J Mater Cycles Waste Manag (2017) 19:560–569
DOI 10.1007/s10163-015-0405-8

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Municipal food waste management in Singapore: practices, challenges and recommendations

Bernard Jia Han Ng[1] · Yu Mao[1,3] · Chia-Lung Chen[1] · Rajinikanth Rajagopal[1,4] · Jing-Yuan Wang[1,2]

Received: 27 August 2014 / Accepted: 7 June 2015 / Published online: 25 June 2015

Abstract Municipal food waste is a global challenge in solid waste management, especially in Singapore. It is scattered in location, non-ignorable in quantity, and non-uniform in quality. This report focuses on the state of the art and challenges of Singapore municipal food waste management for the first time. The previous studies only focus on general food waste from both industry and municipality. The physical properties of municipal food waste are incompatible to landfill and incineration by creating secondary environmental burdens and lowering treatment efficiency. A decentralized anaerobic co-digestion with other substrates, after comparing with other technologies, is recommended, since bio-energy is a recognized valuable final product in Singapore's context. However, there are four major highlighted challenges of food waste recycling, including low final product demand, inefficient waste collection design, cheap disposal cost, and low social awareness. A "food waste management hierarchy" for Singapore is also proposed. The most to least preferred options are listed as: source reduction, industrial uses, renewable energy, and composting then incineration.

Keywords Municipal food waste · Food waste minimization · Food waste recycling · Singapore

✉ Bernard Jia Han Ng
bernhan@ntu.edu.sg

1 Residues and Resource Reclamation Centre, Nanyang Environment and Water Research Institute, Nanyang Technological University, #06-08 CleanTech One, 1 Cleantech Loop, Singapore 637141, Singapore

2 School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

3 School of Energy and Environmental Sciences, Yunnan Normal University, 121 Street, Kunming 650092, China

4 Dairy and Swine Research and Development Centre, Agriculture and Agri-Food Canada, 2000, College Street, Sherbrooke, QC J1M 0C8, Canada

Introduction to food waste management

Food waste (FW) is often considered as smelly, dirty and contagious waste, which deteriorates the recycling value of other inorganic wastes. Improper management of FW will create pollutions in living environment. According to the United Nations, roughly one-third of global food is lost or wasted, which is equivalent to about 1.3 billion tons of FW annually all over the world [1]. In Asia, the largest growth in annual urban FW production was predicted (278×10^9–416×10^9 kg) due to rapid economic development [2].

FW can be categorized into industrial FW and municipal FW based on the origin. Industrial FW originates from food and beverage (F&B) industry. Those waste streams are usually by-products, leftovers, or inferior products of the industry. Industrial FW is specific in characteristics, with which the treatment methods are chosen based on the composition quantity. Hence, industrial FW is easier to be recycled into high-quality products due to high purity [3]. On the contrary, municipal FW is produced in households and food premises, such as coffee shops, food courts, hawker centers, restaurants, markets and hotels. Compared to industrial FW, the generation of municipal FW is scattered in different regions, non-ignorable in quantity, and non-uniform in quality.

Singapore is a highly urbanized country with high food wastage. According to Ministry of Environment and Water Resources (MEWR), Singapore generated 703,200 tons

FW in 2012 (132 kg/year/ca) and only 12 % of them are recycled into animal feeds, organic fertilizer and bio-energy [4], while the remaining portions are incinerated. However, the actual recycling rate in 2012 does not meet the target (30 %) as described in Singapore Green Plan 2012 (SGP2012) [5]. The 30 % target was set by MEWR in 2002 when the FW recycling rate was the second lowest (6 %, 2001) among all waste types. It was believed that the recycling rate could improve by five times so that an overall 60 % recycling rate could be achieved within a decade.

