitution benefit of energy recovery.

### Energy consumption

The two systems have the same direct energy input (higher heat value is  $9519.0 \text{ MJ/t}$ ) and the similar direct energy output, i.e.  $2956.2 \text{ MJ/t}$  for S1 and  $3105.1 \text{ MJ/t}$  for S2, and the CEDs are  $-6290$  and  $-6544 \text{ MJ/t}$ , respectively (Fig. 2b). The recovered electricity is the main reason for energy saving, and the steam output is the second contributor. S2 has a better performance than S1 because the feedstock of incineration in S2 has higher LHV after separating RFW



**Fig. 2** Environmental performance of the two scenarios (S1: Mixed treatment; S2: Separated treatment of restaurant food waste (RFW)); **a** Global warming potential (GWP); **b** Cumulative energy demand (CED); **c** Acidification potential (AP); the stars indicate the total GWP, CED or AP



**Fig. 3** Carbon flow of the two scenarios based on 1 t municipal solid waste (MSW) (S1: Mixed treatment; S2: Separated treatment of restaurant food waste (RFW))

from MSW. In addition, the RFW separation system has other energy recovery pathways including biodiesel production and incineration of sludge cake after digestion and dewatering.

Energy flow analysis is adopted to analyze energy conversion in the two systems in detail (Fig. 4), illustrating the reason that RFW separation system can save more energy. The electricity and steam generated are first used in the plants themselves and then the residual energy is exported, and hence there are some gaps between "high-grade heat" and "exported steam", and between "electricity" and "electricity on the grid". The gaps are related to the electricity consumption and steam consumption, as shown in Tables 2 and 3. In Fig. 4, the by-products refer to the valuable products including electricity, steam recovered from high-grade heat, and biodiesel. In both scenarios, energy products save energy from upstream chains. When considering the energy input (direct and indirect), S1 requires less external energy than S2, and diesel production consumes the

main part (64% of the total energy input). However, the energy input is quite low compared with the recovered energy. Therefore, even if more energy is consumed on waste collection, S2 saves more energy than S1 due to more electricity production and waste oil recovery. In S1, the direct energy output is 2956.2 MJ/t MSW including steam of 2063.1 MJ/t MSW and electricity of 893.1 MJ/t MSW, and the conversion rate from MSW to energy is 31% through incineration. In S2, the conversion rate increases slightly to 32% through incineration due to higher LHV of feedstock, but the conversion rate is only 28% through anaerobic digestion. Overall, the effect of RFW separation on waste utilization is negligible due to the small ratio of RFW in MSW.

The energy efficiency (EE, Eq. 1) of S1 is 67.4% with more steam output, while that of S2 reaches 70.3% because S2 outputs more electricity and biodiesel with more upstream energy saving.



