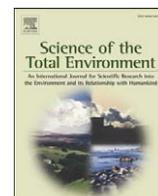




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Food waste conversion options in Singapore: Environmental impacts based on an LCA perspective

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ABSTRACT

Proper management and recycling of huge volumes of food waste is one of the challenges faced by Singapore. Semakau island – the only offshore landfill of the nation – only accepts inert, inorganic solid waste and therefore a large bulk of food waste is directed to incinerators. A remaining small percent is sent for recycling via anaerobic digestion (AD), followed by composting of the digestate material. This article investigates the environmental performance of four food waste conversion scenarios – based on a life cycle assessment perspective – taking into account air emissions, useful energy from the incinerators and AD process, as well as carbon dioxide mitigation from the compost products derived from the digestate material and a proposed aerobic composting system. The life cycle impact results were generated for global warming, acidification, eutrophication, photochemical oxidation and energy use. The total normalized results showed that a small-scale proposed aerobic composting system is more environmentally favorable than incinerators, but less ideal compared to the AD process. By making full use of the AD's Recycling Phase II process alone, the Singapore Green Plan's 2012 aim to increase the recycling of food waste to 30% can easily be achieved, along with reduced global warming impacts.

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1. Introduction

Municipal solid waste (MSW) volumes from modern societies have increased over the years, out of which, a considerable fraction of the solid waste stream is food scraps. The annual generation of food waste in Singapore was 542,700 tons in 2006 and reached about 570,000 tons in the year 2008 (NEA, 2009). Proper treatment and management of food waste is a challenge faced by any developing nation as untreated and unmanaged food waste creates odor, hygiene concerns and cause adverse environmental impacts.

Singapore is a highly populated, industrialized city with limited land area that can be used as landfills. Semakau Landfill is Singapore's only landfill for waste disposal. Singapore's offshore landfill may only accept inert wastes that are inorganic. Therefore, no food waste is sent to the landfill and the majority of food waste is directed to incinerators (Tan and Khoo, 2006). A remaining 10–15% is sent for recycling via anaerobic digestion (AD), followed by composting of the digestate material.

According to the Singapore Green Plan 2012, up to 30% of food waste recycling has to be achieved year 2012 (MEWR, 2008). This article will focus on the present and future options of increasing food waste recycling, which includes a proposed aerobic composting plant. The

environmental impacts of the food waste conversion options are projected based on a life cycle assessment perspective.

2. Food waste conversion options

Since Singapore has become a signatory to the Kyoto Protocol in April 2006, energy efficient and more sustainable waste treatment methods will be sought after. The food conversion methods that are introduced in this article are: incineration, recycling via AD combined with composting of digestate matter, and a proposed aerobic composting plant.

2.1. Incineration (waste-to-energy)

Incineration or waste-to-energy has been employed widely to generate energy from waste materials, as well as to reduce the volume of waste substantially. As land is limited, Singapore has adopted the policy of incinerating all 'incinerable' solid waste, including food waste (NEA, 2009). Incineration is a mature technology that involves the combustion and conversion of MSW into heat and energy (McDougall and Hruska, 2000). Incinerators are able to reduce the volume of solid wastes by 80%, which makes them popular in countries that have limited territory for landfills. Singapore's four incinerators are Ulu Pandan, Tuas, Senoko and Tuas South. The proportions of food waste input treated by the four incinerators are calculated to be 12.88%, 16.52%, 34.66% and 35.95% respectively. A typical incinerator requires the energy input of 70 kWh/ton waste and generates around 20% ash (Tan and Khoo, 2006).

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2.2. Anaerobic digestion and composting

The recycling of food waste is carried out by a Singapore-based company IUT Global Pte. Ltd. (IUT Global, 2006) using anaerobic digestion (AD) method combined with composting. The main product, bio-gas, from the AD process is transferred into gas engines to generate energy, which is then sold to the national grid. An additional step in the process converts the residues from the anaerobic digester, or digestate material, into bio-compost. Fig. 1 describes the process of the AD and the composting of digestate.

The composting process involves the use of microorganisms to break down the residues in the presence of oxygen, thus avoiding the production of methane. The bio-compost material can be used as a replacement of mineral fertilizers. From the compost products, carbon dioxide savings can be achieved by the avoided production of the mineral fertilizers (Schleiss et al., 2008). The nutrient contents of the bio-compost are assumed to be 0.0076 kg N and 0.0011 kg P per kg for digested matter by AD process (Finnveden et al., 2000).

The waste food recycling process by IUT Global is separated into two phases, each with similar AD processes but different capacities. The present Phase I recycling has an installed capacity of 3.5 MW power and treats 300 tons of food waste per day. From here, the digestate material is sent to composting plant I to produce bio-compost. Phase II has an installed capacity of 6 MW power and treats 500 tons of food waste per day; digestate from Phase II is sent to composting plant II (CDM, Clean Development Mechanism, 2006). The combined capacities of phases I and II can achieve the goal of 800 tpd (tons per day) food waste recycling for the whole of Singapore. In this analysis, we assume that the present Phase I recycling plant is able to run at full capacity, and Phase II will be also be operating at full capacity in the near future.

The recycling of food waste into electrical energy and compost is IUT Global's solution to reduce the amount of food waste entering incineration plants, and at the same time earn carbon credits from reduced greenhouse gas emissions (CDM, Clean Development Mechanism, 2006).

