Emission of greenhouse gases from home aerobic composting, anaerobic digestion and vermicomposting of household wastes in Brisbane (Australia)

Author

Chan, YC, Sinha, RK, Wang, W

Published

2011

Journal Title

Waste Management and Research

DOI

10.1177/0734242X10375587

Rights statement

Downloaded from

Griffith Research Online

Emission of greenhouse gases from home aerobic composting, anaerobic digestion and vermicomposting of household wastes in Brisbane (Australia)

Y.C. Chan[1*], R.K. Sinha[1], W. J. Wang[2]

[1] Griffith University, Nathan, QLD 4111, Australia

[2] Department of Environment and Resource Management, 80 Meiers Rd, Indooroopilly QLD 4068, Australia

[*] Corresponding author. Fax: 617 37357459. Email address: a.chan@griffith.edu.au.

Abstract

This study investigated greenhouse gas (GHG) emissions from three different home waste treatment methods in Brisbane, Australia. Gas samples were taken monthly from 34 backyard composting bins from January to April 2009. Averaged over the study period, the aerobic composting bins released lower amounts of CH_4 (2.2 mg m^{-2} hr^{-1}) than the anaerobic digestion bins (9.5 mg m^{-2} hr^{-1}) and the vermicomposting bins (4.8 mg m^{-2} hr^{-1}). The vermicomposting bins had lower N_2O emission rates (1.2 mg m^{-2} hr^{-1}) than the others (1.5-1.6 mg m^{-2} hr^{-1}). Total GHG emissions including both N_2O and CH_4 were 463, 504 and 694 mg CO_2-e m^{-2} hr^{-1} for vermicomposting, aerobic composting and anaerobic digestion, respectively, with N_2O contributing >80% in the total budget. The GHG emissions varied substantially with time and were regulated by temperature, moisture content and the waste properties, indicating the potential to mitigate GHG emission through proper management of the composting systems. Comparing to other mainstream municipal waste management options including centralised composting and anaerobic digestion facilities, landfilling and incineration, home composting has the potential to reduce GHG emissions through both lower on-site emissions and the minimal need for transportation and processing. On account of the lower cost, our results suggested that home composting provides an effective and feasible supplementary waste management method to centralised facility in particular for cities with lower population density such as the Australian cities.

***Keywords*:** greenhouse gases, home composting, vermicomposting, anaerobic digestion, organic waste.

Introduction

Disposal of municipal solid waste (MSW) has been mainly through landfilling, incineration and centralised composting and anaerobic digestion facilities in urban areas around the world. These processes involve direct and indirect emissions of greenhouse gases (GHGs) including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and non-methane hydrocarbons (NMHCs) and contribute to around 3-4% of the anthropogenic GHG emissions in terms of CO_2-equivalent (CO_2-e) (Pipatti and Savolainen 1996, Papageorgiou et al. 2009, Australian Greenhouse Office 2007). More than 70% of MSW is disposed of in landfills in Australian and overseas cities (Queensland Environmental Protection Agency 2002; Aumonier 1996, Ernst 1990, Mohareb et al. 2008). Anaerobic decomposition of these wastes in the landfills results in the emission of CH_4 and as such contributes significantly to the global greenhouse budget (Hobson et al. 2005). Disposal of MSW contributed 17 million tonnes CO_2-e of GHG emissions in Australia in 2005, equivalent to the emissions from 4 million cars or 2.6% of the national emissions (Australian Greenhouse Office 2007).

Due to the challenge of climate change and other environmental concerns on landfills (Lisk 1991), government authorities around the world have introduced regulations to phase out or reduce waste going to landfills (Lee et al. 2007, Murphy and Power 2006, Department of Climate Change 2007) and encouraged alternative waste management options (Nolan ITU Pty Ltd 2004). The reduction of emissions from waste disposal has mainly been achieved by capturing the landfill gases and diversion of MSW (mainly by paper and material recycling) (Australian Greenhouse Office 2007). Domestic food and garden wastes contribute 15-70% of the MSW in urban areas. Composting of domestic wastes in centralised facilities and/or at source by residents has been perceived to have great potential in reducing GHG emissions (Tchobanoglous et al. 1993, Wei et al. 2000). For example, the Victorian, New South Wales and South Australia Governments in Australia have set targets of increasing the recycling rate to up to 75% by 2010 by promoting the composting of organic waste (Victorian Government Department of Sustainability and Environment 2009, Department of Climate Change 2007, Zero Waste South Australia 2005).

