Onsite treatment of urban organic waste using home composting systems

Bijaya Kumar Adhikari

Department of Bioresource Engineering

McGill University, Montreal

December 2011

A thesis to McGill University in partial fulfilment of

the requirements of the degree of doctor of philosophy

Abstract

On-site treatment (home and community composting) of organic waste (OW) reduces cost and environmental issues as opposed to centralized facilities and landfilling. By 2025, such on-site practices could reduce costs and greenhouse gas emissions (GGE) by 50 and 40 %, respectively, and save land as compared to maintaining landfilling practices. However, the shift of municipal solid waste (MSW) management systems from landfill disposal to resource recovery requires technological input, population participation and compost quality assurance. The composting process and quality of composted product depends on the initial compost mixture formulation, design type and management practices of home composting systems (HC).

A project was therefore conducted both in the laboratory and in the field, to establish a home composter design and compost formula, which favours the best organic waste decomposition.

The results indicated that home composter design is important: perforations must be concentrated at the top and bottom to provide an aeration level equivalent to that of a ground pile. Such home composters can reach thermophilic temperatures when fed at least 10 kg $(week)^{-1}$ of organic waste with a dry matter content over 15 % (half yard trimmings and half food waste). The compost produced generally offers acceptable levels of polycyclic aromatic hydrocarbons (PAHs) and heavy metals, but residents must be careful in applying the right amount of garden herbicides. The total GGE from home composters were found to be equivalent to that of centralized composting facilities but eliminate the need to spend energy equivalent to 50 kg CO_2-eq $(tonne\ wet\ waste)^{-1}$ for handling and processing.

Résumé

Le traitement des matières résiduelles organiques (MRO) sur place (centres communautaires de compostage et composteurs maison) est une approche qui réduit les coûts de manipulation et de procédé associés aux centres régionaux de compostage et à l'enfouissement. D'ici 2025 et comparativement à l'enfouissement, cette approche pourrait diminuer les coûts de traitement et les émissions de gaz à effet de serre (GES) de 50 et 40 %, respectivement. D'autre part, la diversion et le recyclage des MRO exigent des connaissances techniques et la participation des gens pour assurer la qualité sanitaire du produit, qui dépend du mélange initial, et de la conception du composteur maison ainsi que de sa gestion. Un projet fut donc réalisé en laboratoire et sur le terrain, dans le but de déterminer les critères de conception des composteurs maison et la formulation du mélange initial qui favorisent la décomposition et la stabilisation des MRO traitées. Les résultats ont démontré que la conception du composteur maison est importante, surtout en ce qui concerne l'emplacement des ouvertures qui, quand concentrées dans le haut et le bas, favorisent l'aération par convection. Cette configuration d'ouvertures fait en sorte que le composteur peut atteindre des température thermophiles, semblables aux amas au sol, s'il est chargé de plus de 10 kg (semaine)$^{-1}$ de MRO possédant une matière sèche de plus de 15 % (moitié résidus de jardin et résidus de table). Le compost produit par résident est généralement propre, avec de faibles teneurs en hydrocarbures aromatique polycyclique (HAP) et en métaux lourds, à la condition d'appliquer des herbicides jardins en quantités raisonnables. Comparativement aux centres régionaux de compostage, les composteurs maison génèrent la même quantité de gaz à effet de serre (GES) mais font économiser 50 kg de CO_2-équ. (tonne de matières résiduelles humides compostées)$^{-1}$ en tant qu'énergie de manipulation et de procédé.

Acknowledgements

First of all, I would like to express my deepest gratitude to my supervisors Prof. Dr. Suzelle Barrington, Department of Bioresource Engineering, McGill University, Canada, Dr. Anne Trémier, Unit GERE, Cemagref, Rennes, France and Prof. Dr. Valérie Orsat, Department of Bioresource Engineering, McGill University, Canada, for their excellent guidance and encouragement for successful completion of this project. Their pragmatic and innovative spirit of dealing is greatly appreciated. I am proud and honoured to be their student.

I would like to extend my sincere thanks to Dr. José Martinez, Director of Research, Cemagref, Rennes, France for providing access to his laboratory and his valuable and intellectual guidance throughout the study period. My deepest gratitude goes to Ms. Mylène Launay, Dr. Annie Resse, Dr. Amaury de-Guardia, Ms. Marie-Noëlle Maudet, Ms. Céline Druilhe, Mr. Jean-Claude Benoist and Mr. Eric le-Saos of Unit GERE, Cemagref, Rennes, France for their valuable input and cooperation from planning to experimental phase of this project. I would like to thank all my colleagues of Cemagref, Rennes, France for their direct or indirect involvement in this project and good company while staying in France.

My deepest gratitude goes to all the staffs and graduate student community within the Department of Bioresource Engineering, McGill University, Canada for their cooperation, valuable suggestions and good company during my study period. I thank my friend Mr. Ajay Singh for his help during field work in Montreal West Island. I would like to thank my comprehensive examination committee members Dr. Joann Whalen, Dr. Grant Clark, Dr. Philippe Seguin for their valuable suggestions.

The cooperation from the municipalities of Montréal's West Island especially Mr. Ronald Patenaude of Dorval Municipality are highly appreciated. I also acknowledge Montréal West Island homeowners who participated in this study.

My father Mr. Lank Bahadur Adhikari, my mother Mrs. Shobha Devi Adhikari and my mother-in-law Mrs. Bhawani Luitel provided support and courage through out the study period.

I thank my wife Anju Adhikari and my son Bibek Adhikari for their patience, encouragement and support for completion of this study.

Authorship and manuscript

This thesis is written in manuscript – based format. The contributions of authors are: 1) first author conducted experimental work, analysed data and wrote the manuscripts, 2) second author supervised, advised on the experimental design and methods of analysis, provided technical information, and revised the content of the manuscripts, 3) third author supervised, advised on the experimental design and methods of analysis, provided technical information, and revised the content of the manuscripts, 4) fourth author provided technical information and revised the content of the manuscripts.

The authorship of the papers is as follows:

First paper (CHAPTER 3): Adhikari BK, Trémier A, Martinez J and Barrington S. This paper is published in the Journal of Waste Management & Research, 28(11): 1039-1053, 2010.

Second paper (CHAPTER 4): Adhikari BK, Trémier A, Barrington S and Martinez J. This paper is submitted for publication to the International Journal of Environmental Technology and Management (IJETM).

Third paper (CHAPTER 5): Adhikari BK, Trémier A, Barrington S and Martinez J. This paper is submitted for publication to the International Journal of Environmental Technology and Management (IJETM).

Fourth paper (CHAPTER 6): Adhikari BK, Trémier A and Barrington S. This paper is submitted for publication to the Journal of Environmental Technology.

Fifth paper (CHAPTER 7): Adhikari BK, Trémier A, Barrington S and Martinez J. This paper will be submitted for publication to the Journal of Environmental Management.

Table of contents

List of tables

Chapter 3

Chapter 4

Chapter 5

List of figures

Chapter 3

Chapter 7

Symbols and abbreviations

ACF	-	autocorrelation function
AR	-	autoregressive analysis
BA	-	bulking agent
Base Sce	-	base scenario
C	-	cellulose
C_i	-	initial mass of total carbon
CCC	-	community composting centres
CCC	-	community composting centres
CCF	-	centralized composting facility
CCME	-	Canadian Council of Ministers of the Environment
CF	-	citrus fruit
CFU	-	colony forming unit
CH_4	-	methane
C/N	-	carbon to nitrogen ratio
CO	-	carbon monooxide
CO_2	-	carbon dioxide
CO_2-eq	-	carbon dioxide equivalent
COD	-	chemical oxygen demand
DA	-	dead animal
DM	-	dry matter
dm	-	dry mass
EH	-	earthy/humus
EU	-	European Union
EUG1	-	European Union group one
EUG2	-	European Union group two
F	-	fishy
FAS	-	free air space
FS	-	fixed solid
FS_i	-	initial fixed solid
FW	-	food waste
GDP	-	gross domestic product
GEE	-	greenhouse gas emission
GH	-	grassy/hay
GHG	-	greenhouse gas
GMP	-	glass, metal and plastics
GP	-	mixed/unmixed ground pile
GPM	-	mixed ground pile
GP1	-	ground pile without BA, batch fed and not mixed
GP2	-	ground pile without BA, weekly fed and mixed
GP3	-	ground pile without BA, batch fed and mixed
H	-	hemillulose
HC	-	home composting systems/home composter
HMs	-	heavy metals
hr	-	hour
IC & I	-	institutions, commercials and industries
ICP – MS	-	inductively coupled plasma mass spectroscopy
L	-	lignin
LF	-	landfilling

LF CH_4	-	landfill methane
LR	-	laboratory reactor
MBT	-	mechanical and biological treatment plants
MD	-	mouldy
M_i	-	initial wet mass
MR	-	mushroom
MSW	-	municipal solid waste
M_t	-	wet mass at time t
N	-	mass of total nitrogen
NH_3	-	ammonia
NH3-N	-	ammonical nitrogen
NH_4	-	ammonium
NO	-	nitric oxide
N_2O	-	nitrous oxide
NUP	-	national urban population
O_2	-	oxygen
OECD	-	Organisation for Economic Co-operation and Development
OM	-	organic matter
OM_i	-	initial mass of organic matter
OW	-	organic waste
P	-	Plastic bin
P1	-	plastic bin without BA, batch fed and not mixed
P2	-	plastic bin without BA, weekly fed and mixed
P3	-	plastic bin without BA, batch fed and mixed
PACF	-	partial autocorrelation function
PAHs	-	polycyclic aromatic hydrocarbons
PB	-	plastic bin
PCB	-	polychlorinated biphenyls
P&PB	-	paper & paperboard
ppm	-	parts per million
R1	-	rotary drum without BA, batch fed and mixed
R2	-	rotary drum with BA, batch fed and mixed
RD	-	rotary drum/ metallic rotary drum
RE	-	rotten eggs
RV	-	rotten vegetable
Sce 1	-	scenario one
Sce 2	-	scenario two
Sce 3	-	scenario three
SE	-	sewage
SF	-	soft fermentation
TA CH_4	-	total anthropogenic methane
TA GHG	-	total anthropogenic greenhouse gas
TC	-	total carbon/ concentration of total carbon
TKN	-	total Kjeldhal nitrogen
TK	-	total potassium
TMSWG	-	total municipal solid waste generated
TN	-	total nitrogen/ concentration of total nitrogen
TN_i	-	initial mass of total nitrogen
TP	-	total population/total phosphorous
T&O	-	textile & others

UOW	-	urban organic waste
UOWPR	-	urban organic waste production rate
UP	-	urban population
US	-	United States
US EPA	-	United States Environmental Protection Agency
VOC	-	volatile organic compounds
v	-	volume
W	-	slatted wood bin/wood bin
W1	-	wood bin with BA, batch fed and mixed
W2	-	wood bin without BA, weekly fed and mixed
W3	-	wood bin with BA, batch fed and not mixed
W4	-	wood bin without BA, batch fed and mixed
WD	-	woody
wm	-	wet mass
wv	-	wet volume
yr	-	year
YT	-	yard trimmings

Chapter 1

General Introduction

1.1 Problem statement

The organic fraction of municipal solid waste (MSW) is the most active in terms of producing greenhouse gases and contaminated leachate (Rasapoor et al., 2009; Turan et al., 2009; Vehlow et al., 2007; Pokhrel and Viraraghavan, 2005; Bou-Zeid and El-Fadel 2004; Zacarias-Farah and Geyer-Allely, 2003; Shin et al., 2001; Legg, 1990) while also representing a major fraction of the MSW mainstream, especially with the recycling of metals, paper, glass and plastics. Over the past decade, the growth of MSW along with its urban organic waste (UOW) fraction has added further environmental and economic pressure to urban centers (Adhikari et al., 2009; Kollikkathara et al., 2009). In industrialized countries such as the European Union and Canada, landfilling is still the most common practice for the disposal of MSW along with its organic fraction because of its relatively low cost (Environment Canada, 2009; Hazra and Goel, 2009; Messineo and Panno, 2008). The landfilled organic wastes emit greenhouse gases which are costly to recover, generate leachate requiring treatment and remove land which otherwise could be used for crop production (Adhikari et al., 2009; Machado et al., 2009; Wagner and Arnold, 2008; EU Directive, 2000). Furthermore, social pressures are such that adequate landfill sites are now much harder to introduce.

In the European Union (EU), waste management is regulated by directives (Vehlow et al., 2007) with emphasis on waste management hierarchy (Hansen et al., 2002). The EU Landfill Directive (1999) has targeted a landfill diversion goal of 65 % for all biodegradable wastes by 2016. Similarly in Canada, in 1989, the Canadian Council of Ministers of the Environment (CCME) adopted a national goal of 50 %

landfill diversion for all MSW by 2000 (Wagner and Arnold, 2008). However, only Nova Scotia achieved 41% diversion and other provinces remained below 32% diversion of MSW (CCC, 2008; Statistics Canada, 2008).

To achieve the goal of organic waste diversion, the recovered waste needs to be treated and utilized. The commonly practiced technologies for treating this waste are anaerobic digestion, composting in centralized facilities, incineration and mechanical biological treatment (Kelleher, 2007). However, these technologies are expensive, both in initial investment and in operating costs (Nas and Bayram, 2008). Centralized composting facilities are not only expensive but can create odour nuisances generated from truck dumping, temporary storage and initial composting operations (US EPA, 1999). Source separated organic waste increases collection and transportation costs because of its separate handling which then adds fuel emissions. The onsite treatment of urban organic waste (UOW) using home systems or community composting centres can resolve these issues by substantially reducing if not eliminating collection and transportation costs. However, the composted product must be safe and of good quality to provide an opportunity for people to play a role in continuing this cycle. Safe compost can be used as a valuable nutrient source for soils while diverting waste from the MSW stream (US EPA, 2005).

1.2 Hypothesis

In this context, the following hypotheses were set to test in this project:

(i) onsite treatment of UOW reduces environmental and economic pressure on the MSW management systems and saves land from landfilling;

(ii) the composting process depends on the home composter design type and management practices of home composting systems (HC);

(iii) HC produces a stable, high-quality finished product; and

(iv) the HC type affects the greenhouse gas emissions (GGE) during the composting processes.

1.3 Objective

In order to test the above hypotheses, the main objective of this project is to study the composting process associated with urban organic waste (UOW) using home composting systems (HC). The scientific objectives pursued by the project were:

(i) to make a comparision of economical and environmental advantages of onsite treatment of UOW by community or individual households composters with centralized composting facility and landfilling;

(ii) to compare the performance of four different types of common home composting systems (HC);

(iii) to investigate the impact of management practices on HC on compost temperature regime and final characteristics;

(iv) to validate laboratory results with compost quality actually produced in the backyard, and to further examine the influence of home composter design and management on compost quality; and

(v) to compare greenhouse gas emissions (GGE) for four common HC used in Canada and France.

1.4 Scope

The environmental and economic aspects of home and community composting of urban organic waste (UOW) were examined and compared with centralized composting facilities and landfilling based on the available information. The

commonly used home composting systems in France and Canada were studied for their process characteristics, quality and greenhouse gas emission (GGE) with the food waste and yard trimmings of Rennes France. The study was further validated with resident managed home composting systems in the West Island of Montreal, Canada.

1.5 Layout of thesis

Chapter 2 presents a general literature review covering the topics of urbanization and waste production, impact on the environment, home composting and factors to be taken into consideration for the composting process. Chapter 3 is a paper presenting home and community composting of organic waste: perspective for Europe and Canada. Chapter 4 is a paper discussing effects of home composting systems on compost characteristics. Chapter 5 describes the effect of home composter management practices on compost characteristics. Chapter 6 is a study of the home composting systems operated by residents of Montreal's West Island, Canada. Chapter 7 is a paper pertaining to greenhouse gas emissions from home composting systems. Chapter 8 is the general conclusion. Chapter 9 is pertaining to the references cited in the thesis. Tables and figures are depicted in sequence at the end of each chapter. The acknowledgement and literature cited within a chapter are presented at the end of each chapter.

1.6 References

Adhikari BK, Barrington SF and Martinez J (2009) Urban food waste generation: challenges and opportunities. International Journal of Environment and Waste Management 3(1/2): 4-21.

Bou-Zeid M and El-Fadel M (2004) Parametric sensitivity analysis of leachate transport simulations at landfills. Waste Management 24: 681-689.

CCC (2010) Composting regulations and guidelines across Canada, Compost Council of Canada (CCC), Toronto, Ontario, Canada: www.compost.org/AboutCompostingindustry.html Accessed 2 Feb 2010.

Environment Canada (2009) National inventory report: Greenhouse gas sources and sinks in Canada 1990 – 2007, National Inventory Report. Cat. No.: En81-4/2007E.

EU Directive (2000) Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste. L 332/91, 28.12.2000.

Hansen W, Christopher M and Verbuecheln M (2002) EU waste policy and challenges for regional and local authorities. Background paper for the seminar on household waste management "Capacity building on European Community's Environmental Policy". Ecologic Institute for International and European Environmental Policy.

Hazra T and Goel S (2009) Solid waste management in Kolkata, India: Practices and challenges. Waste Management 29(1): 470-478.

Kelleher M (2007) Anaerobic digestion outlook for MSW streams. BioCycle 48(8): 51.

Kollikkathara N, Feng H and Stern E (2009) A purview of waste management

evolution: special emphasis on USA. Waste Management 29: 974-985.

Landfill Directive (1999) Council directive 1999/31/EC of 26 April 1999 on the landfill of waste. Official Journal of the European Communities, I. 182/1, Office for official publications of the European Communities, 2, rue Mercier, L – 2985 Luxembourg.

Legg BJ (1990) Farm & food waste: Utilization without pollution. Agricultural and food processing wastes. Proceedings of the sixth international symposium on agricultural and food processing wastes. 17-18 December 1990, pp. xi-xxi. ASAE publication 05-90.

Machado SL, Carvalho MF, Gourc JP, Vilar OM and do Nascimento JCF (2009) Methane generation in tropical landfills: simplified methods and field results. Waste Management 29(1): 153-161.

Messineo A and Panno D (2008) Municipal waste management in Sicily: Practices and challenges. Waste Management 28: 1201- 1208.

Nas SS and Bayram A (2008) Municipal solid waste characteristics and management in Gumushane, Turkey. Waste Management 28(12): 2435-2442.

Pokhrel D and Viraraghavan T (2005) Municipal solid waste management in Nepal: practices and challenges. Waste Management 25: 555–562.

Rasapoor M, Nasrabadi T, Kamali M and Hoveidi H (2009) The effects of aeration rate on generated compost quality, using aerated static pile method. Waste Management 29(2): 570-573.

Shin HS, Han SK, Song YC and Lee CY (2001) Performance of UASB reactor

treating leachate from acidogenic fermenter in two-phase anaerobic digestion of food waste. PII: S0043-1354(01)00041-0.

Statistics Canada (2008) Waste management industry survey: Business and government sectors 2006. Catalogue no. 16F0023X: www.statcan.gc.ca/pub/16f0023x/16f0023x2006001-eng.pdf Accessed 1 February 2010.

Turan NG, Coruh S, Akdemir A and Ergun ON (2009) Municipal solid waste management strategies in Turkey. Waste Management 29(1): 465-469.

USEPA (2005) Tribal composting nourishes land and tradition. United States Environmental Protection Agency. Tribal Waste Journal, Issue 4, EPA530-N-05-001.

USEPA (1999) Waste wise update. United States Environmental Protection Agency, solid waste and emergency response (5306W), EPA530-N-99-007: www.epa.gov/wastewise Accessed 16 October 2008.

Vehlow J, Bergfeldt B and Visser R (2007) European Union waste management strategy and the importance of biogenic waste. J Mater Cycles Waste Manag 9:130-139.

Wagner T and Arnold P (2008) A new model for solid waste management: an analysis of the Nova Scotia MSW strategy. Journal of Cleaner Production 16: 410-421.

Zacarias-Farah A and Geyer-Allely E (2003) Household consumption patterns in OECD countries: trends and figures. Journal of Cleaner Production 11: 819-827.

Chapter 2

Literature Review

2.1 Urbanization and waste production

From 2005 to 2010, the average annual rate of change of world urban and rural population was reported to be 1.92% and 0.45% respectively. The urban population is expected to reach 6.3 billion in 2050 from 3.2 billion in 2009, whereas, the rural population is expected to decrease from 3.41 billion in 2009 to 2.86 billion in 2050 (UN, 2010). In Europe, the urban population is expected to increase to 84.3% in 2050 from 72.1% in 2009. Similarly, in Northern American countries (Bermuda, Canada, Greenland, Saint Pierre and Miquelon, United States of America), the urban population is expected to reach 90.1% in 2050 from 81.9% in 2009 (UN, 2010). In Asia, the urban population will grow from 41.7% in 2009 to 64.7% in 2050 (UN, 2010). This growing urbanization and related economic activities produces higher amount of municipal solid waste (MSW) along with organic waste (OW) that further adds environmental and economic pressure to the urban centres (Parrot et al., 2009; Troschinetz and Mihelcic, 2009; Adhikari et al., 2009a, 2006; Guermoud et al., 2008; Wagner and Arnold, 2008; Vehlow et al., 2007; Düring and Gä th, 2002; Harjula et al., 2001; Ahmed and Jamwal, 2000; Abu Qdais et al., 1997; Hong et al., 1996). The OW represents 20 to 80% of MSW mainstream depending on the economic situation of the urban centres because in develoved economies, MSW is mostly composed of paper and packaging waste compared to less developed economies (Papadopoulos et al., 2009; Adhikari et al., 2006; OECD, 2006-2007; EEA and ETC-WMF, 2002). In 2005, the European Union member states (EU27) generated 251 million tonnes of MSW including about a 31% organic waste

component (Eurostat, 2007; OECD 2006-2007), and OW is expected to reach 105 million tonnes in 2025 which is about a 35% increase over 20 years (2005 to 2025) (Adhikari et al., 2010). Similarly, in North America (United States of America, Canada and Mexico), MSW production was reported to be 272.3 million tonnes, including 77.31 million tonnes of OW (OECD, 2006-2007). In Canada, OW is expected to increase by 25% between 2009 and 2025 (Adhikari et al., 2010).

The management of growing amounts of MSW along with the OW fraction is a challenge for urban centres, which are already under economic and environmental pressure. The European Union (EU) and Canada promulgated legislation with an emphasis on reduction, reuse, recycle, recovery and landfill as a last option. The proper management of OW requires implementation of provisions and the principles of environmental policy and legislation to achieve the goal of sustainability (EC, 2006). Therefore, European and North American countries have introduced a hierarchy concept for waste management practices (Machado et al., 2009; Sakai et al., 1996) and emphasis on resource recovery from the waste (Otegbeye et al., 2009). In this context, EU and Canada have set a target to divert their waste from landfills (Dunne et al., 2008; Burnley, 2007) by promulgation and implementation of waste management legislations and regulations. Many municipalities and waste collection and processing companies are looking at alternate solutions (Diaz, 2008) for diversion of OW from landfilling because of strict legislation, decreasing capacity of existing landfills, and more difficulty finding new ones (US EPA, 1993).

2.2 Waste management legislations in Canada and EU

The waste management legislations emphasize the diversion of MSW from landfilling, and resource recovery. In 1989, the Canadian Council of Ministers of the Environment (CCME) adopted a national goal of 50% landfill diversion of MSW by 2000 with priority on reduction, reuse, recycling and recovery (Wagner and Arnold, 2008; Sawell et al., 1996). The environmental guidelines specified the source separation and composting of OW fraction (food waste, yard trimmings) of MSW for reduction of landfill emissions of methane (CH_4) and leachate (CSC, 2003; EG 318-7, 2003). Under the framework of the CCME guidelines, the Canadian provinces issued legislation for diversion and recovery of resources. For example, in 1989, the Quebec government adopted an integrated solid waste management policy with 50% diversion goal by year 2000; however only 10.8% reduction was achieved (QR MMP, 2008). New Brunswick achieved 40% diversion in 2000 where the target was set of 50% diversion (NBELG, 2001). Under the framework of Environmental Act of 1994-95 and ban on landfilling of compostable organics in 1998, Nova Scotia became the only province to achieve the 50% diversion goal set by CCME in 2000 (NS EAL, 2004; NS DOE, 2000).

In Europe, the promulgation and implementation of waste framework directive 75/442/EEC changed the concept of end-of-pipe solutions of waste management with general advice on waste management and disposal (Vehlow et al., 2007; Pawelczyk, 2005). Currently, the EU waste management policy is based on the hierarchy of waste prevention, reuse, recycle and landfilling as the last option (Eurostat, 2011; Pawelczyk, 2005; Zacarias-Farah and Geyer-Allely, 2003; Hansen et al., 2002). Currently, waste management in the EU is regulated by directives that are issued by the European Council and the European parliament and have to be adopted by all

member states (Vehlow et al., 2007). The important directive for MSW disposal is the Landfill Directive (1999). The Article 5 of Landfill Directive 1999/31/EC sets the strategies of landfill diversion of biodegradable waste fraction of MSW mainstream by specifying 25%, 50% and 65% diversion from landfill by 2006, 2009 and 2016 respectively from the 1995 level. The Commission Decision 2000/738/EC and Directive 2006/12/EC make it mandatory for the EU member states to implement Landfill Directive 1999/31/EC, monitoring and reporting (Official Journal, 2000; Official Journal, 2006). Western European countries successfully implemented the concept of diversion and resource recovery from waste, whereas Canada lags far behind likely due to lack of enforcement of legislations and availability of land for landfilling (Wagner and Arnold, 2008).

2.3 Municipal solid waste (MSW) management and evolution of technology

During the early growth of urban centres, problems associated with MSW generation and management became prominent and often could be associated with disease outbreaks (Vehlow et al., 2007). The first European public MSW dumping site was introduced by the Greeks in 500 BC. With the course of time, the health and environmental issues associated with waste management became better understood and the concept of recycling and sanitary landfilling emerged (Vehlow et al., 2007). The landfilling of UOW along with the MSW mainstream remains attractive considering its low cost and the minimum implication of producers (El-Fadel et al., 2003).

2.3.1 Landfilling

Landfill disposal of MSW is a common practice worldwide (Kollikkathara et al., 2009). The UOW that goes to landfill sites not only pollutes the land and water but also contributes to global warming by producing methane (CH_4), becoming a political priority in the environmental field (Kollikkathara et al., 2009; Marmo, 2008; Baumert et al., 2005; Borjesson and Svenssen, 1997). At any landfill site, 45 to 58% of the UOW on a dry weight basis (dwb) is transformed into CH_4 (Solid Waste Landfill Guidance, 1999). In Canada, 5.5 million tons organic waste were landfilled in 1992 and contributed to global warming process by producing CH_4 (Sawell et al., 1996). In 1997, the US landfills are said to contribute 37% of the anthropogenic CH_4, representing the largest fraction of all the anthropogenic sources (US EPA, 2003). In Europe, an estimated 30% of anthropogenic CH_4 emissions are from landfill sites (EEA, 2001). In 2007, some EU member states such as Malta, Greece and the Czech Republic were still landfilling more than 80 % of their MSW (EEA, 2009) and in Canada, only Nova Scotia was successfully diverting more than 40 % of its MSW (Wagner and Arnold, 2008), a level which stood at 60 % in 2000 because of a smaller population and slower economic growth. In 2009, among all Canadian provinces, Nova Scotia was diverting the highest rate from landfills because of the enforcement of waste management legislations.

2.3.2 Alternative organic waste management technologies besides landfilling

Several alternatives methods can be used to treat urban organic waste (UOW): anaerobic digestion with biogas production, composting through centralized facilities, incineration and mechanical biological treatment (Kelleher, 2007). Amongst these, composting is considered one of the best practices for treating UOW (Pokhrel and

Viraraghavan, 2005), because it can be easily implemented, and its final product is stable and dry, offering organic matter (OM) usable as soil amendment (Wolkowski, 2003; Bari and Koenig, 2001; Hamelers, 1992).

However, this technology is not new, with patents for the mechanization of composting starting to appear in Europe as early as 1932 when the first full scale composting plant was established in the Netherlands by a non-profit company, N.V. Vuilafvoer Mactschapij (VAM) (Hughes, 1980). The principle was expanded and large scale centralized composting plants appeared during the 1970s and 1980s (Slater and Frederickson, 2001) to treat the entire MSW stream by first of all, mechanically separating the organic fraction and then proceeding with its composting. Known as mechanical and biological treatment plants (MBT), these facilities produced poor quality compost and 18 of them were closed in Germany by 1985 (Slater and Frederickson, 2001). At present, source separated organic waste is preferred for composting to assure the quality of the finished product. For example, in Germany, source separation and composting of the organic fraction of MSW is mandatory in many municipalities and at present, 700 to 900 such composting facilities are in operation (ECN, 2009). In France, amongst 119 composting facilities treating MSW, 54 are using source separated UOW as feedstock, and in Canada, 54 facilities compost source separated food waste generated from residences, industries, businesses and institutions (ECN, 2009; Antler, 2009). However, the capital and variable costs of these facilities are high, and collection and transportation add further economic and environmental burden to the municipalities, because the OW must be collected separately (Nas and Bayram, 2008; US EPA, 1999). Therefore, the concept of onsite treatment of UOW has emerged, using home and community composting

systems to treat a significant amount of UOW with little if any collection and transportation cost (Mitaftsi and Smith, 2006).

2.3.3 Home and community composting

The effective management of UOW offers major potential benefits (Shaw and Maynard, 2008). Home composting of UOW provides an opportunity for people to play a role in contributing to recycling by returning valuable nutrients to the soil and diverting waste from its main stream (US EPA, 2005). From 2003 to 2006, a first study was conducted by Smith and Jasim (2009) to evaluate the potential of home composting bins in diverting OW. The study demonstrated that 20 % of all household OW was recycled within the suburban area of West London, where residents have access to gardens. This concept could apply to large Canadian cities such as Toronto, where residents living in single unit homes represent 70 % of the population (Government of Ontario, 2008) and can recycle their OW fraction using home composting, while the other 30 % living in multi-unit apartments can treat their waste at community composting centre (CCC). With the implementation of onsite UOW composting, environmental and economic issues faced by urban centres could be mostly mitigated with trace amounts of greenhouse gas emissions from home composting bins (Colón et al., 2010; Smith and Jasim, 2009; Otten, 2001). If HC can divert a substantial amount of UOW, the final product needs to be demonstrated as safe in terms of composting process, environmental issues and quality of composted product. Nevertheless, the composting process depends on various factors that influence compost quality and environmental issues.

2.4 Factors influencing composting process

Composting is a natural aerobic process of biological stabilization of organic waste that achieves both weight and volume reduction and provides the nutrients required for plant growth (Banegas et al., 2007; Kanat et al., 2006; Pokhrel and Viraraghavan, 2005; Barrington et al., 2002; US EPA, 1998; Sakai et al., 1996; US EPA, 1994; US EPA, 1993). Composting generates considerable heat, CO_2 and water vapour into the air while organic matter (OM) is converted into a potentially reusable soil amendment (Renkow and Rubin, 1996; Pace et al., 1995; Biddestone and Gray, 1985; Haug, 1980). The microbial activity is mainly affected by moisture and oxygen; the aerobic composting process produces the compost, water and carbon dioxide (Epstein, 1997).

Depending on the type of HC and the management practices, composting can also generate volatile organic compounds (VOC such as ethylbenzene, tetrachloroethane, 1,1,1-trichloroethane, and toluene), ammonia (NH_3), carbon monoxide (CO), nitric oxide (NO), N_2O and CH_4 (Colón et al., 2010; Martínez-Blanco et al., 2010; IPCC, 2006; Barton and Atwater, 2002). However, levels of CH_4 and N_2O emissions from home composting systems (HC) depend on the method and management used (Bogner et al., 2008; EPIC, 2002; Beck-Friis et al., 2000). Various factors affect the composting processes and determine the level of biological activities. The main factors are moisture, pH, initial recipe C/N ratio, oxygen and temperature (de Guardia et al., 2008; Berthe et al., 2007; Meunchang et al., 2005; Pace et al., 1995; Zucconi and de Bertoldi, 1986).

2.4.1 Moisture

The moisture content of compost mixture at the starting of composting is an important factor influencing the composting process (Epstein, 1997; Diaz et al., 1993; Haug,

1993). The initial moisture of the composting substrate depends on the type and structural strength of the OW to be composted (Diaz et al., 1993). Depending on the type of composting material, the moisture content varies from 50 to 85% (Day and Shaw, 2001; Haug, 1993; Zucconi and de Bertoldi, 1986). According to Pace et al. (1995), the composting mixtures should be maintained within a range of 40% to 65% moisture and preferably 50- 60%, (Day and Shaw, 2001; Hughes, 1980). Adhikari et al. (2009b) successfully composted organic waste with initial moisture of 80%. According to Haug (1980), composting was possible for mixtures of vegetable trimmings at initial maximum moisture contents as high as 85% when using straw as a bulking agent, and 76% when using paper. A moisture level below 45% is considered rate limiting and under 20%, no biological processes are possible (Day and Shaw, 2001; Bilitewski et al., 1994).