2.3. Proposed small-scale composting facility

An additional composting plant is proposed for the purpose of increasing the recycling options, and also for diverting food waste away from incinerators. The proposed composting process is an aerobic type based on Lee et al. (2007). As shown in Fig. 2, the only output of the composting plant is bio-compost. It is assumed that sawdust material does not impose any additional environmental impacts for the system and is not included in the investigation.

The bio-compost from aerobic composting can also be used to replace mineral fertilizer. Both AD bio-compost (from digestate matter) and aerobic bio-compost products are expected to contain different nutrients. The P and N content of compost product reported by Finnveden et al. (2000) will be assumed in this case, which is 0.0083 kg N and 0.002 kg P per kg per bio-compost.

Table 1 summarizes the energy requirements of each process, and the amounts of the main products – electrical energy and bio-compost.

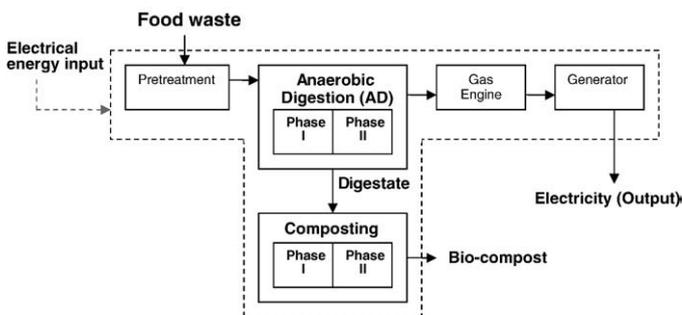


Fig. 1. Food waste recycling facility – adapted from IUT Global (2006).

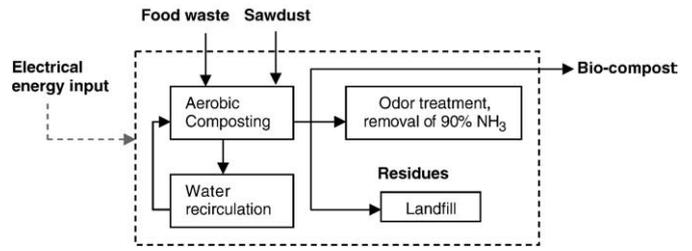


Fig. 2. Aerobic composting food waste – adapted from Lee et al. (2007).

The information was supplied by IUT Global's Clean Development Mechanism report document (CDM, Clean Development Mechanism, 2006) and Lee et al. (2007).

Greenhouse gas savings in terms of CO₂-eq are reported to be 5.3 kg/kg N mineral fertilizer and 0.52 kg/kg P mineral fertilizer (Schleiss et al., 2008).

3. Life cycle assessment

The evaluation of the environmental impacts of waste treatment or conversion options is extremely important for the purpose of protecting the community at large as well as preserving the natural environmental settings of a small island-nation. Life cycle assessment or LCA is seen as an emerging tool to measure and compare the environmental impacts of human activities (Rebitzer et al., 2004; Pennington et al., 2004). LCA models have become the principal decision support tools for policy makers at all levels for waste management strategies (Christensen et al., 2007). One of the benefits of LCA is the identification and quantification of the potential environmental impacts of different waste management technologies (Buttol et al., 2007). In another example, the environmental performances of various solid waste treatment systems were evaluated by Khoo (2009) to support a holistic approach to sustainable waste management and to provide direction for developing environmentally sound strategies.

3.1. Goal and scope

The goal of the LCA is to provide information to governmental-level organizations on technology selection for future food waste conversion in Singapore. The following waste conversion scenarios are modeled to compare their environmental impacts:

- Scenario 1: Recycling of food waste (Phase I and Composting I), with the rest incinerated
- Scenario 2: Recycling of food waste (Phase II and Composting II), with the rest incinerated

Table 1 Information of waste treatment options.

Food waste treatment	Pretreatment (kWh/ton)	Energy consumption (kWh/ton)	Energy output (kWh/ton)	Amount of compost (tons/year)
<i>Recycling by anaerobic digester (AD) and composting by IUT Global (2006)</i>				
Phase I recycling and Composting I	25.0	32.0	260.82	66,000
Phase II recycling and Composting II		24.0	268.27	112,200
<i>Incinerators (waste-to-energy)</i>				
Ulu Pandan	0	70.0	89.0	0
Tuas	0		128.0	0
Senoko	0		136.0	0
Tuas South	0		174.0	0
<i>Proposed aerobic composting plant (Lee et al., 2007)</i>				
Proposed composting plant	62.0		0	25,534.68

Scenario 3: Recycling of food waste (Phases I–II and Composting I–II), with the rest incinerated

Scenario 4: Recycling of food waste (Phases I–II and Composting I–II), with the rest of the food waste incinerated (50%) and treated at a proposed aerobic composting plant (50%)

The LCA scope covers the national boundary of the amount of food waste generated per year for processing at three options – incineration, recycling and aerobic composting. Each stage starts with generation and next, treatment/pre-processing, waste conversion and finally product and co-product generation. Within the system boundary, the following assumptions and limitations are applied:

- transportation emissions are not included. It is estimated that the transportation distances between the waste collection points to each waste processing plants (incinerators, AD, composting) are all within 15 to 20 km, therefore the transport emissions for each scenario will not pose any considerable differences in the LCA results and are left out of the analysis
- the system boundary includes two product outputs: electrical energy and bio-compost
- the LCA system takes into account the use of bio-compost. It is also assumed that the replacement of mineral fertilizers with bio-compost is suitable for the same application in the country
- all electricity requirements come from Singapore national grid power
- Construction materials for all waste treatment plants and chemical inputs are not included in the system boundary.