Three types of methods are common for the recycling of organic wastes, namely aerobic composting, anaerobic digestion and vermicomposting. In aerobic composting the waste is aerated by air flowing constantly through the open system and by intermittent turning of the waste by the operator. Anaerobic digestion is carried out in the oxygen deprived environment inside the closed chamber. Vermicomposting is similar to aerobic composting except that the composting and aeration processes are aided by the use of detritivorous worms. The type and emission rate of GHGs emitted from these processes, in particular household practices, have not been well studied (He et al. 2000). There have only been a small number of studies on the emission of GHGs from centralised composting and anaerobic digestion facilities. The findings from these studies indicate that GHG emissions are dependent on the method used and other factors such as the windrowing rate, age, depth, temperature and pore space of the compost mix (He et al. 2000; Majumdar et al. 2006; Hobson et al. 2005; Amon et al. 2006, Wihersaari 2005, Lundie & Peters 2005). Under aerobic composting conditions, the gas emitted is mainly CO_2 rather than CH_4 (Majumdar et al. 2006). Since this CO_2 is biogenic in origin it is usually not counted in the GHG emission budget (Intergovernmental Panel on Climate Change 2007, Department of Climate Change 2007). Emission of NMHCs has been found to be relatively small compared to emissions of CH_4 and N_2O. Anaerobic digestion has been found to emit more CH_4 than aerated composting (Mata-Álvarez et al. 2000). These findings show that the use of different methods under different conditions could result in very different type and amount of GHGs (Beck-Friis et al. 2000). More information is required on the actual effectiveness of different methods and conditions on GHG reduction.

The aim of this study was to investigate GHG emissions from different types of household organic waste treatment methods (aerobic composting, anaerobic digestion and vermicomposting) in relation to environmental conditions and the properties of the waste materials. The result will assist in the identification of better MSW management systems and practices with maximum GHG mitigation potential.

Materials and methods

Experimental design

This study was undertaken in 15 suburbs within 20 km from the Brisbane Central Business District (27.5°S 153°E) in southeast Queensland of Australia (Figure 1). Brisbane has a population of 1.95 million and a population density of 380 people per km^2 in 2008 (Australian Bureau of Statistics 2009).

22 volunteer households with 11 aerobic composting bins, 12 anaerobic digestion bins and 11 vermicomposting bins in total were involved in this study. The bins were located either in the backyard or front yard of the households.

(Figure 1 here)

Results of a survey conducted at the beginning of the study showed that the households in this study composted on average 4-5 kg of food and green waste in each bin each week. Similar to those reported in literature (Tchobanoglous et al. 1993), the waste the households composted in this study was about 50-70% food waste (mainly fruits and vegetables remnants and food left-over) and 30-50% green waste (mainly grass clipping). The actual mass and composition of waste and the maintenance of the bins varied among the volunteers. Most of the volunteers added the waste daily and retrieved the compost products monthly.

The bins used were commercially available from hardware stores with a volume of approximately 220 L (Figure 2). The aerobic bins have ventilation slots to facilitate airflow through them. The anaerobic bins were only opened during the addition of waste and retrieval of compost, and represent an anaerobic digester when the lid is closed. The vermicomposting bins are similar in structure to the aerobic bins but with a reservoir at the bottom to collect the leachates. The vermicomposting bins normally contained approximately 1500-2000 worms. Tiger Worm (*Eisenia fetida*), Indian Blue Worm (*Perionyx excavatus*), African Night Crawler (*Eudrilus euginae*) and Red Worm (*Lumbricus rebellus*) were the main worm species found in the vermicomposting bins in this study (Sinha et al. 2002). General instructions and guidance were also provided to the volunteers on the proper operation of the three types of systems. The vermicomposting bins were placed in shaded area. Meat products were not used, while dried grass clippings (high in carbon) were added to the food wastes (high in nitrogen) to maintain a carbon to nitrogen (C/N) ratio close to 25 to 1. Bulking agents such as mulches were also added in aerobic composting and vermicomposting bins to increase air pockets. Waste in the aerobic composting bins was turned weekly. Water was sprinkled in the bins to maintain a moisture content of 50-60% for the aerobic composting and anaerobic digestion bins and 60-70% for the vermicomposting bins. A two-bin rotating system was also recommended to allow 2-3 months for the compost to mature, although most of households in this study operated only one bin.

(Figure 2 here)

Sampling of CO_2, CH_4 and N_2O

Gas samples were collected during the last weekend of each month during January-April 2009. This period covers the humid summer and autumn seasons in Brisbane. In total 132 samplings were conducted (43 from aerobic bins, 45 from anaerobic bins and 44 from vermicomposting bins). Gas samples were taken by using the static chamber method (Zhang et al. 2008). A 0.7 L glass funnel with the stem cut off and replaced with a removable septum was used as the collection chamber (Figure 2). Duplicate sampling from different areas on the waste surface indicates good precision in results (relative standard deviation < 25% in general).

In each sampling, the inverted funnel with the septum removed was first pushed approximately 1 cm deep into the waste surface inside the bin. The rim of the funnel was wrapped around with waste and water applied if needed to provide a good air seal. The open funnel was left inside the bin with the lid of the bin closed for approximately 5 minutes before the septum was put back onto the funnel. Then the first air sample was taken from inside the funnel by inserting a 30 mL syringe through the septum. The air sample was then transferred from the syringe into an evacuated container. The bin was closed again for approximately 30 minutes then the second air sample was taken. Results from preliminary samplings show that the 30-minute duration was sufficient to produce precise results comparable to the results of longer duration.