In Singapore, the FW recycling rate is computed by dividing the amount of FW recycled to the sum of FW recycled and FW disposed. The amount of FW disposed is measured by the daily weighing process of garbage trucks in incineration plants and the annual sampling of solid waste composition. On the other hand, the amount of FW recycled is estimated by phone surveys to every potential FW recyclers. Although incineration converts waste into energy, the main purpose is to reduce the volume of municipal solid waste (MSW) up to 90 %. The energy recovery is less significant so incineration is considered as a disposal method rather than recycling.

This study reveals the practices and challenges of municipal FW management in Singapore. A decentralized co-digestion approach is recommended for Singapore and other tropical urban cities as well.

Material flow analysis of Singapore food waste

The material flow of FW in Singapore is less investigated. Singapore has almost no agricultural activities and most of the food is imported from overseas. Both animal and crops farming industries only occupy 0.06 % of the Singapore GDP in 2012 [6, 7]. According to the Singapore Agri-Food and Veterinary Authority (AVA), the total food consumption in 2012 is about 2,153,536 tons [8]. In other words, about 33 % of the food are discarded in 2012, if we account the statistics from MEWR. The result is comparable to the studies from the global [1] and UK [9] data, showing that one-third of the food is lost or wasted.

From the annual FW amount, we should identify the proportion of municipal and industrial FW. A market survey was conducted in 2003 by consolidating responses from 71 local licensed food manufacturers [10]. The result was extrapolated to represent the whole F&B industry with slightly conservative estimation. An error analysis [10] was conducted by comparing the quality and quantity of errors between the survey result and Singapore National Environment Agency (NEA) waste statistics [11]. The analysis estimated that 585 tons FW was generated by F&B industries daily under the most likely scenario. The survey also shows that 27 % of municipal solid waste was organic waste (FW) [10]. This value was very close to 28 % in reference to a waste sampling study in 2012 [12]. Thus, we can deduce that Singaporean municipal FW composition remains unchanged over the last decade.

Figure 1 shows FW material flow of Singapore in 2003. 61 % FW (915 tons per day) are from municipality (out of which 2 % are from the hotel industry) and the remainings are from F&B industries. In this study, we assume that all FW recycled come from F&B industries. Unfortunately, no similar analysis is available after 2003.

Past and current practices in Singapore

The practices of municipal FW management are part of the solid waste management. Centralized solid waste management system, i.e., landfilling and incineration, has been applied to Singapore since 1972 [13]. From 2008 to 2011, a centralized AD facility for organic waste (including FW) had been operated in Tuas, Singapore. Almost all of the Singaporeans adapted to the centralized system as it is systematic, efficient and convenient. At the same time, decentralized aerobic composting (AC) and vermicomposting played a minor role in Singapore.

Landfilling

Landfill is a common disposal method in most of the countries, including developed countries. Before the first incineration technology was applied in 1979, landfilling

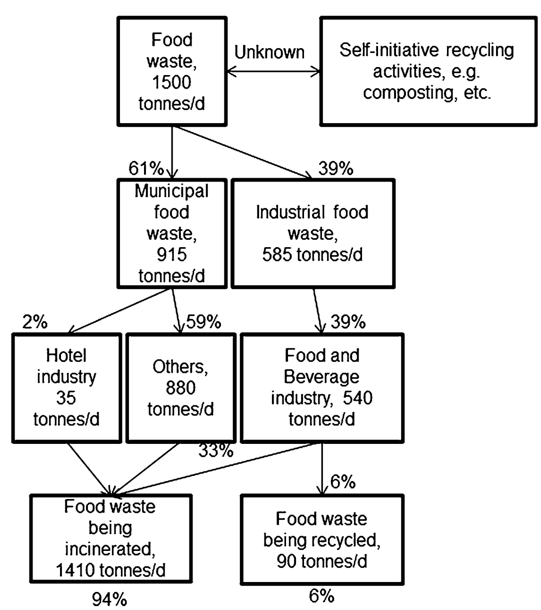

Fig. 1 Material flow of daily food waste in 2003 (raw data obtain from [10])

