Life cycle assessment of the present and proposed food waste management technologies from environmental and economic impact perspectives

A. Ahamed[a,*], K. Yin[a], B.J.H. Ng[a], F. Ren[a], V.W.-C. Chang[a,b], J.-Y. Wang[a,b]

[a]Residues and Resource Reclamation Centre (R3C), Nanyang Environment and Water Research Institute (NEWRI), Nanyang Technological University, 1 Cleantech Loop, CleanTech One, Singapore 637141.

[b]Division of Environmental and Water Resources Engineering, School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798.

*Corresponding author: Ashiq Ahamed

Email address: ashiq@ntu.edu.sg; ashiq.aha@gmail.com

Mailing address: Residues and Resource Reclamation Centre (R3C), Nanyang Environment and Water Research Institute (NEWRI), Nanyang Technological University, #06-08, 1 Cleantech Loop, CleanTech One, Singapore 637141.

Tel.: +65 67904102; Fax: +65 67927319

Abstract

Proper food waste management has been a growing concern for densely populated urban cities, like Singapore. The current practice of incineration is questionable in terms of environmental and economic sustainability. In order to alleviate the environmental impacts and improve resource recovery, alternative solutions for food waste management i.e. food waste-to-energy biodiesel and anaerobic digestion have been proposed through life cycle assessment. The functional unit of the study was set to be 1 tonne of food waste. The system boundary included the collection, processing, waste conversion and disposal of food waste with three product outputs, electrical energy, hydrochar, and glycerol. Process data were obtained from lab-scale experiments, literature, and SimaPro 7.3 libraries. The impact categories were assessed in terms of acidification potential, eutrophication potential, global warming potential for 100 years, and cumulative energy demand using the CML 2 baseline 2000 version 2.05 method and the CED version 1.08 method. A cost-benefit analysis was also performed for the studied scenarios. The life cycle assessment results show that food waste-to-energy biodiesel system is favored for food waste with oil content >5% and anaerobic digestion for those with oil content ≤5%. The cost-benefit analysis results show that anaerobic digestion is the best choice if applicable in the local environment. Otherwise, food waste-to-energy biodiesel is the preferred choice over incineration. In conclusion, this study presents the advantages of anaerobic digestion and food waste-to-energy biodiesel system in comparison with incineration of food waste. The results from this study suggest a need for adaptive strategy based on the food waste type and composition, and provide decision makers in Singapore with insights into the three food waste management strategies and directions to improve the existing system.

Key words: LCA, Food waste, Hydrothermal carbonization, Anaerobic digestion, Incineration

1 Introduction

Tremendous amount of food waste (FW) is generated each year worldwide, and the amount of FW generation has increased over time (Thyberg et al., 2015). For instance, in the United States, FW accounts for 21.1% of the discarded municipal waste stream in 2012 which is equivalent to 31.4 million tonnes (USEPA, 2014). In China, 90 million tonnes of FW was generated in 2010 which made up about 51% of municipal solid waste (MSW) production (Wen et al., 2016). It is estimated that over one-fourth of food produced worldwide yearly (i.e. around 1.6 billion tonnes) is wasted during production, processing, distribution, consumption, and disposal (FAO, 2013). In developed countries such as Japan, the United Kingdom, South Korea and Australia, the amounts of FW generated per year were 9.9 (Kojima and Ishikawa, 2013), 7.0 (WRAP, 2013), 5.7 (Hou, 2013) and 4.4 (National Waste Report, 2010) million tonnes on average. FW presents disposal challenges primarily due to its high moisture content, oil content (OC), and heterogeneous nature (Eriksson et al., 2015; Karmee, 2016). Although reduction is the most preferred option in the FW management hierarchy (Papargyropoulou et al., 2014), subsequent approaches such as reuse, recycling, recovery in terms of waste-to-energy, and disposal also require attention and technical contribution from the research community in order to develop a comprehensive FW management system.

Singapore is a modern city-state with high economic performance despite having little natural resources. Its population density ranks among the highest in the world. It has a population of 5.535 million with land area of about 700 sq.km (Population in Brief, 2015). FW generated in Singapore was 788,600 tonnes in 2014 which is about 0.39 kg per person per day (NEA, 2014). For years, Singapore has been a forerunner in the field of waste management being able to manage most of its MSW through recycling and incineration (NEA, 2013). The current MSW management practice of incineration can reduce the waste volume up to 90% while generating electricity. Nevertheless, the recent economic developments and technological advancements leading to high carbon footprint, and together with the sustainability goals compel to improve the waste management method in the city-state. Singapore, despite having an effective waste management system, now has the calibre to look into more environmental friendly options and keep up with the technology trends and advancements.

A World Bank report (1999) pointed out that the feasibility of an MSW incineration plant is largely dependent on the nature of the waste and its calorific value. At present, one of the issues with incinerating the MSW is the high moisture content which is attributed to FW. Because of a huge amount of vicinal and bound water therein, as well as the relatively high latent heat of water, FW incineration are energy-intensive (He et al., 2014). Removing the FW from MSW stream will significantly improve the calorific value of solid waste (Song et al., 2013, Erses Yay, 2015). Hence, FW should be removed from MSW stream and treated separately for better incineration efficiency and resource recovery. Recycling or other methods of energy recovery from FW seems a more appropriate option (Rajagopal et al., 2014).

Anaerobic digestion (AD) is considered as one of the best alternatives for the FW management (Xu et al., 2015). Extensive research has been conducted over the past few decades showing the benefits of implementing AD for organic fraction of MSW. A study by Eriksson et al. (2015) reported the carbon footprints of different FW management options, and claimed AD as a better alternative than sending FW for animal feed, composting and even donation in some cases, while incineration can be suitable for dry FW such as bread. However, the technology requires thorough sorting of the waste due to its biological nature. This presents a big challenge in Singapore's context due to labour-intensive processes involved. As a proof, there has been a history of failure including the recent closure of IUT Global Company, which used AD for treating municipal FW (Eco-Business.com, 2011).

A novel food waste-to-energy biodiesel (FWEB) technology using hydrothermal carbonization (HTC) has shown prospective results for future application in developed countries like Singapore. The FWEB system mainly comprises two parts, (1) a HTC system and (2) an oil refinery system. HTC is defined as a thermo-chemical process operating at moderate temperatures (180-350 °C) and pressures (2-10 MPa) to convert organic feedstock in the presence of water into carbonaceous product (hydrochar) (Mumme et al., 2011) and bio-oil (depending on the available OC of the feedstock). Oil refinery system involves transesterification of the bio-oil obtained from HTC treatment using strong acid, as the high moisture content of the FW presents a barrier to alkali process.