2.4.2 pH

For active microbial growth during composting, a neutral to slightly alkaline pH range is required. Organic substrates offer a wide range of pH levels ranging from 3 to 11 and this pH must be neutralized (Day and Shaw, 2001; Zucconi and de Bertoldi, 1986). The pH of initial compost mixture varying from 5 to 6.5 can be composted (Day and Shaw, 2001; Haug, 1993) due to the natural buffering capacity of the composting material (Willson, 1993). Generally, the pH level drops below 5 at the beginning of the composting process because of the acids formed by the acid-forming bacteria, which initialize the process by breaking down complex carbonaceous materials (Hughes, 1980). The later break down of proteins and liberation of ammonia account for the subsequent rise in pH (Bilitewski et al., 1994; Zucconi and de Bertoldi, 1986). According to Pace et al. (1995), the preferred range of pH is 6.5 to

8.0. The finished compost may have pH above 7, between 7 and 8.5 (Day and Shaw, 2001; Hughes, 1980).

2.4.3 C/N ratio

The decomposition of OM depends on the carbon to nitrogen ratio (C/N) of the material. During the process of decomposition carbon declines due to the release of carbon as CO_2, while nitrogen remains within the system, hence as composting process continues, the C/N ratio becomes lower (Hughes, 1980). The C/N ratio ensures the necessary nutrients for the synthesis of cellular components of microorganisms (Day and Shaw, 2001). For an active aerobic metabolism, a C/N ratio of 15 to 30 is suggested (Pace et al.,1995; Haug, 1993; US EPA, 1993; Zucconi and de Bertoldi, 1986). The lower C/N ratio produces excess ammonia and unpleasant odour while the high C/N ratio limits the N for microbial growth and lowers the composting process rate (Day and Shaw, 2001; Pace at al., 1995). The C/N ratio of a composted product should not be above 20 or it becomes N deficient in the soil while lower C/N ratio facilitates the N loss by volatilization from the soil and can have a toxic effect on plants (Bilitewski et al., 1994).

2.4.4 Aeration

One of the main parameters to control in the composting process is aeration. If the aeration rate is insufficient, oxygen will decrease and lack of oxygen during composting results in anaerobic conditions; on the other hand if the aeration rate is too high, the compost pile cools and lowers the composting rate (Rasapoor et al., 2009; Barrington et al., 2002; Fernandes et al., 1994; Finstein and Hogan, 1992). Aeration can be assured by implementing three types of techniques: natural, passive and active.

Among these three methods, natural aeration is the cheapest and simplest, as it requires no installations. It consists of ensuring enough compost pile surface area to allow for the proper exchange of oxygen by diffusion. Passive aeration requires the installation of ducts under the compost piles to enhance the convective forces created by the temperature differences between the composting materials and the ambient air (Sartaj et al., 1997). Active aeration is the most expensive system, as it requires the installation of ducts under the compost piles and fans pushing air into these ducts and through the compost piles (Haug, 1993). Oxygen demand is very high during the initial decomposition stage, because of the rapidly expanding microbial population and the high rate of biochemical activity. After this initial high level of activity that generally lasts one to two weeks, oxygen demand decreases (Zucconi and de Bertoldi, 1986).

The previous studies have suggested aeration rates for OW composting. Nickolas and Young (2002) proposed 0.06 to 0.4 L $(min)^{-1}$ (kg of waste)$^{-1}$. Another study conducted by Rasapoor et al. (2009) suggested starting at a rate of 0.6 L $(min)^{-1}$ (kg of waste)$^{-1}$ during first 2 months of the process and continuing at a rate of 0.4 L $(min)^{-1}$ (kg of waste)$^{-1}$ until the end of composting. The natural aeration provided from the holes at the bottom and top of composting bin produces better results for home composting of OW compared to the bins without top and bottom perforations (Karnchanawong and Suriyanon, 2011).

2.4.5 Temperature

Temperature is generally a good indicator of the biological activity (Epstein, 1997). The composting stages are defined by various temperature ranges evolved during the process. According to Diaz et al. (2007), composting stages are categorized by four-temperature ranges namely mesophilic; thermophilic; cooling (second mesophilic

stage) and maturation stages. Home composting of OW takes place within three temperature ranges known as psychrophilic (0 to 20°C), mesophilic (20 to 40°C) and thermophilic (over 45°C) (Smith and Jasim, 2009). Although mesophilic temperatures allow effective composting, experts suggest maintaining thermophilic for few days, because they destroy pathogens, weed seeds and fly larvae (Pace et al., 1995). Thermophilic temperatures above 45°C should be reached within a few days (Adhikari et al., 2009b). Temperatures above 60-65°C may kill microorganisms that are more sensitive and the decomposition process may be slowed. Nevertheless, a continuing high temperature of 55-60°C, lasting beyond 5 to 6 weeks, indicates an abnormally prolonged decomposition and a delayed transition to the maturation stage (Zucconi and de Bertoldi, 1986).

2.5 Compost quality

Composting is a widely used technique for solid waste treatment (Petiot and de Guardia, 2004). The quality of compost depends on initial mixture and process management during the composting treatment (Tremier et al., 2005). Composting is the most important system of material recycling; as for every process of material recycling, the economic efficiency of the process is strongly dependent on the quality of the final product (Marchettini et al., 2007). Compost quality in relation to intended end-use is a frequently discussed issue and compost maturity is a critical factor affecting compost quality for specific agronomic objectives (CEPA, 2002). Immature and poorly stabilized compost creates handling, storage and marketing problems such as producing odour and developing toxic compounds during storage (CCQC 2001). The use of immature compost for soil growth media may have negative impacts on plant growth due to reduced oxygen. The terms compost maturity and stability are

often used interchangeably. There is no one universally accepted and applied method to evaluate the stability and maturity of compost (CCQC, 2001**).**

Compost quality evaluation is essential for regulatory compliance and compost marketing. Regulatory compliance parameters include biological (*Escherichia coli**,*** *Salmonella*), heavy metal concentrations, nutrients, soluble salts, and horticultural characteristics such as water holding capacity (Coker, 2007). The effective and environmental safe utilization of compost products depends on the production of good quality compost, especially, compost that is mature and sufficiently low in metals, pathogens and content of polycyclic aromatic hydrocarbons (PAHs). The quality of compost can be improved by early source separation, perhaps requiring separation to occur before or at curbside collection (Hargreaves et al., 2008). Source separation and home composting are considered to produce safe and stable composted products, however limited information is available about the quality of the compost obtained from home composting of organic waste.

2.6 Conclusion

Landfilling is the commonly used practice for the disposal of OW. Presently, stringent legislations in both EU and Canada have promulgated for diversion OW from landfilling. The diverted OW needs to be treated and recycled with minimal environmental and economic impacts. In this context, home and community composting can be considered one of the viable options for treatment and recycling of OW. There is limited information available on the cost and environmental impacts of home and community composting compared to centralized facilities and landfilling. For successful implementation of onsite treatment of OW, some of the issues such as compost mixtures formulation, process characteristics, quality of composted product

and emissions of odour, greenhouse gases (CO_2, CH_4 and N_2O) need to be further addressed. Therefore, this research aimed to address these issues to provide technological tools for policy makers, implementers and urban residents for successful implementation of onsite treatment of OW. The following chapter 3 deals with environmental and cost examinations of home and community composting compared to centralized composting facilities and landfilling.

2.7 References

Abu Qdais HA, Hamoda MF and Newham J (1997) Analysis of residential solid waste at generation sites. Waste Management & Research 15: 395- 406.

Adhikari BK, Tremier A, Martinez J and Barrington SF (2010) Home and community composting for onsite treatment of urban organic waste: perspective in the EU and Canada. Waste Management & Research 28(11): 1039 – 1053.

Adhikari BK, Barrington SF and Martinez J (2009a) Urban food waste generation: challenges and opportunities. Int. J. Environment and Waste Management 3(1/2): 4-21.

Adhikari BK, Barrington S, Martineze J and King S (2009b) Effectiveness of three bulking agents for food waste composting. Waste Management 29: 197-203.

Adhikari BK, Barrington S and Martineze J (2006) Predicted growth of world urban food waste and methane production. Waste Management & Research 24: 421-433.

Ahmed K and Jamwal N (2000) Garbage: your problem. Down to Earth 31: 30-45.

Antler S (2009) Compost grows stronger. The Compost Council of Canada: www.compost.org/compostinggrowsstronger.html Accessed 3 June 2009.

Banegas V, Moreno JL, Moreno JI, Garcia C, Leon G and Hernandez T (2007) Composting anaerobic and aerobic sewage sludges using two proportions of sawdust. Waste Management 27: 1317-1327.

Bari QH and Koenig A (2001) Effect of air recirculation and reuse on composting of organic solid waste. Resources, Conservation and Recycling 33: 93-111.

Barrington S, Choiniere D, Trigui M and Knight W (2002) Compost airflow resistance. Biosystems Engineering 81(4): 433-441.

Barton PK and Atwater JW (2002) Nitrous oxide emissions and the anthropogenic

nitrogen in wastewater and solid waste. Journal of Environmental Engineering 128(2): 137-150.

Baumert KA, Herzog T and Pershing J (2005) Navigating the Numbers: Green House Gas Data and international climate policy. World Resources Institute, Washington, D.C., USA.

Beck-Friis B, Pell M, Sonesson U, Jönsson H and Kirchmann H (2000) Formation and emission of N2O and CH4 from compost heaps of organic household waste. Environmental Monitoring and Assessment 62(3): 317-331.

Berthe L, Druilhe C, Massiani C, Tremier A and de Guardia A (2007) Coupling a respirometer and a pycnometer, to study the biodegradability of solid organic wastes during composting. Biosystems Engineering 97: 75-88.

Biddestone AJ and Gray KR (1985) Composting. In: Moo-Young M (ed.): Comprehensive Biotechnology, vol. 4. Pergamon Press, Oxford, pp. 1059.

Bilitewski B, Hardtle G and Marek K (1994) Waste Management. Springer-Verlag Berlin Heidelberg, Germany, pp. 1-7, 202-209.

Bogner J (USA), Pipatti R (Finland), Hashimoto S (Japan), Diaz C (Cuba), Mareckova K (Slovakia), Diaz L (USA), Kjeldsen P (Denmark), Monni S (Finland), Faaij A (The Netherlands), Gao Q (China), Zhang T (China), Ahmed MA (Sudan), Sutamihardja RTM (Indonesia) and Gregory R (UK) (2008) Mitigation of global greenhouse gas emissions from waste: conclusions and strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. Working Group III (Mitigation). Waste Management & Research 26: 11–32.

Borjesson G and Svenssen BH (1997) Seasonal and diurnal methane emissions from

a landfill and their regulation by methane oxidation. Waste Management & Research 15: 33 – 54.

Burnley SJ (2007) A review of municipal solid waste composition in the United Kingdom. Waste Management 27: 1274-1285.

CCQC (2001) Compost maturity index. California Compost Quality Council, Nevada City, CA, USA.

CEPA (2002) Compost maturity and nitrogen release characteristics in central coast vegetable production. California Environmental Protection Agency, Integrated Waste Management Board, USA. Publication#442-02-015.

Coker C (2007) Compost data tracking and analysis. BioCycle 48(7): 26.

Colón J, Martínez-Blanco J, Gabarrell X, Artola A, Sánchez A, Rieradevall J and Font X (2010) Environmental assessment of home composting. Resources, Conservation and Recycling 54: 893–904.

CSC (2003) Environmental Guidelines 318-7, solid waste measurement and management, Correctional Service Canada.

Day M and Shaw K (2001) Compost utilization in horticultural cropping systems. In: Stoffella PJ and Kahn BA (eds.): CRS press, USA, eBook ISBN: 978-1-4200-2622-1. www.crcnetbase.com/doi/pdfp/us/10.1201/9781420026221.ch2 Accessed 8 July 2011.

de Guardia A, Petiot C and Rogeau D (2008) Influence of aeration rate and biodegradability fractionation on composting kinetics. Waste Management 28: 73-84.

Diaz LF (2008) The search for solutions to maximize waste diversion from landfills. Waste Management 28: 775.

Diaz LF, de Bertoldi M, Bidlingmaier W and Stentiford E (2007) Compost science and technology, waste management series 8. Elsevier Ltd, Amsterdam, the Netherlands. pp. 31 – 34.

Diaz LF, Savage GM, Eggerth LL and Golueke CG (1993) Composting and Recycling , Municipal Solid Waste. Lewis Publishers, Boca Raton, USA. pp. 121 – 173.

Dunne L, Convery FJ and Gallagher L (2008) An investigation into waste charges in Ireland, with emphasis on public acceptability. Waste Management 28: 2826-2834.

Düring R-A and Gä th S (2002) Utilization of municipal organic wastes in agriculture:

where do we stand, where will we go? J. Plant Nutr. Soil Sci 165: 544-556.

EC (2006) European Parliament and Council Directive 2006/12/EC of 5 April 2006 on Waste.

ECN (2009) Country report, The European Compost Network, ECN/ORBIT e.V., Postbox 22 29, D-99403 Weimar, Germany. www.compostnetwork.info/index.php?id=36 Accessed 3 June 2009.

EEA (2009) Diverting waste from landfill, effectiveness of waste-management policies in the European Union, European Environmental Agency, EEA Report NO. 7/2009, ISSN 17259177, Konges, Nytorv 6, 1050 Copenhagen K, Denmark.

EEA (2001) Climate change, European Environmental Agency:

www.eea.europa.eu/themes/climate Accessed 18 February 2009.

EEA and ETC-WMF (2002) Biodegradable municipal waste management in Europe.

European Environmental Agency (EEA) and European Topic Center on Waste and Material Flows (ETC-WMF), Report Number 15/2001, Copenhagen, Denmark.

EG 318-7 (2003) Correctional Service Canada, Environmental Guidelines 318-7 on solid waste measurement and management.

El-Fadel M, Bou-Zeid E and Chahine W (2003) Landfill evolution and treatability assessment of high-strengh leachate from MSW with high organic and moisture content. Intern. J. Environ. Studies 60(6): 603–615.

EPIC (2002) Opportunities for Reducing greenhouse Gas Emissions through Residential Waste Management. the Environment and Plastics Industry Council (EPIC), a council of the Canadian Plastics Industry Association. 5925 Airport Road, Suite 500, Mississauga, Ontario.

Epstein E (1997) The science of composting. CRS Press LLC, Boca Raton, Florida, USA. pp. 19 - 50.

Eurostat (2011) Generation and treatment of municipal waste – issue number 31/2011. http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home Accessed 19 July 2011.

Eurostat (2007) Environmental expenditure statistics, general government and specialised producers data collection handbook, Cat.NO.KS-RA-07-012-EN-N.

Fernandes L, Zhan W, Patni NK and Jui PY (1994) Temperature distribution and variation in passively aerated static compost piles. Transactions of the ASAE 48: 257-263.

Finstein MS and Hogan JA (1992) Integration of composting process microbiology

facility structure and decision making in science and Engineering of composting, design, environmental microbiological and utilization aspects. In: Hoitink HAJ and Keener HM (eds): Proceedings of an international composting research symposium, 27-29 March 1992. Columbus, OH, USA.

Government of Ontario (2008) 60% diversion of blue box waste material specific targets, municipal bench marks, Waste Diversion Ontario, April 30, 2004.

Guermoud N, Ouadjnia F, Abdelmalek F, Taleb F and addou A (2008) Municipal solid waste in Mostaganem city (Western Africa). Waste Management 29(2): 896-902.

Hamelers HVM (1992) A theoretical model of composting kinetics, Science and engineering of composting, Design, environmental, microbiological and utilization aspects. In: Hoitink HAJ and Keener HM (eds): proceedings of an international composting research symposium, 27-29 March 1992. Columbus, OH, USA.

Hansen W, Christopher M and Verbuecheln M (2002) EU waste policy and challenges for regional and local authorities. Background paper for the seminar on household waste management "capacity building on European Community's Environmental Policy". Ecologic, Institute for International and European Environmental Policy.

Hargreaves JC, Adl MS and Warman PR (2008) A review of the use of composted municipal solid waste in agriculture. Agriculture, Ecosystems and Environment 123: 1-14.

Harjula H, De Tilly S and Stutz J (2001) Waste trends and outlook. Waste: Chapter 20. OECD Environmental Directorate.

Haug RT (1993) The practical handbook of compost engineering, Lewis Publishers. A

CRC press company, Boca Raton, Florida, USA, pp. 205 – 259.

Haug RT (1980) Compost engineering, Principles and practice, ANN ARBOR SCIENCE PUBLISHERS, INC. 230 Collingwood, P.O. Box 1425, Ann Arbor, Michigan 48106, USA, pp. 1, 89, 185, 274-275, 347.

Hong Y, Pan S, Shoa Q, Liu F and Duo Y (1996) A study to define a standard health protection zone for sanitary landfill in Fu Shan City. Waste Management & Research 14: 505 – 510.

Hughes EG (1980) The composting of municipal wastes. In: Bewick MWM (ed): Handbook of organic waste conversion. Chapter 4, Published by Van Nostrand Reinhold Company, 135 West 50th Street, New York, N.Y. 10020, USA, pp. 108-134.

IPCC (2006) IPCC guidelines for national greenhouse gas inventories, Volume 5 Waste. Intergovernmental Panel on Climate Change. www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html Accessed 18 May 2011.

Kanat G, Demir A, Ozkaya B and Bilgili MS (2006) Addressing the operational problems in a composting and recycling plant. Waste Management 26: 1384-1391.

Karnchanawong S and Suriyanon N (2011) Household organic waste composting using bins with different types of passive aeration, Resources, Conservation and Recycling 55: 548–553.

Kelleher M (2007) Anaerobic digestion outlook for MSW streams. BioCycle 48(8): 51. Kollikkathara N, Feng H and Stern E (2009) A purview of waste management evolution: special emphasis on USA. Waste Management 29: 974-985.

Kollikkathara N, Feng H and Stern E (2009) A purview of waste management evolution: special emphasis on USA. Waste Management 29: 974-985.

Landfill Directive (1999) Council directive 1999/31/EC of 26 April 1999 on the landfill of waste. Official Journal of the European Communities, I. 182/1, Office for official publications of the European Communities, 2, rue Mercier, L – 2985 Luxembourg.

Machado SL, Carvalho MF, Gourc JP, Vilar OM, and do Nascimento JCF (2009) Methane generation in tropical landfills: simplified methods and field results. Waste Management 29(1): 153-161.

Marchettini N, Ridolfi R and Rustici M (2007) An environmental analysis for comparing waste management options and strategies. Waste Management 27: 562-571.

Marmo L (2008) EU strategies and policies on soil and waste management to offset greenhouse gas emissions. Waste Management 28: 685-689.

Martínez-Blanco J, Colón J, Gabarrell X, Font X, Sánchez A, Artola A and Rieradevall J (2010) The use of life cycle assessment for the comparison of biowaste composting at home and full scale. Waste Management 30: 983–994.

Meunchang S, Panichsakpatana S and Weaver RW (2005) C0-composting of filter cake and bagasse; by-products from a sugar mill. Bioresource Technology 96: 437-442.

Mitaftsi O and Smith SR (2006) Quantifying household waste diversion from landfill disposal by home composting and kerbside collection. Final report, Centre for environmental control and waste management, department of civil and environmental engineering, Imperial College, London UK.

Nas SS and Bayram A (2008) Municipal solid waste characteristics and

management in Gumushane, Turkey. Waste Management 28(12): 2435-2442.

NB ELG (2001) Waste Reduction division & an action plan for New Brunswick. New Brunswick Environment and Local Government: www.gnb.ca/elg-egl Accessed 18 February 2009.

Nickolas J and Young HK (2002) Material and energy balances in a large scale aerobic bioconversion cell. Waste Management and Research 20: 234-242.

NSDOE (2000) Status report 2000 of solid waste resource management in Nova Scotia, Nova Scotia, Too Good To Waste. Nova Scotia Department of the Environment: www.gov.ns.ca/envi/wasteman Accessed 18 February 2009.

NS EAL (2004) Status report 2004 of solid waste-resource management in Nova Scotia, Nova Scotia, A World Leader in Recycling. Nova Scotia Environment and Labour: www.gov.ns.ca/enla/emc/wasteman Accessed 18 February 2009.

OECD (2006-2007) OECD Environmental Data; Compendium 2006/2007, Waste. Environmental Performance and Information Division OECD, Environmental Directorate. Working Group on Environmental Information and outlooks, Paris, France.

Official Journal (2006) Regulation (EC) No 1013/2006 of the European Parliament and of the council of 14 June 2006 on shipments of waste, 12.7.2006, L190/1.

Official Journal (2000) Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste. L 332/91, 28.12.2000.

Otegbeye M, Abdel-Malek L, Hsieh HN and Meegoda JN (2009) On achieving the state's household recycling target: A case study of North New Jersey, USA. Waste Management 29(2): 647- 654.

Otten L (2001) Wet-dry composting of organic municipal solid waste: Current Status in Canada. Can. J. Civil Eng. 28(Suppl.1): 124-130.

Pace MG, Miller BE and Farrell- Poe KL (1995) The composting process. Utah state University, Extension, October 1995.

Papadopoulos AE, Stylianou MA, Michalopoulos CP, Moustakas KG and Hapeshis KM (2009) Performance of a new household composter during in-home testing. Waste Management 29(1): 204-213.

Parrot L, Sotamenou J, and Dia BK (2009) Municipal solid waste management in Africa: strategies and livelihoods in Yaounde, Cameroon. Waste Management 29(2): 986-995.

Pawelczyk A (2005) EU policy and legislation on recycling of organic wastes to agriculture. ISAH- Warsa, Poland, Vol 1. Wroclaw University of Technology, Institute of Inorganic Technology and Mineral Fertilizers, Wroclaw, Poland.

Petiot C and de Guardia A (2004) Composting in a Laboratory Reactor: A Review. Compost Science & Utilization 12(1): 69-79.

Pokhrel D and Viraraghavan T (2005) Municipal solid waste management in Nepal: practices and challenges. Waste Management 25: 555–562.

QRMMP (2008) Quebec residual materials management policy, 1998-2008.

Rasapoor M, Nasrabadi T, Kamali M and Hoveidi H (2009) The effects of aeration rate on generated compost quality, using aerated static pile method. Waste Management 29(2): 570-573.

Renkow M and Rubin AR (1996) Municipal solid waste composting: does it makes economic sense? AREP 96-3 October 1996: http://www.bae.ncsu.edu/bae/programs/extension/publicat/arep/2arep963.html Accessed 18 February 2009.

Sakai S, Sawell SE, Chandler AJ, Eighmy TT, Kosson DS, Vehlow J, van der Sloot HA, Hartlen J and Hjelmar O (1996) World trends in municipal solid waste management. Waste Management 16(5/6): 341-350.

Sartaj M, Fernandes L and Patni NK (1997) Performance of forced, passive and natural aeration methods for composting manure slurries. Transactions of the ASAE 40(2): 457-463.

Sawell SE, Hetherington SA and Chandler AJ (1996) An overview of municipal solid waste management in Canada. Waste Management 16(5/6): 351-359.

Shaw PJ and Maynard SJ (2008) The potential of financial incentives to enhance householder's kerbside recycling behaviour. Waste Management 28: 1732-1741.

Slater RA and Frederickson J (2001) Composting municipal waste in the UK: some lessons from Europe. Resources, conservation and Recycling 32: 359-374.

Smith SR and Jasim S (2009) Small-scale home composting of biodegradable household waste: overview of key results from a 3-year research program in West London. Waste Management & Research 27 (10): 941-950.

Solid waste landfill guidance (1999) Landfill gas monitoring and mitigation, technical section, division of solid waste management program, Tennessee Division of Solid Waste Management, 3 March.

Tremier A, de Guardia A, Massianic C, Paul E and Martel JL (2005) A respirometric method for characterising the organic composition and biodegradation kinetics and the temperature influence on the biodegradation kinetics, for a mixture of sludge and bulking agent to be co-composted. Bioresource Technology 96: 169-180.

Troschinetz AM and Mihelcic JR (2009) Sustainable recycling of municipal solid

waste in developing countries. Waste Management 29 (2): 915-923.

UN (2010) World Urbanization Prospects: The 2009 Revision. Director, Population Division, Department of Economic and Social Affairs, United Nations, New York,USA: http://esa.un.org/unpd/wup/Documents/WUP2009_Wallchart_Urban-Rural_Final.pdf Accessed 6 July 2011.

US EPA (2005) Tribal composting nourishes land and tradition. United States Environmental Protection agency. Tribal Waste Journal, Issue 4, EPA530-N-05-001.

US EPA (2003) Inventory of US greenhouse gas emissions and sinks 1990-2001, final version, April 2003, EPA 430-R-03-004.

US EPA (1999) Waste wise update. United States Environmental Protection Agency, solid waste and emergency response (5306W), EPA530-N-99-007: www.epa.gov/wastewise (16 October 2008).

US EPA (1998) An analysis of composting as an environmental remediation technology. United States Environmental Protection Agency, solid waste and emergency response (5306W), EPA530-R-98-008.

US EPA (1994) Composting yard trimmings and municipal solid waste. United States Environmental Protection Agency, Solid Waste and Emergency Response (530S), EPA530-R-94-003.

US EPA (1993) Markets for compost. United States Environmental Protection Agency, solid waste and emergency response (5306), EPA/530-SW-90-073A.

Vehlow J, Bergfeldt B and Visser R (2007) European union waste management strategy and the importance of biogenic waste. J Mater Cycles Waste Manag 9: 130-139.

Wagner T and Arnold P (2008) A new model for solid waste management: an analysis of the Nova Scotia MSW strategy. Journal of Cleaner Production 16: 410-421.

Willson GB (1993) In: Day M and Shaw K (2001) Compost utilization in horticultural cropping systems. In: Stoffella PJ and Kahn BA (eds.): CRS press, USA, eBook ISBN: 978-1-4200-2622-1. www.crcnetbase.com/doi/pdfp/us/10.1201/9781420026221.ch2 Accessed 8 July 2011.

Wolkowski R (2003) Nitrogen management considerations for land spreading municipal solid waste compost. J. Environ. Qual. 32: 1844-1850.

Zacarias-Farah A and Geyer-Allely E (2003) Household consumption patterns in OECD countries: trends and figures. Journal of Cleaner Production 11: 819-827.

Zucconi F and de Bertoldi M (1986) Compost specifications for the production and characterization of compost from municipal solid waste in compost: production, quality and use. In: de Bertoldi M, Ferranti MP, L'Hermite P and Zucconi F (eds): Proceedings of a symposium organized by the commission of the European communities, Directorate General Science, Research and Development, 17-19 April.Udine Italy.

Connecting statement to chapter 3

The growing amount of municipal solid waste production along with the organic fraction will add further environmental and economic burdens to the already overloaded urban waste management systems. Considering environmental, economic and social pressures, the EU set targets of landfill diversion of biodegradable waste. The stringent legislations in both the EU and Canada force urban centres to divert organic waste (OW) from landfills. Diverted OW need to be treated and recycled with minimal environmental and economic impact. The onsite treatment of these waste by implementing home and community composting systems can be considered one of the viable options for upcoming decades. In this context, chapter 3 examines the environmental and economic issues of home and community composting systems as opposed to centralized composting facilities and landfilling.

Chapter 3 is drawn from a published article in the Journal of "Waste Management & Research" by the author of the thesis and co-authored by his supervisors, Dr. Anne Trémier, Dr. José Martinez, Cemagef, Rennes, France and Prof. Dr. Suzelle Barrington, Department of Bioresource Engineering, McGill University, Montreal, Canada. The format has been changed to be consistent within this thesis.

Chapter 3

Home and community composting for on-site treatment of urban organic waste: perspective for Europe and Canada

Abstract

Management of municipal solid waste (MSW) is a challenge faced by urban centres worldwide. For many countries including those of the European Union (EU) and Canada, urbanization and economic prosperity accelerated the generation of organic wastes along with that of MSW where urban organic wastes (UOW) represent a major component of the MSW main stream. Within a concept of waste recovery, source separation and on-site treatment of UOW can resolve major environmental and economic issues presently faced by urban centres. In this context and as compared to the traditional landfilling practice (Base Scenario), this paper examines on-site UOW composting strategies using a combination of centralized composting facilities (CCF), community composting centres (CCC) and home composting (HC) (Scenarios 1, 2 and 3). This study consists of a feasibility and economic study based on available data and waste management costs. This study indicates that on-site treatment of UOW using practices such as home and community composting can lower management costs by 50 % and landfill greenhouse gas (GHG) emissions by 40 %. However, the performance of home composters and the quality of the compost products are issues to be further addressed for the successful implementation of UOW on-site composting.

Keywords: municipal solid waste, urban organic waste, greenhouse gas, landfill, composting

3.1 Introduction

Depending on the country's economic activity, organics represent 20 to 80 % of the municipal solid waste (MSW) main stream and therefore constitute one of its major fractions (Adhikari et al., 2009; Papadopoulos et al., 2009; Adhikari et al., 2006; EEA and ETC-WMF, 2002). The improper disposal of urban organic wastes (UOW), composed mostly of food and green wastes, results in well-known health and environmental issues: attraction of insects and rodents; development sites for parasites, pathogens and viruses; contamination of drainage waters, and; emissions of unpleasant odours and greenhouse gases (Kumar et al., 2009; Moghadam et al., 2009; Rasapoor et al., 2009; Turan et al., 2009).

All countries worldwide can benefit from reducing the generation of MSW through recycling and reusing. In Asian countries, the expansion of urban centres along with the growth of their economic activities and population has exponentially increased the production of MSW along with the mass of UOW (Adhikari et al., 2009). Since several major cities in Asia can only afford to collect 30 % of their MSW, MSW growth has further stressed issues associated with collection and disposal (Parrot et al., 2009; Troschinetz and Michelcic 2009; Guermoud et al., 2008; Vehlow et al., 2007; Harjula et al., 2001). In industrialized countries of Europe and North America, landfilling is still the most common practice for the disposal of MSW along with UOW although social pressures are making it harder to find proper sites (Environment Canada, 2009; Messineo and Panno, 2008; De Baere, 2000). Furthermore, landfilled organic wastes (OW) emit greenhouse gases which can be recovered at a cost, generate leachate which requires treatment and remove land which otherwise could be used for agriculture (Machado et al., 2009; Wagner and Arnold, 2008; Official Journal, 2000). In an attempt to reduce the number of landfills

along with their social and environmental impacts, European and North American countries have adopted policies aimed at reducing the generation of wastes through for example recycling and reuse (Landfill Directive, 1999; CCEM, 1989).

To be diverted from landfills, OW must be stabilized with the objective among others of producing a soil amendment. In Canada, composting to produce a soil amendment is likely the most popular treatment, while in Europe, countries such as Germany and the Netherlands have encouraged source separation for composting and biogas production through anaerobic digestion (Table 3.1). Other European countries such as Spain and France, allow the stabilization of the OW fraction by composting of the entire MSW mainstream before landfilling; these countries also mechanically source separate the OW to produce soil amendments (Kelleher, 2007). Although the source separated organic waste produces a compost of higher quality and value, this management option, through centralized composting facilities, increases the collection and transportation costs, besides that of the disposal method. Source separation of UOW for its composting or anaerobic digestion requires a separate collection which increases transportation cost. Cities have generally coped with this issue by collecting UOW weekly and the rest of MSW twice monthly. In terms of treating source-separated UOW and in comparison with landfilling costs of US$30–50 ton^{-1} of MSW including greenhouse gas capture, composting and anaerobic digestion cost from US$50–400 ton^{-1}, with an end product not even meeting the recycling cost at US$5–10 ton^{-1} wholesale.

Therefore, the recycling of OW into a high quality soil amendment requires additional investments as compared to the traditional method of landfilling even where greenhouse gases are captured and treated (Hazra and Goel, 2009; Dunne et al., 2008; Burnley, 2007). This additional investment is an economic burden for

developed as well as developing countries. As an alternative method of reducing if not eliminating collection and transport costs to compensate for the treatment cost, community composting centres (CCC) and home composting systems (HC) are proposed. Nevertheless, such systems have not yet been demonstrated as sanitary, and economically and environmentally advantageous.

Within the recycling legislative framework of Europe and North America, the aim of this study was to investigate the economical and environmental advantages of on-site treatment of UOW by community or individual households composters. The present feasibility and economic study is based on available waste management costs data and environmental knowledge. In this study, food and garden wastes generated from households, institutions and businesses make up the UOW fraction of MSW.

3.2 The European and Canadian UOW generation and management

In this study, the 27 member states of the European Union (EU) will be split into groups 1 and 2 (EUG1 and EUG2) consisting of countries with a gross domestic product (GDP) in excess of and under $25000 US capita^{-1} year^{-1} (Table 3.2), respectively. Canada and the EU are similar in economy but differ in their landmass and population density. The EUG1 and EUG2 have population densities of 136 and 92 persons km^{-2} whereas Canada has a population density of only 4 persons km^{-2} (World population prospects, 2007). Nevertheless, the Canadian population is mainly concentrated along its southern border, for a more representative density of 20 person km^{-2}. To consider the different contexts of economy, urbanization and population density, the following section separately discusses the MSW generation and management for the EU, the EUG1, the EUG2 and Canada.