In LCA, the functional unit is the definition of the functional outputs of the product system. The main purpose of the functional unit is to provide a reference to which the inputs and outputs can be related (Rebitzer et al., 2004). Since the goal is to provide information for future food waste conversion options, the functional unit for all scenarios is the potential future amount of food waste generated in Singapore, that is, 570,000 tons/year.

The distribution of waste sent for recycling, incineration and aerobic composting for each scenario are shown in Table 2. The LCA model representing the four different scenarios of food waste conversion is displayed in Fig. 3. For all four scenarios, the distributed amount of food waste sent to each incinerator is assumed to remain unchanged: a%= 12.88 (Ulu Pandan); b%= 16.52 (Tuas); c%= 34.66 (Senoko); and d%= 35.95 (Tuas South).

3.2. Life cycle inventory (LCI)

In this part of the LCA, the LCI data is compiled and presented. Rebitzer et al. (2004) explained that the aim of LCI is to “calculate the quantities of different resources required and emissions and waste generated per functional unit”. In this evaluation we take into account energy as the main resource, the direct and indirect air emissions from

the processes and energy requirements, and product output per functional unit. The energy inputs for all food waste conversion or recycling plants are supplied by Singapore national grid. The main emissions per kWh power supplied are shown in Table 3. The inventory data for emissions to air for bio-waste sent to incinerators and AD is from Ecolnvent (2009a, 2009b). Emissions from aerobic composting were extracted from Lee et al. (2007). These are compiled in Table 4.

Previous studies of national MSW management in Singapore showed that transportation and landfill emissions hardly contribute to the environmental impacts of waste disposal options (Tan and Khoo, 2006), therefore the emissions from these two stages can be conveniently dismissed.

4. Results and discussions

4.1. Impact assessment

The advantage of conducting an LCA lies in its holistic approach of addressing a wide range of environmental impacts. The impact assessment stage of any LCA case study topic consists of two main procedures. The mandatory steps include the selection of relevant impact categories, based on the substances released to the environment. Further procedures such as grouping (normalized results) and data analysis are considered optional steps (Fig. 4; Table 5).

The category indicator results selected are global warming potential, acidification, eutrophication, photochemical oxidation, and energy use. These were chosen on the basis that they are most relevant to the food waste treatment options being compared. The Environmental Development of Industrial Products or EDIP 2007 is used as the basis for the environmental impact calculation (Hauschild and Potting, 2003).

The last impact category, energy use, is based on the amount of electrical energy measured in MJ-eq that is supplied to, and generated from, all waste conversion options. The inclusion of this fifth impact category allows the evaluation of all scenarios not just based on environmental performance alone, but also on useful product output. The results are displayed in Figs. 5 (global warming), 6 (acidification), 7 (eutrophication), 8 (photochemical oxidation) and 9 (energy use).

As expected, a steady downward trend of environmental impacts is observed for all four incinerators from Scenarios 1 to 4. The impacts of global warming for the recycling of food waste by AD combined with composting are relatively minimal in all four scenarios (Fig. 5). While contributions to global warming are caused by indirect emissions from energy consumption and direct emissions from the AD process itself, these impacts are considerably reduced via carbon savings achieved from compost products. The total amounts of CO₂-eq, from avoided mineral fertilizer production, for all four cases are: – 2.7E+06 kg CO₂-eq (Scenario 1), – 4.58E+06 kg CO₂-eq (Scenario 2), – 7.28E+06 kg CO₂-eq (Scenario 3), and – 8.43E+06 kg CO₂-eq (Scenario 4). Therefore, with the employment of more advanced recycling technologies, the greenhouse gas emissions due to food waste treatment and conversion will likely reduce. An LCA case study by Güereca et al. (2006) on a near similar study of present and future options for processing biowaste also presented results of reduced global warming impacts due to the use of future biowaste management systems. One of the options discussed by the authors was the composting of material from biogasification, while reducing the amount of biowaste sent to incinerators.

The global warming result for the proposed aerobic composting is relatively higher than the incinerators in Scenario 4. This is due to the high energy consumption (62 kWh/ton) for the proposed plant, along with the small compost output, which is reported by Lee et al. (2007) as 0.17 ton/ton food waste. This energy requirements, and associated greenhouse gases from it, corresponds reasonably well with those reported by Lundie and Peters (2005) for the centralized composting of food and garden waste (72 kWh/ton bio-waste).

Table 2

Information of four scenarios for waste treatment.

Scenarios	2009	Future (tons/year)			
	(tons/year)	1	2	3	4
X	570,000	570,000	570,000	570,000	570,000
Y	60,888	387,500	300,408	150,204	
Z (% recycled by AD)	97,092 (17.03%)	182,500 (32.0%)	269,592 (47.3%)	269,592 (47.3%)	
Z' (% recycled by aerobic composting)	0	0	0	150,204 (26.4%)	

X: Amount of food waste generated (functional unit).

Y: Amount of food waste incinerated.

Z: Amount of food waste recycled via AD combined with composting of digestate.

Z': Amount of food waste sent to proposed aerobic composting plant.