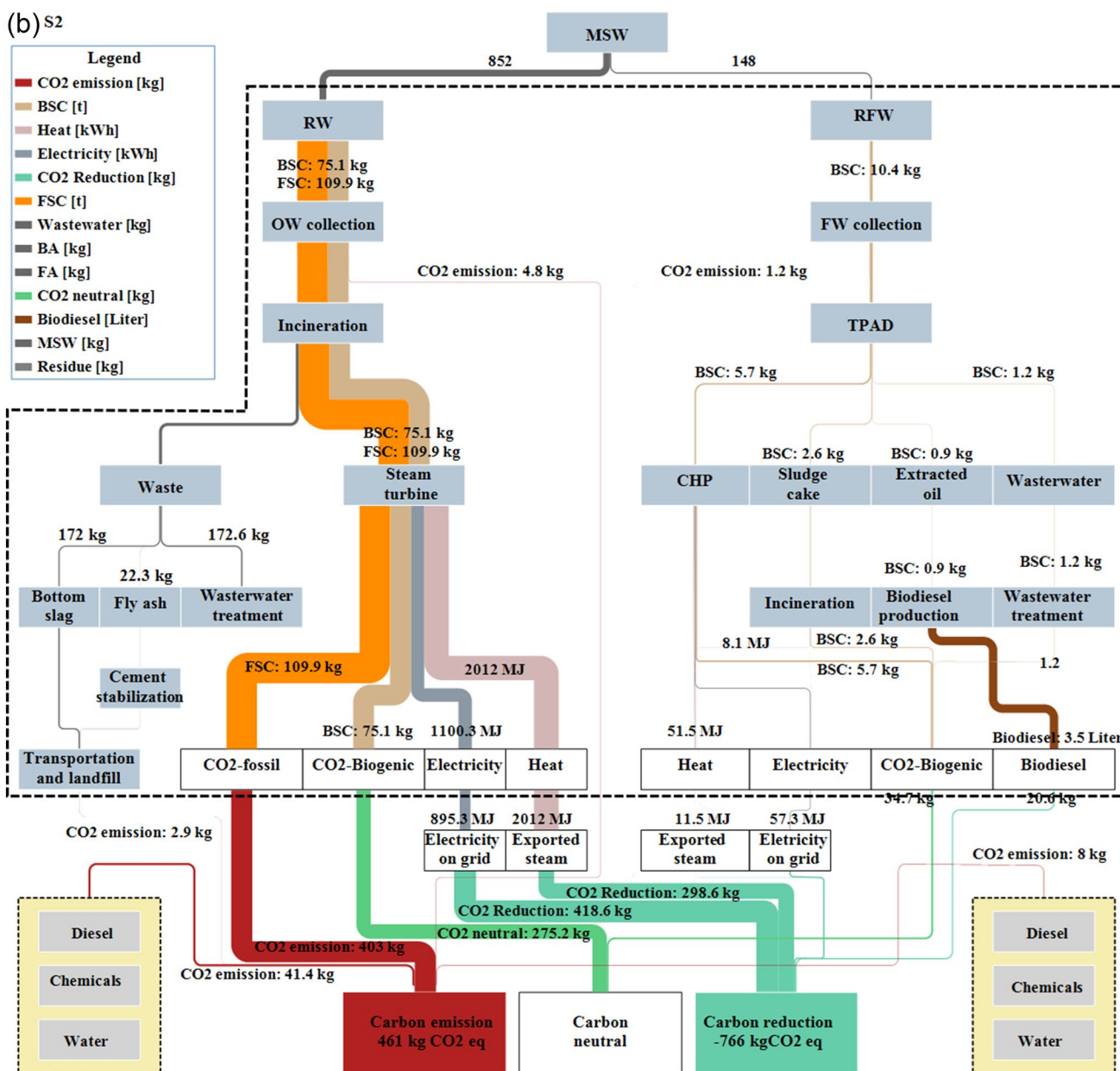


Fig. 3 (continued)

$$EE = \frac{\text{energy output}}{\text{energy input} + \text{energy in MSW}} \times 100\% \quad (1)$$

The energy output and energy input in Eq. (1) include direct and indirect items.

### Acidic gases

NO<sub>2</sub> and SO<sub>2</sub> are the main acidic gases directly released from the processes (including incineration, vehicle emission, biogas utilization, etc.), as shown in Fig. 2c. The values below zero mean the elimination of acidic gases. For the two

systems, the substitution of electricity is the main contributor to the reduction of AP, followed by heat recovery. Higher offset effect of energy products are achieved in S2 with RFW separation due to more electricity output, and the APs of S1 and S2 are -0.915 and -0.973 kg SO<sub>2</sub>-eq/t MSW, respectively. In terms of emission sectors, incineration unit is the main source with NO<sub>x</sub> emission. Chemical production sector is the following source: The AP derived from waste collection accounts for 4.2% in S1 and 5.2% in S2 of the total AP. Among different acidic gases, SO<sub>2</sub> causes most of AP, accounting for more than 70% of the total AP. In China, most of power plants use coal as the fuel which contributes