3.2.1 MSW and UOW generation

The MSW and UOW generated by the EUG1, the EUG2 and Canada are presented in Table 3.2. For Canada, the quantities of MSW and UOW correspond only to household waste whereas for the EU, the quantities correspond to household, institutions and commercial wastes (OECD, 2006-2007). In 2005, the EUG1 generated 207 million tonnes of MSW or 2.0 kg person^{-1} day^{-1}, representing 82 % of total MSW generated by the EU. The OW fraction represented 32 % of the total MSW main stream and amounted to 0.63 kg person^{-1} day^{-1}. Also in 2005, the EUG2 generated 44 million tonnes of MSW or 1.56 kg person^{-1} day^{-1} representing 18 % of the total MSW generated by the EU. The generated OW fraction amounted to 25 % of the MSW production for the EUG2. With an average gross domestic product (GDP) of $35000 US capita^{-1}, the EUG1 produced 28 % more MSW per person than the EUG2 with half the GDP of $17000 US capita^{-1}.

In North America and for 2005, the Canadian urban population of 25.8 million produced 13.4 million tonnes of MSW or 1.42 kg person^{-1} day^{-1} for a GDP of $33400 US capita^{-1}. In comparison, the US and Mexican urban populations of 242.3 and 79.6 million, respectively, produced 180.1 and 27.5 million tonnes of MSW or 2.5 and 1.2 kg person^{-1} day^{-1}, for a GDP of $41400 and $10700 US capita^{-1}. Accordingly, the calculated UOW generation for Canada, the US and Mexico was 0.43, 0.63 and 0.63 kg person^{-1} day^{-1}, respectively.

For the EU and Canada, UOW is one of the major fractions of the MSW main stream (Table 3.3) representing in 2005, 30 and 25 % of the MSW main stream, respectively. Other reported components of the MSW main stream were paper and paperboard, glass, metal, plastics and textile.

3.2.2 European and Canadian UOW management practices

Landfilling is still the most common MSW disposal method in both the European Union and Canada. In 2005, the EUG1 and EUG2 landfilled 36 and 82 % of the total MSW main stream, whereas Canada landfilled 60 % (Table 3.2). Diversion of MSW from landfilling practices vary widely among the EUG1 countries with Germany and the Netherlands reaching over 98% as compared to the UK still at 22 % (Table 3.1). In Malta, Greece and the Czech Republic, more than 80 % of all MSW was still being landfilled in 2005 (EEA, 2009)

The low landfill diversion rate for most European Countries and Canada is far from meeting environmental policy expectations. In 1999 and for the biodegradable fraction of MSW, the EU Landfill Directive 99 (Article 5) set diversion objectives of 25 % by 2006, 50 % by 2009, and 65 % by 2016, based on 1995 levels. Similarly in Canada, the Canadian Council of Ministers of the Environment (CCME) proposed a national diversion goal of 50 % of all MSW by 2000 based on that disposed in 1989, without specifically targeting the organic fraction (Wagner and Arnold, 2008).

Individual country policies have influenced the level of diversion and the technology preferred for this diversion. Incineration is not widely used because of issues of atmospheric emissions and the fact that the high moisture content of UOW reduces the caloric value of the process (Environment Canada, 2009; Zsigraiová et al., 2005; El Asri and Baxter, 2004; Marton and Alwast, 2002). While in the EUG1 countries, 21 % of all MSW was incinerated in 2005, less than 6 % was treated by this process in the EUG2 and Canada. The high EUG1 incineration level results in part from countries such as France, Germany and The Netherlands using this technology to eliminate over 30 % of their MSW while generating energy. In 2007 and within the EUG1, Germany and The Netherlands were diverting 98 to 99 % of

their MSW (Table 3.1), respectively, because of strict and costly landfilling and incineration regulations encouraging composting, and a subsidy on biogas production from the anaerobic digestion of organic wastes. In Canada since 2000, only the province of Nova Scotia succeeded in composting 60 % of its MSW, on the basis of that produced in 1989 (Wagner and Arnold, 2008), through strict regulations prohibiting among others, the disposal of OW through landfills. However, recycling dropped to 41 % in 2006 because of a higher level of waste generation as a result of economic growth and changes in consumer habits. British Columbia is second in Canada with 32 % diversion from landfill through recycling mainly because of a bylaw requiring manufacturers to recover packaging (Table 3.1). With voluntary recycling policies for the rest of the Canadian provinces, less than 20 % of all MSW is diverted from landfills for Quebec thanks to its Recy-Quebec organization managing the recycling of metals, paper and glass (Environment Canada, 2009).

Composting and anaerobic digestion are commonly used to treat and recycle the organic fraction of MSW. In 2006 and for the EU, 124 central composting facilities were treating 4 million tonnes of MSW annually (Kelleher, 2007). In 2005, France, Spain and The Netherlands were composting 14, 33 and 24 % of all MSW, respectively (Table 3.4), while in Canada, 12 % were composted. In the past, centralized mixed MSW composting facilities were built and operated, while at present, the composting of source separated OW facilities are preferred to assure the quality and value of the finished product. In Germany, source separation of the organic fraction of MSW is mandatory in many municipalities and at present, 700 to 900 composting facilities are in operation (Table 3.5). In France, amongst 119 composting facilities treating MSW, 54 use source separated UOW. In Canada, 54 facilities compost source separated food waste generated from residences, industries,

businesses and institutions (Table 3.5). The construction of a centralized composting facility can easily cost $7 million US, for a UOW processing cost of at least $140US ton^{-1}. Anaerobic digestion is another technology used to divert UOW from landfill sites and produce energy, but its application is generally accompanied by an incentive to generate energy (Table 3.1). The highest mass of organic waste diverted using this technology is found in Germany and the United Kingdom with 2000 kilo tonne of oil equivalent (ktoe) followed by Italy and Spain with 300 ktoe and the France, Austria and The Netherlands with 100 ktoe (European Biomass Industry Association, 2006). To encourage such source of green energy, EU countries must generally offer a subsidy equivalent to the cost of electricity produced by conventional technologies. At a crude oil price of $100 US barrel^{-1}, such a green energy policy costs the EU some $4 billion US year^{-1}.

In order to reduce the cost of treating and recycling UOW, a more interesting diversion method needs to be examined. Within this objective, the on-site treatment of source separated UOW was proposed to produce a dry, stabilized and volume reduced soil amendment (Adhikari et al., 2009) readily available for urban gardens. Nevertheless, the real economical impacts are issues to be addressed before recommending the wide use of home and community composting centres. Within this context, the following sections formulate and compare strategies for on-site composting of UOW in the EUG1, EUG2, and Canada.

3.3 Comparison of on-site UOW composting scenarios diverting MSW from landfills

The following sections examine the growth of MSW and UOW over the upcoming 15 years and then, predict the economic and environmental advantages associated with

on-site composting to divert the UOW fraction from the MSW mainstream and landfilling operations.

3.3.1 Estimated growth in MSW and UOW production

Referring to Adhikari et al. (2006), the following is updated study by including rather than estimating the 2005 urban population (UP) and gross domestic product (GDP) data according to UNPD (2007) and UNSD (2008). The growth of MSW and UOW was estimated by correlating the 2005 urban population of each country (UNPD, 2007) with its 2005 GDP (UNSD, 2008) (Figure 3.1a and b). Similarly, MSW and UOW generation rates were correlated with GDP (Figure 3.1c), using a procedure developed by Adhikari et al. (2006). Thus, MSW and UOW production were computed from the following Equations 1 and 2 for 2009, 2016, 2020 and 2025, where future economic improvement was used to estimate urban population expansion in addition to population growth. The short term global economic recession was assumed to have negligible impact on MSW generation and management systems:

$$(MSW)_{CRY} = 3.65 \times 10^{-9} \times (UP)_{CRY} \times (MSWR)_{CRY} \times (TP)_{CRY} \quad (1)$$

$$(UOW)_{CRY} = 3.65 \times 10^{-9} \times (UP)_{CRY} \times (UOWPR)_{CRY} \times (TP)_{CRY} \quad (2)$$

where, $(MSW)_{CRY}$ is the MSW production (million tonne yr^{-1}); $(UP)_{CRY}$ is the urban population (%); $(TP)_{CRY}$ is the total population; $(MSWR)_{CRY}$ is the MSW production rate (kg $capita^{-1}day^{-1}$); $(UOW)_{CRY}$ is the UOW production (million tonne yr^{-1}); $(UOWPR)_{CRY}$ is the UOW production rate (kg $capita^{-1}day^{-1}$), and; in the subscripts *CRY*, *C* refers to the country, R to the continents of Europe and North America and Y to the year.

From Equations (1) and (2), for 2009 to 2025, the estimated growth in MSW and UOW in the EU, the EUG1, the EUG2 and Canada are presented in Figure 3.2. With the largest population, the EUG1 is expected to increase its MSW production from 202 to 263 million tonnes yr^{-1}, over the next 15 years (2009 to 2025), resulting in an UOW production increasing from 75 to 92 million tonnes yr^{-1}. Over the same period, the EUG2 with the second largest population is expected to increase its UOW production from 11 to 13 million tonnes yr^{-1}. The UOW production is expected to increase by 23 % and 18 % in the EUG1 and the EUG2 respectively. With 8 million tonnes yr^{-1} of UOW in 2009, Canada's production is expected to reach 10 million tonnes yr^{-1} in 2025 representing an increase of 25 %.

3.3.2 Scenarios for UOW treatment strategies

The economic and environmental impacts of the proposed scenarios are evaluated in this section for the upcoming decades. The Base Scenario (Base Sce) assumes that all UOW will continue to be landfilled, but that 80% of their biogas generation will be captured; Scenario one (Sce 1) considers the practices of diverting 57, 16, and 44 % of all UOW from landfilling for the EUG1, the EUG2 and Canada respectively, and treating the diverted waste through a centralized composting facility (CCF) except for 1 % which would be treated through home composter (HC); Scenario two (Sce 2) assumes that UOW diversion from landfill increases from 25 % in 2006 to 65 % in 2016 and 80 % in 2025 and the diverted UOW is composted at centralized composting facilities (CCF), and; scenario three (Sce 3) considers zero landfilling with 10, 60, and 30 % of UOW treated using CCF, HC and community composting centres (CCC) respectively by 2025 (Table 3.6).

3.3.3 Economical assumptions

Table 3.7 compares the cost of various composting strategies to that of landfilling UOW. Disposal of UOW through landfilling requires: land acquisition; capital, operating and closure costs, and; collection and transportation of UOW to landfill sites generally located at some distance from the city (Adhikari et al., 2009). Besides the collection and transportation costs estimated at \$115 US tonne^{-1}, a landfill-dumping fee of \$50 US tonne^{-1} is quite common in America and Europe, for a total landfilling costs \$165 US tonne^{-1} of MSW (Eunomia, 2002). The cost of capturing landfill biogases of \$1.50 US tonne^{-1} was added to represent more current practices. Centralized composting facilities (CCF) were assumed to cost 33 % more in collection and transportation as compared to landfilling because of the double collection required, but at a less frequent interval for MSW other than UOW, and the location of CCF within the urban perimeter. With a capacity of 20×10^3 tonne yr^{-1} and at 7 % interest rate, CCF can compost UOW at a cost of \$241 US tonne^{-1}. Community composting centres (CCC) are estimated to treat UOW at a lower cost of \$118 US tonne^{-1} (Table 3.7) because of the time volunteered to operate the centre. Community composters serving 360 person generating 0.63 kg UOW person^{-1} day^{-1} with a 11.5 m^3 capacity were presumed to cost \$30000 US, if not automated and built of polyethylene (Eco-quartier, 2009; OECD, 2006/2007), however, the automation of the system will increase the cost of the CCC. As compared to CCC, HC can cost in the range of \$31 US tonne^{-1} of capacity and are expected to have a 10 yr life. For HC, no collection and transportation costs are involved and the time required to manage the system is free. Purchasing the composter, promoting the use of HC and training the community, are the only costs amounting to \$42 US tonne^{-1}. The cost of bulking

agent is considered negligible when food waste is composted along with yard trimmings.

3.3.4 Environmental assumptions

No matter the management method, UOW generated CH_4. Landfilled UOW contribute to global warming by generating potentially 204 kg CH_4, 500 kg CO_2 and 0.13 kg N_2O tonne^{-1} wet OW (Pettus, 2009; SITA Australia Pty Ltd, 2008; US CESLG, 2008; Barton and Atwater, 2002; Wang et al., 1997), where modern technology can capture 80 % of the CH_4. In addition, the garbage trucks collecting and transporting the MSW generate some 25 kg CO_2 tonne^{-1} wet UOW (Clean Energy, 2007), assuming that UOW constitute 46% of the volume handled.

According to IPCC (2006), CCF generates 4 kg CH_4 and 0.3 kg N_2O tonne^{-1} wet organic waste and the transportation contribution was presumed increased by 33% as compared to landfilling due to higher collection frequency of source separated UOW. This compares favourably with Amlinger et al. (2008) reporting that HC generates 0.8 to 2.2 kg CH_4, 139 to 215 kg CO_2 and 0.076 to 0.186 kg N_2O tonne^{-1} organic waste. Although composting is an aerobic process, some CH_4 is formed by anaerobic pockets within the mass, especially early on in the process because of issues of O_2 transfer to microbes. In the present analysis, CH_4, CO_2 and N_2O emissions from CCC and HC were assumed to respect the upper limits found by Amlinger et al. (2008), because of limited data on CCC emissions. The GHG (CO_2, CH_4 and N_2O) emissions were expressed as units of CO_2 equivalent based on the global warming potential (GWP) of CH_4 and N_2O valued at 21 and 310 times that of CO_2, respectively (US EPA, 2005).

3.4 Comparison of the results for the different scenarios

3.4.1 Economic implications of various scenarios from 2009 to 2025

Considering the Base Sce, the cost of UOW landfilling in the EUG1 will increase from $12293 to $15130 million US from 2009 to 2025, an increase of 23 % based on 2009 values (Figure 3.3a). Compared to the base scenario and for 2025, Sce 1 and 2 will increase the cost of handling and treating UOW by 25 and 37 %, respectively, whereas Sce 3 will lower the cost by 49%. Accordingly from 2009 to 2025 and for Sce 1, 2 and 3, the cost of treating UOW will increase from $15376 to $18919 million US, $15124 to $20705 million US and $6310 to $7767 million US, respectively.

In the EUG2, the landfilling cost for UOW will increase by 14 % from $1822 to $2084 million US. Over the same period, Sce 1, 2 and 3 could increase the cost of handling and treating UOW from $1945 to $2225 million US, $2241 to $2852 million US and $935 to $1070 million US, respectively (Figure 3.3b). In comparison to landfilling, adopting CCF (Sce 2) will increase the cost by 57 % in 2025 while adopting HC (Sce 3) will drop the cost by 41 %.

In the EU27, the cost of UOW landfilling is expected to increase from $14114 to $17214 million US, if the Base Sce is maintained, an increase of 22 % (Figure 3.3c), whereas Sce 1 & 2 will increase this cost by 50 and 67 %, respectively and Sce 3 can drop this cost by 37 %.

For Canada, maintaining the Base Sce will increase UOW handling and treatment costs by 29% %, in 2025 as compared to 2009. If Sce-3 is adopted, the cost will increase from $656 to $844 million US over the same period. By adopting Sce 3, the cost can be lowered by 34% as compared to the Base Sce (Figure 3.3d). Accordingly, Sce 3 appears to be the most feasible option from an economic point of view for the on-site treatment of UOW over the next 15 years.

3.4.2 GHG (CO_2, N_2O and CH_4) emissions under the various scenarios for 2025

From 2009 to 2025, UOW management can increase GHG emission if the Base Sce, mainly landfilling, is maintained along with its fossil fuels consumption for waste collecting and transportation. Considering Base Sce for the EUG1, GHG emission from landfilled UOW will grow from 37 to 45 million tonne CO_2-eq (Figure 3.4a), whereas Sce 1 and 3 could emit 34 and 27 million tonne CO_2-eq, respectively by 2025, representing a drop of 25 and 40 %. The Sce 2, will increase emissions by 7 % in 2025, because non CH_4 capture is assumed from 2016 onwards with the assumption that less UOW landfilling makes CH_4 capture uneconomical. Similarly for the EUG2 by 2025, the GHG emissions for the Base Sce could increase from 5 to 6 million tonne CO_2-eq whereas Sce 1, 2 and 3 could limit GHG emissions to 6, 7 and 3 million tonne CO_2-eq, respectively (Figure 3.4b). Again with the Base Sce, GHG emissions by the EU27 could increase from 42 to 51 million tonne CO_2-eq (Figure 3.4c) whereas Sce 1, 2 and 3 could limit GHG emissions to 40, 55 and 31 million tonne CO_2-eq. Compared with 2005 emissions (Table 3.4), the Base Sce, and Sce 1, 2 and 3 will contribute 1.4, 1.1, 1.5 and 0.8 % of the EUG1 anthropogenic GHG emissions respectively in 2025.

Similarly in Canada, GHG emission from landfilled UOW or the Base Sce is expected to increase from 4 to 5 million tonne CO_2-eq from 2009 to 2025 (Figure 3.4d), but to drop to 4 and 3 if Sce-1 and 3 are adopted and increases to 5.2 if Sce 2 is implemented. Therefore, in the EU and Canada, the implementation of Sce-3 will reduce GHG emissions remarkably in upcoming years.

3.4.3 Land used for UOW landfilling from 2006 to 2025

Landfilling requires 33 ha of tillable land per million tonne of UOW (Adhikari et al., 2009). Accordingly and from 2009 to 2025, maintaining the Base Sce in the EUG1 will waste 32% more land annually for landfilling (Figure 3.5a) which is equivalent to twice the Luxemburg permanent crop area of 1780 ha (CIA, 2009). Similarly, the EUG2 will require 21% more land (Figure 3.5b) which is equivalent to twice the Malta permanent crop area of 990 ha (CIA, 2009). In Canada, maintaining the Base Sce will increase the annual land usage for landfilling by 38 % (Figure 3.5d).

By 2025 in the EUG1, implementing Sce 1, 2 and 3 will reduce the annual land requirements for UOW landfilling by 56, 80 and 100 % as compared to the Base Sce, while for the EUG2, land use will be reduced by 15, 80 and 100 %, respectively (Figure 3.5b). Similarly, in Canada, Sce 1, 2 and 3 will reduce land use by 41, 80 and 100 %, respectively.

3.5 Proposed CCC and HC in Paris, France and Toronto, Canada

Paris, France, and Toronto, Canada, are densely populated cities with respective population densities of 3400 and 2500 km^{-2} (Table 3.8) where the residential, commercial and institutional generation of UOW amounts to 0.63 kg $person^{-1}$ day^{-1} (OECD, 2006/2007). In this projection, it is proposed to use for Paris, 2 CCC km^{-2} with 3 - 15 m^3 in-vessel composters and 438 individual home 400 L composting bins km^{-2}, and for Toronto, 1 CCC km^{-2} with 2 - 15 m^3 in-vessel composters and 255 individual home 400 L compost bins km^{-2} (Table 3.8).

Compared with landfilling, CCC and HC can save annual UOW treatment cost by $25756 and $28905 US km^{-2} in Paris while Toronto can benefit from annual savings of $8131 and $49569 US km^{-2}, respectively. Furthermore, GHG emissions

will drop drastically and urban air quality can benefit from less garbage collection and transportation (Adhikari et al., 2009). Therefore, the on-site composting of source separated UOW can offer interesting environmental and economic benefits for the years to come. However, the successful implementation of on-site composting offers some challenges.

To recycle a high fraction of the UOW, the implementation challenge for CCC and HC are numerous. The first prerequisite is the participation and involvement of waste producers (urban residents), because most need as stimulus, tax incentives or legislative pressures, besides education on the benefits of compost as soil amendment. Finding space for CCC in the highly populated cities like Paris and Toronto is another challenge, although there is a successful example at the Montreal City Tournesol Centre which owes its success to its location on the edge of the large Jeanne Mance park. The compost produced from CCC and not used by the UOW producers will have to be transported to city gardens.

3.6 Conclusion and recommendation

The production of MSW and its UOW fraction is expected to increase exponentially over the next 15 years, as a result of economic growth and urban expansion. If landfilling is maintained as the main treatment option, such growth will further add to already existing waste management issues and resource shortages. To divert the organic fraction from landfills, the EU and Canada have promulgated and implemented waste management legislations with emphasis on reduction, reuse and recycling.

The economic and environmental impact of promoting community composting centres (CCC) and home composters (HC) to recycle UOW was

investigated in this project as an alternative to landfilling. By 2025, such on-site practices could reduce costs and greenhouse gas emissions by 50 and 40 %, respectively, as compared to maintaining landfilling practices. Furthermore and annually, some 3440 and 330 ha of agricultural land could be saved for the generation of food in the EU and Canada. By eliminating collection, transport and labour costs, HC are an interesting solution to the recycling of UOW. However, the shift of MSW management systems from landfill disposal to resource recovery requires technological input, population participation, compost quality assurance and sufficient urban gardens to divert the mass produced (Hargreaves et al., 2008; Burnley, 2007). In this context, the performance of HC is an issue to be addressed for its successful implementation as an on-site treatment system.

3.7 Acknowledgement

The authors gratefully acknowledge the financial and all necessary logistics supported by the regional council of Brittany in France, Cemagref Rennes, France and the Natural Science and Engineering Research Council of Canada.

3.8 References

Adhikari BK, Barrington SF and Martinez J (2009) Urban food waste generation: challenges and opportunities. Int. J. Environment and Waste Management 3(1/2): 4-21.

Adhikari BK, Barington S and Martinez J (2006) Predicted growth of world urban food waste and methane production. Waste Management & Research 24: 421-433.

Alamgir M and Ahsan A (2007) Municipal solid waste and recovery potential: Bangladesh perspective. Iranian Journal of Environmental Health Science & Engineering 4 (2): 67-76.

Al-Yousfi AB (2003) Environmentally sound technologies (EST) for designing and operating solid wastes landfills, United Nations Environment Program (UNEPA), Regional Office for West Asia (ROWA), proceedings of international conference on wastes management and pests control, Muscat Municipality-Oman.

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

Antler S (2009) Compost grows stronger. The Compost Council of Canada: www.compost.org/compostinggrowsstronger.html Accessed 3 June 2009.

Bank of Canada (1995-2010) Public information, Bank of Canada, Ottawa, Ontario, Canada: www.bankofcanada.ca Accessed 24 January 2010.

Barton PK and Atwater JW (2002) Nitrous oxide emissions and the anthropogenic nitrogen in wastewater and solid waste. Journal of Environmental Engineering 128 (2): 137-150.

Bergs C.-G (2005) Separate collection of organic waste-how does it work in Germany?

BMU, Bonn University, Germany.

Bhide AD (1994) Methane emission from landfills. Journal of Indian Association for Environmental Management 21: 1-7.

Burnley SJ (2007) A review of municipal solid waste composition in the United Kingdom.

Waste Management 27: 1274-1285.

CCC (2010) Composting regulations and guidelines across Canada, Compost Council of Canada (CCC), Toronto, Ontario, Canada:

www.compost.org/AboutCompostingindustry.html Accessed 2 Feb 2010.

CCEM (1989) National contamination site remediation program. Environment Canada, Ottawa, Canada.

CIWMB (2008) Technologies and management options for reducing greenhouse gas emissions from landfills. California Integrated Waste Management Board (CIWMB), publication #200-08-001, California, USA.

CIA (2009) The world fact book, Central Intelligence Agency, USA:

www.cia.gov/library/publications/the-world-factbook/geos/us.html Accessed 4 February 2009.

Clean Energy (2007) Refuse truck powered by clean-burning natural gas fuel handles trash collection duties at July 7 live earth New York concert event, USA: www.cleanenergyfuels.com/07/07-6-07.html Accessed 13 January 2010.

De Baere I (2000) Anaerobic digestion of solid waste: state-of-the-art. Water Science and Technology 41: 283-290.

Demographia (2009) Demographia world urban areas & population projections, 5th comprehensive edition, April 2009 revision: http://demographia.com//db-worldua2015.pdf Accessed 5 June 2009.

Dunne L, Convery FJ and Gallagher L (2008) An investigation into waste charges in Ireland, with emphasis on public acceptability. Waste Management 28: 2826-2834.

ECN (2009) Country report, The European Compost Network, ECN/ORBIT e.V., Postbox 22 29, D-99403 Weimar, Germany. www.compostnetwork.info/index.php?id=36 Accessed 3 June 2009.

Eco-quartier (2009) Personnel conversation with respect to the purchase of a new non-automated composter built of polyethylene tubing, and site preparation and installation costs, Montréal, Canada.

EEA (2009) Diverting waste from landfill, effectiveness of waste-management policies in the European Union, European Environmental Agency, EEA Report NO. 7/2009, ISSN 17259177, Konges, Nytorv 6, 1050 Copenhagen K, Denmark.

EEA and ETC-WMF (2002) Biodegradable municipal waste management in The Europe. The European Environmental Agency (EEA) and The European Topic Center on Waste and Material Flows (ETC-WMF), Report Number 15/2001, Copenhagen, Denmark.

El Asri R and Baxter D (2004) Process control in municipal solid waste incinerators: survey and assessment. Waste Management & Research 22: 177-185.

Environment Canada (2009) National inventory report: Greenhouse gas sources and sinks in Canada 1990 – 2007, National Inventory Report. Cat. No.: En81-4/2007E.

Eunomia (2002) Cost for the municipal waste management in the EU, final report to

directorate general environment, The European Commission. The Eunomia research & consulting on behalf of ECOTEC research and consulting: www.edis.sk/ekes/the Eucostwaste.pdf Accessed 26 November 2008.

European Biomass Industry Association (2006) Anaerobic digestion. http://www.eubia.org/108.0.html Accessed 22 February 2010.

Eurostat (2009) Structural indicators, environment, municipal waste generated and municipal waste by type of treatment, European Commission, Eurostat: http://epp.eurostat.ec.europa.eu/portal/page/portal/structural_indicators/environment Accessed 1Feb. 2010.

Eurostat (2008) New country profile interface, The Euro indicators: http://epp.the Eurostat.ec.the Europa.the EU Accessed 31 October 2008.

Gervais C (2002) An overview of UK waste and resource management policies. Royal Society for Nature Conservation, Forum for the future, London, England.

Government of India (2008) Ministry of non-conventional energy sources, energy recovery from wastes, CGO complex, Lodi road, New Delhi – 110 003, India.

Guermoud N, Ouadjnia F, Abdelmalek F, Taleb F and addou A (2008) Municipal solid waste in Mostaganem city (Western Africa). Waste Management 29(2): 896-902.

Hargreaves JC, Adl MS and Warman PR (2008) A review of the use of composted municipal solid waste in agriculture. Agriculture, Ecosystems and Environment 123: 1–14.

Harjula H, De Tilly S and Stutz J (2001) Waste trends and outlook. In: Zacarias-Farah A and Geyer-Allely E (2003) Household consumption patterns in OECD countries: trends and figures. Journal of Cleaner Production 11: 819-827.

Hazra T and Goel S (2009) Solid waste management in Kolkata, India: Practices and challenges. Waste Management 29(1): 470-478.

IPCC (2006) Biological treatment of solid waste, volume 5: waste. Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories.

Kanbour F (1997) General status on urban waste management in west Asia, paper delivered at the United Nations Environment Programme (UNEP) regional workshop on urban waste management in west Asia, Bahrain, 23 – 27 November.

Kelleher M (2007) Anaerobic digestion outlook for MSW streams. BioCycle 48(8): 51.

Kumar S, Bhattacharya JK, Vaidya AN, Chakrabarti T, Devotta S and Akolkar AB (2009) Assessment of the status of municipal solid waste management in metro cities, state cities, class I cities, and class II towns in India: An insight. Waste Management 29(2): 883-895.

Landfill Directive (1999) Council directive 1999/31/EC of 26 April 1999 on the landfill of waste. Official Journal of the European Communities, I. 182/1, Office for official publications of the European Communities, 2, rue Mercier, L – 2985 Luxembourg.

LAP (2003) The national waste management plan (LAP), Part 1 Policy framework: www.vrom.nl/docs/internationaal/National%20Waste%20Management%20Plan.pdf Accessed 1 February 2010.

Machado SL, Carvalho MF, Gourc JP, Vilar OM and do Nascimento JCF (2009) Methane generation in tropical landfills: simplified methods and field results. Waste Management 29(1): 153-161.

Marton C and Alwast H (2002) Report: Operational experiences and legal aspects of co-combustion in Germany. Waste Management & Research 20: 476-483.

Messineo A and Panno D (2008) Municipal waste management in Sicily: Practices and challenges. Waste Management 28: 1201-1208.

MEEDDM (2009) La politique des dechets 2009-2012. Ministere de l'Ecologie,de l'Energie, du Developpement durable et de la Mer, Paris, France.

Moghadam MR, Mokhtarani N and Mokhtarani B (2009) Municipal solid waste management in Rasht City, Iran. Waste Management 29(1): 485-489.

Nash C (1992) Backyard composting: the first step in organic waste management. Resource Recycling, May 1992.

OECD (2006-2007) OECD Environmental Data; Compendium 2006/2007, Waste. Environmental Performance and Information Division OECD, Environmental Directorate. Working Group on Environmental Information and outlooks, Paris, France.

Official Journal (2000) Commission Decision 2000/738/EC of 17 November 2000 concerning a questionnaire for member states reports on the implementation of Directive 1999/31/EC on the landfill of waste, 25.11.2000, L298/24. Office for official publications of the European Communities, 2, rue Mercier, L – 2985 Luxembourg.

Papadopoulos AE, Stylianou MA, Michalopoulos CP, Moustakas KG and Hapeshis KM (2009) Performance of a new household composter during in-home testing. Waste Management 29(1): 204-213.

Pettus A (2009) Methane: Tapping the untapped potential, Clean Air Task Force, 18 Tremont Street, Boston, USA.

Parrot L, Sotamenou J and Dia BK (2009) Municipal solid waste management in

Africa: strategies and livelihoods in Yaounde, Cameroon. Waste Management 29(2): 986-995.

Peavy HS, Rowe DR and Tchobanoglous G (1985) Environmental Engineering McGraw-Hill, Inc. USA. pp 640-644.

Rasapoor M, Nasrabadi T, Kamali M and Hoveidi H (2009) The effects of aeration rate on generated compost quality, using aerated static pile method. Waste Management 29(2): 570-573.

Recycle Works Ltd (2010) Compost bins and composting, Unit 1, Bee Mill, RIBCHESTER, UK: www.recycleworks.co.uk Accessed 28 January 2010.

SITA Australia Pty Ltd. (2008) Methane captured for greenhouse neutrality, prepared by Hyder consulting Pty Ltd., North Sydney, Australia, Report no. NS04054-R01-04.

Statistics Canada (2008) Waste management industry survey: Business and government sectors 2006. Catalogue no. 16F0023X: www.statcan.gc.ca/pub/16f0023x/16f0023x2006001-eng.pdf Accessed 1 February 2010.

Schnurer HL (2000) Regulation on waste management- the situation in Germany. Federal Ministry of the Environment, Nature Conservation and Nuclear Safety, Bonn, Germany.

Sufian MA and Bala BK (2007) Modeling of urban solid waste management system: The case of Dhaka city. Waste Management 27: 858-868.

Turan NG, Coruh S, Akdemir A and Ergun ON (2009) Municipal solid waste management strategies in Turkey. Waste Management 29(1): 465-469.

Troschinetz AM and Michelcic JR (2009) Sustainable recycling of municipal solid waste in developing countries. Waste Management 29(2): 915-923

UN (2007) Urban population development and the environment, United Nations, Department of Economic and Social Affairs, population Division: www.unpopulation.org Accessed 23 May 2008.

UNPD (2007) World urbanization prospects: The 2007 revision population database, department of economics and social affairs, United Nations Population Division: www.unpopulation.org Accessed 21 January 2009.

UNSD (2008) Department of economic and social affairs, United Nations Statics Division: http://unstats.un.org/unsd/snaama/SelectionCountry.asp Accessed 21 January 2009.

US CESLG (2008) Landfill methane utilization, United States Clean Energy Strategies for Local Government . USA.

US EPA (2005) Emission facts: metrics for expressing greenhouse gas emissions: carbon equivalents and carbon dioxide equivalents, United States Environmental Protection Agency. EPA 420-F-05-002. 1200 Pennsylvania Ave., NW (6406J), Washington, DC, USA: www.epa.gov/oms/climate/420f05002.pdf Accessed 15 January 2010

Van der Sloot HA (1996) Present status of waste management in The Netherlands. Waste Management 16 (5/6): 375-383.

Vehlow J, Bergfeldt B, Visser R and Wilen C (2007) The European Union waste management strategy and the importance of biogenic waste. Journal of Material Cycles and Waste Management 9: 130-139.

Wang Y, Odle WS, Eleazer WE and Barlaz (1997) Methane potential of food waste and anaerobic toxicity of leachate produced during food waste decomposition. Waste Management & Research 15: 149- 167.

Wagner T and Arnold P (2008) A new model for solid waste management: an

analysis of the Nova Scotia MSW strategy. Journal of cleaner Production 16: 410-421.

WHO (1995) Solid waste management in some countries – environmental dimensions of waste disposal, World Health Organization regional center for environmental health activities (CEHA), P.O. Box 926967, Amman 111 90, Jordan.

World Resources (1998 – 99) A Guide to the Global Urban Environment, city level, 1993. Data table 9.3, pp. 278.

World Population prospects (2007) United Nations Population Division: http://esa.un.org/unpp Accessed 6 July 2008.

Zhang D, Keat TS and Gersberg RM (2010) A comparison of municipal solid waste management in Berlin and Singapore. Waste Management 30(5): 921 – 933.