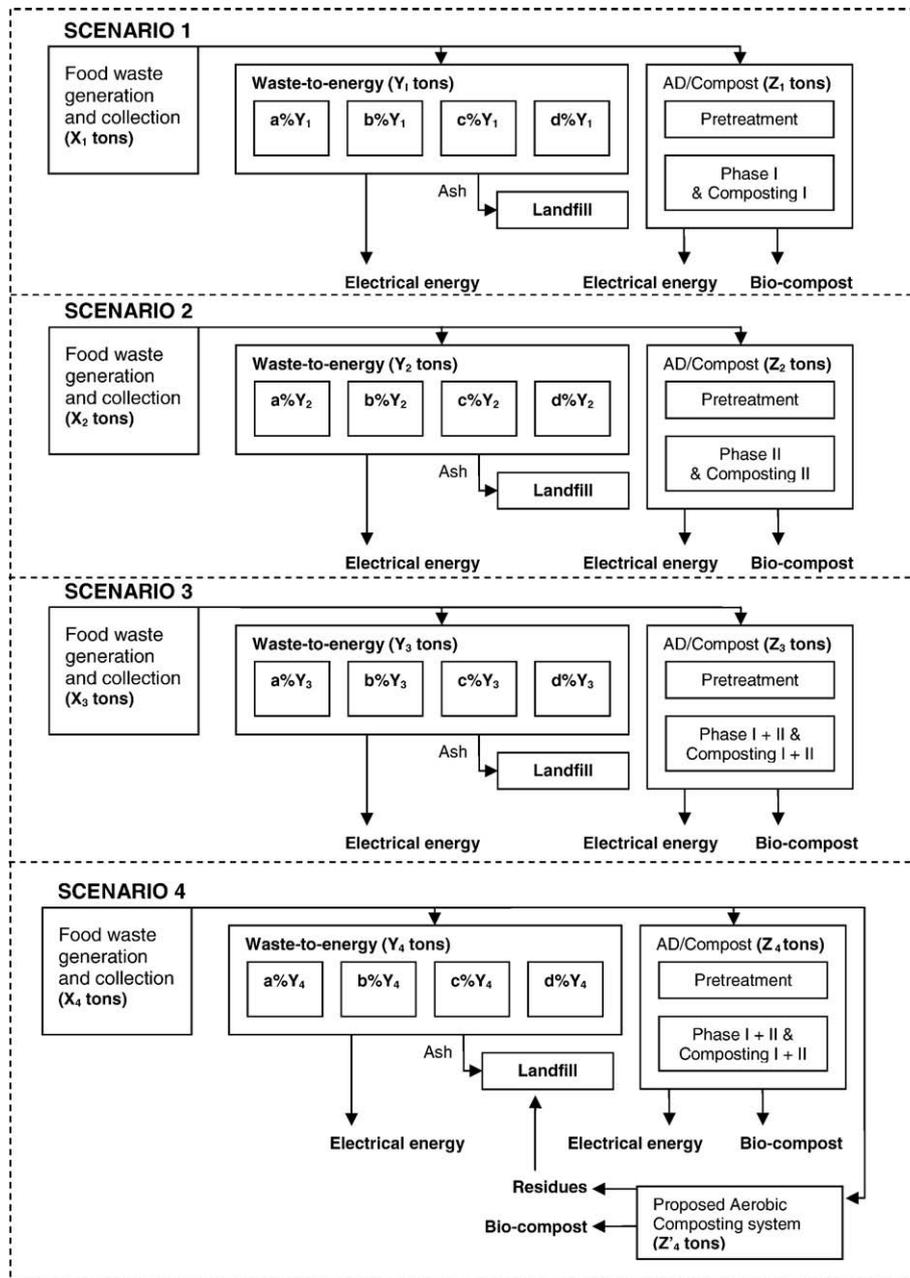


Fig. 3. LCA model for four different scenarios of food waste conversion options.

From Fig. 6, one of the highest impacts is found in Scenario 4, due to the proposed aerobic composting. Composting generates high emissions of ammonia (NH₃). Rather similar acidification result due to NH₃ was also reported by Güereca et al. (2006) on various composting methods. The amount of gaseous NH₃, which is the main available nitrogenous compound from nitrogen transformation depends on the aerobic composting process parameters, types of organic matter treated, and their respective C:N ratios (Cronje et al., 2002). De Guardia et al. (2008) reported that an optimum C:N ratio ranging between 15 and 30 was recommended for rapid composting. Wang et al. (2003), on the other hand, stated that an acceptable C:N ratio in composting material is in the range 20 to 30. It was also

suggested by the authors that sewage sludge can be added to food waste in aerobic composting. The LCA model (Fig. 3), and subsequent environmental impacts, was built based on the aerobic composting conditions by Lee et al. (2007). The reported NH₃ emissions are 6 kg/ton, after assuming a 90% NH₃ removal by biological odor treatment. However, there is still a need for a better understanding of ammonification, ammonia emissions, and nitrification and denitrification processes during aerobic composting.

Also on Fig. 6, the contributions to acidification show an overall steady decrease for all four incinerators from Scenarios 1 to 4. But the opposite is observed for the AD recycling process, where an upward trend is displayed.

Table 3
Singapore electricity grid emissions (Wong, 2002).

Pollutant (kg/kWh)	CO	CO ₂	CH ₄	N ₂ O	NO _x	SO _x	PM	NM VOC
	1.78E-04	5.00E-01	8.15E-06	3.03E-06	1.19E-04	7.34E-04	1.16E-05	2.17E-05

Table 4
Emissions to air from various bio-waste conversion processes.

Air emissions (kg/kg)	Waste-to-energy ^a	Anaerobic digestion and composting ^b	Aerobic composting ^c
CO	1.60E-04	1.13E-06	4.40E-03
CO ₂	5.90E-01	6.00E-03	2.10E-01
CH ₄	3.83E-05	1.64E-05	9.70E-04
N ₂ O	1.25E-05	8.15E-05	2.10E-07
NO _x	3.78E-04	4.50E-05	6.90E-05
SO _x	1.30E-05	3.19E-05	1.10E-04
Ammonia	3.45E-07	1.65E-07	2.40E-05
NMVC	6.99E-05	2.70E-05	Not reported

^a Ecolnvent (2009a) for bio-waste treated at incinerator.