Life cycle assessment (LCA) is a powerful tool for quantifying, evaluating, comparing, and developing goods and services in terms of their potential environmental impacts (Rebitzer et al., 2004). An LCA study provides valuable information to aid government agencies in technology selection for future waste management (Khoo et al., 2010). Environmental LCA studies help the decision makers to understand the technology from an environmental perspective and identify the technology that best suits the region/country.

The main objective of this study is to compare the three technologies, i.e. incineration, AD and FWEB system in Singapore's context from an environmental perspective in terms of acidification potential (AP), eutrophication potential (EP), global warming potential in 100 years (GWP100), and cumulative energy demand (CED) to help identify an appropriate FW management method for urban societies. The results are presented through the LCA software SimaPro 7.3 which is a widely accepted and recognized tool in the LCA community. Additionally, cost-benefit analysis (CBA) was performed. Landfill was not included as Singapore has stopped landfilling MSW except for the incineration residues that are buried off-shore. The demand for composting is limited in Singapore and hence not a choice for the study as well.

2 Methods

The goal and scope of an LCA defines the product system in terms of the system boundaries and a functional unit (FU) (Rebitzer et al., 2004). The FU was set as 1 tonne of FW, which acts as the basis to compare the treatment technologies. The system boundary for the three scenarios included the collection, processing, waste conversion and disposal of FW. The system boundary included three product outputs, i.e. electrical energy, hydrochar from HTC, glycerol as by-product from transesterification. The main processes involved in the system scenarios are shown in Fig. 1.

The scope of this study covers the AP, EP, GWP100, and CED for the three technologies mentioned earlier. The impact categories were selected based on the relevance to the system undergoing comparison. The major factor in consideration was the composition of FW, which comprises minimal amount of heavy metals as compared to other waste in the MSW. Negligible heavy metal concentration signifies very minimal toxicity effect on the environment that precludes the toxicity potentials in this study. The impact categories such as land use, water footprint, abiotic depletion, photochemical oxygen demand and ozone layer depletion were not assessed either due to insufficient data or because they were beyond the scope of this study.

2.1 Impact assessment

ISO 14044 (2006) standard procedure was followed to perform the LCA. Energy consumption & generation and environmental impact were the two major impact groups classified in this study. The LCA methodologies followed were, (i) for the impact group of energy consumption & generation, the impact category of CED was assessed using *CED version 1.08* (Frischknecht et al., 2007); (ii) for the environmental impact group, impact categories of AP, EP and GWP100 were assessed using *CML 2 baseline 2000 version 2.05*. All the emissions from the system, along with supplementary production of utilities, were grouped in the environmental impact group. The different substances were weighed according to their relative impact when released into the environment within each category. In this study, substitution method was followed in which the co-products delivered from the system were substituted to avoid the virgin material production. The substitution was chosen in terms of equivalent calorific value and emissions which were therefore subtracted from the corresponding FW management system.

2.2 Scenario description

Three FW management scenarios were selected. The study compares the existing baseline scenario with two alternatives for FW management. The following scenarios were compared to evaluate their environmental impacts:

Scenario 0 (S0): Incineration of FW in a centralized treatment facility generating electricity on-site with the ash being disposed at the off-shore landfill (Semakau landfill) (current practice in Singapore)

Scenario 1 (S1): AD of FW in a centralized treatment facility using hybrid anaerobic solid-liquid (HASL) system with the biogas being converted to electricity on-site. Conventional single-stage reactors are not suitable for FW (Ahamed et al., 2015). Hence, two-phase system is applied for FW treatment as it is an effective method (Han and Shin, 2002; Lee et al., 1999; Mata-Alvarez et al., 2000; Raynal et al., 1998) with the advantages of better process stability, shorter retention time and higher methane yield (Cho et al., 1995; Ince, 1998; Strydom et al., 1997; Xu et al., 2002).

Scenario 2 (S2): FWEB of FW in a de-centralized facility with bio-oil and hydrochar as products. Bio-oil is further upgraded to bio-diesel and glycerol through transesterification.

The following assumptions were applied in this study,

- Construction and material requirements of the management facility were not included in the system boundary
- No pre-treatment of FW
- All the electricity requirement was supplied from Singapore's national grid
- AD digestate, rich in organic matter and nutrients, could be used as a soil amendment or as a substitute for fertilizer (Borja et al., 2002; Fehr et al., 2002; Muroyama et al., 2001), but since it is difficult to estimate the amount obtainable from AD, it was not included in this study. Nevertheless, AD effluent of 1 tonne was sent to the waste water treatment plant to maintain the volume balance
- Collection and transportation of the final products of S2 was not included as it depends on the on-site demand, and also the location & distance to be transported was not definitive
- Waste water from S0 and S2 were not included as they are converted to steam and does not require further treatment

2.3 Food waste characteristics

The study focuses on municipal FW collected from households, food retail and services in Singapore. The FW in this study contained approximately 75% moisture content, 20% solids content and 5% OC obtained from the samples collected. The higher heating value was found to be 20.333 KJ/g of dried FW, which was analyzed by an IKA C2000 Basic bomb calorimeter. The composition of Carbon (49.72%), Hydrogen (7.81%), Nitrogen (1.89%) and Sulphur (8.91%) was analyzed using CHNS Elemental analyzer (Elementar, Germany).

2.4 Life Cycle Inventory

Life cycle inventory (LCI) is a crucial component in an LCA analysis. The results and outcomes are directly dependant on the LCI. In this study, LCI was carefully selected to justify the circumstances and appropriately represent the scenarios studied.

2.4.1 Incineration and AD

Inventory data for incineration were obtained from the LCI Bioenergy report (Jungbluth et al., 2007) for incinerating the Biowaste, and Bolin's report (2009) for conversion efficiency in Singapore's case. AD data were adopted from HASL system treating FW, with the results of pilot plant experiments (Wang et al., 2005) scaled up to treat centralized facility whereby methane composition is assumed to be 60% as opposed to 70% at the lab-scale setup. The emission was calculated based on Bolin's report (2009). All the data were collected to suit the local scenario.

2.4.2 FWEB

All the data for FWEB were obtained from lab-scale experiments in a HTC reactor of 2L capacity and followed by transesterification of bio-oil using rotary evaporator (Heidolph, Germany). The conversion efficiency of the biodiesel to electricity was assumed to be 35% as supported by the literatures for biodiesel from other sources (The Electropedia, 2015; Lin et al., 2006; Mujahid et al., 2013). The gas composition (methane, carbon dioxide, hydrogen and nitrogen contents) was analyzed by Gas Chromatograph (Agilent Technologies 7890 A, USA) equipped with a thermal conductivity detector. Transportation and other standard data were obtained from the in-built LCA software Ecoinvent database.