Zsigraiová Z, Tavares G, Semião V and Carvalho MG (2005) Municipal solid waste incineration- contribution to sustainable development of energy and environment. Acta Metallurgica Slovaca 11(4): 450-459.

Table 3.1 Legislation to divert MSW from landfill in some EU countries and provinces of Canada in 2006

Country	Diversion	Legislation for diversion
Germany	99 %	- Waste Disposal Act (1972): closure of uncontrolled landfills and introduction of strict and costly regulations for new and larger landfills. - Waste Avoidance and Management Act (1986) and German Packaging Ordinance (1991): obligatory packaging recovery by the producers and users. - Technical Guidelines for Hazardous Wastes (1991) and Solid Household Wastes and Wastes Similar to Household Wastes (1993): more stringent and costly regulations on landfills and incinerators; realisation that organic wastes were at the base of most leachate and gas issues. - Ordinance on Biowaste (1998): control for the sanitary treatment of organic wastes; - Renewable Energy Law (2000): subsidizing of biogas production from organic wastes and municipal support for home composting.
The Netherlands	98 %	- National Environmental Policy (1988): brought awareness for recycling with slow progress in terms of mass recycled. - Regulation Air Emissions on Incineration (1989): strict and costly regulations imposed on incinerators. - Regulation on the anaerobic digestion of UOW: introduction of a high subsidy on the production of electricity from UOW.
France	56 %	- Directive aimed at MSW (2005): has producers share the cost of waste management. - Action Plan for 2009-2012: aims at increasing recycling, by applying a higher tax on waste management and requiring manufacturers to financially contribute to the management of packaging. - Incineration: air quality policies improved from 1995 to 2006, allowing the incineration of 47% of all MSW to generally produce energy.
United Kingdom	22 %	- White paper *Making Waste Work* (1995): despite the 1999 Landfill Directive, 1994 Packaging Waste Directive and 1991 Hazardous Waste Directive, the UK had failed to draw up waste management plans by 1999. - Waste Strategy for England and Wales (2000): making local authorities responsible for waste management has limited impact on landfilled MSW. - Renewable Obligation Order (2002): sets a target for the UK to generate 10 % of its electricity from renewable sources by 2010 with power to be purchased by the Non-Fossil Purchasing Agency (NFPA).
Canada British Columbia	32%	- Emission Criteria for Municipal Solid Waste Incinerators (1991): imposed emission standards and gives all incinerators 5 years to comply. - Landfill Criteria for Municipal Solid Wastes (1993) and Guidelines for Environmental Monitoring (1996): controls and sets standards for the management of landfills; landfill operators have to show that they meet performance criteria. - Compost Facility Requirement Guideline and Land application guidelines for Organic matter recycling (2002): governs then operation of composting facilities and the land application of the compost they produce. - Regional District Solid Waste Management plan Guidelines (1994): each district sets its plan and several have banned the disposal by landfill of recyclable, hazardous and organic materials. - Recycling Regulation - Product Stewardship (revised 2009): industry and the consumer are responsible for the disposal of packaging and containers.
Nova Scotia	41 %	- Nova Scotia Environment Act (1994): proposed to develop a Solid Waste Resource Development Strategy with the 55 municipalities, introduced strict regulations on new landfills and required existing landfills to conform in 2006. - Environment Goals and Sustainable Prosperity Act (1996): committed to recycling 50% of all municipal solid wastes; ban on disposal of all containers and packaging, refillable or recyclable beverage containers, and all organic which can be composted.
Ontario	19 %	- Waste Diversion Act (2002) giving Board the responsibility to develop and implement waste diversion programs: reviewed by public consultation and recommend path towards zero waste.
Quebec	27 %	- Bylaw on landfill tax (2006): a landfill tax of \$10 ton^{-1}. - Bylaw on the disposal by landfill and incineration of municipal solid wastes (2006): revision with strict environmental requirements whereas before, in many instances a landfill liner was not even required. - Law and several bylaws on recovery and recycling (1990): creation of Recy-Quebec to manage the recycling of glass, paper and metal.

Note: regulations on compost quality are excluded. References : Eurostat (2009); Statistics Canada (2008); CCC (2010); MEEDDM (2009); LAP (2003); Zhang et al. (2010); Schnurer (2000); Bergs (2005); van der Sloot (1996); Gervais (2002).

Table 3.2 Countries categorized based on the GDP per capita (US$) in 2005

Category	Countries	GDP[a] per capita US$	TP[b] ('1000)	UP[b] ('1000)	UP %	MSW[c] generated million tonne	UOW[d] generated million tonne	MSW[c] landfilled million tonne
EU Group 1	Luxembourg	64102	457	378	82.8	0.32	0.14	0.06
(EUG1)	Ireland	39040	4143	2507	60.5	3.07	0.77	1.84
GDP>	Denmark	34298	5417	4653	85.9	3.99	1.16	0.21
25000	Netherlands	34289	16328	13095	80.2	10.19	3.57	0.18
	Austria	33299	8292	5514	66.5	5.13	1.80	0.66
	UK	33125	60245	54040	89.7	35.18	13.13*	22.65
	Belgium	32955	10398	10117	97.3	4.95	1.93	0.38
	Sweden	32750	9038	7619	84.3	4.36	2.12*	0.21
	Finland	32467	5246	3274	62.4	2.49	1.13*	1.48
	France	31846	60991	46780	76.7	33.06	10.58	11.89
	Germany	29913	82652	60667	73.4	46.62	6.53	3.97
	Italy	29189	58646	39645	67.6	31.79	9.22	17.30
	Spain	26792	43397	33285	76.7	25.91	12.69	12.67
Total/Average		**34928**	**365250**	**281574**	**77**	**207**	**65**	**74**
EU Group 2	Greece	23386	11100	6704	60.4	4.86	1.40*	4.30
(EUG2)	Slovenia	22294	1999	990	49.5	0.85	0.24*	0.66
GDP	Portugal	21168	10528	6064	57.6	4.70	1.60	2.93
<25000	Czech Republic	20931	10192	7491	73.5	2.95	0.90*	2.13
	Cyprus	19724	836	579	69.3	0.62	0.11*	0.55
	Malta	19239	403	377	93.6	0.25	0.05*	0.22
	Hungary	18257	10086	6687	66.3	4.64	1.35	3.85
	Slovakia	15991	5387	3027	56.2	1.56	0.44*	1.23
	Estonia	15990	1344	933	69.4	0.59	0.10*	0.37
	Lithuania	14538	3425	2281	66.6	1.29	0.21*	1.17
	Poland	14156	38196	23491	61.5	9.36	3.08*	8.63
	Latvia	13692	2302	1565	68	0.71	0.15*	0.56
	Bulgaria	9220	7745	5437	70.2	3.68	0.42*	3.14
	Romania	9067	21628	11614	53.7	8.15	1.17*	6.40
Total/Average		**16975**	**125171**	**77241**	**65**	**44**	**11**	**36**
North Americas	US	41410	299846	242276	80.8	222.90	55.73	121.03
	Canada	33400	32271	25849	80.1	13.40	3.22	8.05[e]
	Mexico	10689	104266	79555	76.3	36.00	18.36	34.81[f]

GDP - Gross domestic product; UP - Urban population; TP - Total population; MSW - Municipal solid waste; OW - Organic waste; [a]UN (2007); [b]World Population Prospects (2007); [c]Eurostat (2008); [d]OECD (2006/2007); *Estimated from Adhikari et al. (2006) with 2005 UOW and GDP data; [e]2004; [f]2006; MSW generated and landfilled data for Americas are from OECD (2006/2007).

Table 3.3 Composition of MSW in some of the EU countries & North Americas in 2005

Country	TMSWG million tonne	OW %	P&PB %	T&O %	GMP %	OW million tonne	P&PB million tonne	T&O million tonne	GMP million tonne
Luxembourg	0.32	45	22	16	16.8	0.14	0.07	0.05	0.05
Ireland	3.07	25	31	23	20	0.77	0.95	0.71	0.61
Denmark	3.99	29	27	32	11.8	1.16	1.08	1.28	0.47
Netherlands	10.19	35	26	12	27	3.57	2.65	1.22	2.75
Austria	5.13	35	22	19	24	1.80	1.13	0.98	1.23
Belgium	4.95	39	17	29	15	1.93	0.84	1.44	0.74
France	33.06	32	20	26	22	10.58	6.61	8.59	7.27
Germany	46.62	14	34	12	39	6.53	15.85	5.59	18.18
Italy	31.79	29	28	22	20	9.22	8.90	6.99	6.36
Spain	25.91	49	21	7	24	12.69	5.44	1.81	6.22
Hungary	4.64	29	15	35	21	1.35	0.70	1.62	0.97
Portugal	4.70	34	21	23	22	1.60	0.99	1.08	1.03
Slovakia	1.56	38	13	31	18	0.59	0.20	0.48	0.28
USA	222.90	25	34	16	25	55.73	75.79	35.66	55.73
Canada	13.40	24	47	8	22	3.22	6.30	1.07	2.95
Mexico	36.00	51	15	16	15	18.36	5.40	5.76	5.40

Source: OECD (2006/2007); Eurostat (2008)
TMSWG - Total municipal solid waste generated; OW - Organic waste;
P&PB - Paper & paperboard; T&O - Textile & others; GMP - Glass, Metal & Plastics.

Table 3.4 Composting of UOW in some of the EU countries & Canada

Country	Composting million tonne	Composting %	Composting million tonne	Composting %
	1995		2005	
Luxembourg	0.02	7.04	0.06[b]	19.28[b]
Ireland	-	-	0.03[a]	1.25[a]
Denmark	0.32	10.69	0.55[b]	15.28[b]
Netherlands	2.01	23.72	2.38[c]	23.49[c]
Austria	0.94	26.56	2.06[c]	44.7[c]
Belgium	0.27	5.95	1.05[b]	22.76[b]
France	2.53	9.14	4.87	14.33
Germany	5.59	10.96	8.30[c]	17.14[c]
Italy	0.12	0.45	10.55	33.30
Spain	2.09	10.38	7.43[c]	32.69[c]
Slovenia	0.00	0.00	0.01[a]	1.15[a]
Portugal	0.50	12.90	0.31	6.26
Hungary	-	-	0.05[b]	1.07[b]
Canada	-	-	1.66[c]	12.50[c]

Source: OECD (2006/2007); Eurostat (2008)
UOW - Urban organic waste
[a]2002; [b]2003; [c]2004.

Table 3.5 Municipal Solid Waste (MSW) composting facilities in some of the EU countries and Canada

Country	No of composting facilities	Description	References
France	119	65 mixed MSW and 54 source separated urban organic waste (UOW) composting facilities	ECN (2009)
Germany	700-900	Source separated UOW composting is the main focus in Germany for the quality assurances	ECN (2009)
Finland	20	In-vessel composting facilities with capacity of 5 million kg to 35 million kg	ECN (2009)
Canada	54	Composting of food waste from institutions, commercials & industries (IC&I) and residential sectors	Antler (2009)

Table 3.6 Various scenarios of Urban Organic Waste (UOW) treatment strategies (%)

Scenarios	LF	CCF	CCC	HC
Base Scenario (Base Sce)	100	0	0	0
Scenario one (Sce 1)				
EUG1	42	57	0	1
EUG2	84	15	0	1
Canada	56	43	0	1
Scenario two (Sce 2)				
Year				
2006	75	25	0	0
2009	50	50	0	0
2016	35	65	0	0
2020	25	75	0	0
2025	20	80	0	0
Scenario three (Sce 3)	0	10	30	60

LF - Landfilling; CCF - Centralized composting facility; CCC - Community composting Centre; HC - Home composting.

Table 3.7 Cost of various composting strategies versus landfilling for UOW (US$ tonne^{-1} wet UOW)

Costs	LF[a]	CCF[b]	CCC	HC
Collection	**115**	**153**	0	0
Capital costs				
Land acquisition	2	4	0	0
[h]Civil works	19	17	20[c]	0
Equipments	0	18	64[d]	0
Site assessment/restoration	2	0	0	0
After care	7	0	0	0
Compost bin	0	0	0	31[f]
Sub-total	**30**	**39**	**84**	**31**
Variable costs				
Annual maintenance	0	7	0	0
[i]Manpower/operation	18	23	28[e]	0
Fuel and disposal of rejects	0	19	0	0
Training/Promotion	0	0	6	11[g]
[j]Gas capturing	2	0		
Sub-total	**20**	**49**	**34**	**11**
Total	**165**	**241**	**118**	**42**

LF - Landfilling; CCF - Centralized Composting Facility; CCC - Community Composting Center; HC - Home Composting; UOW - Urban Organic Waste;

[a&b] values adjusted using an annual inflation rate of 2.5% from 2002 to 2009 and an exchange of $1.00 US = € 0.72 mid-month average for 2009 (Eunomia 2002; Bank of Canada 1995-2010); for EU, collection cost averaged from a range of $50 to $210 US tonne^{-1} ; CCF increased by 33 % because of double collection at a lower frequency for MSW other than UOW; other costs for LF and CCF were based on UK and Italian values;

[c] Site preparation and installation cost for CCC $40000 US (Eco- Quartier 2009);

[d] CCC costing $30000 US for 11.5 m^3 total capacity (Eco-Quartier 2009) serving 360 person generating 0.63 kg UOW person^{-1}day^{-1} (OECD 2006/2007);

[e] Annual management cost of $5700 US;

[f] Wooden composting bin at $200 US of 400L capacity (Recycle works Ltd 2010) serving 4 persons per household generating 0.63 kg UOW person^{-1}day^{-1} (OECD 2006/2007);

[g] Promotion of bins and education of producer (Nash 1992);

[h] Civil works for LF including capital investment and interest;

[i] Manpower/operation for labour, power and equipment maintenance;

[j] Gas capturing cost consisting of vertical extraction wells at $246 US m^{-1} drilling and installation cost with a 25 m influence radius and $525 US wellhead assembly cost with piping and valves (CIWMB 2008), based on a landfill 15 m deep with an average waste density of 380 kg m^{-3} (Peavy et al. 1985; Bhide 1994).

Table 3.8 Proposed community and home composting in Paris, France and Toronto, Canada

Description	Paris		Toronto	
	[a]TP million(2005):	10.4	[a]TP million(2006):	5.671
	[a]Total area (km^2):	3043	[a]Total area (km^2):	2279
	% NUP:	22	% NUP:	22
	Population km^{-2}:	3400	Population km^{-2}:	2500
	[b]UOW$person^{-1}day^{-1}$:	0.63	UOW$person^{-1}day^{-1}$:	0.63
	CCC	HC	CCC	HC
[c]Number of composting centre km^{-2}	2	-	1	-
[d]Number of Compost bins km^{-2}	-	255	-	438
In-vessel composters $centre^{-1}$	3	-	2	-
Specification of each composter	6 m long & 1.8 m dia.	-	6 m long & 1.8 m dia.	-
Capacity of home composter bin^{-1}	-	400L	-	400L
Composting costs	\$118 US $tonne^{-1}$	\$42 US $tonne^{-1}$	\$118 US $tonne^{-1}$	\$42 US $tonne^{-1}$
Total UOW composted yr^{-1} km^{-2}	548 tonne	235 tonne	173 tonne	403 tonne
Cost saving comparing with Landfill	\$47 US $tonne^{-1}$	\$123 US $tonne^{-1}$	\$47 US $tonne^{-1}$	\$123 US $tonne^{-1}$
Cost saving comparing with CCF	\$123 US $tonne^{-1}$	\$199 US $tonne^{-1}$	\$123 US $tonne^{-1}$	\$199 US $tonne^{-1}$

TP - Total population; NUP - National urban population; UOW - Urban Organic Waste; CCC - Community composting centre; HC - Home composting;
[a]Demographia (2009);
[b]OECD (2006/2007) and assuming same for Toronto;
[c]Assuming 30% & 70% population live in multistory buildings in Toronto & Paris respectively; [d]Assuming 70% & 30% people live in single unit house in Toronto & Paris respectively with 4 persons $household^{-1}$.

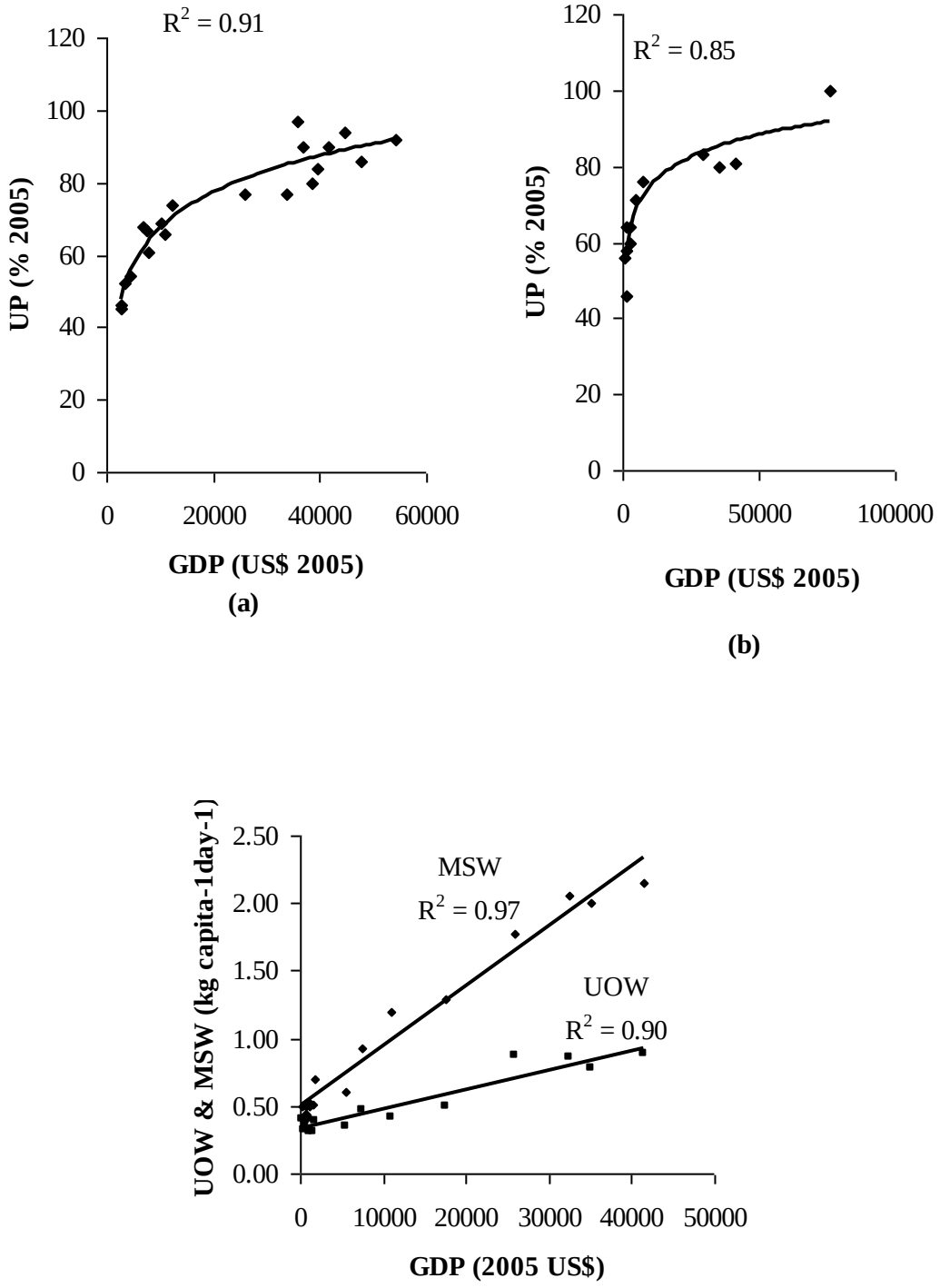
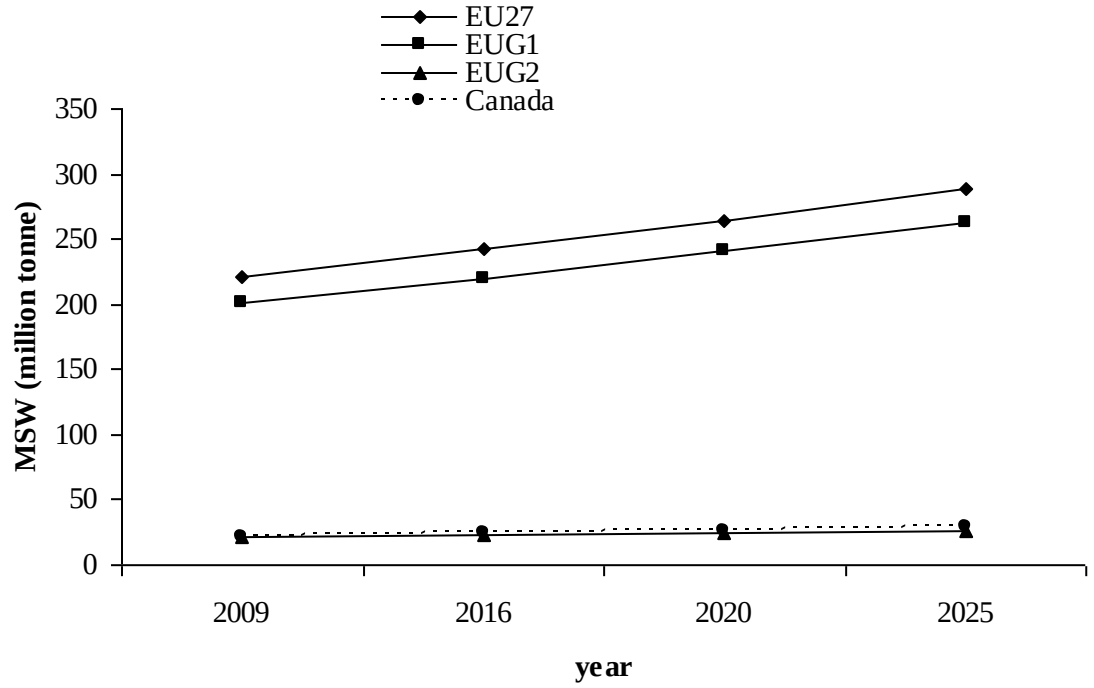
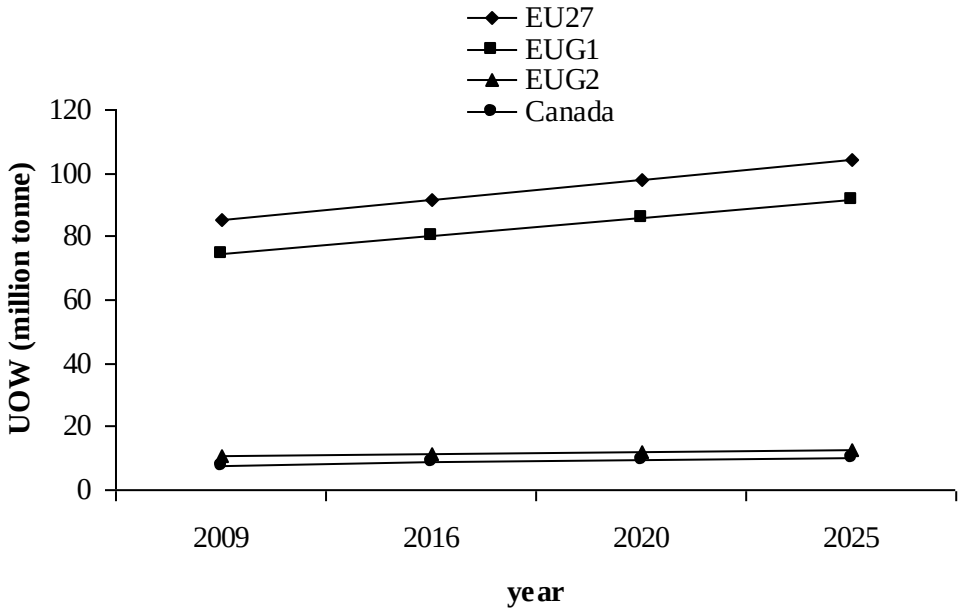


Figure 3.1 Correlation of percentage urban population (%UP) with per capita gross domestic product (GDP) according to UNPD (2007) and UNSD (2008) for (a) Europe; and (b) The Americas. (c) correlation of per capita urban organic waste (UOW) and municipal solid waste (MSW) production with per capita gross domestic production (GDP) according to OECD (2006-2007); Eurostat (2008); Sufian and Bala (2007); Government of India (2008); Kanbour (1997); WHO (1995); Al-Yousfi (2003); Alamgir and Ahsan (2007); and World Resources (1998-99).



(a)



(b)

Figure 3.2 Urban solid waste production in EU and Canada on an annual basis (a) Municipal Solid Waste (MSW); and (b) Urban Organic Waste (UOW).

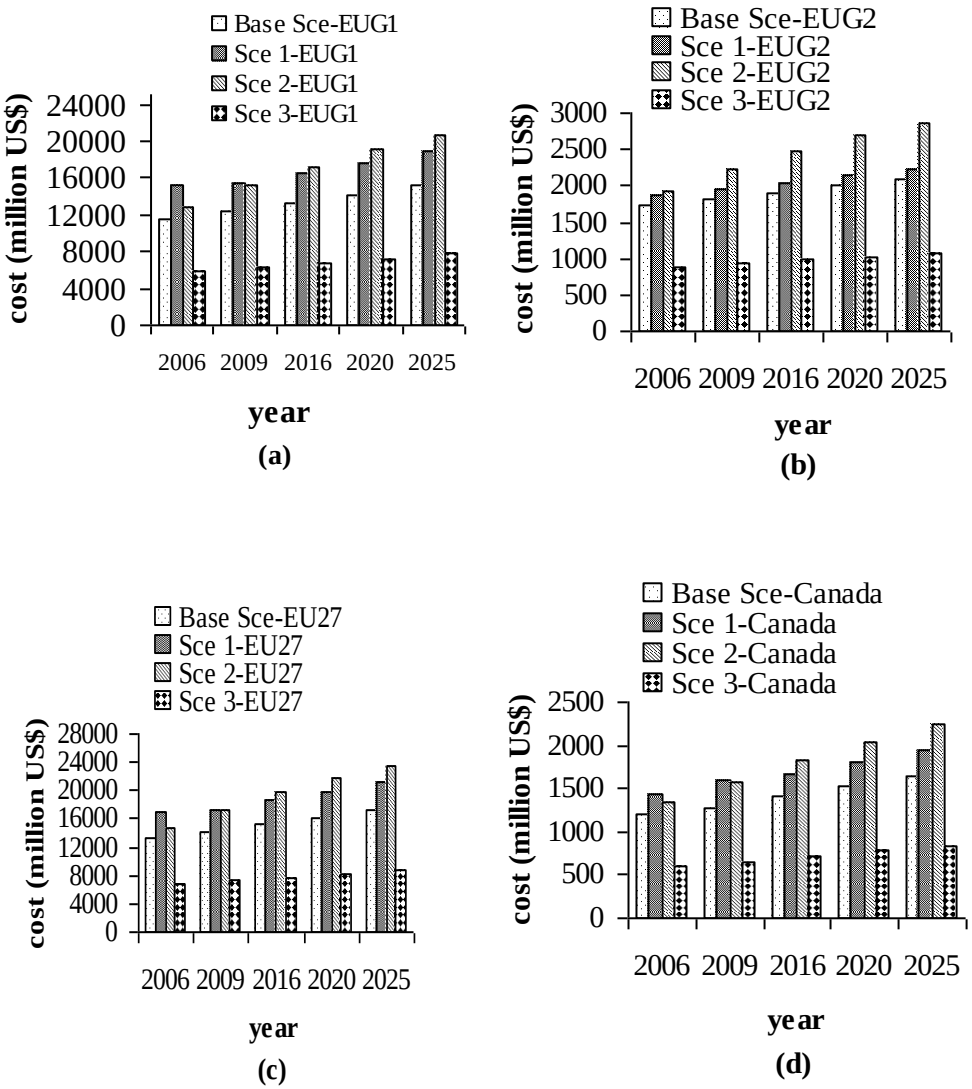


Figure 3.3 Cost of UOW handling and treatment in consideration of various scenarios for (a) The European Union Group one (EUG1); (b) The European Union Group two (EUG2); (c) 27 countries of The European Union (EU27); and (d) Canada.

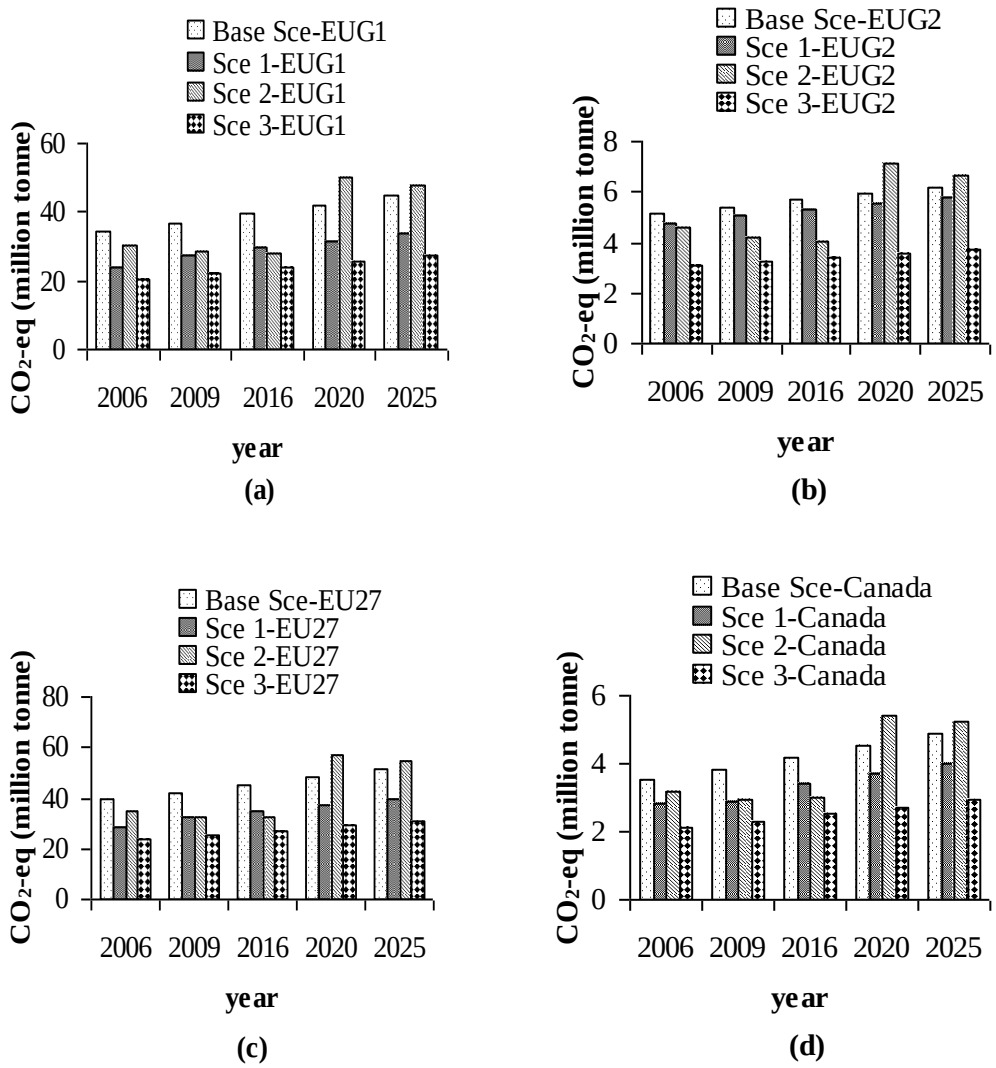


Figure 3.4 Computed Greenhouse Gases (CH_4, CO_2 & N_2O) emissions from UOW treatment in consideration of various scenarios for (a) The European Union Group one (EUG1); (b) The European Union Group two (EUG2); (c) 27 countries of The European Union (EU27); and (d) Canada.