^b Ecolnvent (2009b) for bio-waste treated by AD.

^c Lee et al. (2007).

The same environmental impact trends for the incinerators are repeated for eutrophication (Fig. 7) and photochemical oxidation (Fig. 8) results. Contributions to eutrophication, caused by ammonia and NO_x emissions, for recycling is rather minimal. In Scenario 4, the impacts of eutrophication from proposed aerobic composting is comparable to two of the incinerators. These results differ from those reported by Güereca et al. (2006) in comparing present and future biowaste treatment systems. Their case study in Barcelona, Spain, displayed a significant drop in eutrophication impacts due to the future technology of preventing leachates and other pollution from landfills. As for the case study of food waste disposal in Australia, Lundie and Peters' (2005) report on eutrophication was highest for food waste processor and lowest for home composting. In the present case study for Singapore, landfills are not considered at all in waste food disposal.

From Fig. 8, it is observed that the highest impact of photochemical oxidation is from Senoko and Tuas South (Scenarios 1–2) and next, from the recycling of food waste (Scenarios 3–4). Fig. 9 shows that the best case of net energy generation comes from Scenario 3. The most efficient net energy generation (difference between energy input and output) is from IUT Global, which is an impressive 78% for Recycling Phase I and 82% for Recycling Phase II (CDM, Clean Development Mechanism, 2006). For the last option, the proposed aerobic composting process does not generate any form of energy output and displays a positive graph which indicates the amount of energy spent or consumed.

4.2. Normalized results

Many methods allow the impact category indicator results to be compared by a reference, usually a regional value. In normalization of

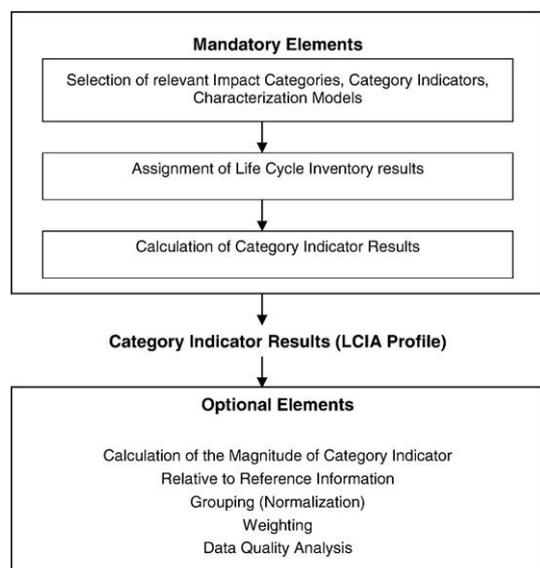


Fig. 4. Elements of life cycle impact assessment according to ISO 14042 (2000).

Table 5
Normalized values for Singapore.

Impact categories	Normalize values for the country	Unit
Global warming potential	10,227.04	kg CO ₂ -eq/capita/year
Acidification	87.38	kg SO ₂ -eq/capita/year
Eutrophication	4.22	kg PO ₄ -eq/capita/year
Photochemical oxidation	16.37	kg C ₂ H ₄ -eq/capita/year
Energy	29,358	MJ-eq/capita/year

results, the previous impacts (from Figs. 5–9) are each divided by the selected reference values. This is done to aid in the interpretation of the individual and separate impact category indicators, and generate a single score for comparison of two or more technological options (Sleeswijk et al., 2008). In other such LCA case studies, normalization was performed to better understand the relative significance of each waste disposal impacts (Lundie and Peters, 2005).

Normalization is made in LCIA to indicate the relative significance of the various environmental impacts of the LCA system, taking into account the geographical area where the activities in the LCA occur. The aim of normalization is typically to place the LCIA indicator results into a broader context and to create a common dimension for all five results (from Figs. 5–9) so that they can be combined to compare Scenarios 1 – 4 side by side (Pennington et al., 2004). In this case study, normalization was carried out based on the national inventory of pollutants in Singapore as the reference system.

Normalization follows a few basic steps. The national inventory of pollutants for Singapore (e.g., country's total greenhouse gas or acidic emissions) is first used to calculate each of the impacts (e.g., country's total kg CO₂-eq or SO₂-eq). The total is then divided by the country's population, which is reported to be 4.84 million in June 2008 (Statistics Singapore, 2009). The emission inventories are extracted from United Nations Statistic Division (2007) and Ohara et al. (2007). As an example, the total acidic gases for Singapore are reported as 287,000 tons of SO₂ and 157,000 tons of NO_x. According to the EDIP 2003, the characterizations for SO₂ and NO_x are 1.2 and 0.5 respectively. Hence the normalized value selected for acidification impact is:

$$[(287,000,000 \times 1.2) + (157,000,000 \times 0.5)] / (4.84 \times 1,000,000) = 87.38 \text{ kg SO}_2\text{-eq/capita}$$

For last impact category on energy use/generation, Singapore's total electricity consumption per capita is taken into consideration, that is, 29,358 MJ-eq/capita (Energy Market Authority, 2009). This is because the results generated in Fig. 9 are all based on electrical energy input and output alone. The normalized results are shown in Fig. 10.