was the only treatment option for FW in Singapore. By landfilling FW directly, many environmental problems started to occur. More specifically, high moisture content of FW promotes high microbial degradation activity, which releases leachate and methane in an anaerobic environment after landfilling that significantly cause secondary pollution to groundwater, soil and atmosphere. Therefore, it is desirable to find a treatment alternative for land-scarce Singapore. At the end, incineration [13] is chosen as the alternative to deal with the ever-growing MSW or FW. Nowadays, only incinerated ash and non-incinerable MSW are disposed into the only landfill in Singapore, the off-shore Semakau landfill. The landfill disposal is predicted to be increasing until 2030. FW is one of the five incinerable waste types that contribute to the increasing trend [14]. Intensive recycling effort is emphasized to achieve the other targets in SGP2012, i.e., extending the lifespan of Semakau Landfill to 50 years (2000–2050), and striving towards “zero landfill” needs [5].

Incineration

Since 1999, all disposed FW has been diverted to incineration plants, with the closure of Lorong Halus Dumping Ground. Incineration then becomes the main FW disposal method for Singapore. The volume reduction of FW after incineration is up to 99.9 %. When the first incineration plant was planned, FW was considered as a challenging input due to its high moisture content. The water content decreases the overall calorific value of MSW. As a result, it may incur higher operating cost. In the end, FW is still included as significant input due to its large proportion in MSW and difficulty in separation [15].

After 30-years’ experience in incineration, Singapore gains more advantages in reducing land shortage pressure. Nevertheless, building more incineration plants may not be economically and environmentally sustainable. For instance, the largest incineration plant in Singapore, Tuas South Incineration Plant, costs about S$900 million with 3000 tons MSW daily [16]. Therefore, a third means of recycling FW, which is anaerobic digestion (AD), has been implemented.

Large-scale anaerobic digestion

AD is a technology where anaerobic microbes consume the organic substances and produce biogas as a by-product. Various microbial bacteria involve in the process converts complex organic matter and mineralize it into methane, carbon dioxide, hydrogen sulfide, ammonium and water. This process of organic matter degradation proceeds in four successive stages, namely: (1) hydrolysis, (2) acidogenesis, (3) acetogenesis, and (4) methanogenesis.

AD is identified as the most desirable food waste treatment in environmental perspective [17], although it has no volume reduction. AD is getting popular as there are over 560 AD plants with more than 7.3 TWh/year capacity worldwide that treat organic portion of MSW in 2013 [18]. The valuable end product of AD is bio-energy so AD of FW is considered as recycling. Electricity consumption in Singapore has been increased from 37.7 TWh in 2009 to 42.6 TWh in 2012. Due to the rise in global fuel price, local electricity tariff has been raised from S$0.205/kWh in 2009 to S$0.279/kWh in 2012 [19, 20]. In Singapore, natural gas is imported as the main fuel for electricity generation. Biogas, which is generated from AD and contains high energy value, can be regarded as a supplementary renewable energy to natural gas.

In 2008, Singapore FW recycling rate increases from 9 to 12 %. The improvement is due to the commencement of a centralized AD plant. The increment of recycling rate continues to hit 16 % by 2010. In these 3 years, the plant was the largest local FW recycler that converted most municipal FW into both bio-energy and organic fertilizer.

With this new development, two LCA studies were conducted to compare the environmental impact of incineration and AD in Singapore’s context [21, 22]. Both studies conclude that environmental impact of AD is lower than incineration, especially in the emission of greenhouse gases.

Decentralized aerobic composting

A centralized composting plant is always unpopular in this city state with only 715 km^2 land resource [23]. A small-scale composting plant is proposed as supplementary component to AD by Khoo [21]. This study concludes that centralized AD performs better than centralized AC. However, environmental impact of both decentralized AC and decentralized AD was not compared.