3 Results and discussion

Fig. 2 shows the characterization results of the AP, EP, GWP100 and CED impact categories. Incineration has the highest impact among all the impact categories compared. The percentage deviation of AP, EP, GWP100 and CED were 287%, 129%, 82% and 498%, respectively for S0 as compared to S2. In a similar way, the deviation of S0 as compared to S1 was 361%, 21%, 185% and 408% for AP, EP, GWP100 and CED, respectively with respect to S2. The positive results of S1 and S2 could be mainly attributed to the appropriate utilization of the waste as compared to incineration. The factual difference between S0 and the other two scenarios was that the organic energy contained in FW was merely used as heat in S0, whereas it was converted to biogas, biodiesel and/or hydrochar in the other two. It shows that S0 has a high negative impact on the process as the energy input is higher than the output. This implicates that even mixing the FW with other MSW was not a favourable option for the sustenance of incinerators (Song et al. 2013). In fact, removing the FW from MSW would increase the overall higher heating value of the MSW. Cheong (2012) mentioned that high quality materials and larger combustion space for the furnace are keys to improve incineration performance. Hence, the results suggest S0 as the least favoured option for FW management.

The comparison between S1 and S2 displayed mixed results for different impact categories. For AP and GWP100, S1 showed 0.74 and 1.03 times lower impact than the S2 whereas for the cases of EP and CED it was 1.08 and 0.91 times higher. The reason for better performance of S1 in the cases of AP and GWP100, which are associated with gas emissions, was utilization of fossil fuel for the operation where AD uses much less electricity while HTC in S2 requires about 2 MJ/kg-FW. Transesterification of the bio-oil in S2 added further stress on AP and GWP100 via gas emissions. Otherwise, there was no direct contribution to GWP100 from FW since all the carbon was assumed to be biogenic in origin (IPCC, 2007). On the other hand, EP shows negative impact because of the inability of the AD system to remove the nutrients (N, P, K, etc.) which were left in waste water treatment plant for further processing while most of the nutrients were retained in the hydrochar from FWEB.

The impact category CED depended on the energy demand for the process, background processes and product contribution. Fig. 2d shows that S2 required almost equivalent amount of energy as S0 in terms of fossil fuel consumption. The primary reason was the requirement of electricity for operation of the HTC system and the chemical requirement for the transesterification process. Nevertheless, the product output surpassed the energy demand by yielding useful products like hydrochar, biodiesel and glycerol. In this regard, the conversion efficiency of the precursors to biodiesel and glycerol is a key factor for the feasibility of S2. S1 was the scenario that had the least fossil fuel consumption and never had the highest score for any of the impact categories, suggesting that it is the most environmental friendly solution among the three scenarios.

As the transportation presents an additional contribution to the impact categories of S0 and S1, a simple impact comparison was discussed. The contribution of transportation in S0 was 11%, 15%, 5% and 5% for AP, EP, GWP100 and CED, respectively. While barring the effect of transportation, the S1 showed a significant difference of 161%, 53%, 291% and 219% reduction in the impact for AP, EP, GWP100 and CED, respectively implying transportation was one of the major process contributors in this scenario. Comparing the sensitivity of transportation, the percentage improvement in S1 was 55.42%, 4.08%, 8.79% and 22.01% for AP, EP, GWP100 and CED, correspondingly with respect to S2. This shows that even though the impact of transportation on S1 was obvious, it was not as significant as compared to S2 except for the impact category AP.

The major process contributor for the impact categories was the energy demand of the treatment process. The electricity demanded from the national grid for the operation of the facilities had the highest impact as the process contributor. The second biggest contributor was the transportation in the form of trucks and barges to carry the collected FW and ash for disposal. According to the results shown in the Fig. 2, the implementation of S2 may result in greater benefits in terms of energy yielded per FU and avoid most of the environmental impacts.

3.1 Normalized results

The aim of normalization is to better understand the order of magnitude and the relative significance of each indicator of a system under study (Lundie and Peters, 2005). Normalization factor varies depending on the geographical location. The calculations were performed by dividing each impact category with their respective normalization factor for Singapore according to Khoo et al. (2010). The normalized results in a common dimension are presented in the Fig. 3. The CED had the highest repercussion as compared to the other impact categories. S1 resulted in the lowest resource usage and cost of all the three FW management systems compared in this study, which was in correlation with the study by Sonesson et al. (2000), who investigated the effects of incineration, composting and AD on solid waste management. On the other hand, the S2 system added more environmental benefits in terms of energy and material yield. The technology generated energy from waste while simultaneously showing significant potential to reduce the effects on eutrophication and the impacts from air emission as compared to incineration. As stated by Sonesson et al. (2000), it could be claimed that FWEB is based on theoretical system developed from laboratory results whereas incineration is an old and proven technology. But, the counter argument could be that incineration is a state-of-the art technology with high efficiency. Hence, there is not much scope to improve further from the current practice. Decisively, the advances made in incineration could hardly compensate to the positive effects of the other two systems.

3.2 Sensitivity analysis of oil content

The sensitivity analysis identifies sensitive parameters, whether a small change in an input parameter would induce a large change in the impact category (Song et al., 2013). OC in FW is one of the most critical factors for the operation of S2 as the output products i.e. biodiesel and glycerol are derived from it. Hence, a sensitivity analysis was performed to study the effect of the OC% in FW. The baseline scenario was set as S0 with 5% OC which was fixed as 100%. The deviation of the rest of the scenarios from the baseline is presented in Table 1. The OC% did not have much influence on the incineration as it burned along with the FW with high moisture content and the amount of carbon was assumed to be similar (the calorific value of raw waste oil and fat from FW is very low). The performance of the S1 deteriorated with increasing OC% due to limited participation of oil and fats in AD. The main reasons were low solubility of oil, poor biodegradability, and surface action whereby biomass flocs are shielded and does not participate in biochemical reactions (Chu et al., 2002; Peng et al., 2014). Hence, in this study, the biogas contribution from oil was neglected as it requires special treatment facility or reactor design to facilitate the biodegradation of oil. In all the impact categories, S1 was around twice as good as S0 except EP. The performance of S2 escalated consistently with increasing oil percentage. This trend suggests that it is more profitable to use the technology for the treatment of waste with high OC% (as the yield of primary product is directly proportional to the OC). For the FW with 10% OC, the impact of S2 in terms of EP and CED were 7.9 and 3.3 times lower than the current incineration practice respectively. On the other hand, when the OC was 2.5%, the GWP100 decreased to 115%, which was similar to any of the incineration scenarios and lower than all of the impact categories of S1 except EP. Hence, it is not recommended to opt to the S2 system when the OC% of FW is lower than 5%. The optimal solution is to implement the S2 for FW when OC >5% and S1 when it is ≤5%. Thus, a decentralized system for FWEB is proposed in this study as the technology is highly dependent on OC of the FW and is not applicable to general FW per se.

