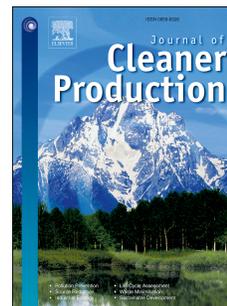


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Life cycle assessment of the present and proposed food waste management technologies from environmental and economic impact perspectives

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

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24 **Abstract**

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

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

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## 57 **1 Introduction**

58 Tremendous amount of food waste (FW) is generated each year worldwide, and the amount of  
59 FW generation has increased over time (Thyberg et al., 2015). For instance, in the United States,  
60 FW accounts for 21.1% of the discarded municipal waste stream in 2012 which is equivalent to  
61 31.4 million tonnes (USEPA, 2014). In China, 90 million tonnes of FW was generated in 2010  
62 which made up about 51% of municipal solid waste (MSW) production (Wen et al., 2016). It is  
63 estimated that over one-fourth of food produced worldwide yearly (i.e. around 1.6 billion tonnes)  
64 is wasted during production, processing, distribution, consumption, and disposal (FAO, 2013). In  
65 developed countries such as Japan, the United Kingdom, South Korea and Australia, the amounts  
66 of FW generated per year were 9.9 (Kojima and Ishikawa, 2013), 7.0 (WRAP, 2013), 5.7 (Hou,  
67 2013) and 4.4 (National Waste Report, 2010) million tonnes on average. FW presents disposal  
68 challenges primarily due to its high moisture content, oil content (OC), and heterogeneous nature  
69 (Eriksson et al., 2015; Karmee, 2016). Although reduction is the most preferred option in the FW  
70 management hierarchy (Papargyropoulou et al., 2014), subsequent approaches such as reuse,  
71 recycling, recovery in terms of waste-to-energy, and disposal also require attention and technical  
72 contribution from the research community in order to develop a comprehensive FW management  
73 system.

74 Singapore is a modern city-state with high economic performance despite having little natural  
75 resources. Its population density ranks among the highest in the world. It has a population of  
76 5.535 million with land area of about 700 sq.km (Population in Brief, 2015). FW generated in  
77 Singapore was 788,600 tonnes in 2014 which is about 0.39 kg per person per day (NEA, 2014).  
78 For years, Singapore has been a forerunner in the field of waste management being able to  
79 manage most of its MSW through recycling and incineration (NEA, 2013). The current MSW

80 management practice of incineration can reduce the waste volume up to 90% while generating  
81 electricity. Nevertheless, the recent economic developments and technological advancements  
82 leading to high carbon footprint, and together with the sustainability goals compel to improve the  
83 waste management method in the city-state. Singapore, despite having an effective waste  
84 management system, now has the calibre to look into more environmental friendly options and  
85 keep up with the technology trends and advancements.

86 A World Bank report (1999) pointed out that the feasibility of an MSW incineration plant is  
87 largely dependent on the nature of the waste and its calorific value. At present, one of the issues  
88 with incinerating the MSW is the high moisture content which is attributed to FW. Because of a  
89 huge amount of vicinal and bound water therein, as well as the relatively high latent heat of  
90 water, FW incineration are energy-intensive (He et al., 2014). Removing the FW from MSW  
91 stream will significantly improve the calorific value of solid waste (Song et al., 2013, Erses Yay,  
92 2015). Hence, FW should be removed from MSW stream and treated separately for better  
93 incineration efficiency and resource recovery. Recycling or other methods of energy recovery  
94 from FW seems a more appropriate option (Rajagopal et al., 2014).

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

103 history of failure including the recent closure of IUT Global Company, which used AD for  
104 treating municipal FW (Eco-Business.com, 2011).