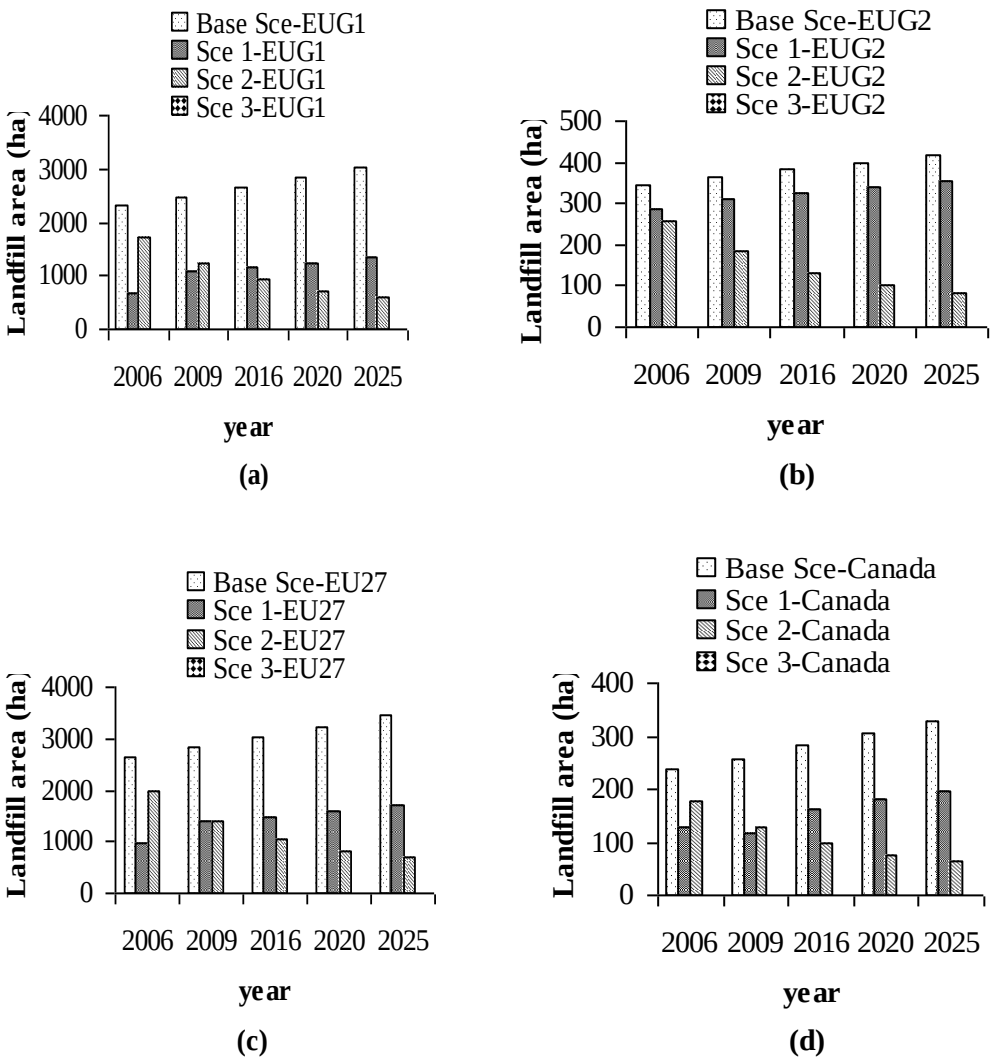


Figure 3.5 Computed landfill area required for UOW landfilling in consideration of various scenarios for (a) The European Union Group one (EUG1); (b) The European Union Group two (EUG2); (c) 27 countries of The European Union (EU27); and (d) Canada.

Connecting statement to chapter 4

The previous chapter demonstrated that onsite treatment of OW rather than disposal in landfills and treating at centralized facilities reduces environmental as well as economic pressure of MSW management systems and saves limited land. However, the shift of MSW management systems from landfill disposal to resource recovery requires technological input, population participation, and compost quality assurance. In this context chapter 4 examines the effect of home composter design type on the composting process and quality of composted product.

Chapter 4 is drawn from a manuscript submitted for publication to the journal of International Journal of Environmental Technology and Management (IJETM) by the author of the thesis and co-authored by supervisors, Dr. Anne Trémier, Cemagef, Rennes, France, Prof. Dr. Suzelle Barrington, Department of Bioresource Engineering, McGill University, Montreal, Canada and Dr. José Martinez, regional director, Cemagef, Rennes, France. The format has been changed to be consistent within this thesis.

Chapter 4

Home composting of organic waste: effect of home composter design

Abstract

Worldwide, health and environmental considerations have recently encouraged the diversion from landfills, of the organic fraction (OW) of the municipal solid waste stream (MSW). As an alternative to centralized facilities, on-site treatments such as home composting can reduce recycling costs, as long as the product is safe and well sanitized. The objective of this study was therefore to compare, against a laboratory forced aeration composter (LR), the performance in terms of temperature regime and compost quality, of four 300 to 400 L home composting systems (HC), namely the Plastic (P) and Wood (W) Bins, the Rotary Drum (RD) and the Ground Pile (GP). All HC and the LR were batch loaded with the same food waste (FW) and yard trimmings (YT) mixture, to monitor under equal conditions, their temperature and compost characteristics. The temperature of the P, RD and GP composts reached 55ºC within 3 days while that of W and LR required 6 and 9 days, respectively. The P, W, and GP composts were exposed to 60 °C temperatures for over 3 days while that of RD and LR peaked at 58 °C. After 150 days and despite different temperature regimes, all HC and the LR composts demonstrated similar dry matter, organic matter, chemical oxygen demand and total carbon (95 % confidence level) concentrations, except for that of RD remaining at 23 % dry matter, because of poor aeration. All composts produced pathogen and parasite counts, trace element levels and polycyclic aromatic hydrocarbons concentrations respecting France and North American regulations. In this study, P and GP performed best among all HC, producing the longest sterilizing thermophilic temperatures as a result of better convective aeration.

Keywords: organic waste, home composters, compost quality, municipal solid waste.

4.1 Introduction

When used to eliminate the organic fraction of the municipal solid waste stream (MSW), landfilling brings about air, water and soil contamination risks for ecosystems, the atmosphere and human health, beside complaints from local residents (Kim and Kim, 2010**;** Montejo et al., 2010)**.** As a major fraction of MSW, organic waste (OW) production has increased considerably worldwide over the past decade as a result of economic growth especially in Asia (Boldrin and Christensen, 2010; Colón et al., 2010; López et al., 2010). Accordingly, legislation such as in Europe and North America, has advocated the recycling and reuse of OW, or its stabilization if it must be landfilled. Composting, anaerobic digestion, incineration and mechanical biological treatment are options with less environmental impact than landfilling, but require more complex collection and transportation systems, besides more costly processing facilities (Adhikari et al., 2010).

Source separation and recycling using a home composting system (HC) is a solution among others to recycle OW while limiting collection, transportation and treatment costs (Adhikari et al., 2010; Colón et al., 2010; Smith and Jasim, 2009). But the management of HC must produce bio-secure compost relatively free of parasites and pathogens, trace elements and toxic organics (Stabnikova et al., 2005). Depending on the care used during source separation, compost produced from OW can contain: trace elements such as those generated from the ink of waste paper and added by atmospheric deposition and small metallic fragments discarded inadvertently (Smith, 2009); organic pollutants such as polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB) from pesticides applied to or aerially deposited on horticultural wastes (Brändli et al., 2007), and; pathogens, parasites and viruses when the compost recipe, made from infected wastes, is not uniformly exposed to

thermophilic temperatures (Gong, 2007). Furthermore, poor compost management can lead to a greater generation of greenhouse gases and odours (Nakasaki et al., 1998; Recyc-Québec, 2006).

Considering the limited number of studies pertaining to aspects of bio-security associated with OW treatment using HC **(**Körner et al., 2008; Smith and Jasim, 2009; Colón et al., 2010), the main objective of this study was to compare the performance of four different types of common HC, by comparing their temperature regime and their compost quality. The four experimental HC, namely the Plastic (P) and Wood (W) bins, the Rotary Drum (RD) and the Ground Pile (GP), were compared to a control, namely a Laboratory Reactor (LR) with forced aeration. All HC and the LR were batch filled to monitor under similar conditions, their temperature and compost characteristics.

4.2 Material and Methods

4.2.1 Experimental composters and substrate

This study compared the performance of four commonly used HC and a control, namely a laboratory reactor (LR). The 4 common HC were: a 400 L Plastic bin (P) measuring 0.70 m x 0.70 m by 0.80 m in height (bottom and top perforated); a 400 L Wood bin (W) measuring 0.78 m x 0.65 m by 0.75 m in height (slatted walls); a 350 L metallic Rotary Drum (RD) (aeration port at the bottom end) with an internal diameter of 0.77 m and a length of 0.76 m, and; a Ground Pile (GP) measuring 0.65 m in height and 0.75 m in base diameter (Figure 4.1). The 300 L laboratory Reactor (LR) had an internal diameter of 0.70 m and a height of 0.80 m and had a manually controlled forced aeration system.

The source separated food waste (FW) was supplied by two restaurants of the city of Rennes, Bretagne, France. All FW was collected within 3 days of being

produced and stored at 4 °C until used. The yard trimmings (YT) were obtained from the grounds of the Cemagref Research Institute of Rennes, France. While being collected, the FW and YT were sampled for physico-chemical characterization.

4.2.2 Experimental procedure

All four HC were randomly placed under a tent outside for rainfall and sunshine protection, while the LR was operated inside a laboratory. Using the same FW and YT mixture in equal wet volumes, all composting systems were filled at once without any pre-treatment for comparison on a similar basis. While filling the HC and LR, several Thermochron iButton temperature sensors (DS1921G-F5, Thermochron iButton, Dallas Semiconductor, USA) were installed in the compost mass: one in the centre; two at 0.1 m above the bottom, and; two more at 0.1 m below the compost surface. All HC were naturally aerated except for their weekly mixing of all compost mass manually, while the LR was aerated at a fixed rate of 188 $L(hr)^{-1}$. During the mixing of compost mass, the Thermochron iBotton temperature sensors were retrieved and reinstalled after completion of mixing.

All composting systems were operated for 150 d. Every week during the first two months and monthly thereafter, all composts were evaluated for their odour characteristics, then hand mixed and sampled in triplicate (100 g) for characterization. The temperature sensors were retrieved after 70 d of composting, during one of the mixing operation. After 150 d, the HC and LR compost mass was weighed and sampled in triplicate for physico-chemical characterization. The characterization at 0 and 150 d provided data to compute the loss in dry matter (DM), total carbon (TC), total Kjeldahl nitrogen (TKN), chemical oxygen demand (COD), and organic matter (OM) fractions, namely soluble OM, hemicellulose, cellulose and lignin.

Furthermore, the final product at 150 d was analyzed for pathogens and parasites, trace elements and polycyclic aromatic hydrocarbon (PAH), to assess the compost quality and thus its suitability as a soil amendment (Mato et al., 1994).

4.2.3 Analytical procedure

The bulk density of the fresh compost samples was determined by filling three 30 L pails without compaction, and weighing their content. The free air space (FAS) of the fresh compost samples was determined using an air pycnometer (Berthe et al., 2007) where an airtight cell is filled with compost and then pressurized while measuring the volume of injected air. At equilibrium pressure, the injected air provides an estimate of the free air space in the compost.

Before being analyzed, all triplicate compost samples were dried in an oven (SR 2000, Thermosi, France) at 80 °C until a constant weight was reached and then ground to less than 0.5 mm (ZM model 1000 grinder, Retsch, Germany). The total carbon (TC) was determined by burning 10 mg samples at 900 °C (Thermo Scientific, FLASH 2000 Series, Organic Elemental Analyser, Courtaboeuf, France) according to AFNOR (2001a). According to AFNOR (1995), TKN was determined using an automatic distilling system (VAP 50c, Gehardt automatic distilator, Gehardt, Germany), after digesting 0.5 to 1.0 g samples with H_2SO_4 (automated Kjeldatherm TZ block digester, Gerhardt, Germany). The COD was determined by titration (Metrohm, Courtaboeuf, France) after digesting 60 mg samples with H_2SO_4 and $K_2Cr_2O_7$ (Kjeldatherm COD digestion block, CSB 20M, Gerhardt, Germany), according to AFNOR (2001b). The OM was determined by burning at 550 °C for 3 hours (Thermolyne 30400, Furnace, F30420 C-33, Essex, UK), according to AFNOR (1985). To correct all analytical results, residual moisture was determined by drying

ground compost samples at 105 ºC for 24 hours (SR 1000, Thermosi, France). The pH of wet samples was determined by soaking for 24 hours without shaking at 5ºC, in just enough distilled water to use a pH electrode (pH-Electode SenTix41, WTW, Weilhein, Germany) according to Adhikari et al. (2009). The soluble OM, hemicellulose, cellulose and lignin fractions were determined using a fibre extractor (VELP Scientific, FIWE 6 Extractor for raw fibre determination, Usmate, Italy) according to Van Soest (1963).

Escherichia coli and fecal *Streptococci* were quantified using microfiltration (AFNOR, 2001c). The presence of Salmonella in 25 g wet samples was verified using Petri plates with XLD agar (AFNOR, 2006). The presence of *helminthe* eggs in 1.5 g of wet sample was determined using the triple flotation technique (AFNOR, 2004). The trace elements were quantified by ICP-MS (Inductively Coupled Plasma Mass Spectroscopy) after digestion with nitric acid, and the PAH were analysed by chromatography and fluorimetric detection after extraction with hexane/acetone (AFNOR, 2000) respectively.

According to a simple method developed by Rosenfeld et al. (2007), compost odour characteristics were subjectively evaluated using 10 panellists trained to recognize the following smells: earthy/humus (EH), mushroom (MR), citrus fruit (CF), grassy/hay (GH), soft fermentation (SF), fishy (F), dead animal (DA), mouldy (MD), rotten vegetable (RV), rotten eggs (RE), sewage (SE) and woody (WD). Odour evaluations were conducted every two weeks for the first month and monthly thereafter. Panellists took a three minute break between each HC evaluation, and described the odour using as many smell types as required. Each smell type associated with a HC at a given time was expressed in terms of the percentage of reporting panellists.

4.2.4 Statistical procedure

Consisting of the four HC and the LR, the treatments were tested with same initial compost mixture, fed all at once on the same day. The statistical significance of the treatment (HC type and LR as control) effect on the compost characteristics during 150 d was tested over time with triplicate samples for each HC and the LR. Accordingly, the physico-chemical characteristics were compared by the repeated measure ANOVA using PROC GLM procedure at 95 % confidence level (SAS Institute Inc., 2008).

4.3 Results and discussion

4.3.1 Initial physico-chemical characteristics of the experimental materials

The FW and YT composition is described in Table 4.1. On a wet mass basis, vegetable residues formed the largest fraction of FW at 49 %, followed by roots and tuber, fruit and cooked food residues ranging between 15 and 18 %. The various fractions of FW had a similar DM ranging from 20 to 29 % and averaging 25 %. On a wet mass basis, the YT consisted of 89.9% grass clippings at 58 % dry matter (DM) and 10.1 % tree leaves at a 64 % DM.

The physico-chemical characteristics of the initial compost mixture loaded into each HC and the LR are presented in Table 4.2. The compost mixture consisted of FW and YT at a wet volumetric ratio of 1:1 with a DM of 23 to 24% (±1.2 %), a C/N ratio of 17, a pH of 6.1 (±0.17), and an OM of 75 to 77 % (dm basis). The properties of the initial compost mixture respected those recommended for an active aerobic microbial activity, namely a C/N ratio in the range of 15 to 35 (Stabnikova et al., 2005; Haug, 1993; Zucconi and de Bertoldi et al., 1986), a pH between 6 and 8 (Haug, 1993) and a DM of 20 to 40 % (Haug, 1993; Adhikari et al., 2009). The fresh

compost offered FAS of 66 % which according to Eftoda and McCartney (2004) respects the minimum of 30 % required for good aeration. The OM fractions consisted of 51 % soluble OM, 23 % hemicellulose, 17 % cellulose and 8.5 % lignin, for a chemical oxygen demand (COD) of 1120 g O_2 /kg dm.

4.3.2 Temperature regime

Temperature is considered to be an excellent indicator of aerobic microbial activity (Diaz et al., 1993). The temperature regime developed by all HC and the LR composts during the initial 70 d of testing is presented in Figure 4.2. Quickly developing thermophilic temperatures, the P, GP and RD composts reached 55 ºC within 3 days, while that of W and LR reached 55 ºC later, on day 6 and 9, respectively. Thermophilic temperatures above 55 ºC were maintained during 6, 5, 4 and 2 days for GP, P/W, RD and LR, respectively. The P, W, and GP composts were exposed to 60 °C temperatures for over 3 days while that of RD and LR peaked at 58 °C. The composts of all HC were fully reacted by day 21, at which time their temperatures had dropped to near ambient. The LR compost temperature of 25 ºC as of day 18 corresponded to the ambient laboratory temperature.

The difference in temperature regime among all HC and LR composts resulted from their different aeration modes, where the HC were exposed to natural convection while the LR was force aerated. When aerating compost, Barrington et al. (2002) demonstrated that convective (passive) aeration is better able to provide an aeration rate corresponding to the requirements of the microbial activity, as opposed to forced aeration without a control algorithm. Under uncontrolled forced aeration, ventilation rates often either exceed or do not meet the microbial requirements resulting in a temperature drop below thermophilic levels. Under convective forces, the microbial

community creates its own aeration rate based on the heat generated from its level of activity. Nevertheless, convective aeration requires proper air flow conditions with bottom and top air access. Large compost masses require floor ducts to enhance convection as opposed to HC where wall perforations can suffice.

The temperature regime developed by each HC reflected their ability to generate convective aeration forces. The GP was free of obstacles and provided the best temperature regime along with that of P with perforations concentrated at its bottom and top. In contrast, W did not perform as well, with aeration slots distributed over it full height. Initially providing sufficient aeration to quickly reach thermophilic temperatures above 55 °C, RD suffered from the later clogging of its aeration ports located at lower end of the RD with wet compost mass also preventing moisture evacuation. Accordingly, its compost remained wet, developing thermophilic temperatures of 58 °C for a short while, and generating malodours, as will be seen later.

The temperature distribution was similar within the compost mass for all HC with the highest values recorded in the centre. For all HC, the compost surface temperature was close to ambient indicating the need for mixing to achieve a more uniform maturation process.

The duration and temperature required for sanitization of compost from parasites, pathogens and viruses varies between the country standards, at least 3 days of to 60 °C and 55 °C are required in Europe and Canada respectively (Chroni et al., 2009; Hogg et al., 2002). In this experiment, the P, GP and W composts respected both the European and Canadian norms, while that of RD respected the Canadian norms only. The LR compost respected neither norm achieving temperatures between 55 and 60 °C only for 2 days.

4.3.3 Compost characteristic evolution

Figure 4.3 illustrates the evolution of the physico-chemical characteristics of all compost during 150 d of composting. When comparing the final characteristics among treatments, namely the four HC and the LR, only the RD compost DM, TKN and pH and the LR compost TKN were significantly different ($p < 0.05$). Thus, Figure 4.3 groups the results of all treatments except for DM, TKN and pH associated with RD and TKN associated with LR.

After 150 days of composting, all composts demonstrated the same final TC and OM of 26 % (±1) and 49 % (±2), respectively, resulting in a final COD of 705 g O_2 (kg dm)$^{-1}$ (±28), with the highest rate of change occurring during the first 15 days. The compost DM differed only for that of RD ($p<0.01$) remaining at 23 %, as compared to all other treatments at 80 % (±4). The RD compost maintained a low DM because of its aeration port clogging resulting in moisture accumulation as observed during mixing operations. This also resulted in a shorter thermophilic composting period.

The compost TKN showed little evolution over the 150 day composting period, (Figure 4.3b), with that of LR showing a significantly higher final level of 26.6 (±0.46) g (kg dm)$^{-1}$ and that of RD showing a significantly lower levels of 19.9 (±0.26) g (kg dm)$^{-1}$ ($p<0.01$). A final pH ranging between 8 and 9 was reached by all treatments, except for that of the RD which remained lower between 7 and 8 especially from day 15 to 90, because of its wet compost. Nevertheless, a pH ranging from 7 to 8.5 exerts no negative effect on the microbial degradation process, even during the early stages of composting (Nakasaki et al., 1993).

Figure 4.4 presents the evolution of the different organic fractions during the 150 d composting period. The soluble, hemicellulose and cellulose fractions dropped

to 43.6% (±3.4), 11% (±2.3) and 13.5% (±3.4) from an initial concentration of 51% (±0.3), 22.9% (±0.3) and 17.5% ((±0.1), respectively. In parallel with TC and OM, the soluble fraction was degraded at a fast rate during the initial 15 days, but still remained high at 43.6 % after 150 days of composting. Following the degradation of easily available soluble OM after 15 days, hemicelluloses decomposition dominated for the following 135 days, reaching a low of 11 %. The cellulose concentration dropped at a constant rate during the entire composting period, whereas the lignin concentration increased as the other fractions disappeared. Simple carbon compounds such as soluble sugars and organic acids are easily metabolized by the compost microbial population whereas natural long chain polymers such as lignin remain, being harder to breakdown (Epstein, 1997; de Bertoldi et al., 1983).

Table 4.3 presents the substrate losses for all five treatments after 150 d. Although compost composition was similar among all five treatments, higher losses were observed for the RD treatment, except for COD. The RD compost had a dry mass loss of 63 % whereas the other HC and the LR suffered a loss of 52 to 59 %. In terms of moisture, RD lost only 62 %, compared to 93 to 98 % with the other treatments. The RD losses of TC, TKN and OM at 77, 68 and 77 %, exceeded those of the other treatments ranging from 70 to 72 %, 52 to 53 % and 70 to 73 %, respectively. To explain the difference in OM losses, RD lost more soluble and lignin fractions at 80 and 20 %, compared to 72 to 75 %, and 9 to 11 %, respectively, for the other treatments. Under limited aeration reflected by the achievement of shorter thermophilic temperatures, the higher MC of the RD compost enhanced the loss of TC, OM and TKN as compared to the other treatments.

4.3.4 Compost odour emission

Figures 4.5a to f illustrate the odour characteristics of each HR and the LR composts during the 150 d treatment. The objectionable odours were defined as MD (mouldy), RV (rotten vegetables) and RE (rotten eggs), and are grouped to the right of the vertical dotted line in Figures 4.5 a to f. After 15 d of composting, the GP compost offered the least odour, followed by that of W and P offering limited odour levels and that of RD and LR offering objectionable odours. Accordingly, the GP compost offered no odour as reported by 80 % of the panellists, while 20 % characterized its odour as grass/hay. For that of W, 10 % of the panellists reported no odour, while 60 % reported an earthy odour and 20 % reported a grass/hay odour. For that of P, its odour was mostly characterized as grass/hay by 50 % of the panellists, mouldy by 20 %, and earthy and mushroom each by 10 % of the panellists. The RD and LR composts offered the most odours, with that of RD reported as mostly a grass/hay odour by 60 % of the panellists, mouldy by 20%, and rotten vegetables and eggs by 10%. The LR compost offered a grass/hay odour reported by 70 % of the panellists, mouldy by 20%, and rotten vegetable by 10 % of the panellists.

For the rest of the composting period, only the RD compost produced objectionable odours with 20, 20, 50 and 10 % of the panellists reporting an odour of mushroom, soft fermentation, mouldy and rotten eggs respectively (Figure 4.5f). The stronger odour associated with the RD likely resulted from the low DM of its compost encouraging anaerobic conditions and the production of smelly reduced gases. After 150 days of composting, the LR, GP, and P compost had no odour, as reported by 90 % of the panellists, while 40 and 60 % reported either earthy/humus or no odour respectively for the W compost.

4.3.5 Pathogens/parasites and trace element levels

Table 4.4 presents the level of pathogens and parasites found in all composts. Despite variations in *Escherichia coli* and *Streptococcus* faecalis counts, all compost respected regulations imposed by France. The presence of *Streptococcus* faecalis resulted from the YT obtained from a lawn where manure was spread. The low P compost level likely resulted from the high thermophilic temperatures sustained over 5 days, combined with less compost surface exposed to ambient temperatures. The high levels observed in the LR compost resulted from the poor thermophilic conditions achieved. *Salmonella* and *Helminthes* were absent in all compost likely because of their absence in the original materials, especially considering that the LR compost was not exposed to stabilizing thermophilic temperatures.

Since the initial compost mixtures were derived from the same source, polycyclic aromatic hydrocarbons (PAH) and trace elements were analysed only for the W compost. In Table 4.5, all PAH levels respect regulations for mixed MSW compost in Canada and Europe, as a result of its proper source separation. Also, trace elements (Table 4.6) respected the various regulations found in the US, Canada and Europe, because of the low level of pesticides applied on the grounds providing the YT.

4.4 Conclusion and recommendations

Before home composting systems (HC) can be advocated as a safe management practice to recycle the organic waste (OW) fraction of the Municipal Solid Waste stream (MSW), its best practices must be defined. Accordingly, the objective of this project was to compare the performance of four common HC against that of a laboratory composter (LR). The common HC studied were the Plastic (P) and Wood

(W) Bins, the Rotary Drum (RD) and the Ground Pile (GP). To equally compare all five systems, the same compost was fed all at once and observed for 150 d.

All four HC produced thermophilic temperatures with P, W and GP achieving 60 ºC during at least 3 d, and RD and LR achieving 55 ºC for 4 and 2 d, respectively. The difference in temperature regime between all four HC was attributed to the extent of convective aeration, with GP offering no air movement obstacles and P offering top and bottom perforation favouring convection. With opening distributed uniformly over its height, W offered less effective convective aeration. The aeration ports of the RD became clogged, resulting in poor aeration and a short thermophilic period.

Despite differences in aeration, all five treatments produced similar final composts except for RD producing a wetter product because of poorer aeration. In terms of substrate losses, and because of its lower DM as compared to the other treatments, the RD compost lost more TC, OM and TKN and offered more offensive odours after 150 d. Despite differences in levels of Streptococcus faecalis explained by the extent of thermophilic temperatures, all four HC and the LR produced compost respecting regulations in terms of pathogens and parasites. Produced from the same clean waste, all composts offered aromatic hydrocarbons and trace element levels respecting European and North American regulations.

HC, GP and P performed best, quickly producing thermophilic temperatures lasting long enough to sanitize the compost. The W was slower in developing thermophilic temperatures but sustained them as long as P. The RD provided poor aeration as a result of its aeration ports becoming clogged, while the LR should have been aerated at a higher rate. The higher performance of GP and P was attributed to better convective aeration conditions, resulting respectively, from the absence of obstacles and perforations concentrated at the bin top and bottom. The higher

performance of GP and P will be confirmed by an experiment in chapter 5 comparing the effect of the HC management practices (Adhikari et al., 2011b).

4.5 Acknowledgements

This study is part of a larger project entitled ECCOVAL, conducted in partnership with Rennes Métropole, CRPCC LAUREPS and CIELE, and funded by the regional council of Brittany, France. The authors also acknowledge the financial and logistics support by the Cemagref of Rennes, France and the Natural Science and Engineering Research Council of Canada.

4.6 References

Adhikari BK, Trémier A, Martinez J and Barrington S (2011a) Home composting of organic waste. Part II. Effect of management practices. International Journal of Environmental Technology and Management, presented for publication along with this part 1.

Adhikari BK, Trémier A, Martinez J and Barrington S (2010) Home and community composting for on-site treatment of urban organic waste: perspective for Europe and Canada. Waste Management & Research 28(11): 1039-1053.

Adhikari BK, Barrington S, Martinez J and King S (2009) Effectiveness of three bulking agents for food waste composting. Waste Management 29: 197-203.

AFNOR (2006) Amendements organiques, dénominations, spécifications et marquage, NF U44-051. Association Française de Normalisation, Paris, France.

AFNOR (2004) Characterization of sludges - Enumeration and viability of parasite helminth eggs - triple flotation technique, XP X33-017. Association Française de Normalisation, Paris, France.

AFNOR (2002) Organic soil improvers-composts containing substances essential to agriculture, NF U44-095. Association Française de Normalisation, Paris, France.

AFNOR (2001a) Caractérisation des déchets-Dosage du carbone organique total (COT) dans les déchets, boues et sédiments, NF EN 13137. Association Française de Normalisation, Paris, France.

AFNOR (2001b) Qualité de l'eau-Détermination de la demande chimique en oxygène (DCO), NF T 90-101. Association Française de Normalisation, Paris, France.

AFNOR (2001c) Microbiology of food and animal feeding stuffs-Horizontal method for the enumeration of B-glucuronidase-positive Escherichia coli-Part 2:colony-

count technique at 44 °C using 5-bromo-4-chloro-3-indolyl B-D-glucuronate, NF ISO 16649-2. Association Française de Normalisation, Paris, France.

AFNOR (2000) Characterisation of sludges-Determination of polynuclear aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB), XP X33-012. Association Française de Normalisation, Paris, France.

AFNOR (1995) Qualité du sol -Dosage de l'azote total - Méthode de Kjeldahl Modifiée, NF ISO 11261. Association Française de Normalisation, Paris, France.

AFNOR (1985) Amendements organiques et supports de culture-Détermination de la matière organique totale - Méthode par calcination, NF U 44-160. Association Française de Normalisation, Paris, France.

Barrington S, Choinière D, Trigui M and Knight W (2002) Compost convective airflow under Passive aeration. Journal of Bioresource Technology 86: 259-266.

Berthe L, Druilhe C, Massiani C, Tremier A and de Guardia A (2007) Coupling a respirometer and a pycnometer, to study the biodegradability of solid organic wastes during composting. Biosystem Engineering 97: 75-88.

Boldrin A and Christensen TH (2010) Seasonal generation and composition of garden waste in Aarhus (Denmark). Waste Management 30: 551–557.

Brändli RC, Bucheli TD, Kupper T, Mayer J, Stadelmann FX and Tarradellas J (2007) Fate of PCBs and PAHs and their source characteristic ratio during composting and digestion of source-separated organic waste in full-scale plants. Environmental Pollution 148: 520-528.

Brinton WF (2000) Compost quality standards & guidelines: an international view. Final reports presented for New York State association of Recyclers, Woods End Laboratories, Inc. Mt Vernon, ME, USA.

CCME (2005) Guidelines for compost quality', PN 1340, ISBN 1-896997-60-0.Canadian Council of Ministers of the Environment, Winnipeg, Manitoba, Canada.

Chroni C, Kyriacou A, Georgaki I, Manios T, Kotsou M and Lasaridi K (2009) Microbial characterization during composting of biowaste. Waste Management 29(5): 1520-1525.

Colón J, Martínez-Blanco J, Gabarrell X, Artola A, Sánchez A, Rieradevall J and Font X (2010) Environmental assessment of home composting. Resources, Conservation and Recycling 54: 893–904.

de Bertoldi M, Vallini G and Pera A (1983) The Biology of Composting: a Review. Waste Management & Research 1: 157.

Déportes I, Benoit-Guyod J-L and Zmirou D (1995) Hazard to man and the environment posed by the use of urban waste compost: a review. The Science of the Total Environmrnt 172: 197-222.

Diaz LF, Savage GM, Eggerth LL and Golueke CG (1993) Composting and Recycling. Municipal Solid Waste. Lewis Publishers, Boca Raton, USA. pp. 121 – 173.

EC (2006) Establishing revised ecological criteria and the related assessment and verification requirements for the award of the Community eco-label to growing media. European Commission - notified under document number C(2006) 6962, Official Journal of the European Unio, L32/137, Office for Official Publications of the European Communities, Luxembourg.

Eftoda G and McCartney D (2004) Determining the critical bulking agent requirement for municipal solid waste biosolids composting. Compost Science & Utilization 12(3): 208 – 218.

Epstein E (1997) The science of composting. CRC Press, Boca Raton, Florida, USA, pp. 77 – 103.

Epstein E, Chaney RL, Henrys C and Logan TJ (1992) Trace elements in municipal solid waste compost. Biomass and Bioenergy 3(3-4): 227-238.

Gong C-M (2007) Microbial safety control of compost material with cow dung by heat treatment. Journal of Environmental Science 19: 1014-1019.

Groeneveld E and Hébert M (2003) Dioxins, furans, PCBs and PAHs in eastern Canada compost. Quebec Ministry of Environment, Québec, Canada. www.mddep.gouv.qc.ca/matieres/articles/compost-en.pdf Accessed 16 July 2010.

Haug RT (1993) The practical handbook of compost engineering. Lewis Publishers. A CRC press LLC, Boca Raton, Florida, USA, pp. 248.

Hogg D, Barth J, Favoino E, Centemero M, Caimi V, Amlinger F, Devliegher W, Brinton W and Antler S (2002) Comparison of compost standards within the EU, North America and Australasia. The Waste and Resources Action Programme, The Old Academy, Banbury, Oxon, UK.

Iwegbue CMA, Emuh FN, Isirimah NO and Egun AC (2007) Fractionation, characterization and speciation of heavy metals in composts and compost-amended soils. African Journal of Biotechnology 6(2): 067-078.

Kim MH and Kim JW (2010) Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery. Science of the Total Environment 408(19): 3998 – 4006.

Körner I, Saborit-Sánchez I and Aguilera-Corrales Y (2008) Proposal for the integration of decentralised composting of the organic fraction of municipal solid

waste into the waste management system of Cuba. Waste Management 28: 64–72.

López M, Soliva M, Martínez-Farré FX, Bonmatí A and Huerta-Pujol O (2010) An assessment of the characteristics of yard trimmings and recirculated yard trimmings used in biowaste composting. Bioresource Technology 101: 1399–1405.

Martínez-Blanco J, Colón J, Gabarrell X, Font X, Sánchez A, Artola A and Rieradevall J (2010) The use of life cycle assessment for the comparison of biowaste composting at home and full scale. Waste Management 30: 983–994.

Mato S, Orto D and Garcia M (1994) Composting of <100 mm fraction of municipal solid waste. Waste Management & Research 12 (4): 315-325.

Montejo C, Ramos P, Costa C and Márquez MC (2010) Analysis of the presence of improper materials in the composting process performed in ten MBT plants. Bioresource Technology 101(21): 8267-8272.

Nakasaki K, Kuratomi H, Wakizaka H, Hiyama R and Akakura N (1998) Quantitative analysis of ammonia and odorous sulphur compounds evolved during thermophilic composting. Waste Management & Research 16(6): 514-524.

Nakasaki K, Yaguchi H, Sasaki Y and Kubota H (1993) Effects of pH Control on composting of garbage. Waste Management & Research 11: 117.

Recyc-Québec (2006) Odour related preoccupations during the composting or organic wastes. Quebec, Canada.