3.3 Cost-benefit analysis

Cost-benefit analysis (CBA) is a method for assessing the total economics involved of products or systems. Besides technical screenings and LCA studies, cost benchmarking is needed in the search for sustainable alternatives (Schiettecatte et al., 2014). In this section, the running costs were estimated for the three scenarios. The balance sheet of the CBA is presented in Table 2. All the fundamental cost data were acquired from standard commercial sources as indicated. In this section, for the purpose of estimating CBA, the FU was changed to 1 tonne FW/day. All the manpower cost involved were assumed to be the same for all the scenarios except for the sorting of FW. Sorting and macerating the FW for S1 were included in the CBA as it primarily involves manpower or a mechanical system. The sorting of FW is a necessity in the case of S1 as FW would contain items that are not suitable for AD such as bones, shells, and seeds/pits which does not undergo decomposition inside a bioprocess system. Air emission treatment was disregarded for the processes as all the CO_2 emissions are of biogenic origin.

Operation cost was the major contributor for the overall cost in S0 and S2 scenarios, mainly due to high electricity consumption. The chemical consumption cost for S2 was especially high because of the transesterification process that required methanol in equivalent amount as the bio-oil and sulphuric acid for acid catalysis (due to the high moisture content of FW alkali process is not feasible). Transport and land occupation were relatively minor contributors for all the three scenarios. When considering the revenue, electricity from heat and biogas were largest for S0 and S1, respectively. However, revenue from material output surpassed the electricity in the case of S2.

S1 showed the highest economic benefit despite the sorting fee. S2 was the second best option after S1. The major contributor to the cost was the operation expenses followed by the material/chemical demand. The least beneficial choice was incineration, which could be considered as a waste management option rather than a waste-to-energy/material alternative in the case of FW.

The economic value of FW was calculated to estimate the percentage recovery through the three studied scenarios. According to Numbeo (2015), the recommended minimum amount of money for Asian food types in Singapore was S$9.35 for approximately 1.75 kg/day per person. From the Singapore FW statistics, the amount of food wasted was 0.39 kg/day per person, which is about 22% of the total food purchased per person. In other words, on average, about S$2/day per person gets wasted that amounted to S$4.04 billion/year. With the recycling rate of 13% in Singapore (NEA, 2014) and 19% of unavoidable FW such as peels and bones (Ventour, 2008), approximately S$2.75 billion value of food gets wasted every year. The estimated value of 1 FU in this study is S$3631 (excluding the 13% recycling and 19% unavoidable FW). Hence, the benefits from S0, S1 and S2 would recover a value of 0.44%, 0.28% and 2.63%, respectively. It could be concluded that S2 is a more promising option in terms of material recovery as it recovered about S$72 million/year from the wasted food. Nevertheless, sustainable research and development to the technology could further cut down the costs incurred.

3.4 General outlook and future options

Overall, this study shows that S1 is a simple and efficient treatment option without involving high energy consumption and generation while S2 is a more sophisticated and advanced choice. The major advantages of S2 over S1 are, (1) maximized oil separation from FW mixture, (2) minimized waste volume via formation of hydrochar, (3) up to 85% of the carbon from the initial feed stock are retained in the hydrochar (Kammann et al., 2012), (4) efficient dewatering, (5) evolved gas amount is small and mainly consisted of CO_2 (Berge et al., 2011; Kammann et al., 2012), (6) hydrochars are biologically sterilized due to thermal treatment (Park et al., 2011), (7) flexible waste composition - impurities in waste composition does not affect the operation but only the quality of the product. On the contrary, S1 is a biological process that requires strict FW purity standards, which was one of the main reasons behind its history of failure in Singapore. The disadvantages of S2 are (1) sophisticated design, construction, operation and maintenance, (2) very high capital cost that requires investors to fund projects up front, (3) high pressure treatment that requires thoroughly controlled environment.

Moreover, direct usage of biogas or biodiesel products from AD and FWEB instead of converting them into electricity would have higher benefits, as the conversion efficiency was only 35-40%. Hence, it is necessary to either improve the conversion efficiencies or find an appropriate domestic usage for the biogas or biodiesel products. Using clean and compressed biogas in place of natural gas or in diesel engines (Sonesson et al., 2000) and biodiesel from

MSW or FW in place of biodiesel from cultivated crops would further reduce the environmental impacts to a significant extent. For example, Linkoping, Sweden had adopted to use 100% biogas-fuelled public transport buses in an effort to reduce waste, produce renewable fuel, improve air quality and develop sustainable transport (Sustainability Writer, 2012). Fallde and Eklund (2015) described the 30-year-long-way Linkoping moved towards a sustainable socio-technical system of biogas for transport. The biogas development process endured hardly a long time span considering it as a development of an entirely new socio-technical system. Currently, there are 229 plants that produce biogas in Sweden amounting to 1387 GWh biogas, of which 44% is upgraded and used as vehicle fuel (Fallde and Eklund, 2015). Additionally, as the FW source is biogenic in origin it prevents the emission of fossil CO_2. With the recent concerns about climate change, there is a pressing need to switch to renewable fuels from fossil fuels. Further, the political, economic and environmental benefits of biofuels are more obvious as discussed briefly in the review by Demirbas (2009).

Market demand is a key factor to make the best use of the available resources and technologies, and provide economic feasibility for resource constraint governments. In the current scenario, Singapore might not have the market demand for biodiesel, hydrochar, or biogas, but it is possible to extend the existing facilities to accommodate them. For instance, if the physicochemical properties of the biodiesel from FW meet the requirements for diesel engine combustion, then there could be higher potential for commercial application by blending it with diesel fuel. Besides, diesel engines need to be designed to accommodate fuel with large fraction of biodiesel in the future (Lin et al., 2006) in order to further expand the application of biodiesel.

Participation of communities and general public, along with their environmental awareness, is another important factor of this FW conversion option. Especially for S1 and S2, it would make a considerable difference if the local communities participate in the waste sorting process. For moving towards an educated and civilized community, public contribution to efficient usage of the available resources is essential. To establish a foothold in Singapore, the S2 systems could be introduced in the food courts/centers where the wastes are generally high in OC and are consistent in the generation amount.