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

114 Life cycle assessment (LCA) is a powerful tool for quantifying, evaluating, comparing, and  
115 developing goods and services in terms of their potential environmental impacts (Rebitzer et al.,  
116 2004). An LCA study provides valuable information to aid government agencies in technology  
117 selection for future waste management (Khoo et al., 2010). Environmental LCA studies help the  
118 decision makers to understand the technology from an environmental perspective and identify  
119 the technology that best suits the region/country.

120 The main objective of this study is to compare the three technologies, i.e. incineration, AD and  
121 FWEB system in Singapore's context from an environmental perspective in terms of acidification  
122 potential (AP), eutrophication potential (EP), global warming potential in 100 years (GWP100),  
123 and cumulative energy demand (CED) to help identify an appropriate FW management method  
124 for urban societies. The results are presented through the LCA software SimaPro 7.3 which is a

125 widely accepted and recognized tool in the LCA community. Additionally, cost-benefit analysis  
126 (CBA) was performed. Landfill was not included as Singapore has stopped landfilling MSW  
127 except for the incineration residues that are buried off-shore. The demand for composting is  
128 limited in Singapore and hence not a choice for the study as well.

## 129 **2 Methods**

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

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

### 145 *2.1 Impact assessment*

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

## 158 *2.2 Scenario description*

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

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

165 Scenario 1 (S1): AD of FW in a centralized treatment facility using hybrid anaerobic solid-liquid  
166 (HASL) system with the biogas being converted to electricity on-site. Conventional single-stage  
167 reactors are not suitable for FW (Ahamed et al., 2015). Hence, two-phase system is applied for  
168 FW treatment as it is an effective method (Han and Shin, 2002; Lee et al., 1999; Mata-Alvarez et

169 al., 2000; Raynal et al., 1998) with the advantages of better process stability, shorter retention  
170 time and higher methane yield (Cho et al., 1995; Ince, 1998; Strydom et al., 1997; Xu et al.,  
171 2002).

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

174 The following assumptions were applied in this study,

175 - Construction and material requirements of the management facility were not included in the  
176 system boundary

177 - No pre-treatment of FW

178 - All the electricity requirement was supplied from Singapore's national grid

179 - AD digestate, rich in organic matter and nutrients, could be used as a soil amendment or as a  
180 substitute for fertilizer (Borja et al., 2002; Fehr et al., 2002; Muroyama et al., 2001), but since it  
181 is difficult to estimate the amount obtainable from AD, it was not included in this study.

182 Nevertheless, AD effluent of 1 tonne was sent to the waste water treatment plant to maintain the  
183 volume balance

184 - Collection and transportation of the final products of S2 was not included as it depends on the  
185 on-site demand, and also the location & distance to be transported was not definitive

186 - Waste water from S0 and S2 were not included as they are converted to steam and does not  
187 require further treatment

### 188 *2.3 Food waste characteristics*

189 The study focuses on municipal FW collected from households, food retail and services in  
190 Singapore. The FW in this study contained approximately 75% moisture content, 20% solids  
191 content and 5% OC obtained from the samples collected. The higher heating value was found to

192 be 20.333 KJ/g of dried FW, which was analyzed by an IKA C2000 Basic bomb calorimeter.  
193 The composition of Carbon (49.72%), Hydrogen (7.81%), Nitrogen (1.89%) and Sulphur  
194 (8.91%) was analyzed using CHNS Elemental analyzer (Elementar, Germany).

#### 195 *2.4 Life Cycle Inventory*

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

##### 199 *2.4.1 Incineration and AD*

200 Inventory data for incineration were obtained from the LCI Bioenergy report (Jungbluth et al.,  
201 2007) for incinerating the Biowaste, and Bolin's report (2009) for conversion efficiency in  
202 Singapore's case. AD data were adopted from HASL system treating FW, with the results of pilot  
203 plant experiments (Wang et al., 2005) scaled up to treat centralized facility whereby methane  
204 composition is assumed to be 60% as opposed to 70% at the lab-scale setup. The emission was  
205 calculated based on Bolin's report (2009). All the data were collected to suit the local scenario.