(a) S1

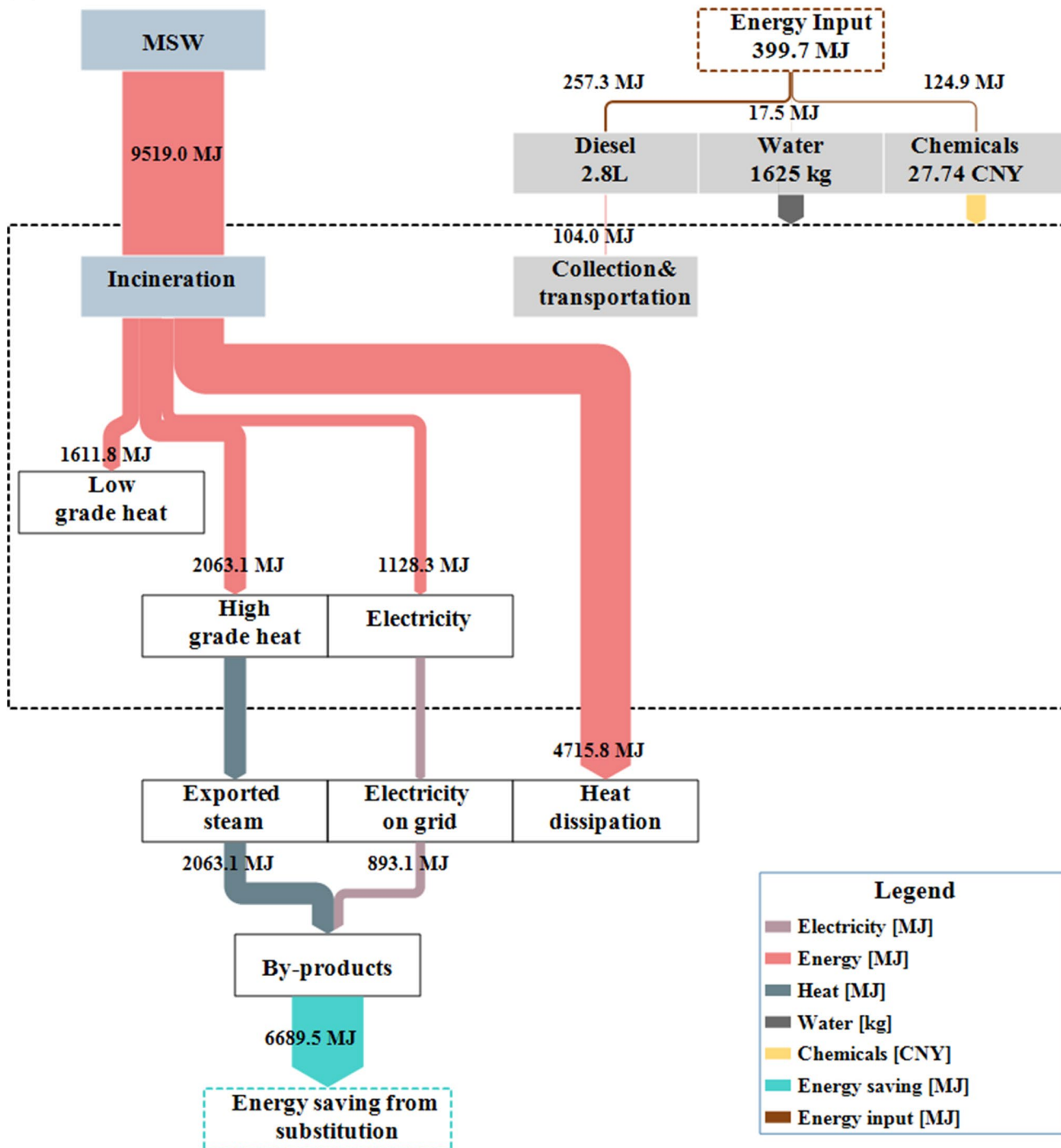


Fig. 4 Energy flow of the two scenarios based on 1 t municipal solid waste (MSW) (S1: Mixed treatment; S2: Separated treatment of restaurant food waste (RFW))

to a vast amount of SO<sub>2</sub> emission. Hence, the substitution effect of electricity exported from the systems results in the decrease of SO<sub>2</sub> emission and reduces the AP significantly.