4 Conclusion

The LCA results have shown that FWEB is favored for FW with OC >5% and AD for OC ≤5%, under the assumptions made in this study. The CBA results have shown that AD is the best choice if applicable in the local environment. Otherwise, FWEB is the preferred choice over incineration. The FWEB system utilizes FW as a resource and was proved to be an appealing alternative for the current practice in Singapore. The case of Linkoping serves as an example for transition towards a sustainable socio-technical system. It should be noted that, however, FWEB is a method based on technology not yet fully developed and there could be practical difficulties associated with the implementation that has not been realized thus far. Hence, in addition to providing decision makers with insights into the three FW management strategies and directions to improve the existing MSW management system, the result suggests a need for adaptive strategy based on the food waste type and composition.

Acknowledgements

The authors are grateful to the JTC Corporation, Singapore and the Nanyang Environment and Water Research Institute (NEWRI), NTU, Singapore for their financial support and contribution to the research program.

References

1. Ahamed, A., Chen, C.-L., Rajagopal, R., Wu, D., Mao, Y., Ho, I.J.R., Lim, J.W., Wang J.Y., 2015. Multi-phased anaerobic baffled reactor treating food waste. Bioresour. Technol. 182, 239-244.

2. Berge, N.D., Ro, K.S., Mao, J.D., Flora, J.R.V., Chappell, M.A., Bae S.Y., 2011. Hydrothermal carbonization of municipal waste streams. Environ. Sci. Technol. 45, 5696–703.

3. Bolin, L., 2009. Environmental impact assessment of energy recovery from food waste in Singapore - Comparing biogas production to incineration. Examensarbete 2009:09, Department of Energy and Technology, Swedish University of Agricultural Sciences, SLU, Uppsala, Sweden.

4. Borja, R., Rincon, B., Raposo, F., Alba, J., Martin A., 2002. A study of anaerobic digestibility of two-phases olive mill solid waste (OMSW) at mesophilic temperature. Process Biochem. 38, 733–42.

5. Cheong, H.L., 2012. Planning the Integrated waste management facility. International symposium on Waste resource management & Incineration ash utilization, NEWRI-R3C, NTU, Singapore.

6. Cho, J.K., Park, S.C., Chang, H.N., 1995. Biochemical methane potential and solid state anaerobic digestion of Korean food wastes. Bioresour. Technol. 52, 245–53.

7. Chu, C., Lee, D., Chang, B.-V., You, C., Tay J., 2002. ‘‘Weak’’ ultrasonic pre-treatment on anaerobic digestion of flocculated activated biosolids. Water Res. 36(11), 2681–2688.

8. Demirbas, A., 2009. Political, economic and environmental impacts of biofuels: A review. Applied energy 86, 5108-17.

9. Eco-Business.com, 2011. http://www.eco-business.com/news/food-waste-recycler-folds/ (Date: 04/02/2015).

10. Eriksson, M., Strid, I., Hansson, P.-A., 2015. Carbon footprint of food waste management options in the waste hierarchy - a Swedish case study. J. Clean. Prod. 93, 115-25.

11. Erses Yay, A.S., 2015. Application of life cycle assessment (LCA) for municipal solid waste management: a case study of Sakarya. J. Clean. Prod. 94, 284-93.

12. FAO, 2013. Food Wastage Footprint: Impacts on Natural Resources. FAO, Rome.

13. Fallde, M., Eklund, M., 2015. Towards a sustainable socio-technical system of biogas for transport: the case of the city of Linkoping in Sweden. J. Clean. Prod. 98, 17-28.

14. Fehr, M., Calcado, M.D.R., Romao D.C., 2002. The basis of a policy for minimizing and recycling food waste. Environ. Sci. Policy 5, 247–53.

15. Frischknecht, R., Jungbluth, N., Althaus, H.J., Bauer, C., Doka, G., Dones, R., Hischier, R., Hellweg, S., Humbert, S., Kollner, T., Loerincik, Y., Margni, M., Nemecek T., 2007.

Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3, v2.0. Swiss Centre for Life Cycle Inventories, Duebendorf, CH.

16. Han, S.K., Shin H.S., 2002. Enhanced acidogenic fermentation of food waste in a continuous-flow reactor. Waste Manage. Res. 20, 108–10.

17. He, C., Wang, K., Yang, Y., Wang ,J.-Y., 2014. Utilization of Sewage-Sludge-Derived Hydrochars toward Efficient Cocombustion with Different-Rank Coals: Effects of Subcritical Water Conversion and Blending Scenarios. Energy fuels 28, 6140-50.

18. Hou, L., 2013. South Korea’s food waste solution: you waste, you pay. Common Wealth Mag. <http://english.cw.com.tw/article.do?action=show&id=14067>.

19. Ince, O., 1998. Performance of a two-phase anaerobic digestion system when treating dairy wastewater. Water Res. 32, 2707–13.

20. IPCC, 2007, Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report: Climate Change 2007, Cambridge University Press, Cambridge, United Kingdom.

21. ISO 14044, 2006. Environmental Management-life cycle assessment-requirements and guidelines. Geneva, Switzerland: International Standards Organization (ISO).

22. Jungbluth, N., Chudacoff, M., Dauriat, A., Dinkel, F., Doka, G., Faist Emmenegger, M., Gnansounou, E., Kljun, N., Schleiss, K., Spielmann, M., Stettler, C., Sutter, J., 2007. Life Cycle Inventories of Bioenergy. ecoinvent report No. 17, Swiss Center for Life Cycle Inventories, Dubendorf, CH. Pg No 668.

23. Kammann, C., Ratering, S., Eckhard, C., Muller, C., 2012. Biochar and Hydrochar Effects on Greenhouse Gas (Carbon Dioxide, Nitrous Oxide, and Methane) Fluxes from Soils. J. Environ. Qual. 41, 1052-66.

24. Karmee, S.K., 2016. Liquid biofuels from food waste: Current trends, prospect and limitation. Renew. Sustain. Energy Rev. 53, 945-53.

25. Khoo, H.H., Lim, T.Z., Tan, R.B.H., 2010. Food waste conversion options in Singapore: Environmental impacts based on an LCA perspective. Sci. Total Environ. 408, 1367-73.

26. Kojima, R., Ishikawa, M., 2013. Prevention and Recycling of Food Wastes in Japan: Policies and Achievements. Poster presented at the 4th Global Forum on Urban Resilience & Adaptation, Bonn, Germany.