Municipal FW could be the potential feedstock for commercial compost by scaling down the capacity of composter. Compared to FW from households, FW from institutions is larger in amount and easier in collection. Nowadays, there are some local companies, which promote onsite bioconversion from FW into compost, with enzymes enrichment. The targeted markets include hotels, restaurants, and schools, with the input of 40–1000 kg/day [24].

Vermicomposting

Vermicomposting has been recognized as an environmental-friendly technology that both earthworms and microbes are introduced to produce plant hormones and high level of soil enzymes compost. *Eisenia foetida* (red wigglers) and *Lumbricus rubellus* are the common worm species for vermicomposting [3]. *Perionyx excavatus* (blue worm) is also common for vermicomposting in tropical region, including Singapore.

From a personal interview of a local vermicomposting expert, vermicomposting has a relatively small local market, with the monthly sales of 4–5 kg of worm (S$1000–1500). Most of purchasers are retirees, who practice gardening in condominium and private estate. The local barriers of vermicomposting include labor-intensive worm management, high land requirement, low revenue in investment, and immature social culture accepting vermicompost. These barriers suggest that vermicomposting might not be a feasible alternative to increase FW recycling rate. However, the practice could be promoted as personal hobby in condominium and private estate.

Current challenges in Singapore

Figure 2 shows the important indicators of FW management from 2001 to 2013 based on NEA. In these 13 years, FW generation per capita increases from 0.35 to 0.4 kg/day, but the FW recycling rate improves slowly from 6 to 13 %.

From Fig. 2, FW recycling rate drops from 16 to 10 % in 2011, mainly due to the closure of the centralized AD plant in May 2011. By March 2011, the plant only collected 120–130 tons of FW daily from cafeterias, markets, food manufacturers and hotels [25]. It is important to realize that the FW recycling rate before this plant is 9 % [26]. In fact, the growth of other FW recycling capacity between 2008 and 2011 was only 1 % of total FW in 2011.

Low feedstock and high operating cost are two main possible reasons for the closure of the centralized AD plant

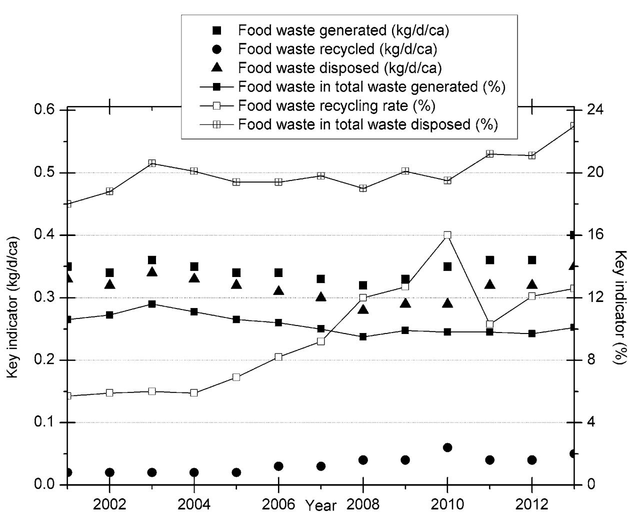

Fig. 2 Key indicators of FW management from 2001 to 2013 based on NEA

[25, 27]. Low feedstock collection is related to Singapore recycling culture. These reports showed that up to 40 % of feedstock are mixed with 30–40 % impurities and are contained with plastic bags. The segregation of them adds up labor cost and leads to high operating cost. Furthermore, the first-phase capacity of the plant was 300 tons FW daily (single reactor). However, the actual daily feedstock was only half of the design capacity. In short, the plant could not operate under optimal condition.

The closure leads to the discussion about the potential challenges of municipal FW management in Singapore. We indentify four major challenges, i.e., low final product demand, inefficient waste collection design, cheap disposal cost, and low social awareness. These challenges are discussed below.