Rosenfeld PE, Clark JJJ, Hensley AR and Suffet IH (2007) The use of an odour wheel classification for the evaluation of human health risk criteria for compost facilities. Water Science & Technology 55(5): 345–357.

Saha JK, Panwar N and Singh MV (2010) An assessment of municipal solid waste compost quality produced in different cities of India in the perspective of developing quality control indices. Waste Management 30:192–201.

SAS Institute Inc. (2008) SAS version 9.2, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC, USA.

Smith SR (2009) A critical review of the bioavailability and impacts of heavy metals in municipal solid waste composts compared to sewage sludge. Environment International 35: 142–156.

Smith SR and Jasim S (2009) Small-scale home composting of biodegradable household waste: overview of key results from a 3-year research programme in West London. Waste Management & Research 27: 941–950.

Stabnikova O, Ding HB, Tay JH and Wang JY (2005) Biotechnology for aerobic conversion of food waste into organic fertilizer. Waste Management & Research 23: 39 – 47.

Van Soest PJ (1963) Use of detergents in the analysis of fibrous feeds. I. Preparation of fibre residues of low nitrogen content. Journal of the Association of Official Agricultural Chemists 46: 825–829.

Zucconi F and de Bertoldi M (1986) Compost specifications for the production and characterization of compost from municipal solid waste in compost: production, quality and use. In: de Bertoldi M, Ferranti MP, L'Hermite P and Zucconi F (eds): Proceedings of a symposium organized by the commission of the European communities, Directorate General Science, Research and Development, 17-19 April.Udine Italy.

Table 4.1 Composition of experimental organic waste

Organic waste description		DM	Compost mass content	
Primary	Secondary	(%)	Dry (%)	Wet (%)
Food waste				
Fruits	Apple	15.7	3.6	3.6
	Passion fruit	12.8	0.7	0.9
	Avocado peel	25.9	1.8	1.1
	Avocado seed	50.8	1.1	0.3
	Banana	18.9	2.3	1.9
	Date fruit	68.1	6.7	1.5
	Mango	19.3	1.0	0.8
	Citrus fruits	18.3	6.3	5.3
	Pineapple	15.4	0.7	0.7
	Average/Sub-total	**27.2**	**24.2**	**16.1**
Roots and tubers	Onion/garlic leaves	13.5	0.8	1.0
	Onion/garlic flesh	19.1	4.7	3.8
	Carrot/peel	11.9	9.0	11.7
	Radish	34.9	4.9	2.2
	Average/Sub-total	**19.8**	**19.4**	**18.7**
Cooked food	Rice and bread	25.7	3.9	2.3
	Carrot and cabbage	16.0	7.1	6.8
	Potato	17.3	5.5	5.0
	Spaghetti	33.3	2.0	0.9
	Egg white	36.0	0.3	0.1
	Peas and beans	39.0	0.2	0.1
	Egg shells	66.3	3.5	0.7
	Average/Sub-total	**27.9**	**24.2**	**14.4**
Vegetable	Celery	10.1	8.3	11.9
	Green leafy vegetables	10.8	4.5	6.6
	Cauliflower/cabbage	10.5	20.0	29.6
	Pumpkin	17.1	1.2	1.1
	Peas and beans	39.0	0.2	0.1
	Average/Sub-total	**23**	**34.2**	**49.4**
Overall average		**25**	**100**	**100**
Yard trimmings				
	Grass clippings	58.0	89.0	89.9
	Tree leaves	63.7	11.0	10.1
	Average/Total	**61**	**100**	**100**

Note: DM – dry matter

Table 4.2 Initial experimental compost characteristics

Characteristic		Treatment				
Primary	Secondary	Wood bin (W)	Plastic bin (P)	Ground Pile (GP)	Rotary Drum (RD)	Laboratory Reactor (LR)
FW:YT	Dry mass	0.94:1	0.93:1	0.96:1	1:1	1:1
	Wet mass	3.67:1	3.63:1	3.77:1	3.95:1	3.87:1
	Wet volume	1:1	1:1	1:1	1:1	1:1
Physical	Mass – wet (kg)	72.2	75.5	75.0	75.2	67.2
	- dry (kg)	17.1	17.9	17.6	16.8	15.5
	Volume (L)	320	320	320	320	250
	Bulk density (wet kg(m^{-3}))	230	240	240	230	280
	Dry matter (%)	24.1 (1.2)	24.1 (1.2)	23.7 (1.2)	23.3(1.2)	23.3 (1.2)
	Free air space (%)	66	66	66	66	66
Chemical	pH	6.1 (0.2)	6.1 (0.2)	6.1 (0.2)	6.1 (0.2)	6.1 (0.2)
	Total carbon (g (kg dm^{-1}))	392 (0.7)	392 (0.7)	393 (0.7)	395 (0.7)	395 (0.7)
	Total Kjeldahl nitrogen (g (kg dm)$^{-1}$)	23 (0.2)	23 (0.2)	23 0.2)	23 (0.2)	23 (0.2)
	Chemical oxygen demand (gO_2 (kg dm)$^{-1}$)	1117 (24)	1115 (24)	1113 (24)	1115(24)	1139 (24)
	Carbon:nitrogen (C/N)	17	17	17	17	17
Organic fraction	Organic matter (% dm)	75 (0.2)	75 (0.2)	75 (0.2)	75 (0.2)	77 (0.2)
	Soluble fraction (%)	50.7	50.7	51.1	51.5	51.2
	Hemicellulose (%)	23.1	23.1	23.0	22.9	22.4
	Cellulose (%)	17.6	17.6	17.5	17.4	17.5
	Lignin (%)	8.6	8.6	8.4	8.3	8.9

Note: the value in parenthesis is the standard deviation (n=3) and all the HC were loaded with the same compost mixture.

Table 4.3 Compost substrate losses after 150 days

Characteristic		Treatment				
Primary	Secondary	Wood bin (W)	Plastic bin (P)	Ground Pile (GP)	Rotary Drum (RD)	Laboratory Reactor (LR)
Physical	Mass loss					
	- % (wet)	87	83	87	62	89
	- % (dry)	56	52	55	63	59
	Volume loss					
	- % (wet)	88	88	89	89	89
Chemical	Moisture loss					
	- (kg(kg dm)$^{-1}$)	3.12	2.99	3.18	2.06	3.26
	- %	97	93	98	62	98
	COD loss					
	- (gO_2 (kg dm)$^{-1}$)	805	797	802	845	839
	- %	72	72	72	76	74
	Total carbon loss					
	- (kg (kg dm)$^{-1}$)	0.28	0.27	0.28	0.30	0.29
	- %	70	70	71	77	72
	TKN loss					
	- (g ((kg dm)$^{-1}$)	12.3	12.0	12.0	15.7	12.3
	- %	53	52	52	68	53
	Organic mass loss					
	- (kg (kg dm)$^{-1}$)	0.53	0.53	0.53	0.58	0.56
	- %	71	70	70	77	73
Organics	Soluble loss					
	- %	76	74	72	80	75
	- (kg (kg OM)$^{-1}$)	0.39	0.37	0.37	0.41	0.38
	Hemicellulose loss					
	- (kg (kg OM)$^{-1}$)	0.21	0.19	0.19	0.20	0.20
	- %	90	83	83	88	89
	Cellulose loss					
	- (kg (kg OM)$^{-1}$)	0.13	0.15	0.15	0.14	0.13
	- %	72	83	84	80	77
	Lignin loss					
	- (kg (kg OM)$^{-1}$)	0.01	0.01	0.01	0.02	0.01
	- %	9	10	11	20	10

Note: dm – dry mass; OM – organic matter; CO – chemical oxygen demand; TKN – total Kjeldhal nitrogen.

Table 4.4 Pathogens and parasites levels after 150 days of composting

Organism	Organism level					Standard for France[a]
	Wood bin (W)	Plastic bin (P)	Ground Pile (GP)	Rotary Drum (RD)	Laboratory Reactor (LR)	
Escherichia coli (CFU(g)$^{-1}$)	600	<400	<10	70	<10	<1000
Salmonella (count (25 g)$^{-1}$)	ab	ab	ab	ab	ab	Ab
Streptococcus faecalis (CFU (g)$^{-1}$)	3800	<400	2500	2600	86000	-
Helminthes eggs (count (1.5 g)$^{-1}$)	ab	ab	ab	ab	ab	Ab

Note : ab- absent based on standard test procedure. [a]AFNOR (2006; 2002)

Table 4.5 Polycyclic aromatic hydrocarbons (PAH) at 150 days for the Wood bin compost

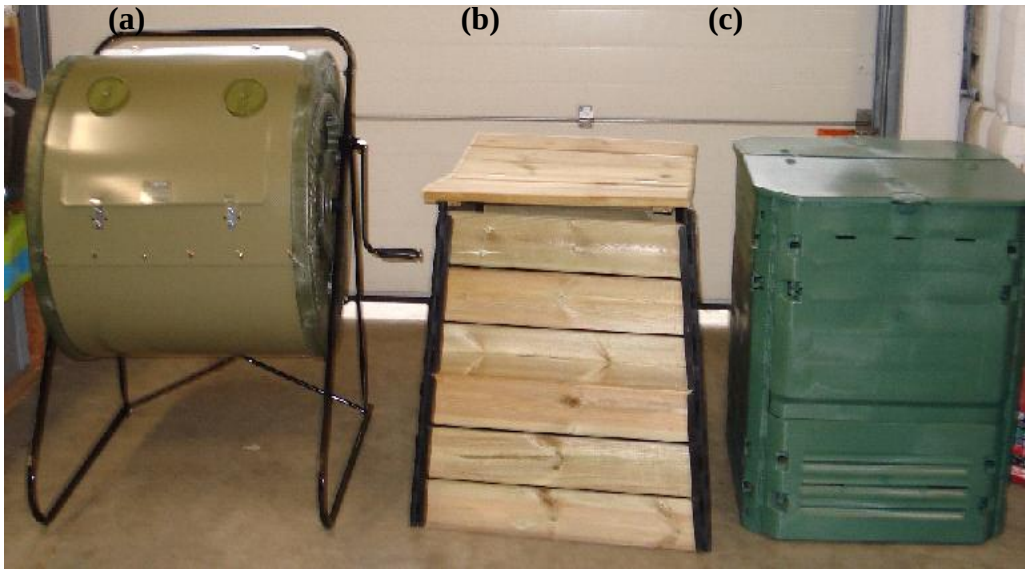
Compound		Wood bin (W)	Compost from MSW		Regulations
Primary	Secondary		Canada[a]	European union[b]	France[c]
PAH (µg (kg dm)$^{-1}$)	Naphthalene	<73	-	41000	-
	Methyl (2) fluoranthene	<14	-	-	-
	Phenanthrene	<14	1800	224-45900	-
	Anthracene	<14	-	2-6700	-
	Fluoranthene	<14	1800	79	4000
	Pyrene	<14	1400	100-9400	-
	Benzo(a) anthracene	<14	-	205	-
	Chrysene	<14	-	150-500	-
	Benzo (3,4) (b) fluoranthene	<14	-	67	2500
	Benzo (11,12) (k) fluoranthene	<14	-	42	-
	Benzo (3,4) (a) pyrene	<14	-	9-40	1500

Note: MSW – municipal solid waste. [a]Groeneveld and Hébert (2003); [b]Déportes et al. (1995); [c]AFNOR (2006).

Table 4.6 Trace elements at 150 days for the Wood bin (W) compost

Compost source	Trace Elements (mg (kg dm)$^{-1}$)								
	Cd	Cr	Cu	Ni	Zn	Hg	Pb	Se	As
Experimental wood bin	0.3	1.6	31.1	5.9	179.3	<0.1	5.3	0.2	3.8
Miscellaneous references									
USA mixed MSW[a]	2.9	34.8	154	24.8	503	1.27	215	-	2.6
European source separated MSW[a]	1.1	29.4	57	19.9	281	0.9	112	-	-
India mixed MSW[b]	2.3	142	370	41	414	-	252	-	-
India source separated MSW[b]	0.8	53	81	21	153	-	41	-	-
Spain home[c]	0.3	9	44	9	156	-	28	-	-
Spain source separated centralized facility[c]	0.24	8	47	9	150	-	32	-	-
France MSW[d]	7	270	250	190	1000	4	600	-	-
Canada MSW[d]	2	11	270	-	610	1	14	1	2
Trace element limits									
USA biosolids[e]	39	1200	1500	420	2800	17	300	-	-
European Union range[e]	0.7 - 10	70 - 200	70 - 600	20 - 200	210 - 4000	0.7 - 10	70 - 1000	-	-
Canada[f]									
- category A	3	210	400	62	700	0.8	150	2	13
- category B	20	-	-	180	1850	5	500	14	75
France[g]	3	120	300	60	600	2	180	12	18
European Commission - organic growing medium[h]	1	100	100	50	300	1	100	1.5	10

Note: [a]Epstein et al. (1992); [b]Saha et al. (2010); [c]Martínez-Blanco et al. (2010); [d]Iwegbue et al. (2007); [e]Brinton (2000); [f]CCME (2005); [g]AFNOR (2006); [h]EC (2006).



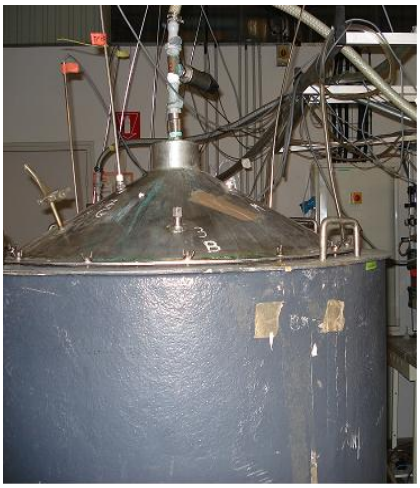


Figure 4.1 Home composting systems tested for their performance: (a) Rotary Drum (RD), (b) Wood bin (W), (c) Plastic bin (P), (d) Ground Pile (GP), and (e) Laboratory Reactor (LR).

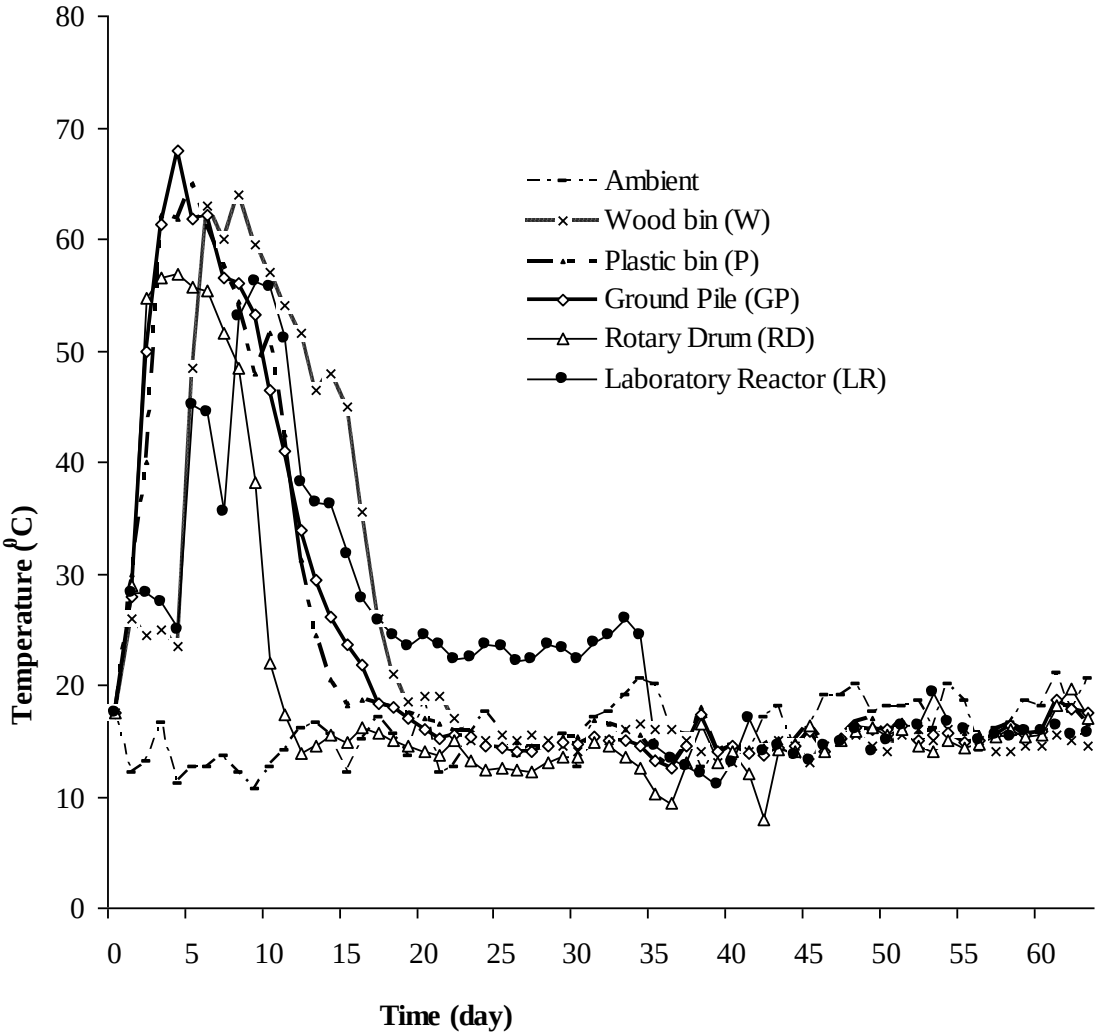


Figure 4.2 Temperature regime of the four home composting systems (HC) and the laboratory reactors, compared to daily ambient temperatures.

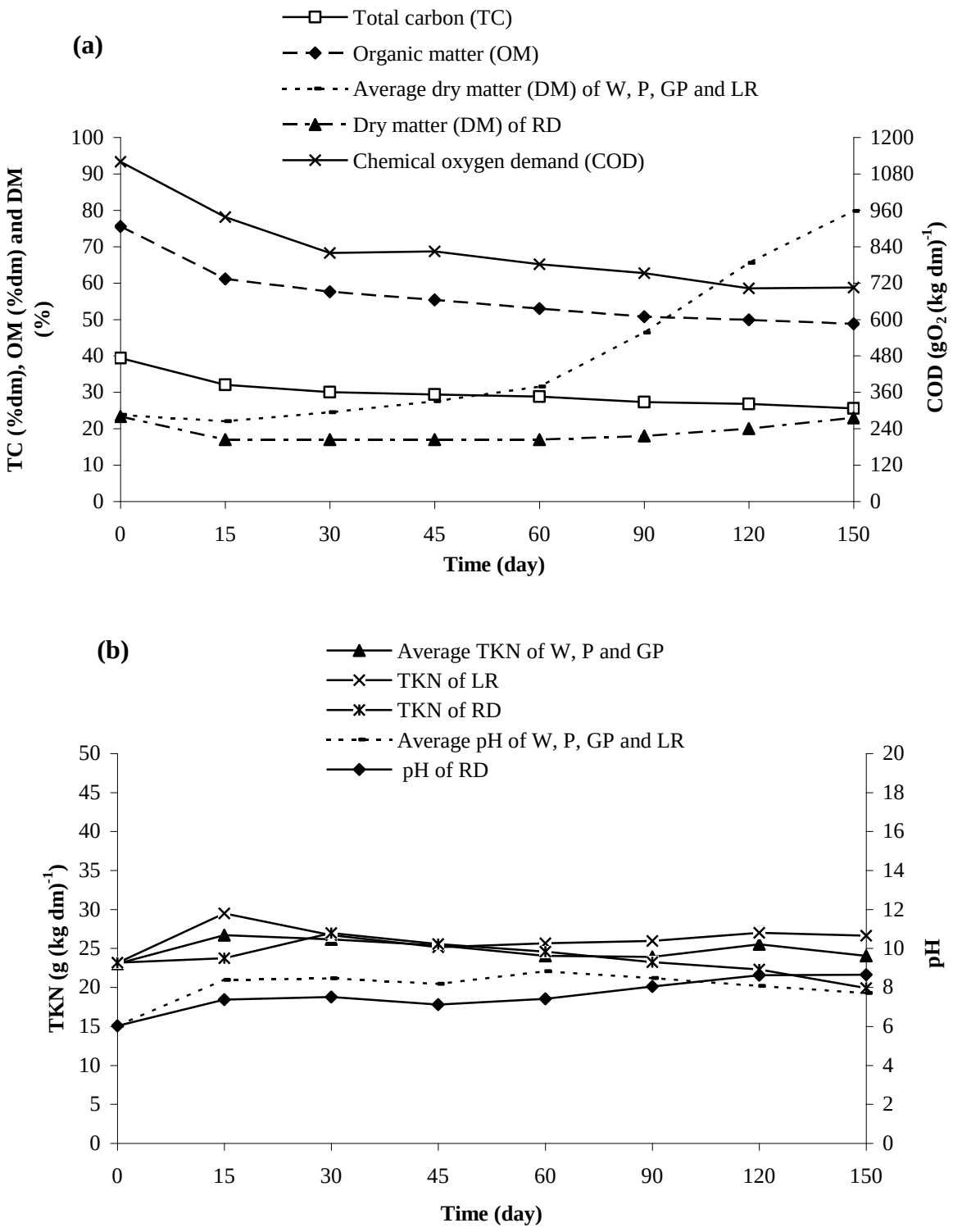


Figure 4.3 Evolution of the compost characteristics for the home composting systems (HC) and laboratory reactor: (a) TC, OM, DM, COD, and (b) TKN, pH.
COD – chemical oxygen demand, TC – total carbon, TKN – total Kjeldahl nitrogen, DM – dry matter, OM – organic matter, dm – dry mass, W- Wood bin, P – Plastic bin, GP – Ground Pile, RD – Rotary Drum, and LR – Laboratory Reactor.

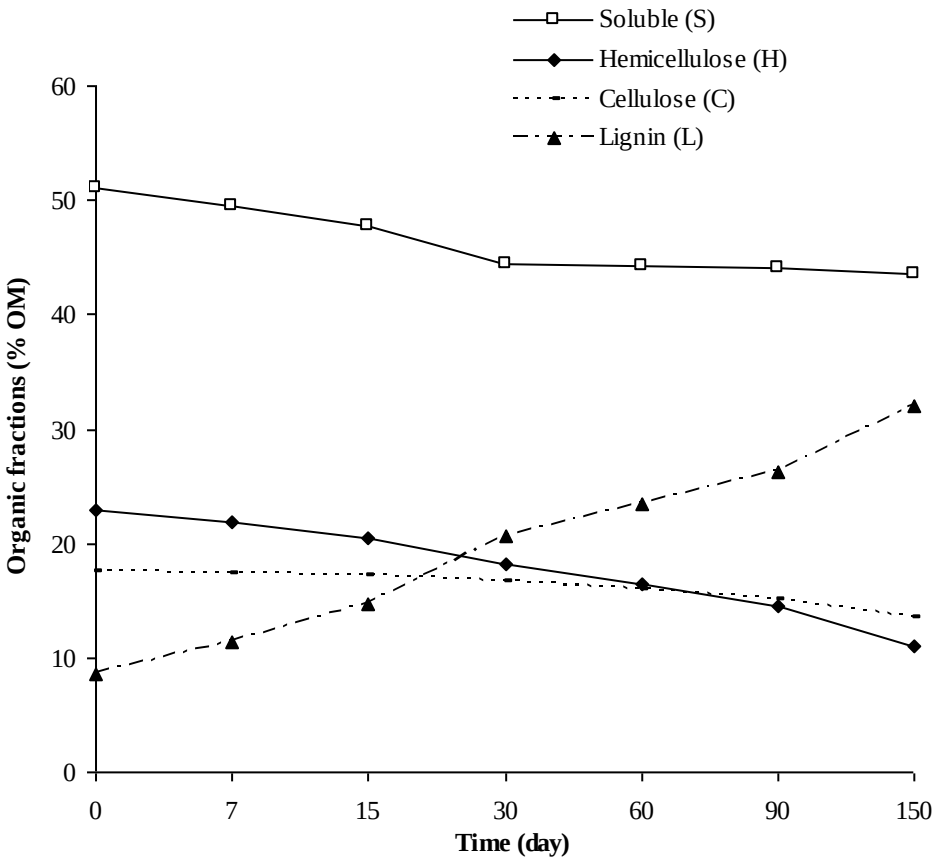


Figure 4.4 Evolution of the organic fractions for all treatments during 150 d of composting.

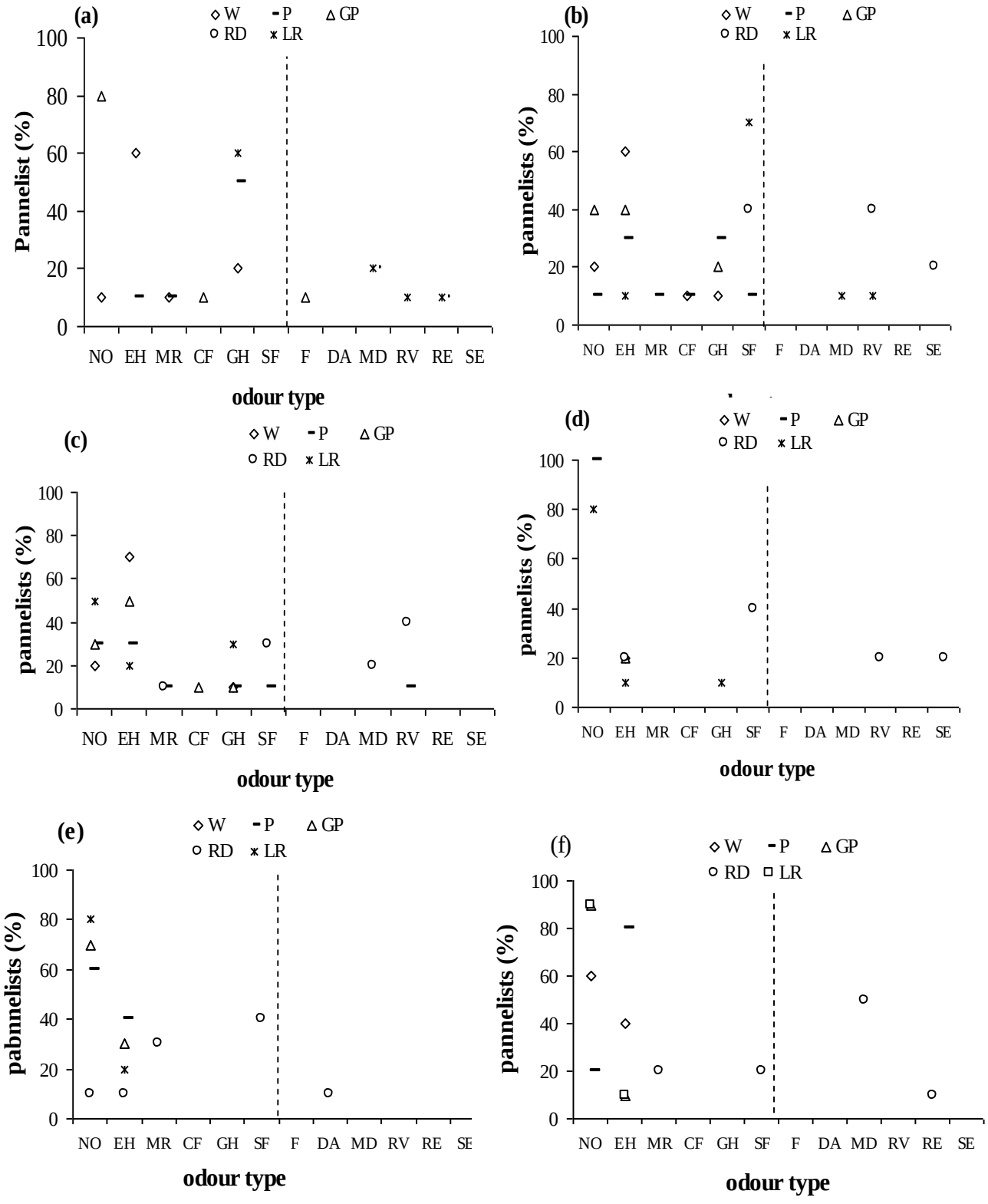


Figure 4.5 Compost odour characteristics for the home composting systems and the laboratory composter assessed by directly smelling: (a) 15 days, (b) 30 days, (c) 2 months, (d) 3 months, (e) 4 months, and (f) 5 months. W- Wood bin, P – Plastic bin, GP – Ground Pile, RD – Rotary Drum, and LR – Laboratory Reactor. No – no odour, EH-earthy/humus, MR-mushroom, CF-citrus fruits, GH-grassy/hay, SF-soft fermentations, F-fish, DA-dead animals, MD-mouldy, RV-rotten vegetable, RE-rotten eggs, SE-sewage.

Connecting statement to chapter 5

Chapter 4 demonstrated the effect of composter design type on the composting process and quality of composted product. However, the effect of management practices of home composting systems (HC) on composting process and quality of finished product is another important aspect of HC. Therefore, chapter 5 studied the effect of management practices of HC on the composting process and quality of finished product.

Chapter 5 is drawn from a manuscript submitted for publication to the journal of "International Journal of Environmental Technology and Management (IJETM)" by the author of the thesis and co-authored by supervisors, Dr. Anne Trémier, Cemagef, Rennes, France, Prof. Dr. Suzelle Barrington, Department of Bioresource Engineering, McGill University, Montreal, Canada and Dr. José Martinez, regional director, Cemagef, Rennes, France. The format has been changed to be consistent within this thesis.

Chapter 5

Home composting of organic waste: effect of management practices

Abstract

Home composting systems (HC) can potentially produce high quality compost if properly managed, while eliminating collection, transportation and treatment operations at the municipal level. To further investigate safe practices following the performance evaluation of four common types of HC, this second experiment looks at the influence of three general management practices (with/without bulking agent, batch/weekly feeding, with/without regular mixing). The four common HC used were the Plastic (P) and Wood (W) bins, the Rotary Drum (RD) and the Ground Pile (GP). The compost formula consisted of equal wet volumes of food waste (FW) and yard trimmings (YT), and when used, also equal wet volume of crushed wood pallets as bulking agent (BA). The compost temperature regime was continuously monitored during 70 days while the evolution of the compost characteristics was measured biweekly during 150 days. Thermophilic temperatures were obtained only for the batch fed HC, while for the weekly fed, temperatures remained mesophilic. Mixing the HC compost improved the duration of thermophilic temperatures for W with limited convective aeration, but reduced the duration for P with good convective aeration and had no impact on GP benefiting from both convective and diffused aeration. Tested only with W and RD, BA addition reduced the length of thermophilic temperatures, by increasing the compost dry matter from 20 to 40 %, lowering the pH from 6.1-7.7 to 5.7, and diluting the biodegradable organic matter. Overall, FW and YT compost without BA and batch fed in P and GP, produced the best compost, with the lowest level of parasites and pathogens and the least odours. Weekly mixing only helped reduce objectionable odours.

K**eywords:** Organic waste, onsite treatment, management practices, compost, quality

5.1 Introduction

Being most active biologically, the organic fraction of the municipal solid waste stream is a growing concern for municipalities (Domingo and Nadal, 2009; Montejo et al., 2010). Accordingly, recycling this organic fraction through diversion and treatment has become a priority in Europe and North America (Wagner and Arnold, 2008; Burnley et al., 2007), with composting being recognized as the most practical and feasible method (Kim and Kim, 2010).

Home composting systems (HC) are recognized as a possible onsite treatment capable of reducing collection, transportation and processing costs for municipalities. Nevertheless, limited scientific studies pertain to the influence of their management practices on the quality and safety of the finished product (Körner et al., 2008; Papadopoulos et al., 2009; Chiemchaisri et al., 2010). In West London, Smith and Jasmin (2009) studied the effectiveness of 290 L home composters in reaching thermophilic temperatures when fed kitchen waste, paper and yard trimmings (YT). The organic waste in these HC remained mostly at psychrophilic (0-20^{0}C) and mesophilic (20-45 °C) stages except for a few cases reaching the thermophilic range during summer months with higher ambient temperature and as a result of a large input of waste that retains the heat within the compost mass by its insulating effect. Nevertheless, the compost obtained was of good quality. In Thailand, Karnchanawong and Suriyanon (2011) evaluated the performance of six different polyethylene composting bins with a 200L capacity, batch fed with food waste (FW) and YT. The study concluded that improved temperature regimes where obtained with bins aerated through lateral perforations located mainly at their top and bottom, enhancing convective air displacement. The laboratory experiment described in chapter 4 (Adhikari et al., 2011a) compared the performance of four different types of common

HC to also conclude that the temperature regime is highly influenced by the design and location of the bin perforations such as top and bottom perforated plastic bin.

To pursue the performance study of HC and the quality of compost produced by Adhikari et al. (2011a) in chapter 4, this project investigated the impact of management practices on compost temperature regime and final characteristics. The three general management practices studied were: with/without bulking agent (BA), batch/weekly feeding, and with/without regular mixing. The four common HC used to test the management combinations were the Plastic (P) and Wood (W) bins, the Rotary Drum (RD) and the Ground Pile (GP).