##### 206 *2.4.2 FWEB*

207 All the data for FWEB were obtained from lab-scale experiments in a HTC reactor of 2L  
208 capacity and followed by transesterification of bio-oil using rotary evaporator (Heidolph,  
209 Germany). The conversion efficiency of the biodiesel to electricity was assumed to be 35% as  
210 supported by the literatures for biodiesel from other sources (The Electropedia, 2015; Lin et al.,  
211 2006; Mujahid et al., 2013). The gas composition (methane, carbon dioxide, hydrogen and  
212 nitrogen contents) was analyzed by Gas Chromatograph (Agilent Technologies 7890 A, USA)

213 equipped with a thermal conductivity detector. Transportation and other standard data were  
214 obtained from the in-built LCA software Ecoinvent database.

### 215 **3 Results and discussion**

216 Fig. 2 shows the characterization results of the AP, EP, GWP100 and CED impact categories.  
217 Incineration has the highest impact among all the impact categories compared. The percentage  
218 deviation of AP, EP, GWP100 and CED were 287%, 129%, 82% and 498%, respectively for S0  
219 as compared to S2. In a similar way, the deviation of S0 as compared to S1 was 361%, 21%,  
220 185% and 408% for AP, EP, GWP100 and CED, respectively with respect to S2. The positive  
221 results of S1 and S2 could be mainly attributed to the appropriate utilization of the waste as  
222 compared to incineration. The factual difference between S0 and the other two scenarios was that  
223 the organic energy contained in FW was merely used as heat in S0, whereas it was converted to  
224 biogas, biodiesel and/or hydrochar in the other two. It shows that S0 has a high negative impact  
225 on the process as the energy input is higher than the output. This implicates that even mixing the  
226 FW with other MSW was not a favourable option for the sustenance of incinerators (Song et al.  
227 2013). In fact, removing the FW from MSW would increase the overall higher heating value of  
228 the MSW. Cheong (2012) mentioned that high quality materials and larger combustion space for  
229 the furnace are keys to improve incineration performance. Hence, the results suggest S0 as the  
230 least favoured option for FW management.

231 The comparison between S1 and S2 displayed mixed results for different impact categories. For  
232 AP and GWP100, S1 showed 0.74 and 1.03 times lower impact than the S2 whereas for the cases  
233 of EP and CED it was 1.08 and 0.91 times higher. The reason for better performance of S1 in the  
234 cases of AP and GWP100, which are associated with gas emissions, was utilization of fossil fuel

235 for the operation where AD uses much less electricity while HTC in S2 requires about 2 MJ/kg-  
236 FW. Transesterification of the bio-oil in S2 added further stress on AP and GWP100 via gas  
237 emissions. Otherwise, there was no direct contribution to GWP100 from FW since all the carbon  
238 was assumed to be biogenic in origin (IPCC, 2007). On the other hand, EP shows negative  
239 impact because of the inability of the AD system to remove the nutrients (N, P, K, etc.) which  
240 were left in waste water treatment plant for further processing while most of the nutrients were  
241 retained in the hydrochar from FWEB.

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

252 As the transportation presents an additional contribution to the impact categories of S0 and S1, a  
253 simple impact comparison was discussed. The contribution of transportation in S0 was 11%,  
254 15%, 5% and 5% for AP, EP, GWP100 and CED, respectively. While barring the effect of  
255 transportation, the S1 showed a significant difference of 161%, 53%, 291% and 219% reduction  
256 in the impact for AP, EP, GWP100 and CED, respectively implying transportation was one of  
257 the major process contributors in this scenario. Comparing the sensitivity of transportation, the

258 percentage improvement in S1 was 55.42%, 4.08%, 8.79% and 22.01% for AP, EP, GWP100  
259 and CED, correspondingly with respect to S2. This shows that even though the impact of  
260 transportation on S1 was obvious, it was not as significant as compared to S2 except for the  
261 impact category AP.