Low final product demand

Among the challenges, low demand of final product creates the greatest resistance. Other than bioenergy, both animal feeds and organic fertilizer have little demand in this urbanized city state. Most of the final products from FW recycling activities in Singapore are actually externally orientated.

Before 2008, the amount of FW recycled per capita maintains at 0.1–0.3 kg/day. The amount is mainly contributed by F&B industry, which recycles their waste for economic reasons. F&B industry is one of the highest contributors to the total solid waste generation, i.e., about 20 % of the total waste streams [28]. For the industrial solid waste, direct collection method is applied and collection fee is charged based on waste volume [13]. Through market forces, this “pay-as-you-throw” policy encourages industrial sector to minimize their waste. Industries prefer recycling when the cost of recycle is lower than that of waste disposal [15].

Table 1 shows a summary of FW recycling in 2003 [10]. FW were recycled into spent grain, spent yeast, soybean waste, bread waste, and other flour-based waste from industrial F&B manufacturers. Most of them were semi-processed locally and recycled as animal feeds for farms in neighboring countries, especially in Malaysia [10]. Small portions of them were recycled as compost for local use. Animal feeds are favored than organic fertilizer due to higher demand in neighboring countries.

Inefficient waste collection design

More than 80 % of Singapore residents live in Housing and Development Board (HDB) dwelling units [29]. Individual system and centralized refuse-chute system are designed to reach every apartment and floor, respectively, for general waste disposal. Residents always mix FW with other MSW

Table 1 Summary of food waste being recycled in 2003

Types of food waste	Collection/sorting	Recycling
Soya bean waste, spent grains and yeast	From breweries and soy bean factories	Raw waste collected is broken down into finer pieces and are steam cooked before being fed into the autoclave machine for sterilization
Bread and other flour-based waste	From industrial sources	Resulting product is broken into small pieces, dried, crushed and exported as animal feeds
Coffee grounds	From packaged beverage company	Grounds and all waste incinerated on-site to generate steam for manufacturing process
Sub-standard biscuits	From biscuit manufacturer	Sent to fish farms for feed

and then deposit the waste through the collection system. This waste collection method is too convenient and creates resistance in waste minimisation and recycling over years [30]. One of the possible solutions is the installation of FW disposal unit that grinds households FW with some flush water flowing along pipelines [31]. For private estates and shop houses, wastes are collected by door-to-door kerbside collection method. This method is labor-intensive and time-consuming, and thus FW segregation is difficult.

Cheap disposal cost

From a personal interview with former employee from the centralized AD plant, the plant charged contributors with the standard solid waste disposal fee (S$77/ton) for every ton of FW. This disposal fee is same with the standard incineration disposal fee [32]. However, rebate will be given to the individual contributors based on the quality of FW, i.e. the percentage of organic matter. Low-impurity FW was rewarded with high rebate rate. Although the disposal cost of centralized AD plant is slightly cheaper than incineration plants, FW feedstock was insufficient and inconsistent. It may suggest that disposal cost is a low-sensitivity factor in FW recycling. The low sensitivity may be related to the social awareness in Singapore.

Low social awareness

At this moment, no extensive study is available for the effect of "social awareness" in local FW recycling. A local study has analyzed eating habit of 114 inhabitants in Singapore (23–35 years old) and found that 73 % of them always throw away the unfinished food in their plates [33]. Food wastage becomes a habit among young residents. Awareness has yet to be created in reducing food wastage.

A bottom–up approach in environmental management may create strong awareness. For instance, a comparison on solid waste recycling was made between Sweden and Singapore [34]. Sweden government adopts a bottom–up approach in environmental management. The involvement of local authority is high as they are given freedom in implementing common objectives. These approaches encourage persistence in recycling habits due to their internal motives and initiatives. In contrast, top-down approach is more common in Singapore. Two opposite approaches create different degrees of social awareness. As a result, Sweden has one of the highest recycling rates worldwide, i.e., 96 % in 2012, with garbage imported from other European countries to generate energy [35]. Also, a local study recognizes the importance of social norm in the generation of FW [36].