5.2 Material and methods

5.2.1 Experimental composters, management practices and organic waste

In this study, four common HC were used to test the various management practice combinations (Figure 5.1): the 400L Wood bin (W) measuring 0.78 m x 0.65 m by 0.75 m in height; the 400 L Plastic bin (P) measuring 0.70 m x 0.70 m by 0.80 m in height; the 350 L Rotary Drum (RD) offering an internal diameter of 0.77 m and a length of 0.76 m, and; the Ground Pile (GP) measuring 0.65 m high and 0.75 m in base diameter. The management practices tested were: batch or weekly fed; with and without bulking agent (BA) and; with or without mixing. The components of the experimental food waste (FW) are presented in Table 5.1. The management practice combination arbitrarily tested in each HC is presented in Table 5.2 with their respective identification, starting with a letter pertaining to HC type followed by a number pertaining to the management practice combination.

The compost mixture consisted of equal wet volumes of food waste (FW) and yard trimmings (YT), and when used, equal wet volume of BA. Three day old, source separated FW was collected from two restaurants of the city of Rennes, France and

stored at 4ºC until used. During the 10 week feeding period (70 d), fresh FW was collected from the two restaurants and accordingly, the composition of the FW varied among treatments, but remained mostly composed of fruit and vegetable residues. The yard trimmings (YT) were obtained from the grounds of the Cemagref Research Institute of Rennes, France. When used, the bulking agent (BA) consisted of purchased pine chips measuring, 5 to 20 mm in width by 30 to 90 mm in length. While being collected, samples of FW were manually sorted to establish their composition. Triplicate samples of FW and YT were also collected for physico-chemical characterization.

5.2.2 Experimental procedure

At the Cemagref Research Centre, Rennes, France, all experimental HC were randomly set-up outside under a tent to avoid rainfall and sunshine. All HC were naturally aerated except for weekly mixing if the management practice combination called for such treatment. The compost mixture was manually mixed and loaded without compaction into the HC. All batch fed HC were loaded at once on the same day, while the weekly fed HC were loaded weekly for 10 weeks at a rate of 8.3 to 8.5 kg $(week)^{-1}$. While filling each HC, Thermochron iButton temperature sensors (DS1921G-F5, Thermochron iButton, Dallas Semiconductor, USA) were installed at the center of each HC compost mass.

All HC were operated for 150 d, during which they were hand mixed weekly, unless otherwise required, and sampled in triplicate 100 g aliquots for characterization. Thus, all treatments requiring no mixing were analyzed only on day 0 and 150. The odour characteristics of each HC were evaluated biweekly from day 0 to 30, and then monthly thereafter, by having 10 trained panellist directly smell the

compost surface before the mixing session. The temperature sensors were retrieved after 70 d of maturation where temperature remained at ambient, during one of the mixing and sampling operation. After 150 d, the content of all composters was weighed and sampled in triplicate for physico-chemical characterization. The evolution of the compost characteristics during the 150 d period provided data to compute the loss in: dry matter (DM); total carbon (TC); total Kjeldahl nitrogen (TKN); chemical oxygen demand (COD), and; organic matter (OM) as well as its different fractions namely soluble, hemicellulose, cellulose and lignin. Furthermore, analyses were conducted on the final 150 d composts to quantify pathogens and parasites, trace elements and polycyclic aromatic hydrocarbon (PAH). These parameters assessed their quality, loss of carbon and nitrogen, and thus suitability as soil amendment (Mato et al., 1994).

5.2.3 Analytical procedure

The bulk density of the fresh compost samples was determined by filling three 30 L pails without compaction, and weighing their content. The free air space (FAS) of the fresh compost samples was determined using an air pycnometer (Berthe et al., 2007) where a compost sample is used to fill an airtight cell and then pressurized while measuring the volume of injected air. At equilibrium pressure, the injected air provides an estimate of the free air space in the compost.

The chemical analyses conducted on the compost mixture had to exclude the wood chips when present as BA because of their size, except for dry matter and pH. Before being analyzed, triplicate compost samples were dried in an oven (SR 2000, Thermosi, France) at 80 °C until a constant weight was reached and then ground to less than 0.5 mm (ZM model 1000 grinder, Retsch, Germany). The TC was

determined by burning 10 mg samples at 900 °C (Thermo Scientific, FLASH 2000 Series, Organic Elemental Analyser, Courtaboeuf, France) according to AFNOR (2001a). According to AFNOR (1995), TKN was determined using an automatic distilling system (VAP 50c, Gehardt automatic distilator, Gehardt, Germany), after digesting 0.5 to 1.0 g samples with H_2SO_4 (automated Kjeldatherm TZ block digester, Gerhardt, Germany). The COD was determined by titration (Metrohm, Courtaboeuf, France) after digestion of 60 mg samples with H_2SO_4 and $K_2Cr_2O_7$ (Kjeldatherm COD digestion block, CSB 20M, Gerhardt, Germany), according to AFNOR (2001b). The OM was determined by burning at 550 °C for 3 hours (Thermolyne 30400, Furnace, F30420 C-33, Essex, UK), according to AFNOR (1985). To correct all analytical results, residual moisture was determined by drying ground compost samples at 105 ºC for 24 hours (SR 1000, Thermosi, France). The pH of wet samples was determined by soaking for 24 hours without shaking at 5ºC, in just enough distilled water to use a pH electrode (pH-Electode SenTix41, WTW, Weilhein, Germany) according to Adhikari et al. (2009).

The soluble organic, hemicellulose, cellulose and lignin fractions were determined using a fibre extractor (VELP Scientific, FIWE 6, Usmate, Italy) according to Van Soest (1963). Because of the size of the wood chips used as BA, the compost samples used to determine the evolution of the organic matter fractions excluded the BA.

The *Escherichia coli* and fecal *Streptococci* were quantified using microfiltration (AFNOR, 2001c). The presence of Salmonella in 25 g wet samples was determined using Petri plates with XLD agar (AFNOR, 2006). The presence of *Helminthe* eggs in 1.5 g of wet sample was determined by the triple flotation technique (AFNOR, 2004). Trace elements were quantified by ICP-MS (inductively

coupled plasma mass spectroscopy) after digestion with nitric acid, and the PAH were analysed by chromatography and fluorimetric detection after extraction with hexane/acetone (AFNOR, 2000), respectively.

According to Rosenfeld et al. (2007), compost odour characteristics for each management practice combination were subjectively evaluated using 10 panellists trained to recognize the following smells: no-odour (NO), Earthy/humus (EH), woody (WD), mushroom (MR), citrus fruit (CF), grassy/hay (GH), soft fermentation (SF), fishy (F), dead animal (DA), mouldy (MD), rotten vegetable (RV0), rotten eggs (RE), and sewage (SE). Odour evaluations were conducted every two weeks for the first month and monthly thereafter. Panellists took a three minute break between each HC evaluation, and described the odour using as many smell types as required. Each smell type associated with a composting management practice at a given time was expressed in terms of the percentage of reporting panellists.

5.2.4 Statistical procedure

During the 150 d experiment, the triplicate compost samples were regularly collected for characterization. Thus, the process physico-chemical characteristics were compared by the repeated measure ANOVA using the PROC GLM procedure at 95% confidence level (SAS Institute Inc., 2008). Factorial experimental design might be helpful for future studies to conduct this type of experiment.

5.3 Results and discussion

5.3.1 Initial physico-chemical characteristics of compost mixture

Table 5.1 described the FW and YT used to feed the HC. For the batch fed HC and on a wet mass basis, FW consisted of 49.9 % vegetables, 16.1 % fruit, 18.0 % root and

tuber and 16.0 % cooked food residues, respectively. For the weekly fed HC, the FW consisted of 43.0 % vegetable, 6.5 % fruit, 32.6 % roots and tuber, and 18.2 cooked food residues. The YT was mainly composed of grass (90 % wet basis) but also contained tree leaves (10 % wet basis) with a respective dry matter (DM) of 58 and 64 %. The composting formula consisted of equal wet volumes of FW and YT, or equal wet volumes of FW, YT and BA when used. The weekly fed HC received organic waste at a rate of 8.3 to 8.5 kg $(week)^{-1}$ during 10 consecutive weeks. The variation in FW properties between the batch and weekly fed treatments resulted in a slight variation only in total carbon (TC) with batch fed HC at 38-40 % (dm) compared to weekly fed at 42 % (dm) (Table 5.2).

Table 5.2 described the initial compost characteristics where batch fed HC received 54 to 75 kg of organic waste on day 0. The weekly fed HC received organic waste at a rate of 8.3 to 8.5 kg $(week)^{-1}$, for a total wet mass of 83 to 85 kg. For HC fed BA (W1, W3 and RD2), the compost mixture consisted of equal wet volume of FW, YT and BA, offering a dry matter (DM) of 41 to 42 % (±1.6 – 2.5 %), a C/N of 65, and a FAS of 78 %. For HC fed no BA, (W4, RD1, P1, P3, GP2 and GP3), the compost mixture offered a dry matter of 22.6 to 24.1%, a C/N ratio of 17 to 17.4 and a FAS of 66%. As compared to a pH of 6.1 to 7.7 without BA, adding BA dropped the compost pH to 5.7. Adding BA also changed the OM fractions, dropping by half the soluble, hemicelluloses and cellulose fractions, while increasing the average lignin from 8 to 63 %. For an active microbial activity, initial compost mixtures should offer a C/N ratio ranging between 15 and 35 and a pH between 6 and 8 (Stabnikova et al., 2005; Haug 1993; Zucconi and de Bertoldi, 1986), indicating that adding BA in this experiment may have a negative impact.

5.3.2 Temperature regime

Figures 5.2 a, b, c and d illustrate respectively, the temperature profile obtained for the W, P, RD and GP composts exposed to the various management practice combinations. For W, only the batch fed and weekly mixed composts produced temperatures exceeding 55 ºC, with W4 (without BA) reaching 64 ºC on day 6 compared to W1 (with BA) reaching 58 ºC one day later, on day 7. For W with BA, batch fed but not mixed (W3), the compost temperature peaked at 52 ºC on day 10. Compost treatment W2 (weekly fed without BA) produced a peak temperature of 32 ºC on day 10, indicating that 8.3-8.5 kg $(week)^{-1}$ of OW was not sufficient to produce thermophilic temperatures. Accordingly, and for the Wood bin (W), adding BA did not produce as high temperature because of a lower microbial activity and a greater free air space (FAS) allowing for a higher rate of aeration. As opposed to adding BA, mixing activated the process and produced higher temperatures. The perforation location for W could therefore be improved, a finding which reinforces the observations concluded by Adhikari et al. (2011a).

The batch fed Plastic bin (P) compost reached thermophilic temperature above 60 ºC on days 3 and 6 for the treatments without BA and not mixed (P1) and without BA and mixed (P2), respectively. As for the weekly fed treatment (P3), the compost temperature remained in the mesophilic range. For P, mixing retarded the microbial activity by releasing heat which reduced the convective aeration forces. Adhikari et al. (2011a) in chapter 4 demonstrated that P generated convective aeration forces equivalent to those of GP as indicated by temperature profile, with the appropriate location of its perforations at its top and bottom (Barrington et al., 2002; Karnechanawong and Suriyanon, 2011).

For the Rotary Drum (RD), both management practice combinations were batch fed and mixed, but without BA (RD1) and with BA (RD2). Although both treatments quickly reached peak temperature of 57 ºC after 3 days, they also quickly dropped to ambient on days 8 and 10, with BA (RD2) and without BA (RD1), respectively. Once more, BA lowered the temperature because of a reduced microbial activity, a lower biodegradable formula content, and a greater FAS resulting in a higher convective aeration rate. Nevertheless, RD produced thermophilic temperatures much faster than W, indicating its initial excellent capacity for aeration. The lack of sustained thermophilic temperatures resulted from the clogging of its aeration ports.

All Ground Pile (GP) composts were mixed without BA. On day 4, both batch fed treatments reached thermophilic temperatures of 69 and 67 ºC, for the mixed (GP3) and not mixed (GP1) treatments, respectively, indicating a slight positive effect for mixing. The weekly fed compost never developed temperatures exceeding 30 ºC.

In summary, management practices had an effect on temperature regime. In terms of OW loading rate, batch feeding produced thermophilic temperatures exceeding 55 ºC for all HC except W3 (not mixed) reaching 52 °C, while weekly feeding at 8.3-8.5 kg $(week)^{-1}$ produced at best mesophilic temperatures. Adding BA to the compost mixture both retarded and reduced the duration of thermophilic temperatures. This was the result of reduced microbial activity because of the pH and moisture drop respectively from 6.1-7.7 to 5.7, and from 78 to 58 %, and the lower formula content biodegradability. Furthermore, adding BA increased the FAS, which enhance aeration and heat removal. Mixing the HC compost had a variable effect, being positive for W, practically neutral for GP and positive for P. This effect reflected the capacity of the HC type in generating convective aeration forces, where

W with perforations distributed over its height, lacked convective aeration as indicated by the temperature profile during the first 20 days of composting, GP relied on both diffusive and convective aeration and P generated good convective aeration with perforations located at its top and bottom (Barrington et al., 2002; Karnechanawong and Suriyanon, 2011). The present experiment also reinforces the findings of Adhikari et al. (2011) indicating that P and GP were better able to produce convective aeration as opposed to W.

5.3.3 Evolution of compost characteristics

The evolution of the compost characteristics (TC, DM, COD, OM and pH) are presented in Figures 5.3, 5.4, 5.5 and 5.6 for W, P, RD and GP, respectively. For W, the addition of BA had a significant impact ($p<0.01$) on DM, with the initial mixture with BA (W1 and W3) starting at 40% and finishing at 80%, as opposed to treatments without BA (W2 and W4) starting at 20% and finishing at 65 to 80%. Mixing had no impact on final compost DM, whether BA was used or not. Finally, weekly feeding produced a lower DM of 65 % after 150 days compared to batch feeding at 80 %. In terms of TC, OM and COD for the W compost, the management practice combinations had no significant effect ($p>0.05$). The addition of BA produced lower pH compost, through the experimental period, whereas weekly feeding produced a dip in compost pH between days 15 to 60, indicating poor decomposition. The mineralization of organic nitrogen and formation of ammonia (NH_3) increases compost pH while formation of ammonium (NH_4^+) decreases (The water planet company, 2010).

For the RD compost, BA addition produced a significantly drier initial and final mixture during the 150 day experimental period ($p<0.01$). The addition of BA

also produced a higher TC, OM and COD compost as a result of its reduced microbial activity reflected by a shorter thermophilic period ($p<0.01$). The addition of BA had an impact on pH evolution during the full treatment period, increasing the pH from day 15 to 60 but dropping it thereafter.

All management practice combinations applied to P excluded BA. In terms of DM, batch feeding produced a significantly ($p<0.05$) drier final product at 68 % rather than 45 % for weekly feeding. Mixing exerted no significant effect ($p<0.01$), in this case because of sufficient convective aeration. In terms of TC, OM, and COD, the weekly fed treatment produced compost consistently higher than batch fed, as a result of a slower microbial activity demonstrated by the temperature regime never reaching thermophilic conditions. No significant difference was observed in terms of COD, while the pH of the weekly fed treatment tended to remain lower from day 15 to 90.

The GP management practice combinations excluded the addition of BA. Weekly feeding produced wetter final compost with a DM of 60 % as opposed to batch feeding at 70 % when not mixed and at 85 % when mixed. Thus, mixing improved the final dry matter content of the compost. From day 15 to 90, mixing also significantly reduced the compost COD and OM, as opposed to not mixed ($p<0.01$), with final values at 150 days being the same. Thus mixing had a beneficial effect on microbial activity during the process, as also demonstrated by a slight difference in thermophilic temperatures. Weekly feeding produced compost with a lower pH from day 15 to 90, as opposed to batch feeding.

As illustrated in Figure 5.7, management practices had no impact on the concentration of TKN and the relative fractions of OM, excluding the impact of BA which could not be analyzed because of its wood chip size.

The loss of water, dry matter, organic matter and TKN is summarized in Table 5.3. Most management practices produced high loss of water equal to and exceeding 2.7 kg $(kg)^{-1}$ of initial dm, except for the BA mixtures losing from 1.0 to 1.2 kg water/kg initial dm and the RD mixture without BA losing 2.1 kg water (kg initial $dm)^{-1}$ as a result of aeration port clogging. Mixing improved water loss only for P and W, where despite its lower temperature regime, the weekly fed produced just as much water loss as batch fed when mixed. The loss of COD, TC, TKN and OM was especially low for the W compost with BA, batch fed but not mixed (W3), in parallel with the lower water loss, but not for the other treatment with BA (W1 and RD2) also losing as little water. Accordingly, W3 suffered not only less aeration drying but also less microbial activity after the thermophilic phase. For the OM fractions, only W3 suffered less losses especially for the cellulose and lignin fractions, illustrating once more, less microbial activity in the later part of the treatment period.

In conclusion, management combination practices and especially BA addition, and HC type especially W, had an impact on final compost composition and compound losses. Addition of BA produced drier initial and final compost which lowered the microbial activity. Mixing and batch feeding generally helped produce a drier final product. In terms of losses, water was most influenced by management combination practices and type of HC, with GP and P performing best under all management practices. The W3 compost, with BA, batch fed and not mixed was the only treatment producing a significantly different loss in dry mass, COD, TC and OM fraction, because of poor aeration and microbial activity during the maturation phase.

5.3.4 Odour effects

Figure 5.8 illustrates the evolution in odour characteristics for all composts as influenced by HC type and management practice combination. The dotted vertical line separates the acceptable (left) from the objectionable (right) odours. Treatments weekly fed, not mixed or without BA tended to produce odours with a higher objectionable character. For example, on day 15, 80 and 60 % of the odour characteristics were objectionable for P1 (no BA, batch fed but not mixed) and P2 (no BA, weekly fed and mixed), but 0 % for P3 (no BA, batch fed and mixed). Still on day 30, 80 % objectionable odours were reported for P2 (no BA, weekly fed and mixed), 60 and 40 % for GP1 (no BA, batch fed and not mixed) and GP2 (no BA, weekly fed and not mixed), and 35 % for W2 (no BA, weekly fed and mixed). On day 60, 80 % objectionable odours were still reported for P2 (no BA, weekly fed and mixed). In terms of BA impact, the RD1 compost started to produce objectionable odours on days 60 and 90 at 40 % while RD2 with BA only produced 20 % objectionable odours on day 90. On day 120, very little objectionable odours were reported for any of the compost, whereas on day 150, 60 % objectionable odours were now being reported for RD1. Accordingly, batch feeding, mixing and adding BA tended to prevent the generation of objectionable odours.

5.3.5 Parasites/pathogens, PAH and trace elements

Parasite and pathogen levels were analyzed for all treatments (Table 5.4). The W compost with BA showed *E. coli* levels exceeding the French Standard of 1000 CFU $(g)^{-1}$, because of poor microbial activity during the the first 20 days of composting, especially for W3 not mixed. Besides the W compost, thermophilic temperatures had no impact on *E. coli* counts, with weekly fed treatments showing acceptable levels

under 1000 CFU $(g)^{-1}$ while remaining in the mesophilic temperature range. *Salmonella* and *Helminthe* eggs were absent from all compost likely because the original organic waste was clean. Not impacted by thermophilic temperature regimes, *Streptococcus* faecalis counts were high for the RD1 and RD2 (batch fed, mixed and without/with BA) and W3 (with BA, batch fed and not mixed), once more because of poorer microbial activity during the first 20 days of composting. Analyzed for W only because all HC were fed with the same sources of OW, the PAH and trace elements respected French and North American standards because of the clean and well sorted organic waste used to make the compost mixtures (Table 5.5).

5.4 Conclusion and recommendations

Whereas home composting systems (HC) can have a major impact on the collection, transportation and treatment cost for organic waste contained in the municipal solid waste stream, the quality of the compost produced has received limited scientific attention. Therefore, this study evaluated the impact of management practice combinations on compost quality using four common types of HC. The main management practices tested were: use of bulking agent (BA) besides yard trimmings (YT) with food waste (FW); batch versus weekly feeding, and; weekly mixing or not. The four common HC used were: the Plastic (P) and Wood (W) bins, the Rotary Drum (RD) and the Ground Pile (GP).

During the initial composting phase, management practice combinations had an impact both on the development and extent of the thermophilic period. Feeding at a rate of 8.3-8.5 kg $(week)^{-1}$ resulted in mesophilic conditions at the very best while all batch filled HC produced thermophilic temperatures above 55 °C except for W3 (with BA, batch fed and not mixed) reaching 52 °C. The practice of weekly mixing had a

positive impact on HC lacking a perforation configuration conducive to convective aeration, such as for W, but had a negative impact on HC capable of generating convective aeration, such as P. Benefiting from both diffused and convective aeration, mixing had little impact on GP. For all management practice combinations and HC, the addition of BA slowed down the microbial activity, retarding and reducing the extent of thermophilic conditions. The use of equal wet volumes of FW and YT produced a good mixture with sufficient free air space to quickly generate thermophilic temperatures. The RD suffered from clogged aeration ports early in the composting process, thus producing fast but short lived thermophilic conditions.

In terms of the evolution of compost characteristics among treatments, the addition of BA had the most impact on initial and final dry matter (DM), free air space and pH. The organic components, mainly TC and OM were impacted by feeding rate, with weekly feeding resulting in higher levels as a result of less intense microbial activity. Losses in water were mainly impacted by the use of BA and, for W, weekly mixing. The lowest dry and organic matter losses were experienced by W3 (with BA, batch fed and not mixed) because of poor microbial activity during the first 20 days of composting as a result of a drier and less biodegrable formula content. Such lack of microbial activity was also reflected in terms of higher *E. coli* and fecal *Streptococci* counts. Objectionable odours were generally produced by the compost weekly fed, without BA or not mixed.

Overall, the FW and YT compost batch fed in P and GP, without BA produced the best compost, with the lowest level of parasites and pathogens and the least odours. Weekly mixing only helped reduce objectionable odours.

5.5 Acknowledgements

This study is part of a larger project entitled ECCOVAL, conducted in partnership with Rennes Métropole, CRPCC LAUREPS and CIELE, and funded by the regional council of Brittany, France. The authors also acknowledge the financial and logistics support by the Cemagref of Rennes, France and the Natural Science and Engineering Research Council of Canada.

5.6 References

Adhikari BK, Trémier A, Martinez J and Barrington S (2011a) Home composting of organic waste. Part I. Effect of home composter design. International Journal of Environmental Technology and Management, presented for publication along with this part 1.

Adhikari BK, Barrington S, Martinez J and King S (2009) Effectiveness of three bulking agents for food waste composting. Waste Management 29:197-203.

AFNOR (2006) NF U44-051 Amendements organiques, Dénominations, spécifications et marquage. Association Française de Normalisation, Paris, France.

AFNOR (2004) XP X33-017- Characterization of sludges - Enumeration and viability of parasite helminth eggs - Triple flotation technique. Association Française de Normalisation, Paris, France.

AFNOR (2002) NF U44-095 Organic soil improvers – composts containing substances essential to agriculture. Association Française de Normalisation, Paris, France.

AFNOR (2001a) NF EN 13137 - Caractérisation des déchets - Dosage du carbone organique total (COT) dans les déchets, boues et sédiments. Association Française de Normalisation, Paris, France.

AFNOR (2001b) NF T 90-101 - Qualité de l'eau - Détermination de la demande chimique en oxygène (DCO). Association Française de Normalisation, Paris, France.

AFNOR (2001c) NF ISO 16649-2 - Microbiology of food and animal feeding stuffs – Horizontal method for the enumeration of B-glucuronidase-positive Escherichia coli - Part 2 : colony-count technique at 44 °C using 5-bromo-4-

chloro-3-indolyl B-D-glucuronate. Association Française de Normalisation, Paris, France.

AFNOR (2000) XP X33-012- Characterisation of sludges - Determination of polynuclear aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB). Association Française de Normalisation, Paris, France.

AFNOR (1995) NF ISO 11261 - Qualité du sol - Dosage de l'azote total - Méthode de Kjeldahl Modifiée. Association Française de Normalisation, Paris, France.

AFNOR (1985) NF U 44-160 - Amendements organiques et supports de culture - Détermination de la matière organique totale - Méthode par calcination. Association Française de Normalisation, Paris, France.

Barrington S, Choinière D, Trigui M and Knight W (2002) Compost convective airflow under passive aeration. Journal of Bioresource Technology 86: 259-266.

Berthe L, Druilhe C, Massiani C, Tremier A and de Guardia A (2007) Coupling a respirometer and a pycnometer, to study the biodegradability of solid organic wastes during composting. Biosystem Engineering 97: 75-88.

Brinton WF (2000) Compost quality standards & guidelines: an international view. Final reports presented for New York State association of Recyclers. Woods End Laboratories, Inc. Mt Vernon, ME, USA.

Burnley SJ, Ellis JC, Flowerdew R, Poll AJ and Prosser H (2007) Assessing the composition of municipal solid waste in Wales. Resources, Conservation and Recycling 49: 264–283.

CCME (2005) Guidelines for compost quality. PN 1340, ISBN 1-896997-60-0. Canadian Council of Ministers of the Environment, Winnipeg, Manitoba, Canada.

Chiemchaisri C, Putthamilinprateep P, Promsamai N and Phetcha M (2010) Application of household compost wastes in small communities of Thailand. International Journal of Environment and Waste Management 6(1/2): 117-127.

Domingo JL and Nadal M (2009) Domestic waste composting facilities: A review of human health risks. Environment International 35: 382–389.

Haug RT (1993) The practical handbook of compost engineering. Lewis Publishers, A CRC press company, Boca Raton, Florida, USA, pp. 205 – 259.

Karnchanawong S and Suriyanon N (2011) Household organic waste composting using bins with different types of passive aeration. Resources, Conservation and Recycling 55: 548–553.

Kim MH and Kim JW (2010) Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery. Science of the Total Environment 408: 3998-4006.

Kö rner I, Saborit-Sánchez I and Aguilera-Corrales Y (2008) Proposal for the integration of decentralised composting of the organic fraction of municipal solid waste into the waste management system of Cuba. Waste Management 28: 64–72.

Mato S, Orto D and Garcia M (1994) Composting of <100 mm fraction of municipal solid waste. Waste Management & Research 12 (4): 315-325.

Montejo C, Ramos P, Costa C and Márquez MC (2010) Analysis of the presence of improper materials in the composting process performed in ten MBT plants. Bioresource Technology 101(21): 8267-8272.

Papadopoulos AE, Stylianou MA, Michalopoulos CP, Moustakas KG, Hapeshis KM, Vogiatzidaki EEI and Loizidou MD (2009) Performance of a new household composter during in-home testing. Waste Management 29: 204–213.

Rosenfeld PE, Clark JJJ, Hensley AR and Suffet IH (2007) The use of an odour wheel classification for the evaluation of human health risk criteria for compost facilities. Water Science & Technology 55(5): 345–357.

SAS Institute Inc. (2008) SAS version 9.2, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC, USA.

Smith SR and Jasim S (2009) Small-scale home composting of biodegradable household waste: overview of key results from a 3-year research programme in West London. Waste Management & Research 27: 941–950.

Stabnikova O, Ding HB, Tay JH and Wang JY (2005) Biotechnology for aerobic conversion of food waste into organic fertilizer. Waste Management & Research 23: 39 – 47.

The water planet company (2010) Nitrification and denitrification. The Water Planet Company, Connecticut, USA.

Van Soest PJ (1963) Use of detergents in the analysis of fibrous feeds. I. Preparation of fibre residues of low nitrogen content. Journal of the Association of Official Agricultural Chemists 46: 825–829.

Wagner T and Arnold P (2008) A new model for solid waste management: an analysis of the Nova Scotia MSW strategy. Journal of cleaner Production 16: 410-421.

Zucconi, F. and de Bertoldi, M. (1986) 'Compost specifications for the production and characterization of compost from municipal solid waste in compost: production, quality and use', In: de Bertoldi M, Ferranti MP, L'Hermite P and Zucconi F (eds): Proceedings of a symposium organized by the commission of the European communities, Directorate General Science, Research and Development, 17-19 April.Udine Italy.

Table 5.1 Composition of the experimental waste for batch and weekly composter loading

Waste	Batch feeding (% by mass)		Weekly feeding (weeks) (% by mass)										Average weekly Feeding (% by mass)	
			1-2		3-4		5-6		7-8		9-10			
	dry	wet	dry	wet	dry	wet	dry	wet	dry	wet	dry	wet	dry	wet
Food Waste (FW)														
Fruit														
Apple	3.6	3.6	5.0	5.2	2.5	5.3	0.2	0.2	3.3	3.0	-	-	2.2	2.7
Passion fruit	0.7	0.9	1.7	2.2	-	-	-	-	-	-	-	-	0.3	0.4
Avocado peel	1.8	1.1	-	-	-	-	-	-	-	-	-	-	-	-
Avocado seed	1.1	0.3	-	-	-	-	-	-	-	-	-	-	-	-
Banana	2.3	1.9	1.3	1.4	-	-	-	-	-	-	-	-	0.3	0.3
Date fruit	6.7	1.5	-	-	-	-	-	-	-	-	-	-	-	-
Mango	1.0	0.8	-	-	-	-	-	-	-	-	-	-	-	-
Citrus fruit	6.3	5.3	9.0	8.2	-	-	4.2	3.3	1.6	1.4	0.4	0.4	3.0	2.7
Pineapple	0.7	0.7	-	-	-	-	-	-	-	-	-	-	-	-
Cucumber	-	-	-	-	-	-	-	-	0.6	1.1	0.5	1.1	0.2	0.4
Sub-total	**24.2**	**16.1**	**17.0**	**17.1**	**2.5**	**5.3**	**4.4**	**3.5**	**5.5**	**5.5**	**0.8**	**1.5**	**6.0**	**6.5**
Roots and tubers														
Onion/garlic leaves	0.8	1.0	0.2	0.3	1.2	6.6	7.5	10.2	1.3	1.7	6.5	7.3	3.3	5.2
Onion/garlic flesh	4.7	3.8	6.1	5.0	13.3	10.5	10.0	6.4	6.3	5.3	26.6	23.6	12.5	10.2
Potato/carrot peels	9.0	11.0	12.6	14.3	8.2	10.0	11.2	17.0	15.2	16.3	4.4	5.7	10.3	12.7
Radish leaves	4.9	2.2	12.0	5.7	7.6	7.5	1.3	1.9	2.3	2.6	0.2	0.3	4.7	3.6
Sweet potato	-	-	-	-	-	-	3.4	4.1	-	-	-	-	0.7	0.8
Ginger roots/peels	-	-	-	-	-	-	0.8	0.6	-	-	-	-	0.2	0.1
Sub-total	**19.4**	**18**	**30.9**	**25.3**	**30.3**	**34.6**	**34.3**	**40.2**	**25.2**	**25.9**	**37.7**	**36.9**	**31.7**	**32.6**
Cooked food														
Rice and bread	3.9	2.3	9.5	6.1	5.1	6.2	13.4	8.7	33.5	20.7	31.2	17.3	18.5	11.8
Carrot and cabbage	7.1	6.9	-	-	19.7	15.4	-	-	-	-	-	-	3.9	3.1
Potato	5.5	5.0	-	-	4.1	3.8	-	-	-	-	-	-	0.8	0.8
Spaghetti	2.0	0.9	0.6	0.3	-	-	-	-	-	-	-	-	0.1	0.1
Egg white	0.3	0.1	-	-	-	-	-	-	-	-	-	-	-	-
Egg shells	3.5	0.8	7.4	1.9	8.2	6.4	9.7	2.0	5.2	1.1	2.2	0.4	6.5	2.4
Sub-total	**22.3**	**16.0**	**17.5**	**8.3**	**37.1**	**31.8**	**23.1**	**10.7**	**38.7**	**21.8**	**33.4**	**17.7**	**29.8**	**18.2**

Table 5.1 Composition of the experimental waste for batch and weekly composter loading – continued

Waste	Batch feeding (% by mass)		Weekly feeding (weeks) (% by mass)										Average weekly Feeding (% by mass)	
			1-2		3-4		5-6		7-8		9-10			
	dry	wet	dry	wet	dry	wet	dry	wet	dry	wet	dry	wet	dry	wet
Vegetables														
Mushroom	-	-	-	-	-	-	9.6	10.1	-		-	-	1.9	2.0
Celery	8.3	11.9	11.0	15.4	17.1	10.9	1.8	2.7	6.6	11.2	-	-	7.3	8.0
Green leafy vegetables	4.4	6.6	5.9	9.0	5.5	6.6	4.6	5.7	12.4	14.9	12.9	24.0	8.3	12.0
Cauliflower/cabbage	20.0	30.2	15.7	23.3	3.9	4.3	22.1	27.2	8.6	13.6	9.6	11.5	12.0	16.0
Pumpkin	1.2	1.1	1.5	1.5	-	-	-	-	2.7	7.0	-	-	0.8	1.7
Egg plant	-	-	-	-	-	-	-	-	-	-	5.6	8.5	1.1	1.7
Peas and beans	0.2	0.1	0.4	0.2	3.7	6.5	-	-	0.2	0.1	-	-	0.9	1.4
Sub-total	**34.1**	**49.9**	**34.5**	**49.4**	**30.2**	**28.3**	**38.1**	**45.7**	**30.5**	**46.8**	**28.1**	**44.0**	**32.3**	**42.8**
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
Yard trimmings (YT)														
Grass	89.0	90.0	91.79	91.8	65.9	67.2	69.7	72.1	71.5	74.9	99.7	99.8	79.7	81.2
Tree leaves	11.0	10.0	8.21	8.2	34.1	32.8	30.3	27.9	28.5	25.1	0.3	0.2	20.3	18.8
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Note: Values presented as percentage of total dry and wet mass for each fraction.