Environmental and waste parameters including ambient temperature, temperature near the waste surface (at 2 cm below the surface) and inside the waste (at 8 cm below the surface), and the pH and moisture content in the waste were also determined. pH and moisture content were determined with a soil pH and moisture tester (Takemura Electric Works Model DM-15) by inserting the tester at 3 random positions to approximately 7 cm deep into the surface. DM-15 scales moisture content from 1 to 8. Most of the composting bins in this study returned a high moisture scale of 8 or beyond. Moisture scale readings beyond 8 were treated as 9 in the statistical analysis. The measured values from the replicate samplings were within ±2.8 ^{o}C, ±1.0 pH and ±1.2 moisture scale. Measurements of a set of compost-water mixtures with varying mass percentage of moisture showed that moisture scale 1 was equivalent to a moisture content of approximately 20%, while moisture scale 8 was equivalent to approximately 33%.

Analysis of CO_2, CH_4 and N_2O and estimation of GHG emission rates

The gas samples in the containers were analysed by a gas chromatograph (Varian 3800) within one week after the sampling. The Gas Chromatograph was equipped with a Thermal Conductivity Detector (GC-TCD), a Flame Ionisation Detector (GC-FID) and an Electron Capture Detector (GC-ECD) for the analysis of CO_2, CH_4 and N_2O, respectively. Dual Porapak columns using helium as the carrier gas for CO_2 and CH_4, and nitrogen as the carrier gas for N_2O were used in the analysis. CO_2 standards of 513, 1000, 2009 and 4020 ppm were used for the calibration of results, while 1.8 and 5.1 ppm standards were used for CH_4 and 0.50, 5.02, 12.1 and 18.7 ppm standards were used for N_2O.

The concentrations of CO_2, CH_4 and N_2O in the two samples collected from each sampling were used to estimate the emission rate of the GHGs from the bin. The emission rate in mg m^{-2} hr^{-1} was calculated by Eq. 1, based on the Ideal Gas Equation:

$$\text{Rate (mg m}^{-2}\text{ hr}^{-1}) = (C_2 - C_1) \times MW \times V / (0.08206 \times T \times A_1 \times D) \quad (1)$$

where C_1 and C_2 are the concentrations of the GHG in ppm in the two samples. MW is the molecular weight of the GHG. V is the volume of air above the waste surface inside the funnel = 5.44×10^{-4} m^3. A_1 is the area of the waste surface inside the funnel = 1.42×10^{-2} m^2 (Figure 2). T is the temperature in

Kelvin. D is the duration between the two samples in hour. The emission rate in terms of kg GHG kg^{-1} waste was estimated by Eq. 2:

$$\text{Rate (kg GHG kg}^{-1}\text{ waste)} = \text{Rate (mg m}^{-2}\text{ hr}^{-1}) \times A_2 \times 24 \times 7 \times 10^{-6} / W \qquad (2)$$

Where A_2 is the area of the waste surface inside the composting bin and W is the amount of food and green waste treated each week. The area of the waste surface was approximately 0.24 m^2 for the anaerobic bins and 0.25 m^2 for the aerobic and vermicomposting bins. The volunteers in this study added waste and retrieved compost products on a regular basis and W was assumed to be 4.5 kg. The CO_2-equivalents (CO_2-e) of CH_4 and N_2O were estimated using the global warming potential of 21 and 310, respectively (Intergovernmental Panel on Climate Change 2007).

Statistical analysis

Five of the 132 samplings conducted were found to have extreme CH_4 and/or N_2O emission rate values (beyond average + 4 s.d.) and were thus excluded from the statistical analysis. All the measured parameters were tested for normality by using the Kolmogorov-Smirnov test (Beck-Friis et al. 2000). At the significance level of 0.05, the emission rates of CO_2, CH_4 and N_2O were found to be lognormally distributed, and consequently the natural logarithmic values of these parameters were used in statistical comparison.

Pearson correlation analysis was used to investigate the correlation between the emission rates of the GHGs and the other measured parameters (Beck-Friis et al. 2000). ANOVA F-test was used to identify the influencing factors (waste treatment method, month of sampling and time of the day of sampling) of the GHG emission rates. Then t-test (Least Significant Difference, LSD) was used to investigate the influence of the identified factors on the emission rates. The significance level of 0.05 was used in these statistical tests. In this study, the samplings were conducted between 8 am and 7 pm, therefore the time of the day of sampling was categorised as ‘am’ (8- 10 am), ‘noon’ (11 am – 1 pm), ‘pm’ (2 – 4 pm) or ‘late pm’ (5 – 7 pm).

Results and Discussion

Emission rates of GHGs

A summary of the GHG emission rates and the environmental and waste parameters measured in this study is listed in Table 1. Anaerobic bins and vermicomposting bins emitted significantly higher amounts of CO_2 and CH_4 than the aerobic bins. This indicates that anaerobic bins and vermicomposting bins were more efficient in decomposing the carbon in waste into CO_2 and more favourable for CH_4 production than the aerobic bins.

(Table 1 here)

On the other hand, aerobic bins and anaerobic bins emitted significantly higher amounts of N_2O than the vermicomposting bins. Presumably, the N_2O emitted from the composting bins were mainly from the denitrifying process in anaerobic zones in the compost, but might also be created in the nitrifying process in aerobic zones (Beck-Friis et al. 2000) and the activities of the denitrifying bacteria within the earthworm gut (Hobson et al. 2005). The lower emission of N_2O from vermicomposting bins indicated that the emission of N_2O from worm gut was probably offset by the reduction of anaerobic denitrification, due to the burrowing action of the earthworms.