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

### 268 *3.1 Normalized results*

269 The aim of normalization is to better understand the order of magnitude and the relative  
270 significance of each indicator of a system under study (Lundie and Peters, 2005). Normalization  
271 factor varies depending on the geographical location. The calculations were performed by  
272 dividing each impact category with their respective normalization factor for Singapore according  
273 to Khoo et al. (2010). The normalized results in a common dimension are presented in the Fig. 3.  
274 The CED had the highest repercussion as compared to the other impact categories. S1 resulted in  
275 the lowest resource usage and cost of all the three FW management systems compared in this  
276 study, which was in correlation with the study by Sonesson et al. (2000), who investigated the  
277 effects of incineration, composting and AD on solid waste management. On the other hand, the  
278 S2 system added more environmental benefits in terms of energy and material yield. The  
279 technology generated energy from waste while simultaneously showing significant potential to

280 reduce the effects on eutrophication and the impacts from air emission as compared to  
281 incineration. As stated by Sonesson et al. (2000), it could be claimed that FWEB is based on  
282 theoretical system developed from laboratory results whereas incineration is an old and proven  
283 technology. But, the counter argument could be that incineration is a state-of-the art technology  
284 with high efficiency. Hence, there is not much scope to improve further from the current  
285 practice. Decisively, the advances made in incineration could hardly compensate to the positive  
286 effects of the other two systems.

### 287 *3.2 Sensitivity analysis of oil content*

288 The sensitivity analysis identifies sensitive parameters, whether a small change in an input  
289 parameter would induce a large change in the impact category (Song et al., 2013). OC in FW is  
290 one of the most critical factors for the operation of S2 as the output products i.e. biodiesel and  
291 glycerol are derived from it. Hence, a sensitivity analysis was performed to study the effect of  
292 the OC% in FW. The baseline scenario was set as S0 with 5% OC which was fixed as 100%. The  
293 deviation of the rest of the scenarios from the baseline is presented in Table 1. The OC% did not  
294 have much influence on the incineration as it burned along with the FW with high moisture  
295 content and the amount of carbon was assumed to be similar (the calorific value of raw waste oil  
296 and fat from FW is very low). The performance of the S1 deteriorated with increasing OC% due  
297 to limited participation of oil and fats in AD. The main reasons were low solubility of oil, poor  
298 biodegradability, and surface action whereby biomass flocs are shielded and does not participate  
299 in biochemical reactions (Chu et al., 2002; Peng et al., 2014). Hence, in this study, the biogas  
300 contribution from oil was neglected as it requires special treatment facility or reactor design to  
301 facilitate the biodegradation of oil. In all the impact categories, S1 was around twice as good as  
302 S0 except EP. The performance of S2 escalated consistently with increasing oil percentage. This

303 trend suggests that it is more profitable to use the technology for the treatment of waste with high  
304 OC% (as the yield of primary product is directly proportional to the OC). For the FW with 10%  
305 OC, the impact of S2 in terms of EP and CED were 7.9 and 3.3 times lower than the current  
306 incineration practice respectively. On the other hand, when the OC was 2.5%, the GWP100  
307 decreased to 115%, which was similar to any of the incineration scenarios and lower than all of  
308 the impact categories of S1 except EP. Hence, it is not recommended to opt to the S2 system  
309 when the OC% of FW is lower than 5%. The optimal solution is to implement the S2 for FW  
310 when  $OC > 5\%$  and S1 when it is  $\leq 5\%$ . Thus, a decentralized system for FWEB is proposed in  
311 this study as the technology is highly dependent on OC of the FW and is not applicable to  
312 general FW per se.