Few studies conducted LCA on RFW management, but they only investigated some treatment technologies other

than the whole MSW management system influenced by RFW separation. Grosso et al. evaluated the environmental burden of the scenario where RFW was separately treated, and indicated GWP of - 107 kg CO<sub>2</sub>-eq/t MSW, CED of - 4678 MJ/t MSW, and AP of - 1.01 kg SO<sub>2</sub>-eq/t

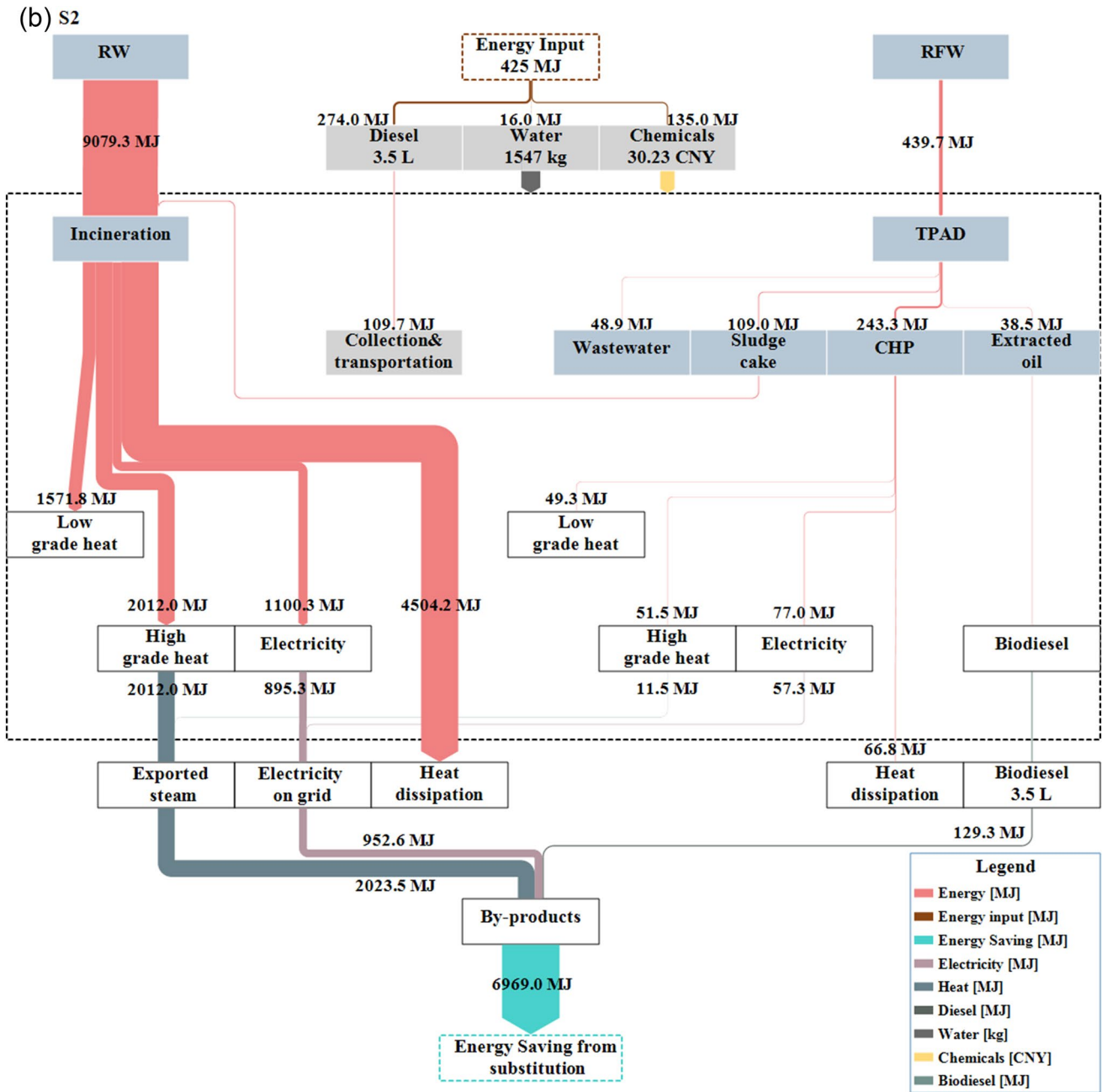


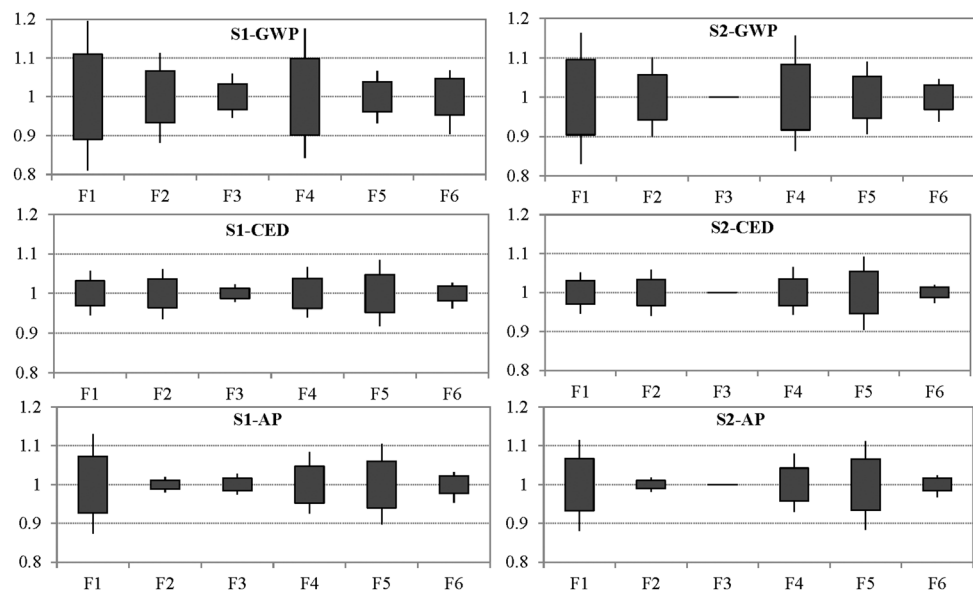
Fig. 4 (continued)

MSW (based on the figures) [33]. These results had the same order of magnitudes as reported in our study. Certainly, they are not completely the same, because in Grosso’s study, the proportion of RFW in MSW was 4.8% (lower than the proportion in our study) and RFW was treated through composting other than anaerobic digestion.

### Sensitive parameters

Sensitivity analysis is conducted to analyze the performance of the two systems under varied conditions. According our preliminary analyses, six key parameters with obvious influence are selected for further discussion (Fig. 5). The variation of three impact categories (GWP, CED, and AP)

**Fig. 5** Sensitive analyses on six key factors (F1: electricity yield; F2: heat yield; F3: water content in restaurant food waste (RFW); F4: water content in household kitchen waste; F5: household kitchen waste proportion in municipal solid waste (MSW); F6: dewatering degree after storing in pits)



corresponding to the fluctuation 10% of six parameters are quantified. Among the six parameters, electricity yield and heat yield are related to the efficiency of energy generation systems when the energy in feedstock is fixed.