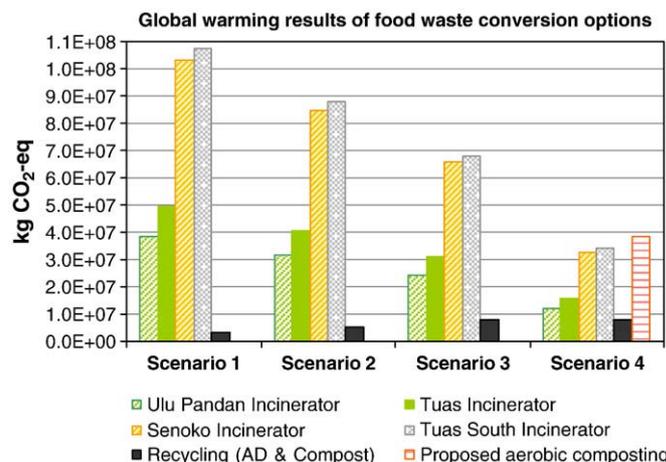


Fig. 5. Global warming results.

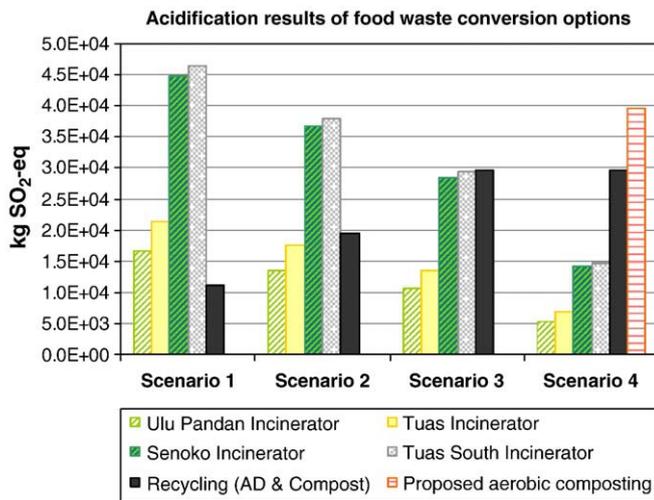


Fig. 6. Acidification results.

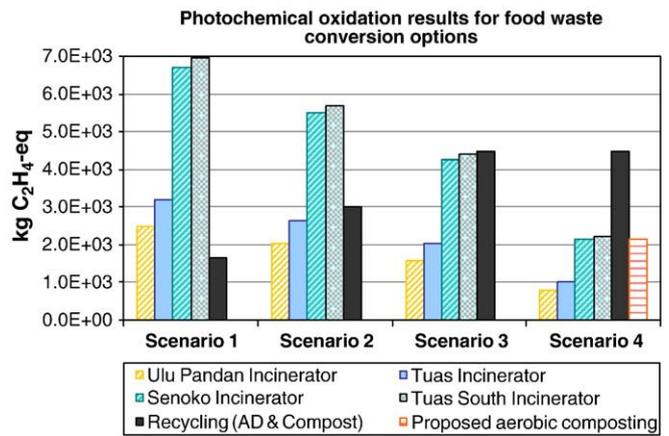


Fig. 8. Photochemical oxidation results.

Step-by-step efforts to divert food waste away from incinerators towards recycling or composting facilities are known to deliver environmentally improved results. Fig. 9 shows the environmental improvements that can potentially be obtained: 25.5% from Scenario 1 to 2; 38.0% from 2 to 3; and finally 30.3% from 3 to 4. The final results from Fig. 10 agree with other near similar waste treatment studies. Sonesson et al. (2000) indicated that anaerobic digestion (AD) results in the lowest environmental impact of all solid waste management systems, while composting offers environmental advantages over incineration methods.

Although the proposed aerobic composting system delivers low yield of compost material without the benefit generating energy outputs, Scenario 4 is still environmentally favorable compared to treating solid waste in incinerators. Compost materials are rich in organic matter, so its ability to replace mineral fertilizers is difficult to estimate. In this article we estimated the P and N output of compost from AD and aerobic systems as suggested by Finnveden et al. (2000): 0.0076 kg N and 0.0011 kg P per kg compost from AD digested material; and 0.0083 kg N and 0.002 kg P per kg bio-compost from aerobic composting. It is also worth noting that other amounts of P and N values were reported from the output products of various bio-solids and wastes treatment processes (Peters and Rowley, 2009; Lundin et al., 2000). Peters and Rowley (2009) tested the reuse of biosolids content from sludge, whereas Lundin et al. (2000) examined different treatments of wastewater.

Compared to the AD combined with the composting facility by IUT Global (2006), aerobic composting can only be proposed or recommended as a small scale facility. Björklund et al. (1999) concluded that large-scale centralized composting might increase environmental impacts relative to AD processes. Another study performed by Komilis and Ham (2004) reported that high gaseous emissions of CO₂ and NH₃ were produced during aerobic composting process of solid waste, which is in accordance with the results shown in Figs. 5 (global warming) and 6 (acidification). Therefore, the long-term sustainable solution that should be recommended is to expand the capacity or the AD recycling plants employed by IUT Global (2006).

As opposed to LCA investigations of bio-waste or food/garden wastes carried out by others (Güereca et al., 2006; Lundie and Peters, 2005), transportation was not included in the system boundary. This may be one of the limiting factors in the case study. However, it should be highlighted that the estimated travel distances are approximately the same (15–20 km) from waste collection points to all waste processing centers – therefore no considerable differences will be shown on all LCA results. It is also worth noting that the management of food waste, or any other organic or biowaste, in Singapore is a unique case since the nation's only offshore landfill in Semakau island only accepts inert and non-organic waste materials.