### 313 *3.3 Cost-benefit analysis*

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

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

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

339 The economic value of FW was calculated to estimate the percentage recovery through the three  
340 studied scenarios. According to Numbeo (2015), the recommended minimum amount of money  
341 for Asian food types in Singapore was S\$9.35 for approximately 1.75 kg/day per person. From  
342 the Singapore FW statistics, the amount of food wasted was 0.39 kg/day per person, which is  
343 about 22% of the total food purchased per person. In other words, on average, about S\$2/day per  
344 person gets wasted that amounted to S\$4.04 billion/year. With the recycling rate of 13% in  
345 Singapore (NEA, 2014) and 19% of unavoidable FW such as peels and bones (Ventour, 2008),  
346 approximately S\$2.75 billion value of food gets wasted every year. The estimated value of 1 FU  
347 in this study is S\$3631 (excluding the 13% recycling and 19% unavoidable FW). Hence, the  
348 benefits from S0, S1 and S2 would recover a value of 0.44%, 0.28% and 2.63%, respectively. It

349 could be concluded that S2 is a more promising option in terms of material recovery as it  
350 recovered about S\$72 million/year from the wasted food. Nevertheless, sustainable research and  
351 development to the technology could further cut down the costs incurred.

### 352 *3.4 General outlook and future options*

353 Overall, this study shows that S1 is a simple and efficient treatment option without involving  
354 high energy consumption and generation while S2 is a more sophisticated and advanced choice.  
355 The major advantages of S2 over S1 are, (1) maximized oil separation from FW mixture, (2)  
356 minimized waste volume via formation of hydrochar, (3) up to 85% of the carbon from the initial  
357 feed stock are retained in the hydrochar (Kammann et al., 2012), (4) efficient dewatering, (5)  
358 evolved gas amount is small and mainly consisted of CO<sub>2</sub> (Berge et al., 2011; Kammann et al.,  
359 2012), (6) hydrochars are biologically sterilized due to thermal treatment (Park et al., 2011), (7)  
360 flexible waste composition - impurities in waste composition does not affect the operation but  
361 only the quality of the product. On the contrary, S1 is a biological process that requires strict FW  
362 purity standards, which was one of the main reasons behind its history of failure in Singapore.  
363 The disadvantages of S2 are (1) sophisticated design, construction, operation and maintenance,  
364 (2) very high capital cost that requires investors to fund projects up front, (3) high pressure  
365 treatment that requires thoroughly controlled environment.

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

371 MSW or FW in place of biodiesel from cultivated crops would further reduce the environmental  
372 impacts to a significant extent. For example, Linköping, Sweden had adopted to use 100%  
373 biogas-fuelled public transport buses in an effort to reduce waste, produce renewable fuel,  
374 improve air quality and develop sustainable transport (Sustainability Writer, 2012). Falde and  
375 Eklund (2015) described the 30-year-long-way Linköping moved towards a sustainable socio-  
376 technical system of biogas for transport. The biogas development process endured hardly a long  
377 time span considering it as a development of an entirely new socio-technical system. Currently,  
378 there are 229 plants that produce biogas in Sweden amounting to 1387 GWh biogas, of which  
379 44% is upgraded and used as vehicle fuel (Falde and Eklund, 2015). Additionally, as the FW  
380 source is biogenic in origin it prevents the emission of fossil CO<sub>2</sub>. With the recent concerns  
381 about climate change, there is a pressing need to switch to renewable fuels from fossil fuels.  
382 Further, the political, economic and environmental benefits of biofuels are more obvious as  
383 discussed briefly in the review by Demirbas (2009).

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

392 Participation of communities and general public, along with their environmental awareness, is  
393 another important factor of this FW conversion option. Especially for S1 and S2, it would make a

394 considerable difference if the local communities participate in the waste sorting process. For  
395 moving towards an educated and civilized community, public contribution to efficient usage of  
396 the available resources is essential. To establish a foothold in Singapore, the S2 systems could be  
397 introduced in the food courts/centers where the wastes are generally high in OC and are  
398 consistent in the generation amount.

#### 399 **4 Conclusion**

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

#### 411 **Acknowledgements**

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414 to the research program.