On the contrary, Hobson et al. (2005) found that for larger scale systems windrow composting emits more CH_4 but less N_2O than vermicomposting. This indicates that the process and rate of decomposition of organic materials in larger scale systems could be very different to those in home systems, due to the different level of ventilation and different worm density in the two types of systems. Beck-Friis et al. (2000) found that the co-existence of both anaerobic and aerobic conditions is not apparent in small, intensively managed compost heaps, therefore resulting in less CH_4 and N_2O emissions. In their study, a very high level of CH_4 emission was found from large compost heaps. They also found that N_2O emissions tend to be higher in compost heaps after prolonged storage. In this sense home composting systems reduce N_2O emissions because the owners retrieve compost products more frequently.

In terms of CO_2-e, CO_2 emissions contributed approximately 64% on average of the total GHG emissions in the aerobic bins, and about 80% of the total GHG emissions in the anaerobic bins and vermicomposting bins. When CO_2 emission was excluded from the accounting as is common practice, the three waste treatment methods emitted 463-694 mg CO_2-e m^{-2} hr^{-1} on average, largely attributable to N_2O emissions. LSD t-test showed that in terms of CO_2-e and with CO_2 emission included, anaerobic bins and vermicomposting bins emitted significantly higher amount of GHGs than the aerobic bins. But when CO_2 emission is excluded, there was no significant difference in the total GHG emissions between the 3 waste treatment methods.

Variation in GHG emissions in relation to environmental conditions and waste properties

The environmental conditions and waste properties for the three waste treatment methods are shown in Table 2. The temperature inside the waste in this study (26-48 ^oC) was lower than the optimum temperature (45-55 ^oC) suggested by Jäckel et al. (2005) for the oxidation of CH_4. However, given the much smaller size of the waste heaps for the home systems, attaining the optimum temperature may not be possible under normal circumstances. The temperature at 8 cm below the waste surface was higher than that at 2 cm below the waste surface in the aerobic and anaerobic bins. They were correlated to and higher than the ambient temperature ($r>0.32$), reflecting the biological activities in the waste. However, in the vermicomposting bins the temperature inside the waste was rather uniform and slightly lower than the ambient temperature. This could be due to the movement of the earthworms inside the waste making the temperature in the waste more uniform. Also the owners of the vermicomposting bins tend to moisturise their bins more often, therefore effectively reducing the temperature in the waste in the summer months. The moisture content was also significantly higher in the vermicomposting bins.

(Table 2 here)

The pH value of the waste was acidic to neutral (5.8-7.0) in all the waste treatment methods, which was within the range of international control standards on pH of composts (6.0-8.5; Wei et al. 2000, Tsai 2008).

Large variation in emission rates has been reported by other researchers for samples taken at different time of the day (Christensen et al. 1996). The temporal trends of GHG emissions in this study are shown in Table 3. The emission of CO_2 was not significantly different in the different months, and was higher at noon and lower in late afternoon. This is probably due to the higher temperature at noon speeding up the decomposition of organic material in waste. On the other hand the emissions of CH_4 and N_2O did not show any consistent temporal trends.

(Table 3 here)

In the aerobic composting and vermicomposting bins, CO_2 ($r>0.45$) and CH_4 ($r>0.63$) emissions were related to the temperature inside the waste, while N_2O emission was not. These findings are different to those of Beck-Friis et al. (2000) and Amlinger et al. (2008) in which N_2O emission was found to be related to waste temperature, perhaps because of the different size of the compost heaps in their studies and this study. Higher emission of CH_4 from wet waste stock has been reported by Brown and Subler (2007) but this relationship was not significant in this study. In the anaerobic bins, CO_2 emission was correlated to both the temperature ($r>0.33$) and moisture content ($r=0.32$) inside the waste. CH_4 emission correlated to moisture content only ($r=0.32$), while N_2O emission correlated to temperature in the waste only ($r>0.48$). There were smaller variations in temperature, pH and moisture content in the vermicomposting bins. No significant relationship between these factors and CO_2 and N_2O emissions was found, but CH_4 emission increased with increasing temperature in the vermicompost ($r>0.40$).

Implications on the environmental benefits of home aerobic composting, vermicomposting and anaerobic digestion

The equivalent emission rate of GHGs in kg CO_2-e kg^{-1} waste for the 3 waste treatment methods, excluding CO_2 emissions, are listed in Table 1. The average GHG emissions from the home systems in this study (0.0043-0.0062 kg CO_2-e kg^{-1} waste) were generally lower than those estimated in studies of the centralised waste management options (Mata-Álvarez et al. 2000, Fukumoto et al. 2003, Department of Climate Change 2008, Amlinger et al. 2008, Lou and Nair 2009). These studies were generally based on the life cycle analysis approach, using default GHG emission factors for MSW (Intergovernmental Panel on Climate Change 2007, Department of Climate Change 2007). For example, in the case of landfilling, the emission of N_2O is regarded as negligible (Pipatti and Savolainen 1996, Department of Climate Change 2007). There are no GHG emission rate values available for household systems in these protocols. This raises the question of the applicability of these default average GHG emission rates to different waste treatment processes and under different climate conditions (Beck-Friis et al. 2000).