27. Lee, J.P., Lee, J.S., Park, S.C., 1999. Two-phase methanization of food wastes in pilot scale. Appl. Biochem. Biotechnol. Spring 77–79, 585–93.

28. Lin, Y.C., Lee, W.J., Hou, H.C., 2006. PAH emissions and energy efficiency of palm-biodiesel blends fueled on diesel generator. Atmos. Environ. 40, 3930-40.

29. Lundie, S., Peters G.M., 2005. Life cycle assessment of food waste management options. J. Clean. Prod. 13, 275-86.

30. Mata-Alvarez, J., Mace´, S., Llabre´s, P., 2000. Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. Bioresour. Technol. 74, 3–16.

31. Mujahid, M., Mohyuddin, A., Bhatti, A.A., Nasir, M., 2013. Energy sustainability: Study on fuel efficiency and engine properties by using biodiesel and fossil diesel. Proceedings on international conference on energy and sustainability.

32. Mumme, J., Eckervogt, L., Pielert, J., Diakité, M., Rupp, F., Kern, J., 2011. Hydrothermal carbonization of anaerobically digested maize silage. Bioresour. Technol. 102, 9255–60.

33. Muroyama, K., Mochizuki, T., Wakamura, T., 2001. Methane fermentation of bean curd refuse. J Biosci. Bioeng. 92, 208–12.

34. National Waste Report, 2010. Department of the Environment, Water, Heritage and the Arts, Australian Government. ISBN: 978-1-921173-53-0. Pg.No.140

35. NEA, 2013. Waste statistics, National Environmental Agency, Singapore. http://www.nea.gov.sg/energy-waste/waste-management/waste-statistics-and-overall-recycling (Date: 04/02/2015).

36. NEA, 2014. http://www.nea.gov.sg/energy-waste/waste-management/waste-statistics-and-overall-recycling (Date: 28/12/2015).

37. Numbeo, 2015. http://www.numbeo.com/food-prices/country_result.jsp?country=Singapore (Date: 29/12/2015)

38. Papargyropoulou, E., Lozano, R., Steinberger, J.K., Wright, N., Ujang, Z.b., 2014. The food waste hierarchy as a framework for the management of food surplus and food waste. J Clean. Prod. 76, 106-15.

39. Park, S.J., Bae, J.S., Lee, D.W., Ra, H.W., Hong, J.C., Choi, Y.C., 2011. Effects of hydrothermally pretreated sewage sludge on the stability and dispersibility of slurry fuel using pulverized coal. Energ. Fuel 25, 3934–9.

40. Peng, L., Bao, M., Wang, Q., Wang, F., Su, H., 2014. The anaerobic digestion of biologically and physicochemically pretreated oily wastewater. Bioresour. Technol. 151, 236-43.

41. Population in Brief, 2015. National population and talent division, Prime minister's office, Singapore department of statistics, Ministry of home affairs and immigration & checkpoints authority.

42. Rajagopal, R., Ahamed, A., Wang, J.-Y., 2014. Hydrolytic and acidogenic fermentation potential of food waste with source segregated feces-without-urine as co-substrate. Bioresour. Technol. 167, 564-8.

43. Raynal, J., Delgenes, J.P., Moletta, R., 1998. Two-phase anaerobic digestion of solid wastes by a multiple liquefaction reactors process. Bioresour. Technol. 65, 97–103.

44. Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment Part 1:

Framework, goal and scope definition, inventory analysis, and applications. Environ. International 30, 701-20.

45. Schiettecatte, W., Tize, R., De Wever, H., 2014. Comparison of costs for three hypothetical alternative kitchen waste management systems. Waste Manage. Res. 32(11), 1094-102.

46. Sonesson, B., Bjorklund, A., Carlsson, M., Dalemo, M., 2000. Environmental and economic analysis of management systems for biodegradable waste. Res. Conser. Rec. 28, 29-53.

47. Song, Q., Wang, Z., Li, J., 2013. Environmental performance of municipal solid waste strategies based on LCA method: a case study of Macau. J. Clean. Prod. 57, 92-100.

48. Strydom, J.P., Britz, T.J., Mostert, J.F., 1997. Two-phase anaerobic digestion of three different dairy effluents using a hybrid bioreactor. Water SA 23, 151-6.

49. Sustainability Writer, 2012. https://sustainabilitywriter.wordpress.com/2012/07/27/100-biogas-fuelled-public-transport-in-linkoping-sweden/ (Dated: 09/02/2015)

50. The Electropedia, 2015. http://www.mpoweruk.com/energy_efficiency.htm (Date: 22/01/2015).

51. The World Bank, 1999. The International Bank for Reconstruction and Development, The World Bank. Decision makers' guide to Municipal Solid Waste Incineration. Washington, D.C. 20433, U.S.A.

52. Thyberg, K.L., Tonjes, D.J., Gurevitch, J., 2015. Quantification of Food Waste Disposal in the United States: A Meta-Analysis. Environ. Sci. Technol. 49, 13946-53.

53. USEPA, 2014. Municipal Solid Waste generation, Recycling, and Disposal in the United States: Facts and Figures for 2012. United States Environmental Protection Agency, Solid Waste and Emergency Response, Washington, D.C. 20460, U.S.A.

54. Ventour, L., 2008. The food we waste. Food waste report. Waste and Resources Action Programme (WRAP) and Exodus Market Research, ISBN: 1-84405-383-0.

55. Wang, J.-Y., Zhang, H., Stabnikova, O., Tay, J.H., 2005. Comparison of lab-scale and pilot-scale hybrid anaerobic solid–liquid systems operated in batch and semi-continuous modes. Process Biochem. 20, 3580-6.

56. Wen, Z., Wang, Y., De Clercq, D., 2016. What is the true value of food waste? A case study of technology integration in urban food waste treatment in Suzhou City, China. J Clean. Prod. 118, 88-96.

57. WRAP, 2013. Household Food and Drink Waste in the United Kingdom 2012, The Waste and Resources Action Program (WRAP). ISBN: 978-1-84405-458-9.

58. Xu, H.L., Wang, J.Y., Tay, J.H., 2002. A hybrid anaerobic solid–liquid bioreactor for food waste digestion. Biotechnol. Lett. 24, 757-61.

59. Xu, C., Shi, W., Hong, J., Zhang, F., Chen, W., 2015. Life cycle assessment of food waste-based biogas generation. Renew. Sust. Energ. Rev. 49, 169-77.

"Figure captions"

Figure 1. Flowchart showing the main processes involved in the three system scenarios, S0: Incineration, S1: Anaerobic digestion, and S2: Food waste-to-energy biodiesel.