For GWP, electricity yield and water content in household kitchen waste are the two key factors influencing carbon emission from the whole systems. The GWPs of the two systems change 10%, corresponding to the fluctuation 10% of the two factors. Therefore, it is effective for carbon emission reduction to improve the efficiency of power generators and decrease the water content in household kitchen waste, which substantially determines the water content of MSW.

For CED, the proportion of household kitchen waste in MSW and its water content are the vital influencing factors since household kitchen waste is the main component of MSW. Low water content of household kitchen waste is beneficial to both systems, but it does not change the advantage of S2 over S1. Similarly, low proportion of household kitchen waste in MSW would improve the performance of the two systems because this component has a relatively low LHV. Heat yield causes a bigger fluctuation than electricity yield. Advanced technology and equipment would increase the energy recovery rate, which is 14% in the form of electricity and 25.6% in the form of heat in this study, while as high as 19.5 and 65.4% for incineration in Denmark [34]. Water content in RFW only influences LHV of feedstock to incineration other than to anaerobic digestion, and this factor shows a slight contribution to the fluctuation of S1 at 0.8–2%, and almost no effect on S2. The decrease of water content in RFW would narrow the advantage of S2 with RFW separation. For example, when the water content of RFW is reduced to 60%, the mixed incineration scenario (S1) will perform better than S2.