Although life cycle analysis is beyond the scope of this study, the findings from this study have implications on the environmental benefits of home aerobic composting, vermicomposting and anaerobic digestion of MSW in countries such as Australia. Results from life cycle analysis studies often indicate centralised composting and anaerobic digestion facilities as preferable to landfilling and incineration, due to lower GHG emissons in the processes and the higher potential of recovery of methane gas for fuel use (Murphy and Power 2006). It has been found that for a centralised composting facility, the GHG emissions due to kerbside separation and collection of waste and the use of machinery for processing and turning the waste at the facility could contribute a considerable amount of GHG emissions (Lou and Nair 2009, Lundie and Peters 2005). Apart from greenhouse impacts, the waste separation, transportation and processing activities contribute substantially to the management cost. For example, in Victoria (Australia) the cost of kerbside collection is approximately

18% of the management costs (Victorian Government Department of Sustainability and Environment 2009). This cost is particularly higher for cities with low population density, such as Australian cities (Lundie and Peters 2005, Victorian Government Department of Sustainability and Environment 2009). Home composting of organic waste in urban areas will reduce the GHG emissions and cost not only from the above mentioned processes, but also from transportation of compost products and chemical fertilisers to the households and crop growers (Lou and Nair 2009).

As discussed in the previous section, all the 3 types of systems investigated in this study have similar potential in reducing GHG impacts compared to the other waste treatment options. However, the findings from this study show that properly maintained vermicomposting systems have a greater potential of reducing N_2O emissions whilst producing more neutral compost products compared to the other methods. Vermicomposting also results in more efficient digestion of the carbon content in organic waste. As such the compost products from these processes should have lower C/N ratios and better quality. In addition, Mitchell et al. (1980) found that earthworms also decrease emission of volatile sulfur compounds which are readily emitted from the conventional microbial composting process. Lazcano et al. (2008) found that earthworms promote the retention of nitrogen and gradual release of phosphorus as well as reduction in electrical conductivity, therefore producing improved organic fertilizers for agricultural uses as compared to aerobic thermophilic composting.

According to the Queensland Environmental Protection Agency (2002), about half of the domestic solid wastes in Brisbane are food and green waste. Approximately 130 kg green waste and 190 kg food waste were generated per person per year in Queensland (Australia). This is equivalent to about 3.5 kg green and food waste per day for a typical family of 2 adults and 2 children. From the survey and observation made in the study, the households composted approximately 4-5 kg of food and green waste each week on average. This amount is equivalent to about 20% of the food/green waste generated and is also well within the typical treatment capacity of 30-50 kg per month of the home systems. A combination of home composting and other MSW management alternatives including recycling and centralised composting and anaerobic digestion will have a great potential in reducing the GHG impact and management cost in the waste sector.

Conclusion

This study investigated the rate of emission of GHGs from different types of home composting bins. On average, aerobic composting, anaerobic digestion and vermicomposting bins released 504, 694 and 463 CO_2-e m^{-2} hr^{-1} as N_2O and CH_4, with N_2O accounting for >80% of total emissions. These emission rates are equivalent to 0.0043-0.0062 kg CO_2-e kg^{-1} waste of GHGs assuming 4.5 kg green wastes were processed in each bin each week. Among the 3 types of bins, vermicomposting bins had the lowest emission of N_2O.

The GHG emissions generally increased with increasing temperature and/or moisture content. This indicates the importance of proper maintenance of the bins to minimise GHG emissions. Overall, vermicomposting provides more stable and favourable composting conditions than the other two systems.

The findings from this study indicate that smaller scale home systems tend to emit less GHGs when compared with larger scale systems. Other studies on the environmental impacts of the mainstream MSW management options have found centralised composting and anaerobic digestion facilities preferable to landfilling and incineration. Home composting and anaerobic digestion have the potential to further reduce GHG emissions associated with separation, transport and processing of the wastes as well as transport of the compost products and fertilisers to the users. Among the 3 systems, vermicomposting has greater potential to provide better composting conditions and compost products with lower carbon/nitrogen ratio.

Acknowledgements

Special thanks to the Brisbane households who participated in the sampling program. Also thanks to Mr Kurnal Chauhan and Mr Kulvaibhav Singh for conducting the sampling program and to Mr Steven Reeves for analysing the gas samples and proof reading the manuscript. This project was supported by the NRMA Insurance's Community Help Grants Program 2008.

References

Amlinger, F. Peyr, S. & Cuhls, C. (2008) Greenhouse gas emissions from composting and mechanical biological treatment. *Waste Management and Research*, 26, 47-60.

Amon, B., Kryvoruchko, V., Amon, T. & Sechmeister-Boltenstern, S. (2006) Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. *Agriculture, Ecosystems and Environment*, 112, 153-162.

Australian Greenhouse Office (2007) *National Greenhouse Gas Inventory 2005*. Australian Greenhouse Office.