In Singapore, series of educational campaigns have been initiated to increase the social awareness on food waste management since 2002. In 2002, "Food from the Heart" (FFTH) was found to distribute food (especially unsold bread) to needy children [37]. After 5 years, "Food for All" becomes the pioneer of youth initiative that fights for hungers and food appreciation [38]. Since then, various campaigns are launched by Non-governmental organizations (NGOs), which are "Food Waste Republic" [36], "Food Bank Singapore" [39], "Save Food Cut Waste" [40] and "Makan mantra" [41]. The efforts of these NGOs were subsequently supported by Ministry of National Development (MND) in July 2012 when MND officially announced the formation of an Inter-Ministry Committee to reduce food wastage and enhance food security [42].

Comparison among Four Asian Tigers

Table 2 compares the FW statistics in Four Asian Tigers, i.e. South Korea [43], Taiwan [44], Hong Kong [45] and Singapore [46]. The Asian Tigers experienced rapid growth in economy as well as waste volume between the early 1960s and 1990s. Although the countries share similar socio-economic background, the FW recycling rates have big variation, i.e., from 2.15 to 94 %.

Among the countries, South Korea has the highest recycling rate, which is more than 90 %. In addition, the Korean government promotes FW recycling since 1994 and the effort is also the earliest among the Asian Tigers. Both central and local government shows a strong determination

Table 2 Comparison of FW statistics among four Asian tigers

FW statistics	South Korea	Taiwan	Hong Kong	Singapore
Year of statistics	2006	2013	2013	2013
FW generated (kg/day/capita)	0.28	0.86	0.51	0.40
FW recycled (kg/day/capita)	0.26	0.09	0.01	0.05
FW direct-disposed to landfill (kg/day/capita)	<0.01	N.A.[b]	0.50	0.00
FW incinerated (kg/day/capita)	>0.01	N.A.	0	0.35
FW recycling rate (% of FW generated)	94	11	2.15	13
Animal feeds (% of FW recycled)	45	71	<1	N.A.
Compost (% of FW recycled)	45	28	≈99	N.A.
Others[a] (% of FW recycled)	10	<1	<1	N.A.
Final product (I: internally oriented; E: externally oriented)	I	I	I	E
Year of banning FW direct landfilling	2005	Not yet	Not yet	1999

[a] Others refer to food donation, anaerobic digestion, vermicomposting, biofuel, etc.

[b] Not available

in working together with NGOs and private sectors to create public awareness and complete product life cycle. The high public awareness is reflected on the volume of daily FW generated per capita, which is 30 % less than Singapore. Nowadays, South Korea has more diversified final product, especially in anaerobic digestion and vermicomposting. The strong and stable final product demand is also another key factor of this success.

Compared to Singapore, Taiwan has similar recycling rate but its daily volume of FW generated per capita is doubled. Apart from incineration and landfilling, 11 % FW are sent to recycling facilities. 71 % of the final products are used for animal feeding because Taiwan has strong demand in livestock industry. The low technology barrier in processing animal feed also contributes to the recycling activities. In 2003, Taipei city government started a compulsory FW recycling program to the residents with the fining if the residents do not segregate FW out of household wastes [47]. However, the local governments show different progress in FW management over the island. All towns and townships have been fully carried out FW recycling only by March 2006.

Both Hong Kong and Singapore have less autonomous local governments and limited land areas. However, Singapore is one step ahead of Hong Kong in terms of the establishment of incineration technology. In Hong Kong, 3648 tons of FW that accounts for 38 % of MSW are disposed of in landfill daily, with only 78 tons of FW are recycled [45]. After rounds of negotiations, a MSW incinerator with the capacity of 3000 tons per day will finally be in operation by 2018. According to the future plan of Hong Kong Environment Bureau (ENB), a private FW recycling facility and two organic waste treatment facilities (OWTFs) will be established by 2018 [48]. The treatment capacities of these facilities are designed as 100, 200 and 300 tons per day after referring to the case of Singapore centralized AD plant (2008–2011). In short, Hong Kong is learning from Singapore past experience.