5. Conclusions

Proper management and recycling of food waste is one of the challenges faced by Singapore in its pursuit to maintain a good 'Clean and Green' image of a garden-city state. The environmental impacts of food waste distribution to the following were compared: incineration,

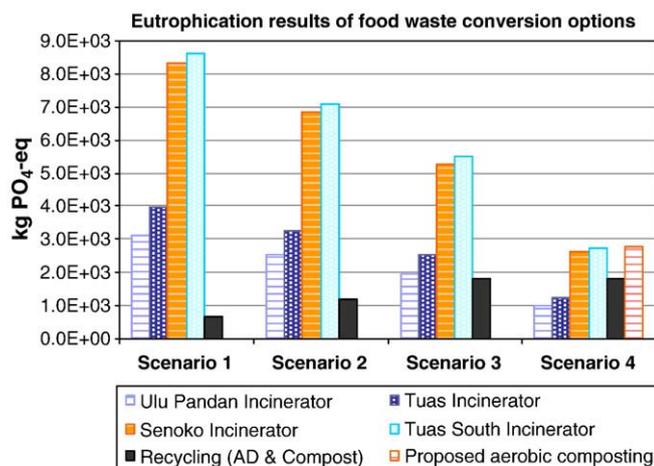


Fig. 7. Eutrophication results.

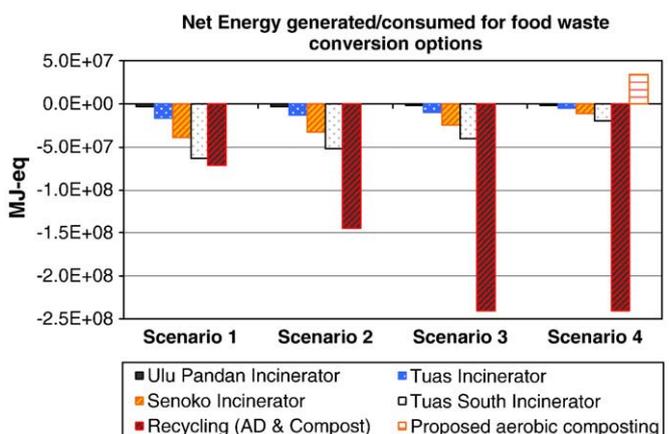


Fig. 9. Energy use/generation results (due to electricity).

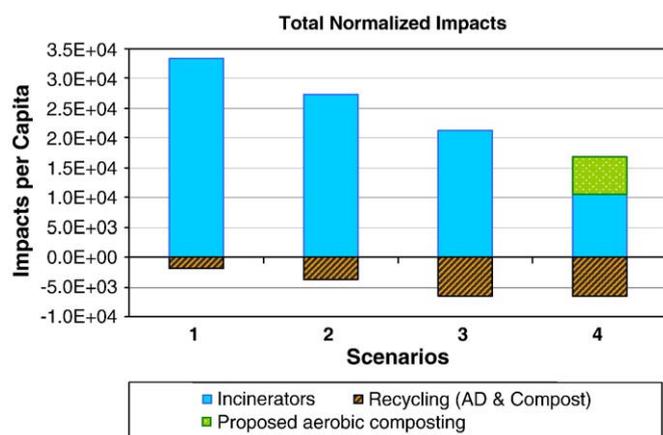


Fig. 10. Total normalized results.

recycling via AD combined with composting of digestate matter, and a proposed small-scale aerobic composting plant. The conclusions can be summarized as follows:

- Significant reduction of global warming impacts can be realized by implementing the food waste AD recycling process. This was achieved by both reduced energy requirements for the process itself and CO₂ savings from the compost produced from the digestate material.
- Aerobic composting showed environmentally favorable results compared with the mass incineration of food waste. However, aerobic composting is less preferred compared to AD due mainly to CO₂ and NH₃ emissions, as well as, low amount of bio-compost produced.
- It was suggested, however, that further investigations is needed to test the value of N and P nutrients of the compost products from both methods. Additional studies are also required to examine aerobic composting on local food waste samples to test its potential to obtain higher output.
- Energy generation from the food waste AD recycling process was projected to be an impressive 78% for Recycling Phase I and 82% for Recycling Phase II, assuming that both recycling phases are operating at full capacity.
- The AD's Recycling Phase II operating at full capacity alone will allow Singapore Green Plan's 2012 aim to increase the recycling of food waste to 30% to be achieved; combined Phase I and II increases the recycling rate to about 47%; further increase in recycling rate is possible with a proposed aerobic composting plant.
- Small-scale composting can be recommended as a way to divert food waste away from incinerators, however, a more sustainable solution will be to expand the operating capacity of the AD recycling facility.

References

- Buttol P, Masoni P, Bonoli A, Goldoni S, Belladonna V, Cavazzuti C. LCA of integrated MSW management systems: case study of the Bologna District. *Waste Manage* 2007;27:1059–70.
- Björklund A, Dalemo M, Sonesson U. Evaluating a municipal waste management plan using OWARE. *J Clean Prod* 1999;7:271–80.
- CDM (Clean Development Mechanism). 9.5 MW Food Waste Based Grid Connected Power Project Implemented by IUT Singapore Pte Ltd, Singapore. UNFCCC Clean Development Mechanism Project Design Document; 2006.