Aumonier, S. (1996) The greenhouse gas consequences of waste management – identifying preferred options. *Energy Conversion Management*, 37, 1117-1122.

Australian Bureau of Statistics (2009) http://www.abs.gov.au/. (October 1, 2009)

Beck-Friis, B., Sonesson, U., Jönsson, H. & Kirchmann, H. (2000) Formation and emission of N_2O and CH_4 from compost heaps of organic household waste. *Environmental Monitoring and Assessment*, 62, 317-331.

Brown, A. & Subler, S. (2007) Composting and greenhouse gas emissions: a producer's perspective. *Biocycle*, March/2007, 37-41.

Christensen, S., Ambus, P., Arah, J., Clayton, H., Galle, B., Griffith, D., Hargreaves, K., Klemedtsson, L., Lind, A., Maag, M., Scott, A., Skiba, U., Smith, K., Welling, M. & Wienhold, F. (1996) Nitrous oxide emission from an agricultural field: comparison between measurements by flux chamber and micrometeorological techniques. *Atmospheric Environment*, 30, 4183-41990.

Department of Climate Change (2007) *Australian methodology for the estimation of greenhouse gas emissions and sinks 2006*. National Greenhouse Gas Inventory Committee.

Department of Climate Change (2008) *National Greenhouse and Energy Reporting (Measurement) Determination*. Chapter 5. Waste. Department of Climate Change.

Ernst, A.A. (1990) A review of solid waste management by composting in Europe. *Resources, Conservation and Recycling*, 4, 135-149.

Fukumoto, Y., Osada, T., Hanajima, D. & Haga, K. (2003) Patterns and quantities of NH_3, N_2O and CH_4 emissions during swine manure composting without forced aeration – effect of compost pile scale. *Bioresource Technology*, 89, 109-114.

He, Y., Inamori, Y., Mizuochi, M., Kong H., Iwami, N. & Zun, T. (2000) Measurements of N_2O and CH_4 from the aerated composting of food waste. *The Science of the Total Environment*, 254, 65-74.

Hobson, A., Frederickson, J. & Dise, N. (2005) CH_4 and N_2O from mechanically turned windrow and vermicomposting systems following in-vessel pre-treatment. *Waste Management*, 25, 345-352.

Intergovernmental Panel on Climate Change (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Chapter 2. Changes in Atmospheric Constituents and in Radiative Forcing. Cambridge University Press.

Jäckel, U., Thummes, K. & Kämpfer, P. (2005) Thermophilic methane production and oxidation in compost. *FEMS Microbiology Ecology*, 52, 175-184.

Lazcano, C., Gómez-Brandón, M. & Domínguez, J. (2008) Comparison of the effectiveness of composting and vermicomposting for the biological stabilization of cattle manure. *Chemosphere*, 1013-1019.

Lee, S.H., Choi, K.I., Osako, M. & Dong, J.I. (2007) Evaluation of environmental burdens caused buy changes of food waste management systems in Seoul, Korea. *Science of the Total Environment*, 387, 42-53.

Lisk, D.J. (1991) Environmental effects of landfills. *The Science of the Total Environment*, 100, 415-468.

Lou, X.F. & Nair, J. (2009) The impact of landfilling and composting on greenhouse gas emissions – a review. *Bioresource Technology*, 100, 3792-3798.

Lundie, S. & Peters, G. (2005) Life cycle assessment of food waste management options. *Journal of Cleaner Production*, 13, 275-286.

Majumdar, D., Patel, J., Bhatt, N. & Desai, P. (2006) Emission of methane and carbon dioxide and earthworm survival during composting of pharmaceutical sludge and spent mycelia. *Bioresource Technology*, 97, 648-658.

Mata-Álvarez, J., Mace, S. & Llabrés, P. (2000) Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. *Bioresource Technology*, 74, 3-16.

Mitchell, M.J., Horner, S.G. & Abrams, B.L. (1980): Decompostion of Sewerage Sludge in Drying Beds and the Potential Role of the Earthworm *Elsenia fetida*; *Journal of Environmental Quality*, Vol. 9; pp. 373-378.

Mohareb, A.K., Warith, M.A. & Diaz, R. (2008) Modelling greenhouse gas emissions for municipal solid waste management strategies in Ottawa, Ontario, Canada. *Resources, Conservation and Recycling*, 52, 1241-1251.

Murphy, J.D. & Power, N.M. (2006) A technical, economic and environmental comparison of composting and anaerobic digestion of biodegradable municipal waste. *Journal of Environmental Science and Health Part A*, 41, 865-879.

Nolan ITU Pty Ltd (2004) *Assessment of domestic waste and recycling systems. Final report*. New South Wales Department of Environment and Conservation.

Papageorgiou, A., Barton, J.R. & Karagiannidis, A. (2009) Assessment of the greenhouse effect impact of technologies for energy recovery from municipal waste: A case for England. *Journal of Environmental Management*, 90, 2999-3012.

Pipatti, R. & Savolainen, I. (1996) Role of energy production in the control of greenhouse gas emissions from waste management. *Energy Conversion Management*, 37, 1105-1110.