Future recommendation for Singapore

USEPA establishes a "Food Recovery Hierarchy" that lists down the most to the least preferred options: source reduction, feeding hungry people, feeding animals, industrial uses, composting, and lastly incineration or landfill [49]. A "Food Waste Pyramid" from UK suggests similar hierarchy [50] without the option "industrial uses". The hierarchy varies according to the country context.

Hence, we propose a new "Food Recovery Hierarchy" for Singapore (Fig. 3). In Singapore, feeding hungry people and feeding animals are not the main concern, so these two options can be taken out from the hierarchy. Source reduction is followed by industrial uses, for which most of the industrial food waste is recycled. Then, renewable energy (e.g., AD) should be inserted before composting. Hong Kong ENB also recognizes bio-energy as the top prioritized final product [48]. Anaerobic co-digestion of FW with sewage sludge or brown water is recommended due to high availability in Singapore. Integrated decentralized municipal FW management could be developed by prioritizing AD, and then AC.

The following sections further discuss about the small-scale AD, anaerobic co-digestion and other emerging FW treatment technologies.

Small-scale anaerobic digestion

The closure of centralized AD plant demonstrates the limitation of centralization. Anaerobic digester for food

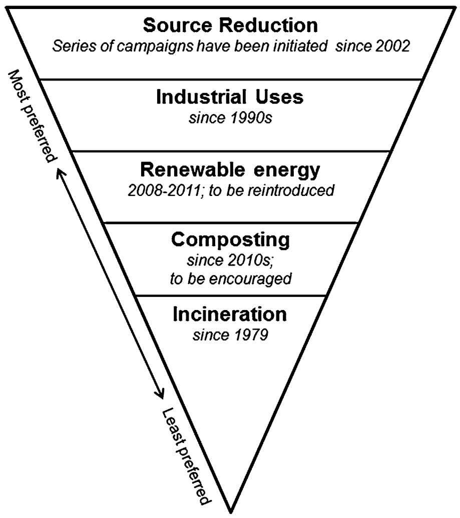

Fig. 3 Proposed food waste management hierarchy for Singapore

waste in community scale has been implemented since late 1990s, such as Freiburg-Vauban, Germany and Lübek-Flintenbreite, Germany [51].

Globally, most of the AD system with FW as substrate is wet AD. Total solid (TS) content of the AD feedstock is suggested to be maintained at 6–8 % to ensure the success of AD [52]. In real cases, FW collected in food courts has comparatively high solid content (TS about 30 %) after the manual removal of bones, egg shells and other non-biodegradable components [53]. In other words, additional water is needed to decrease the solid content of FW.

A decentralized AD pilot plant, "Hybrid anaerobic solid–liquid (HASL) system", was operated from November 2005 to February 2008 in Nanyang Technological University (NTU) campus. It is a two-phase AD system using two reactors as acidification reactors, and an up-flow anaerobic sludge blanket reactor as methanogenic reactor [54]. The advantages of this system are higher efficiency of methane production and smaller volume of AD effluent. The addition of clean water to reduce solid content of FW should be avoided as clean water is valuable commodity in Singapore. Therefore, 20 % of the AD effluent (pH $\approx$ 7) was recycled to dilute the solid content of FW and increased the pH of feedstock, while 80 % of the AD effluent was used for dilution of the effluent from acidogenic reactor to maintain an optimal pH for further methanogenesis [55].

HASL system was demonstrated successfully from technical point of view. The main difficulty during the demonstration is low feedstock. The system only received one-third of the total 3-ton capacity [56, 57]. Again, the HASL case study let us focus on the possibility to the increment of the quantity and quality of the collected FW.