- Christensen TH, Bhandar G, Lindvall H, Larsen AW, Fruergaard T, Damgaard A, Manfredi S, Boldrin A, Riber C, Hauschild M. Experience with the use of LCA-modelling (EASEWASTE) in waste management. *Waste Manage Res* 2007;25:257–62.
- Cronje AL, Barker AJ, Guy S, Turner C, Williams AG. Ammonia emissions and pathogen inactivation during composting. In: Michel FC, Rynk RF, Hoitink HAJ, editors. *Composting and compost utilization*. Emmaus, PA: The J.G Press Inc; 2002. p. 845–56.
- De Guardia A, Petiot C, Rogeau D, Druilhe C. Influence of aeration rate on nitrogen dynamics during composting. *Waste Manage* 2008;28:575–87.
- EcolInvent. Waste treatment: biowaste to municipal incinerator; 2009a.
- EcolInvent. Waste treatment: biowaste to anaerobic digestion; 2009b.
- Energy Market Authority. Overview of the energy situation in Singapore; 2009. <http://www.lowcarbonsingapore.com/2009/05/14/overview-of-the-energy-situation-in-singapore>.
- Finnveden G, Johansson J, Lind P, Moberg Å. Life cycle assessments of energy from solid waste, Stockholm; 2000. <http://www.infra.kth.se/fms/>.
- Güereca LP, Gasso S, Baldasano JM, Jimenez-Guerrero P. Life cycle assessment of two biowaste management systems for Barcelona. *Spain Res Rec Conserv* 2006;49:32–48.
- Hauschild M, Potting J. Spatial differentiation in life cycle impact assessment – the EDIP 2003 methodology. Institute for Product Development Technical University of Denmark; 2003.
- ISO 14042. Environmental management—life cycle assessment—life cycle impact assessment. Geneva, Switzerland: International Standards Organisation (ISO); 2000.
- IUT Global. Innovative waste technologies and solutions, 2006 (<http://www.iutglobal.com/>).
- Khoo HH. Life cycle impact assessment of waste conversion technologies. *Waste Manage* 2009;29:1892–900.
- Komilis DP, Ham RK. Life cycle inventory of municipal solid waste and yard waste windrow composting in the United States. *J Env Engr* 2004;1390–400.
- Lee SH, Choi LI, Osako M, Dong JI. Evaluation of environmental burdens caused by changes of food waste management systems in Seoul. *Korea Sci Total Environ* 2007;387:42–53.
- Lundie S, Peters GM. Life cycle assessment of food waste management options. *J Clean Prod* 2005;13:275–86.
- Lundin M, Bengtsson M, Molander S. Life cycle assessment of wastewater systems: influence of system boundaries and scale on calculated environmental loads. *Env Sci Technol* 2000;34:180–6.
- McDougall FR, Hruska JP. Report: the use of Life Cycle Inventory tools to support an integrated approach to solid waste management. *Waste Manage* 2000;18:590–4.
- MEWR (Ministry of the Environment and Water Resources). Singapore Green Plan 2012, 2008 (<http://app.mewr.gov.sg/web/Common/homepage.aspx>).
- NEA (National Environmental Agency). Solid Waste Management, 2009 (<http://app2.nea.gov.sg/index.aspx>).
- Ohara T, Akimoto H, Kurokawa J, Horii N, Yamaji K, Yan X, Hayasaka T. An Asian emission inventory of anthropogenic emission sources for the period 1980–2020. *Atmos Chem Phys* 2007;7:4419–44.
- Pennington DW, Potting J, Finnveden G, Lindeijer E, Joliet O, Rydberg T, Rebitzer G. Life cycle assessment – part 2: current impact assessment practice. *Env Intl* 2004;30:721–39.
- Peters GM, Rowley HV. Environmental comparison of biosolids management systems using life cycle assessment. *Env Sci Technol* 2009;43:2674–9.
- Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, Schmidt WP, Suh S, Weidema BP, Pennington DW. Life cycle assessment – part 1: framework, goal and cope definition, inventory analysis, and applications. *Env Intl* 2004;30:701–20.
- Sonesson B, Björklund A, Carlsson M, Dalemo M. Environmental and economic analysis of management systems for biodegradable waste. *Res Conser Rec* 2000;28:29–53.
- Schleiss, K., GHG savings from biological treatment and application of compost, prod. moving organic waste recycling towards resource management and biobased economy. In: 6th international conference, ECN/ORBIT e.v. workshop, Oct 13–15, Wageningen, The Netherlands, 2008.
- Sleeswijk AW, van Oers LFCM, Guinée JB, Struijs J, Huijbregts MAJ. Normalisation in product life cycle assessment: an LCA of the global and European economic systems in the year 2000. *Sci Tot Env* 2008;11:227–40.
- Statistics Singapore. Government of Singapore, 2009 (<http://www.singstat.gov.sg/>).
- Tan RBH, Khoo HH. Impact assessment of waste management options in Singapore. *J Air Waste Manage Assoc* 2006;56:244–54.
- United Nations Statistics Division, Environment statistics country snapshot: Singapore, United Nations Publications Board, United Nations, New York, US, 2007 (http://unstats.un.org/unsd/environment/envpdf/Country%20Snapshots_apr2007/Singapore.pdf).
- Wang JY, Stabnikova O, Tay STL, Ivanov V, Tay JH. Intensive bioconversion of sewage sludge and food waste by *Bacillus thermoamylovorans*. *World J Microbio Biotech* 2003;19:427–32.
- Wong CK. Development of LCI database for Singapore electricity production. Final Year Report. Department of Chemical and Environmental Engineering, National University of Singapore; 2002.