Queensland Environmental Protection Agency (2002) *Green and organic waste processing and marketing in Queensland*. Queensland Environmental Protection Agency.

Sinha, R.K., Herat, S., Agarwal, S., Asadi, R. & Carretero, E. (2002) Vermiculture technology for environmental management: study of action of earthworms *Elsinia foetida, Eudrilus euginae* and *Perionyx excavatus* on biodegradation of some community wastes in India and Australia; *The*

Environmentalist, 22(2), 261 – 268.

Tchobanoglous, G., Theisen, H. & Vigil, S. (1993) *Integrated solid waste management: engineering principles and management issues*. McGraw-Hill.

Tsai, W.T. (2008) Management considerations and environmental benefit analysis for turning food garbage into agricultural resources. *Bioresource Technology*, 99, 5309-5316.

Victorian Government Department of Sustainability and Environment (2009) *Metropolitan Waste and Resource Recovery Strategic Plan*. Victorian Government Department of Sustainability and Environment.

Wei, Y.S., Fan, Y.B., Wang, M.J. & Wang, J.S. (2000) Composting and compost application in China. *Resources, Conservation and Recycling*, 30, 277-300.

Wihersaari, M. (2005) Evaluation of greenhouse gas emission risks from storage of wood residue. *Biomass and Bioenergy*, 28, 444-453.

Zero Waste South Australia (2005) *South Australia's Waste Strategy 2005-2010*. Zero Waste South Australia.

Zhang, H., He, P., Shao, L., Qu, X. & Lee, D. (2008) Minimizing N_2O fluxes from full-scale municipal solid waste landfill with properly selected cover soil. *Journal of Environmental Sciences*, 20, 189-194.

Figure 1. The 15 Brisbane suburbs of the volunteer households in this study (represented by the round dots in the figure)

Figure 2. Examples of anaerobic digester, aerobic composting and vermicomposting bins (a), and funnel static chamber used to collect the greenhouse gas samples (b)

Table 1. Summary of GHG emission rates and regulating factors (min - max values in bracket)

Table 2. Comparison of the environmental conditions and waste properties for different composting systems and at different times

Table 3. Temporal variations in GHG emissions (averages in mg CO_2-e m^{-2} hr^{-1})

Figure 1. The 15 Brisbane suburbs of the volunteer households in this study (represented by the round dots in the figure)

Figure 2. Examples of anaerobic digester, aerobic composting and vermicomposting bins (a), and funnel static chamber used to collect the greenhouse gas samples (b)

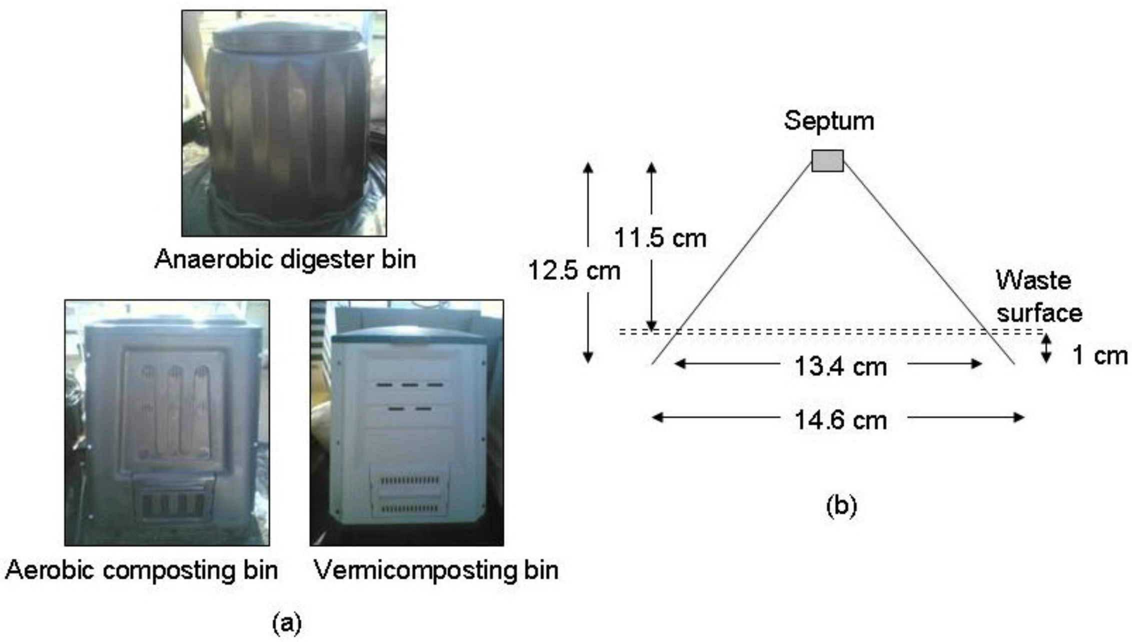

Table 1. Summary of GHG emission rates and regulating factors (min - max values in bracket)