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580 **"Figure captions"**

581 **Figure 1.** Flowchart showing the main processes involved in the three system scenarios, S0:

582 Incineration, S1: Anaerobic digestion, and S2: Food waste-to-energy biodiesel.

583 **Figure 2.** Bar chart representation of the characterization results of (a) AP, (b) EP, (c) GWP100,

584 and (d) CED for the three system scenarios.

585 **Figure 3.** Bar chart representation of the normalized comparison for the impact categories AP,

586 EP, GWP100, and CED.

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604 **"Table captions"**

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

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

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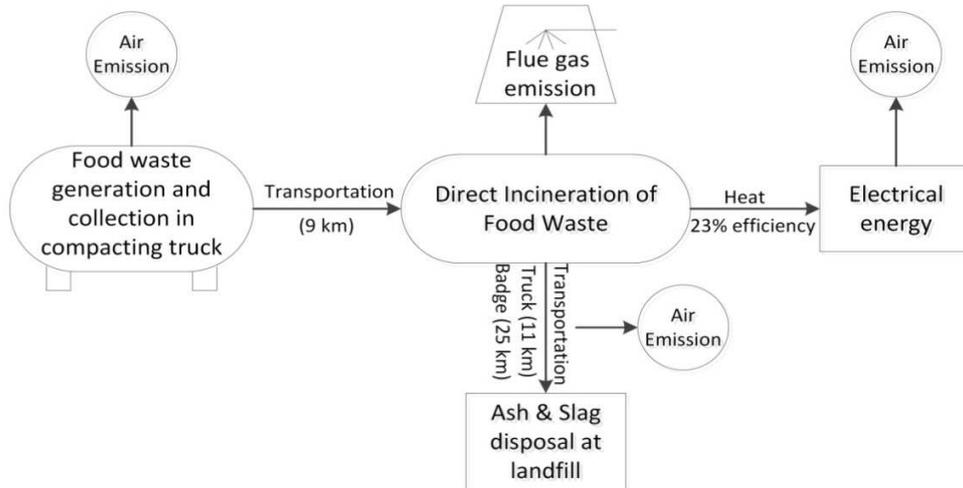
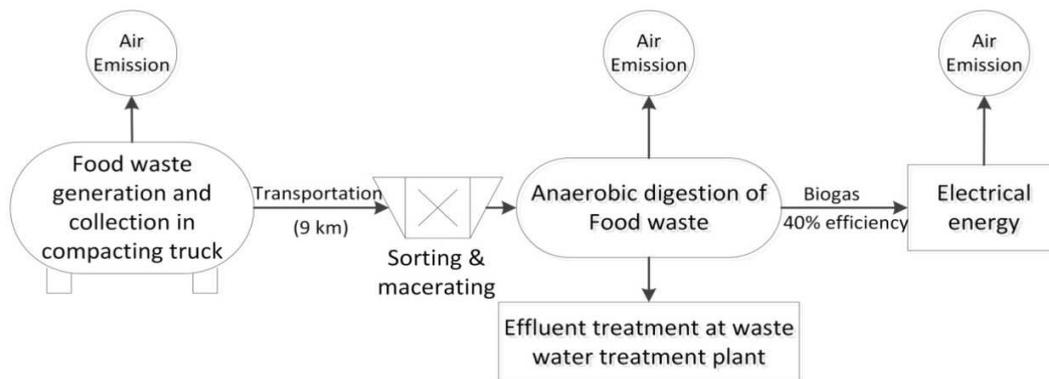
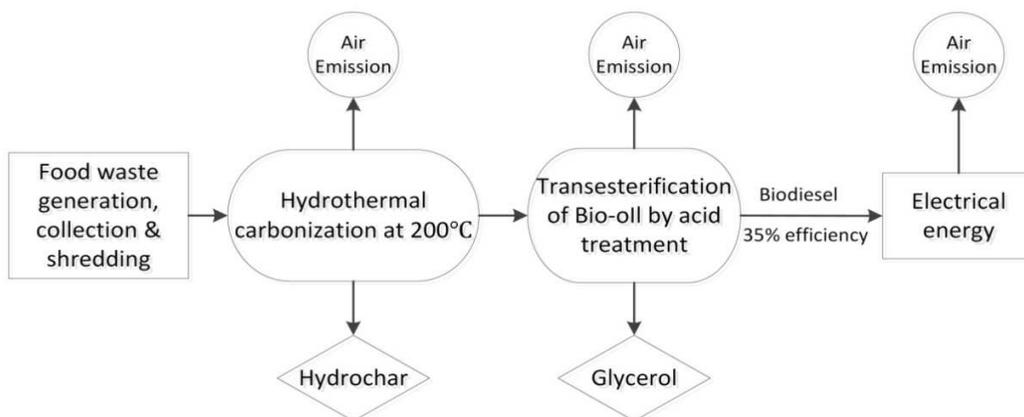
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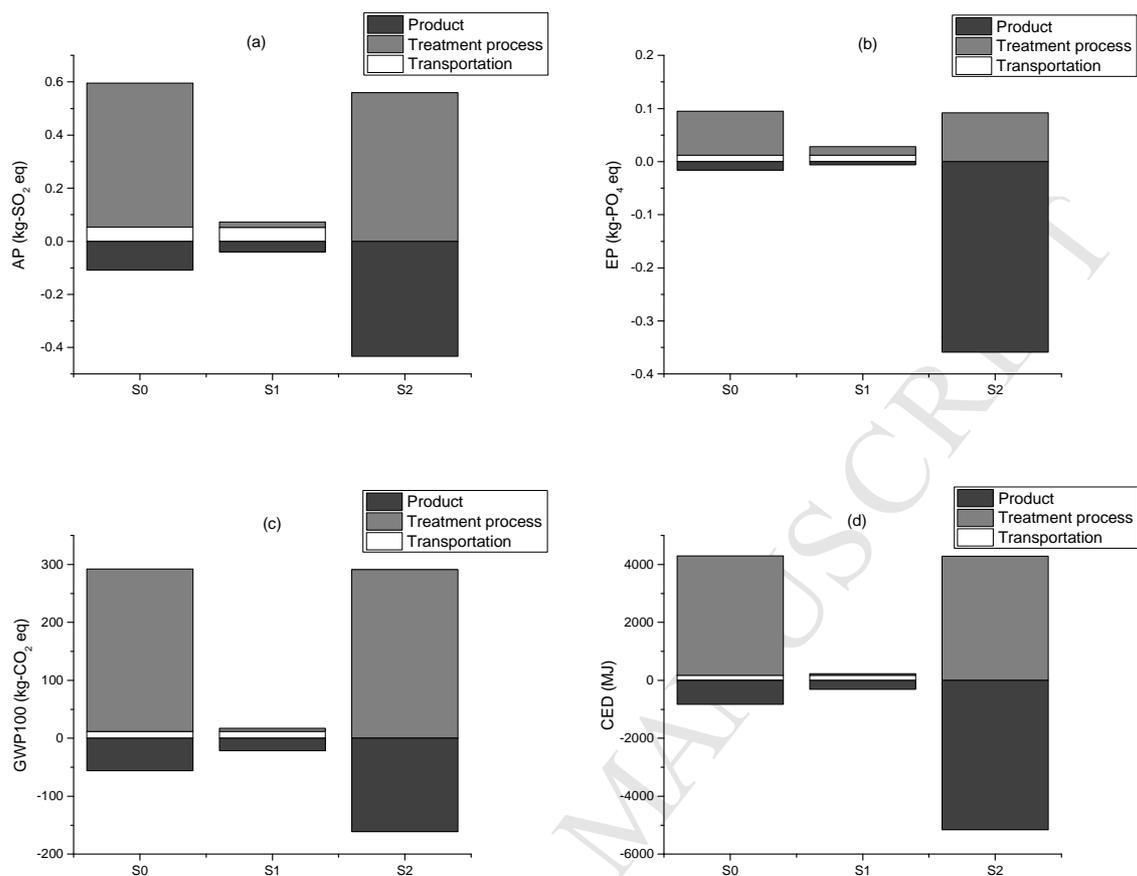
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**S0: Incineration****S1: Anaerobic digestion****S2: Food waste-to-energy biodiesel**