Figure 2. Bar chart representation of the characterization results of (a) AP, (b) EP, (c) GWP100, and (d) CED for the three system scenarios.

Figure 3. Bar chart representation of the normalized comparison for the impact categories AP, EP, GWP100, and CED.

"Table captions"

Table 1. Chart showing the sensitivity analysis based on different oil content (2.5%, 5%, 7.5% and 10%) of food waste.

Table 2. Chart showing the cost-benefit analysis of the three scenarios.

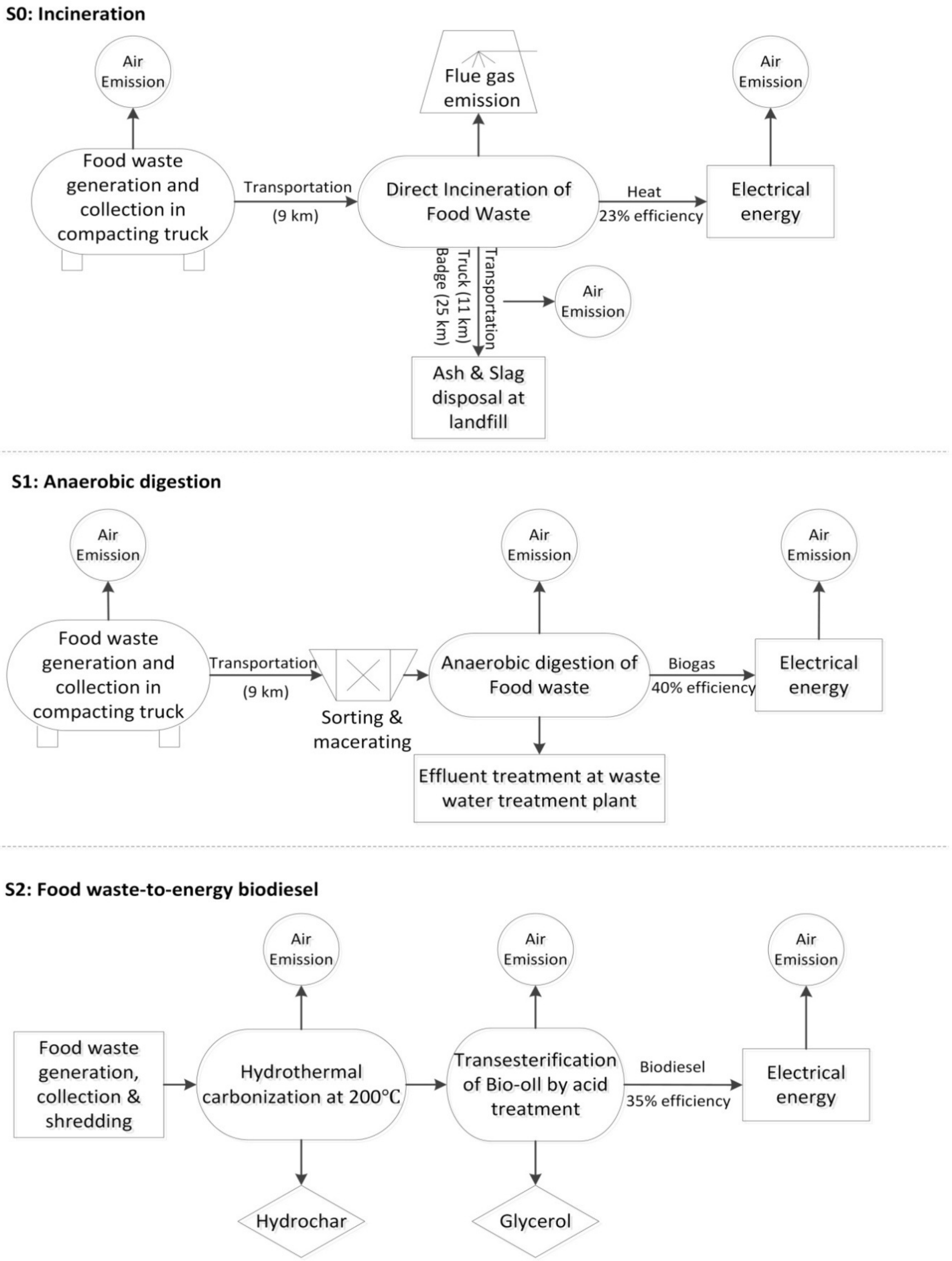

Figure 1. Flowchart showing the main processes involved in the three system scenarios, S0: Incineration, S1: Anaerobic digestion, and S2: Food waste-to-energy biodiesel.