Parameters		Aerobic bins	Anaerobic bins	Vermicomposting bins
Number of samples		40	45	42
GHG emissions (mg m^{-2} hr^{-1})				
CO_2 [1]		882 ^{B} (23 – 5764)	2950 ^{A} (91 – 10069)	1675 ^{A} (146 – 5669)
CH_4 [2]		2.17 ^{B} (0.00 – 38.05)	9.54 ^{A} (0.00 – 52.90)	4.76 ^{A} (0.00 – 40.89)
N_2O [3]		1.48 ^{A} (0.01 – 16.25)	1.59 ^{A} (0.00 – 16.37)	1.17 ^{B} (0.00 – 24.78)
Total emissions (mg CO_2-e m^{-2} hr^{-1})				
Excluding CO_2		504 (4 – 5038)	694 (0.76 – 5073)	463 (4 – 8475)
Including CO_2 [4]		1386 ^{B} (28 – 7554)	3644 ^{A} (259 – 14351)	2138 ^{A} (189 – 14144)
Average % of GHG emissions				
Excluding CO_2	CH_4	9.1	28.8	21.7
	N_2O	90.9	71.2	78.3
Including CO_2	CO_2	63.6	80.9	78.3
	CH_4	3.3	5.5	4.7
	N_2O	33.1	13.6	17.0
Average GHG emissions				
(kg CO_2-e kg^{-1} waste)				
Excluding CO_2		0.0047	0.0062	0.0043
Ambient temperature (^{o}C)		28.7 (20.0 – 35.0)	28.1 (20.0 – 34.5)	28.5 (20.0 – 34.0)
Temperature below 2 cm (^{o}C)		30.2 (26.0 – 41.5)	31.6 (24.0 – 45.0)	26.9 (22.5 – 32.0)
Temperature below 8 cm (^{o}C)		31.2 (26.0 – 48.0)	32.4 (25.0 – 46.0)	27.1 (22.0 – 31.0)
pH		5.7 (3.1 – 6.7)	5.9 (4.1 – 6.7)	6.6 (5.8 – 7.0)
Moisture scale		6.4 (2.0 – 9.0)	6.8 (2.0 – 9.0)	8.2 (2.9 – 9.0)
Equivalent moisture content (%)		31 (25 – >33)	31 (25 – >33)	32 (26 – >33)

Remarks: [1] LSD t-test shown that the waste treatment methods denoted by a superscript ‘A’ on their CO_2 emission values emitted significantly more CO_2 on average than those denoted by a superscript ‘B’ at the significance level of 0.05; [2,3,4] and similarly for CH_4, N_2O and total emissions.

Table 2. Comparison of the average environmental conditions and waste properties for different composting systems and at different times

	Ambient temperature (°C) [1]	Temperature at 2 cm below the waste surface (°C) [2]	Temperature at 8 cm below the waste surface (°C) [3]	pH [4]	Moisture scale (Equivalent % moisture) [5]
Aerobic	28.7	30.2^{A}	31.2^{A}	5.7^{C}	6.4 (31) ^{B}
Anaerobic	28.1	31.6^{A}	32.4^{A}	5.9^{B}	6.8 (31) ^{B}
Vermicomposting	28.5	26.9^{B}	27.1^{B}	6.6^{A}	8.2 (>33) ^{A}
January	25.9^{B}	30.1	31.5^{A}	5.8^{B}	8.0 (>33) ^{A}
February	31.3^{A}	30.6^{A}	30.9	6.1^{A}	7.4 (31) ^{D}
March	29.8^{A}	29.2	29.8	6.2^{A}	6.2 (31) ^{B,E}
April	26.2^{B}	28.5^{B}	28.7^{B}	6.1^{A}	6.9 (31) ^{B}
am	29.3^{A}	29.0	29.6	5.9^{A}	5.9 (30) ^{B,E}
noon	29.3^{A}	30.0	30.7	6.3^{A}	7.4 (31) ^{D}
pm	30.0^{A}	30.1	30.6	6.1^{A}	6.8 (31) ^{B}
late pm	22.4^{B}	28.3	29.1	5.6^{B}	8.2 (>33) ^{A}

Remarks:

[1,2,3] The waste treatment methods (and similarly the months and the times of the day) denoted by a superscript 'A' on the temperature values were significantly higher in the temperature on average than those denoted by a superscript 'B', and so forth; [4,5] and similarly for pH and moisture scale. Also those denoted by a superscript 'D' were significantly higher in moisture scale on average than those denoted by a superscript 'E'.

Table 3. Temporal variations in GHG emissions (averages in mg CO_2-e m^{-2} hr^{-1})

	Total GHG excluding CO_2	Total GHG including CO_2 [1]	CO_2 [2]	CH_4	N_2O
January	321	2371	2050	5.51	0.66
February	805	2903	2099	6.41	2.16
March	751	2710	1959	6.32	1.99
April	317	1652	1335	4.13	0.74
am	639	2661 ^{A}	2023	6.05	1.65
noon	848	3143 ^{A}	2295 ^{A}	6.95	2.27
pm	313	1822 ^{B}	1509	4.18	0.73
late pm	338	1910 ^{B}	1572 ^{B}	5.33	0.73

Remarks:

[1] The months (and similarly the times of the day) denoted by a superscript 'A' on their GHG emission values emitted significantly more GHG on average than those denoted by a superscript 'B'; [2] and similarly for CO_2 emission.