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620 **Figure 1.** Flowchart showing the main processes involved in the three system scenarios, S0:

621 Incineration, S1: Anaerobic digestion, and S2: Food waste-to-energy biodiesel.



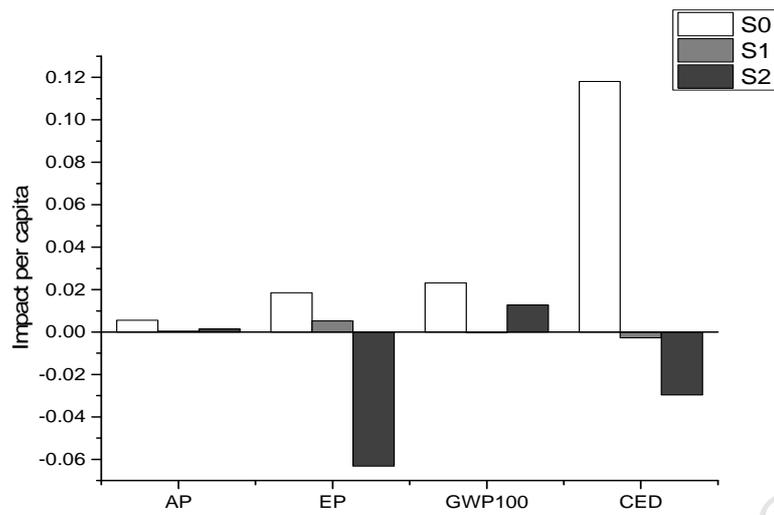
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624 **Figure 2.** Bar chart representation of the characterization results of (a) AP, (b) EP, (c) GWP100,  
 625 and (d) CED for the three system scenarios.

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629 **Figure 3.** Bar chart representation of the normalized comparison for the impact categories AP,

630 EP, GWP100, and CED.

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Impact Category	AP	EP	GWP100	CED
Incineration 5% as baseline <sup>a</sup>			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%

634 <sup>a</sup>Current practice in Singapore

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

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Item <sup>a</sup>	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 <sup>2</sup>	20	20	10
Internal electricity consumption per tonne FW	MJ	2055	23.27	2000
Wastewater generation per tonne FW	t	0	1	0

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Item <sup>b</sup>	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 <sup>2</sup> *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 <sup>3</sup>	0.6

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Cost <sup>c</sup>	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 <sub>2</sub> SO <sub>4</sub> , 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

641 <sup>a</sup>Key inventory for each scenario642 <sup>b</sup>The fundamental cost for all scenarios643 <sup>c</sup>Cost and benefit calculations for the three scenarios (SGD/t\*d)

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

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648 **APPENDIX**

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**Source citation for the CBA (Dated:29/01/2015)**

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Caltex, 2014	Caltex Fuel Prices - Latest updates on Fuel Prices, Vol. 2014. <a href="http://www.caltex.com/sg/resources/fuel-price/">http://www.caltex.com/sg/resources/fuel-price/</a>
SP, 2014	Electricity tariff revision for the period 1 October to 31 December 2014, Vol. 2014. Media release dated September 2014, SP services Ltd.
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This study is novel and advantageous in the following aspects:

- Food waste management strategies were overviewed with crucial environmental impacts
- Food waste-to-energy biodiesel system was proposed as a novel FW management option
- Oil content plays a key role for sustainable food waste-to-energy biodiesel system