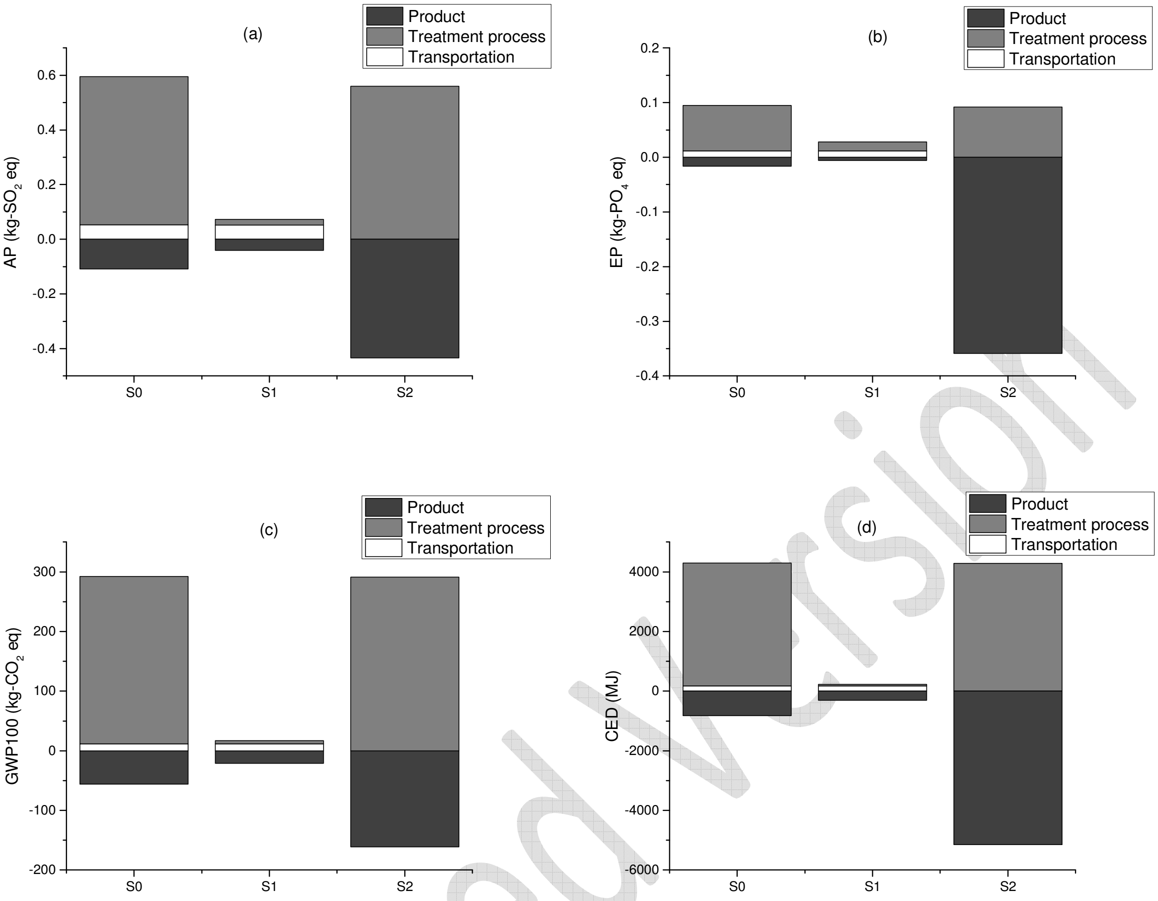

Figure 2. Bar chart representation of the characterization results of (a) AP, (b) EP, (c) GWP100, and (d) CED for the three system scenarios.

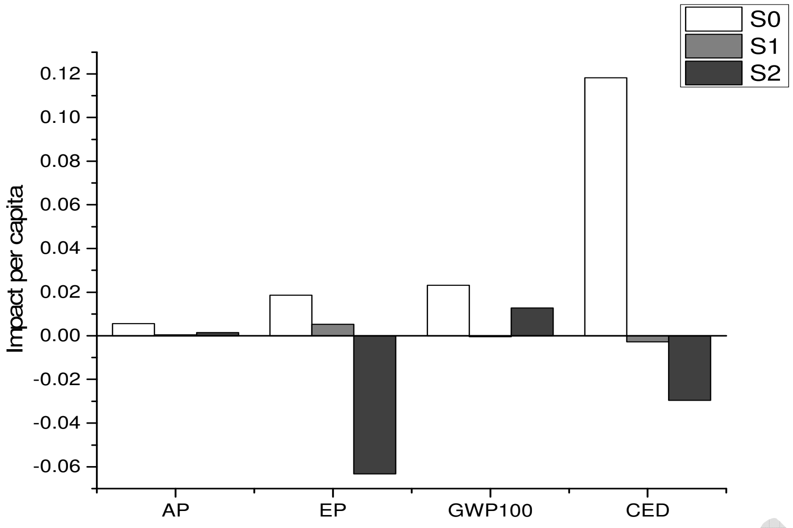

Figure 3. Bar chart representation of the normalized comparison for the impact categories AP, EP, GWP100, and CED.

Impact Category	**AP**	**EP**	**GWP100**	**CED**
Incineration 5% as baseline[a]	100%			
S0 (2.5 - 10%)	99-102%			
S1 (2.5 - 10%)	194 - 192%	172 - 170%	203 - 200%	203 - 200%
S2: 2.5%	141%	417%	115%	175%
S2: 5%	174%	541%	145%	225%
S2: 7.5%	207%	665%	175%	275%
S2: 10%	240%	789%	206%	326%

[a] Current practice in Singapore

Table 1. Chart showing the sensitivity analysis based on different oil content (2.5%, 5%, 7.5% and 10%) of food waste.

Item[a]	Unit	Incineration	AD	FWEB
Distance to treatment facility	km	9	9	0
Distance to the port	km	11	0	0
Distance from the port to Semakau	km	25	0	0
Land occupation per tonne FW	m^2	20	20	10
Internal electricity consumption per tonne FW	MJ	2055	23.27	2000
Wastewater generation per tonne FW	t	0	1	0

Item[b]	Unit	Cost, SGD
Diesel (Caltex, 2014)	L	1.62
Electricity (SP, 2014)	MJ	0.07
Glycerine (Malaysia, 2014)	kg	0.6277
Land occupation (HDB, 2014)	m^2*day	0.3653
Lignite (India, 2014)	kg	0.4725
Manpower for sorting FW (MOM, 2014)	Person*day	54.17
Methanol (Methanex, 2014)	kg	0.4615
Petrol (Caltex, 2014)	L	2.35
Wastewater treatment (PUB, 2014)	m^3	0.6

Cost[c]	Incineration	AD	FWEB
FW sorting	0.00	54.17	0.00
Transportation	0.25	0.23	0.00
Land occupation	7.31	7.31	3.65
Operation (Electricity input)	143.85	1.63	140.55
Chemicals (H_2SO_4, Methanol)	0.00	0.00	24.76
Wastewater treatment	0.00	0.60	0.00
Benefits	**Incineration**	**AD**	**FWEB**
Electricity output	15.97	10.18	40.85
Products (Hydrochar, Glycerol)	0.00	0.00	54.66
Balance	-135.43	-53.75	-73.44

[a] Key inventory for each scenario

[b] The fundamental cost for all scenarios

[c] Cost and benefit calculations for the three scenarios (SGD/t*d)

Table 2. Chart showing the cost-benefit analysis of the three scenarios.

APPENDIX

Source citation for the CBA (Dated:29/01/2015)	
Caltex, 2014	Caltex Fuel Prices - Latest updates on Fuel Prices, Vol. 2014. http://www.caltex.com/sg/resources/fuel-price/
SP, 2014	Electricity tariff revision for the period 1 October to 31 December 2014, Vol. 2014. Media release dated September 2014, SP services Ltd.
Malaysia, 2014	http://www.alibaba.com/product-detail/crude-glycerine_134173033.html
HDB, 2014	HDB Pricing, Vol 2014.
India, 2014	http://www.alibaba.com/product-detail/Coking-Coal-Coking-Coal_50008606848.html
MOM, 2014	Singapore Yearbook of Manpower Statistics (2014). Manpower Research and Statistics Department, Ministry of manpower, Republic of Singapore.
Methanex, 2014	https://www.methanex.com/our-business/pricing
PUB, 2014	Water Pricing in Singapore Vol. 2014. http://www.pub.gov.sg/general/Pages/WaterTariff.aspx