The dewatering degree in pits has considerable impact on the result. Certainly, the loss of water in pits would improve the performance of incineration and decrease the dominance of S2 with RFW separation over S1 without RFW separation. Nevertheless, there is a limit for the dewatering effect of MSW in pits. It is impossible to reduce the water content to less than 50% and would not change the advantage of RFW separation. Certainly, water content of RFW, proportion and water content of household kitchen waste, and dewatering degree in pits are all related to the LHV of feedstock to incineration. The S1 system based on mixed incineration would have better effect of energy saving than S2 with RFW separation, when water content of RFW is 65% and water content of household kitchen waste is 55% after pit storage.

For AP, electricity yield and household kitchen waste proportion are the top sensitive parameters, and they result in similar fluctuation range of 6–7%. This is because AP is basically connected with electricity generation, which can reduce  $\text{SO}_2$  emission from coal burning through energy substitution.

### Economic performance

The two scenarios are economically evaluated based on their financial reports, and the operational revenue of energy products is calculated using market prices. The treatment cost covers water use, electricity consumption, wastewater treatment, diesel consumption, chemical consumption, and labor, while the cost of collection and transportation consists of labor cost, diesel consumption, and vehicle maintenance expenses and insurance. The treatment cost is approximately 219 CNY/t for the incineration plant, and 110 CNY/t for

**Table 4** Economic performance of different FW management strategies (CNY/t MSW)

Item	S1	S2
Operational expenditure	399	381
Collection of OW	180	153
Collection of FW		25
Incineration	219	187
TPAD	–	16
Revenue	510	535
From TPAD	–	65
Steam	–	1
Electricity	–	12
Waste oil	–	8
Treatment payment	–	44
From incineration	510	470
Steam	99	96
Electricity	162	162
Treatment payment	249	212
Net revenue	111	154

the TPAD plant, while the cost of collection and transportation is 180 CNY/t for RW or MSW, and 170 CNY/t for FW. The benefit of the incineration plant is derived from the sale of electricity and steam and the waste treatment payment from government (249 CNY/t), while the benefit of the TPAD plant is from the sale of energy products (electricity, steam, and waste oil) and treatment payment (300 CNY/t). The market price of waste oil is 2800 CNY/t, the price of steam is 143.5 CNY/t. According to the pricing policy, the price of on-grid electricity generated from incineration is 0.65 CNY/kWh within 280 kWh/t and 0.453 CNY/kWh above 280 kWh/t. Based on the investigation, the operational expenditure and revenue of S1 and S2 are listed in Table 4.

The revenue consists of energy products sale and treatment payment from government. In terms of revenue structure, treatment payment is the top contributor which accounts for 47–48% of the total income, followed by electricity sale revenue which accounts for 31–32%. On account of high operational expenditure, the systems would have a financial deficit if without government subsidy. In S1, the net profit of the incineration plant is 111 CNY/t MSW. In S2, a higher revenue from incineration is obtained from the feedstock with higher LHV, generating a higher net profit of 154 CNY/t MSW. Excluding government subsidy (treatment payment), the net operational cost is –138 CNY/t MSW in S1 and –102 CNY/t MSW in S2, indicating S2 could save more treatment cost of MSW than S1. Overall, S2 has a better economic performance than S1 because of higher profit level and lower investment cost.

Certainly, there are many complex factors influencing the economic performance of waste management, for example,

the location and service zone of different treatment plants. If there is not enough demand in near area or heat supply pipeline, the revenue of waste-to-energy facilities would decrease. Since treatment payment is the key revenue, the variation of government subsidy to FW or MSW would change the selection of management modes from the economic aspect. High government subsidy of FW treatment would drive an increase of investment on FW treatment facilities and the implementation of FW separation strategy.

## Conclusion

Two restaurant food waste (RFW) management strategies in Shenzhen, including mixed treatment with other MSW and individual treatment, are analyzed from the view of point of life cycle environmental impact. The source sorting of RFW leads to higher LHV of incineration feedstock and more energy recovery than mixed treatment only using incineration. In detail, RFW separation reduces the emission of greenhouse gases and acidic gases and saves more energy through electricity output and biodiesel production. The RFW separation scenario shows a higher energy efficiency than the mixed treatment mode due to less heat loss from water gasification and extra biodiesel production. Overall, RFW separation should be the optimal strategy for Shenzhen with better environmental performance.

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