As discussed in section "challenges", improvements in collection design, disposal cost and social norm are required to increase the efficiency in collecting FW. Apart from that, co-digestion of FW with other organic substrates could stabilize the inflow of feedstock. Substrates from various sources could complement each other when one of the sources is in low supply.

Anaerobic co-digestion of food waste

Table 3 shows the potential co-substrates of FW and their availability in Singapore context. Anaerobic co-digestion of FW with sewage sludge and animal manure are being practiced oversea. Brown water (feces with flush water) and slaughterhouse waste are new co-substrates in AD of FW. All potential substrates can decrease the solid content of FW into desirable range. Besides, all of the anaerobic co-digestion shows synergistic effect in biogas production when compared to single-substrate AD.

In term of availability, both sewage sludge and brown water are recommended as co-substrates in Singapore. The

Table 3 Proposed anaerobic co-digestion of food waste in Singapore

Substrate	Available sources	Comment
Sewage sludge	439 tons/day from wastewater treatment plants [58]	This option has high feasibility due to consistent supply and better alternative. Righi et al. [59] indicates that the anaerobic digester of dewatered sludge and FW combined with composting post-treatment may offer an environmentally sustainable option
Animal manure	At least 58 tons/day, from Kranji and other animal farms [60, 61]	Co-digesters need to be built in between FW collection points and animal farms to reduce the transportation cost and carbon footprint
Brown water	Approximately 22,410 tons/day from every toilet	Source separation of brown water from yellow water (urine and flushing water) and gray water (used water from bathroom, pantry and laundry) is required [53]. Brown water is a better diluting solution than AD effluent. Other than increasing pH and diluting FW, brown water has high strength organic wastewater is suitable for AD, normally above 10,000 mg/L with 6 l flush volume (feces 93.4 ± 12.6 gCOD/L) [62, 63]
Abattoir waste	There are some slaughterhouses in Singapore but the amount of abattoir waste might not be much	The co-digestion of slaughterhouse waste and FW is still at laboratory scale and pilot scale. The low availability makes abattoir waste not a feasible co-substrate of FW for Singapore

co-digestion of sewage sludge and FW can be simply conducted in the anaerobic digesters of municipal wastewater treatment plants. However, the collection of brown water is more challenging than sewage sludge. Brown water could be collected by changing the design of toilets and piping systems. No-mixed toilet that diverts yellow water (urine with flush water) out of brown water has to be installed. The co-digestion of FW and brown water involves more installation work. The system might be more suitable for new residential units instead of existing units [64].

The feasibility of installing a no-mixed toilet and decentralized AD system in Singapore has been discussed [59, 65, 66]. These studies show the feasibility of the system in terms of material and energy flow analysis. Another life cycle assessment of the proposed system has been studied, in comparison to existing incineration and wastewater treatment system. The unpublished work shows that decentralized AD system including additional piping system is slightly favorable than the existing system.

Other emerging technologies

There are several emerging technologies of FW recycling, such as hydrothermal carbonization or liquefaction [67] and integrated biohydrogen refinery [68]. Renewable aviation fuel is another final product that has great market demand in Singapore, by recycling certain FW, such as vegetable oil, animal fats, and greases [69]. These FW is converted into synthesized paraffric kerosene that has less environmental burden through low capital cost processes, such as Bio-Synfining™ (Syntroleum), Ecofining™ (UOP) and C-LTM process (Tianjin University). In brief, the feasibility of these technologies has yet to be further assessed.

Acknowledgments This study is supported by the National Research Foundation, Singapore; program number NRF408 CRP5-2009-02, for the School of Civil and Environmental Engineering/Residues and Resource Reclamation Centre, Nanyang Technological University, Singapore. We appreciate Mr. Harley Chia Guo Wei, Ms. Lim Jun Wei, Mr. Ivan Ho, and Mr. Ashiq Ahamed for their assistance in the experimental work.

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