Table 5.2 Characteristics of the fresh experimental compost formula

Characteristics	Wood bin				Rotary Drum		Plastic bin			Ground Pile		
	BA batch fed mixed	No BA weekly fed mixed	BA batch fed not mixed	No BA batch fed mixed	No BA batch fed mixed	BA batch fed mixed	No BA batch fed not mixed	No BA weekly fed mixed	No BA batch fed mixed	No BA batch fed not mixed	No BA weekly fed mixed	No BA batch fed mixed
	W1	W2	W3	W4	RD1	RD2	P1	P2	P3	GP1	GP2	GP3
Mixture ratio												
FW:YT:BA (wet volume)	1:1:1	1:1:0	1:1:1	1:1:0	1:1:0	1:1:1	1:1:0	1:1:0	1:1:0	1:1:0	1:1:0	1:1:0
FW:YT:BA (dry mass)	1.03:1:2.9	1.14:1:0	1:1:2.72	0.94:1:0	1:1:0	1:1.23:2.92	1:1:0	1.18:1:0	0.93:1:0	1.21:1:0	1.2:1:0	0.96:1:0
Physical												
Wet mass (kg)	55.9	84.9	54.9	72.2	72.5	54.2	73.0	84.7	75.5	87.6	63.3	75.0
Dry mass (kg)	23.1	18.8	22.5	17.1	16.8	22.9	16.9	18.6	17.9	19.4	14.1	17.6
Dry matter (%)	41.2 (1.6)	22.6 (1.0)	41 (2.7)	24.1 (1.2)	23.3 (1.2)	41.9 (2.5)	23.4 (2.1)	22.5 (2.0)	24.1 (1.2)	21.9 (1.9)	22.6 (1.9)	23.7 (1.2)
Wet volume (L)	255	366	255	320	320	225	320	366	320	386	250	320
Wet bulk density (kg (m^{-3}))	220	230	240	230	230	240	230	230	240	230	260	240
Free air space (FAS, %)	78	66	78	66	66	78	66	66	66	66	66	66
Chemical*												
pH	5.7 (0.2)	7.7 (0.3)	5.7 (0.2)	6.1(0.2)	6.1 (0.2)	5.7 (0.2)	6.1 (0.2)	7.7 (0.3)	6.1(0.2)	7.7 (0.3)	6.1 (0.2)	6.1(0.2)
Total carbon (TC, % dm)	38 (0.3)	42 (0.6)	38 (0.2)	39.2(0.7)	40 (0.7)	38 (0.2)	40 (0.2)	42 (0.6)	39.2(0.7)	42 (0.6)	40 (0.2)	39.3(0.7)
TKN (g (kg dm)$^{-1}$)	5.8 (0.7)	25 (0.2)	5.8 (0.7)	23(0.2)	23 (0.2)	5.8 (0.7)	23 (0.7)	24 (0.2)	23(0.2)	24 (0.2)	23 (0.7)	23.1(0.2)
COD (g (kg dm)$^{-1}$)	1110 (24)	1125 (14)	1100 (23)	1117 (24)	1115 (24)	1095 (23)	1115 (24)	1130 (15)	1115 (24)	1105 (14)	1145 (24)	1113 (23.7)
C/N	65	17.3	65	17.1	17.0	65	17.1	17.4	17.1	17.2	17.2	17.1

Table 5.2 Characteristics of the fresh experimental compost formula – continued

Characteristics	Wood bin				Rotary Drum		Plastic bin			Ground Pile		
	BA batch fed mixed	No BA weekly fed mixed	BA batch fed not mixed	No BA batch fed mixed	No BA batch fed mixed	BA batch fed mixed	No BA batch fed not mixed	No BA weekly fed mixed	No BA batch fed mixed	No BA batch fed not mixed	No BA weekly fed mixed	No BA batch fed mixed
	W1	W2	W3	W4	RD1	RD2	P1	P2	P3	GP1	GP2	GP3
Organic Fractions*												
Total organics (% dm)	73 (0.2)	78 (0.3)	73 (0.2)	75.3(0.2)	75 (0.2)	72 (0.2)	75 (0.2)	79 (0.3)	75.2(0.2)	77 (0.3)	77 (0.3)	75.2(0.2)
Soluble organic fraction (% total)	20	52	20	50.73	51	50	51	52	50.70	53	52	51.09
Hemicellulose (% total organics)	10	24.4	10	23.05	22.9	24.0	23.0	24.2	23.06	24.6	22.4	23.02
Cellulose (% total organics)	7	17.0	7	17.59	17.4	18.1	17.4	16.8	17.62	16.4	17.1	17.50
Lignin (% total organics)	63	6.9	63	8.63	8.3	8.0	8.3	6.9	8.61	6.4	8.4	8.39

Note: Figures in parenthesis – standard deviations, BA – bulking agent, YT – yard trimming, FW – food waste, TKN – total Kjeldahl nitrogen, dm – dry mass, COD – chemical oxygen demand, C/N – carbon to nitrogen ratio.

* For the compost supplemented with BA, the TKN, C/N ratio and OM fraction values were estimated, since the crushed wood pallets were too large to analyse.

Table 5.3 Loss of components in compost after 150 days of maturity

Loss of compounds	Wood bin				Rotary Drum		Plastic bin			Ground Pile		
	BA batch fed mixed W1	No BA weekly fed mixed W2	BA batch fed not mixed W3	No BA batch fed mixed W4	No BA batch fed mixed RD1	BA batch fed mixed RD2	No BA batch fed not mixed P1	No BA weekly fed mixed P2	No BA batch fed mixed P3	No BA batch fed not mixed GP1	No BA weekly fed mixed GP2	No BA batch fed mixed GP3
Water (%)	85	91	84	97	62	71	83	84	93	94	90	98
(kg (kg dm)$^{-1}$)	1.2	3.2	1.2	3.2	2.1	1.0	2.7	3.0	3.0	3.3	3.1	3.2
COD (%)	62	70	39	72	76	69	70	72	72	69	66	72
(g (kg dm)$^{-1}$)	691	792	426	805	845	787	801	819	797	760	783	802
TC (%)	60	70	38	70	77	69	70	72	70	69	66	71
(g (kg dm)$^{-1}$)	230	290	140	280	300	260	280	300	270	290	260	300
TKN (%)	44	48	18	53	68	59	52	54	52	44	48	52
(g (kg dm)$^{-1}$)	10.5	11.5	4.2	12.3	15.7	13.6	12.0	12.9	12.0	10.3	11.1	12.0
Dry mass (%)	43	50	18	56	63	61	55	54	52	50	47	55
(g (kg wm)$^{-1}$)	100	110	40	130	150	150	130	120	120	110	110	130
Organic mass (%)	56	76	31	71	77	69	70	68	70	82	66	70
(g (kg dm)$^{-1}$)	410	590	230	530	580	500	530	530	530	630	500	530
Wet volume (%)	48	85	37	88	89	58	81	84	88	87	78	89
Wet mass (%)	61	82	58	87	62	60	76	77	83	84	80	87

Table 5.3 Loss of components in compost after 150 days of maturity – continued

Loss of compounds	Wood bin				Rotary Drum		Plastic bin			Ground Pile		
	BA batch fed mixed	No BA weekly fed mixed	BA batch fed not mixed	No BA batch fed mixed	No BA batch fed mixed	BA batch fed mixed	No BA batch fed not mixed	No BA weekly fed mixed	No BA batch fed mixed	No BA batch fed not mixed	No BA weekly fed mixed	No BA batch fed mixed
	W1	W2	W3	W4	RD1	RD2	P1	P2	P3	GP1	GP2	GP3
Organic fractions												
Soluble (%)	64	76	56	76	79	82	76	75	74	77	74	72
(g (kg OM)$^{-1}$)	330	400	280	390	410	410	390	390	370	400	380	370
Hemicellulose (%)	65	76	40	90	87	84	82	81	83	77	74	83
(g (kg OM)$^{-1}$)	160	190	100	210	200	200	190	190	190	190	170	190
Cellulose (%)	58	76	8	72	78	52	73	81	83	71	73	84
(g (kg OM)$^{-1}$)	100	130	10	130	140	90	130	140	150	120	130	150
Lignin (%)	12.3	11.4	6.3	9	11.1	10.7	31.1	10.3	11.0	16.5	17.7	11
(g (kg OM)$^{-1}$)	10	10	10	10	10	10	30	10	10	10	20	10

Note: dm – dry mass, wm – wet mass, OM – organic matter, TKN – total Kjeldahl nitrogen, COD – chemical oxygen demand, TC – total carbon; BA – bulking agent.

Table 5.4 Pathogens and parasites in mature compost of 150 days

Organism	French Standard [a] (MPN (g dm)$^{-1}$	Wood bin				Rotary Drum		Plastic bin			Ground Pile		
		BA batch fed mixed W1	No BA weekly fed mixed W2	BA batch fed not mixed W3	No BA batch fed mixed W4	No BA batch fed mixed RD1	BA batch fed mixed RD2	No BA batch fed not mixed P1	No BA weekly fed mixed P2	No BA batch fed mixed P3	No BA batch fed not mixed GP1	No BA weekly fed mixed GP2	No BA batch fed mixed GP3
Escherichia coli (CFU (g)$^{-1}$)	< 1000	2100	740	63 000	600	< 10	< 10	< 400	170	<400	570	850	<10
Salmonella (count (25 g)$^{-1}$)	absent	absent	absent	absent	absent	absent	absent	absent	absent	absent	absent	absent	absent
fecal *Streptococci* (CFU (g)$^{-1}$)	-	3 700	< 400	16 000	3800	86 000	2 100	< 400	< 100	<400	< 400	5 000	2500
Helminthe eggs (count (1.5 g)$^{-1}$)	absent	absent	absent	absent	absent	absent	absent	absent	absent	absent	absent	absent	absent

Note: dm – dry mass; [a] AFNOR (2002; 2006); BA – bulking agent.

Table 5.5 Polycyclic aromatic hydrocarbons (PAH) and trace elements for 150 day Wood bin compost

Compound	Wood bin (W) compost			Regulations		
	BA batch fed mixed W1	No BA weekly fed mixed W2	No BA batch fed mixed W4	Canada[a]	European union[b]	France[c]
PAH ($\mu g\ (kg\ dm)^{-1}$)						
Naphthalene	< 86	< 52	<73	-	-	-
Methyl (2) fluoranthene	24	< 10	<14	-	-	-
Phenanthrene	123	< 10	<14	-	-	-
Anthracene	24	< 10	<14	-	-	-
Fluoranthene	313	< 10	<14	-	-	4000
Pyrene	180	< 10	<14	-	-	-
Benzo(a) anthracene	68	< 10	<14	-	-	-
Chrysene	87	< 10	<14	-	-	-
Benzo (3,4) (b) fluoranthene	35	< 10	<14	-	-	2500
Benzo (11,12) (k) fluoranthene	27	< 10	<14	-	-	-
Benzo (3,4) (a) pyrene	22	< 10	<14	-	-	1500
Trace elements ($mg\ (kg\ dm)^{-1}$)						
Arsenic	4.9	3.8	3.8	13	-	18
Cadmium	0.4	0.1	0.3	3	0.7-10	3
Chromium	4.2	6.9	1.6	210	70-200	120
Copper	21.9	18.1	31.1	400	70-600	300
Lead	31	1.4	5.3	150	70-1000	180
Mercury	<0.1	<0.1	<0.1	0.8	0.7-10	2
Nickel	4.8	3.7	5.9	62	20-200	60
Selenium	0.1	0.1	0.2	2	-	12
Zinc	130	70.1	179.3	700	210-4000	600

Note: [a]CCME (2005), [b]Brinton (2000), [c]AFNOR (2006); BA – bulking agent.

(a) **(b)**

(c) **(d)**

Figure 5.1 Home composters used to test the management practice combinations: (a) Wood bin (W); (b) Plastic bin (P); (c) Rotary Drum (RD); and (d) Ground Pile (GP).

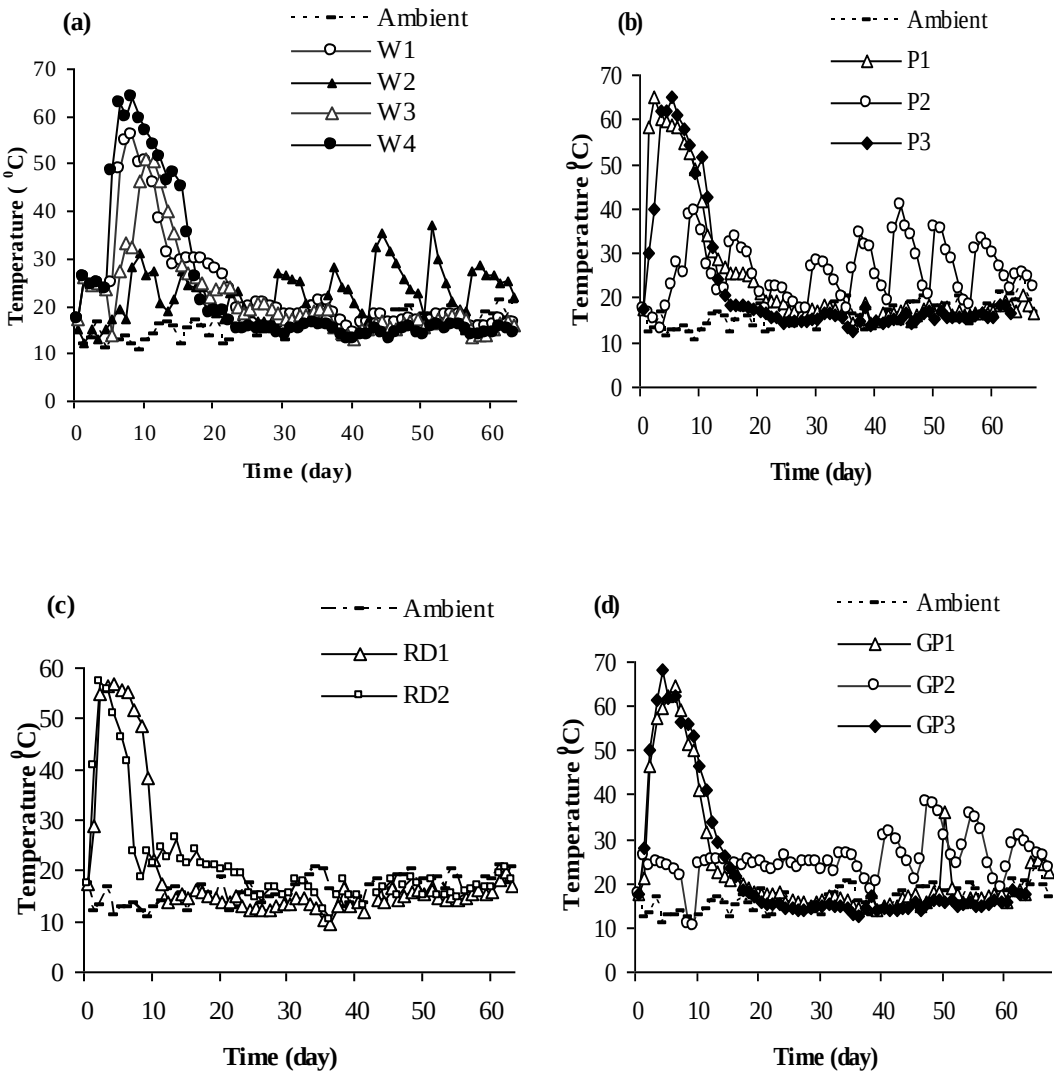


Figure 5.2 Temperature regimes for all HC and management practices measured in the centre of the compost mass for: (a) Wood bins; (b) Plastic bins; (c) Rotary Drums; and (d) Ground Piles. The management treatments were : W1 – Wood bin with BA, batch fed and mixed; W2 – Wood bin without BA, weekly fed and mixed; W3 – Wood bin with BA, batch fed and not mixed; W4 – Wood bin without BA, batch fed and mixed; P1 – Plastic bin without BA, batch fed and not mixed; P2 – Plastic bin without BA, weekly fed and mixed; P3- Plastic bin without BA, batch fed and mixed; RD1 – Rotary Drum without BA, batch fed and mixed; RD2 – Rotary Drum with BA, batch fed and mixed; GP1 – Ground Pile without BA, batch fed and not mixed; GP2 – Ground Pile without BA, weekly fed and mixed; GP3 – Ground Pile without BA, batch fed and mixed; BA – bulking agent.

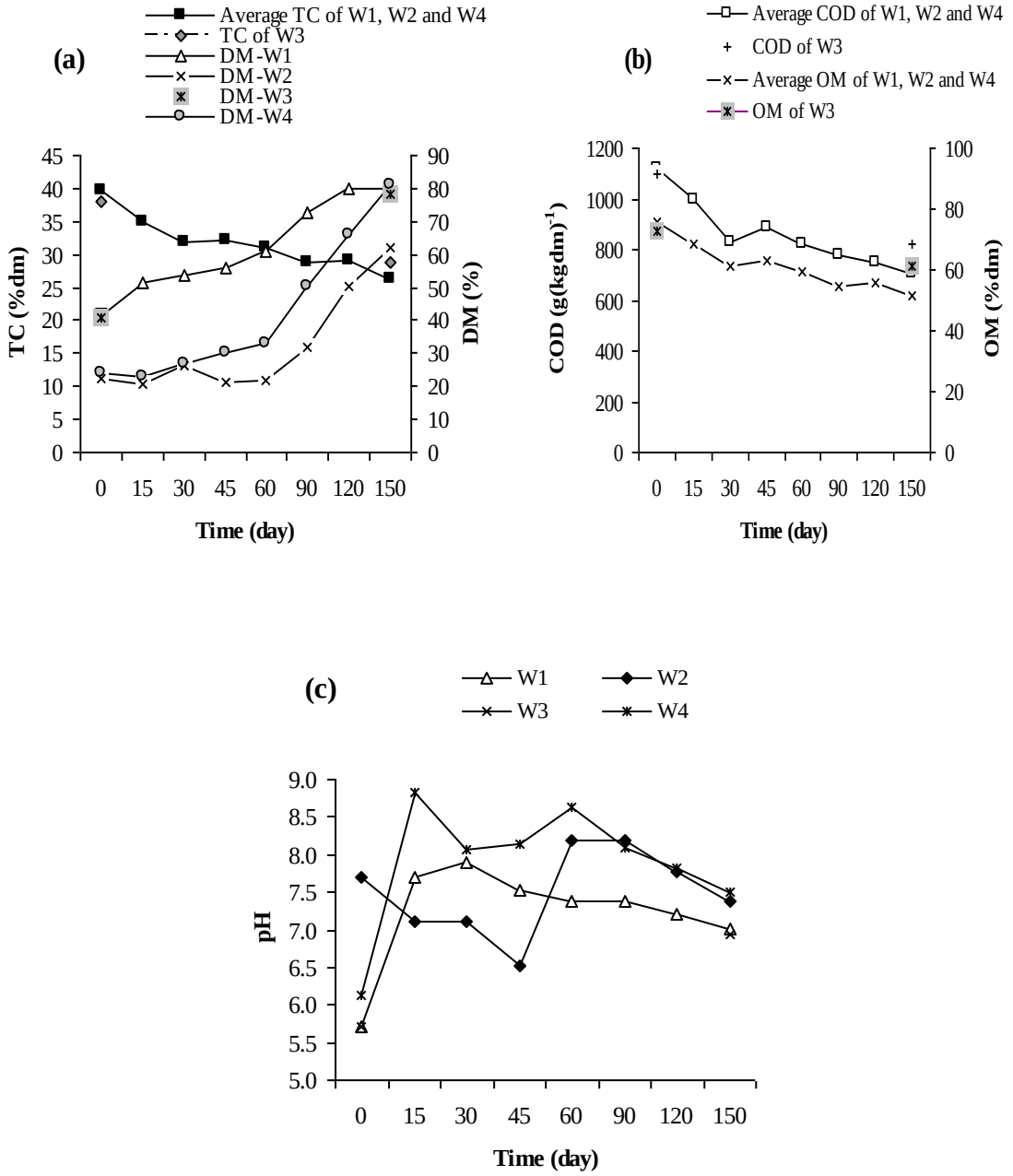


Figure 5.3 Wood bin evolution of compost characteristics as influenced by management practice combination: (a) TC and DM; (b) COD and OM; and (c) pH. TC – total carbon; DM – dry matter; COD – chemical oxygen demand; OM – organic matter; W1 – Wood bin with BA, batch fed and mixed; W2 – Wood bin without BA, weekly fed and mixed; W3 – Wood bin with BA, batch fed and not mixed; W4 – Wood bin without BA, batch fed and mixed. Since W3 was not mixed and sampled regularly, only day 0 and 150 values are illustrated.

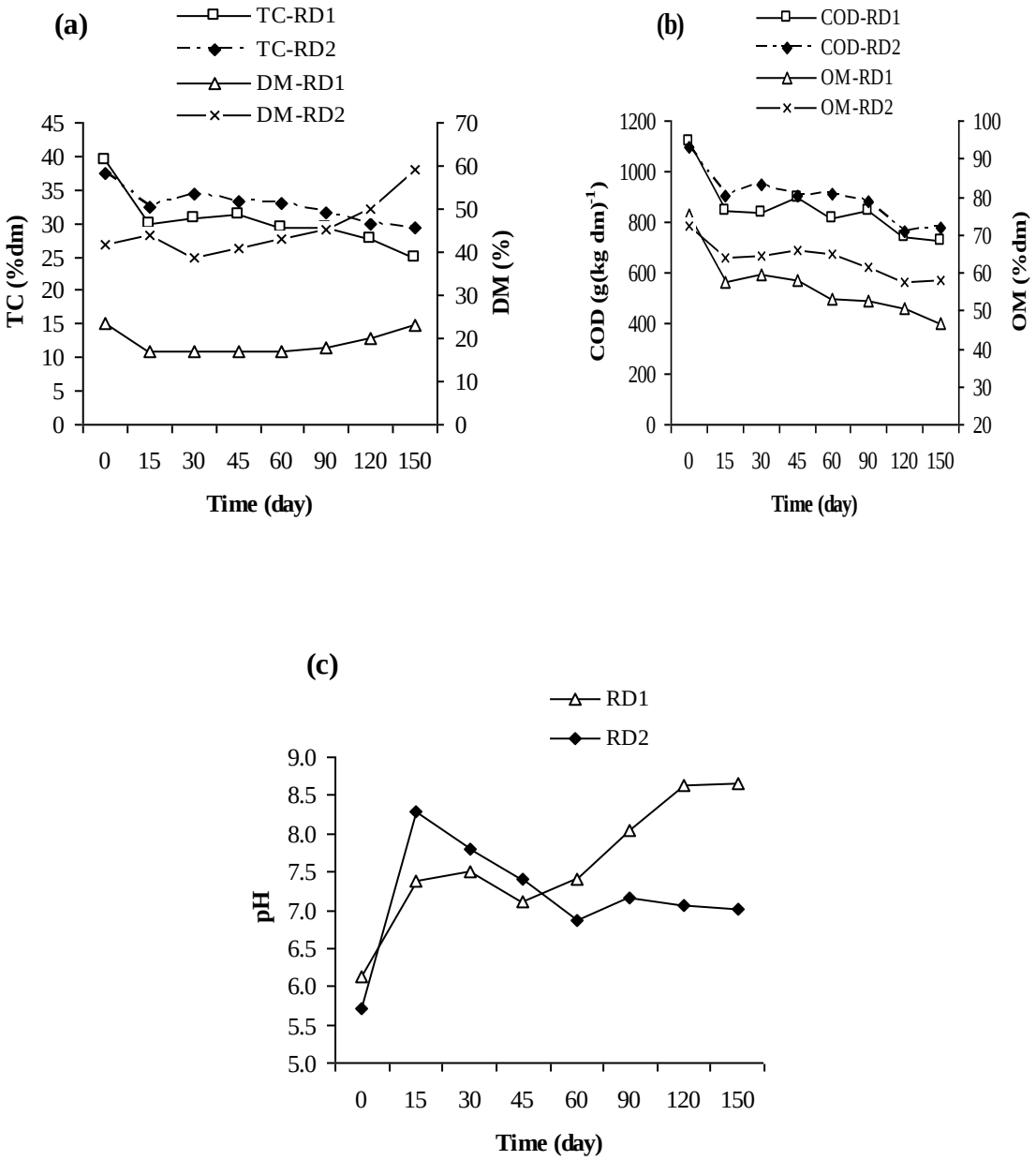


Figure 5.4 Rotary Drum evolution of compost characteristics as influenced by management practices: (a) TC and DM; (b) COD and OM; and (c) pH. TC – total carbon; DM – dry matter; COD – chemical oxygen demand; OM – organic matter; RD1 – Rotary Drum without BA, batch fed and mixed; RD2 – Rotary Drum with BA, batch fed and mixed.

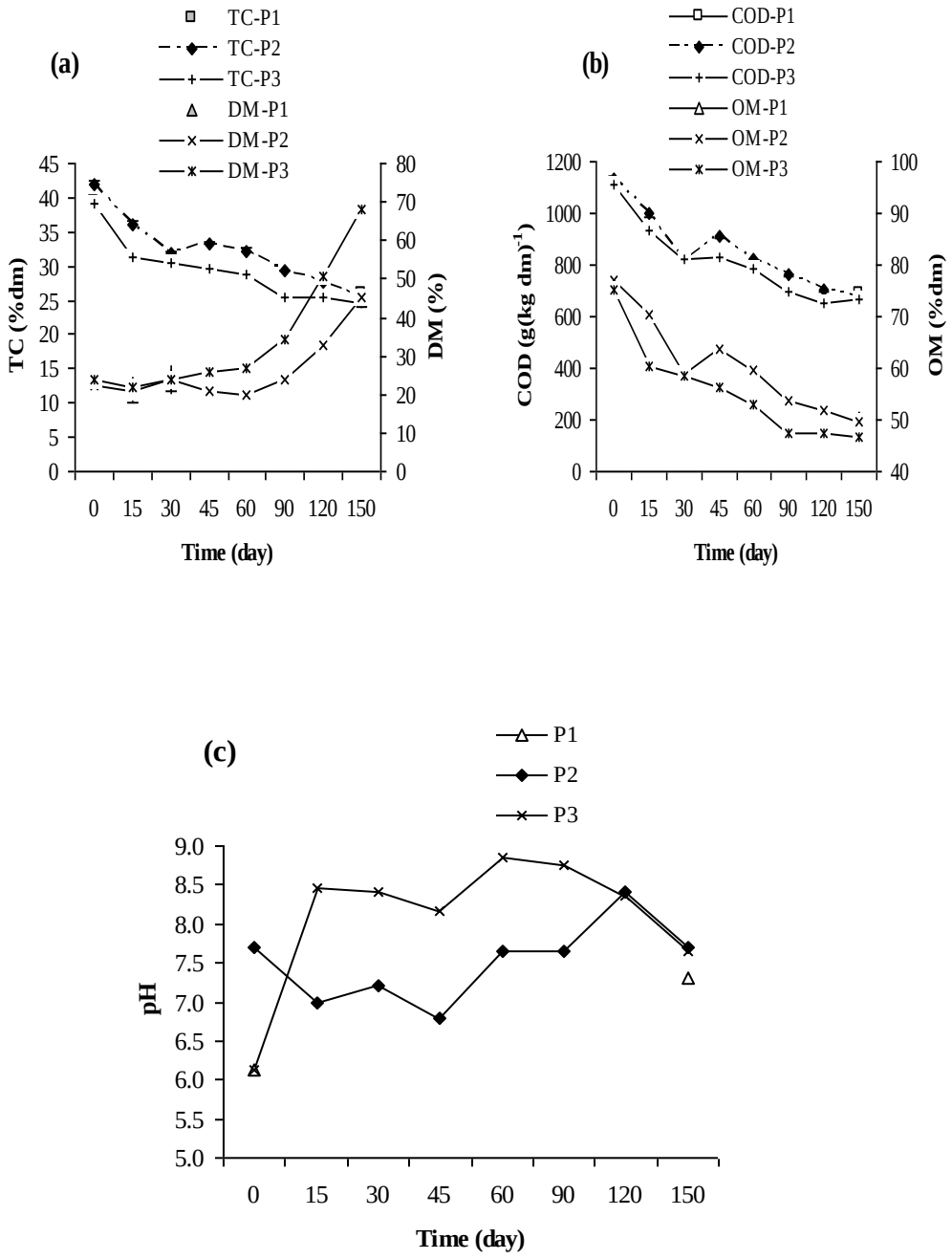


Figure 5.5 Plastic bin evolution of the compost characteristics as influenced by management practices: (a) TC and DM; (b) COD and OM; and (c) pH. TC – total carbon; DM – dry matter; COD – chemical oxygen demand; OM – organic matter; P1 – Plastic bin without BA, batch fed and not mixed; P2 – Plastic bin without BA, weekly fed and mixed; P3 – Plastic bin without BA, batch fed and mixed. Since P1 was not mixed and sampled regularly, only day 0 and 150 values are illustrated.

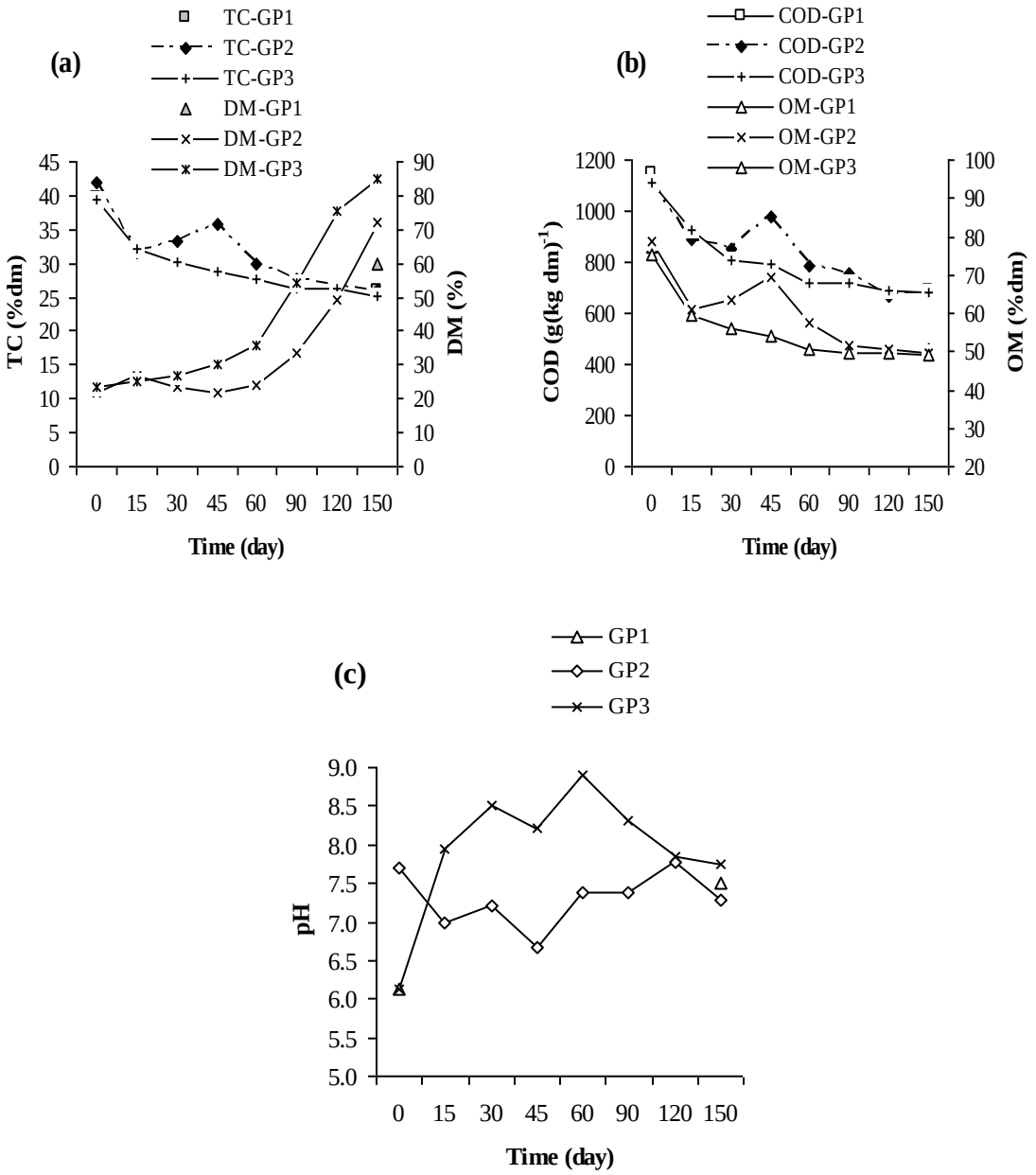


Figure 5.6 Evolution of the compost characteristics as influenced by management practices for the ground pile: (a) TC and DM; (b) COD and OM; and (c) pH. TC – total carbon; DM – dry matter; COD – chemical oxygen demand; OM – organic matter; GP1 – Ground Pile without BA, batch fed and not mixed; GP2 – Ground Pile without BA, weekly fed and mixed; GP3 – Ground Pile without BA, batch fed and mixed. Since GP2 was not mixed and sampled regularly, only day 0 and 150 values are illustrated.

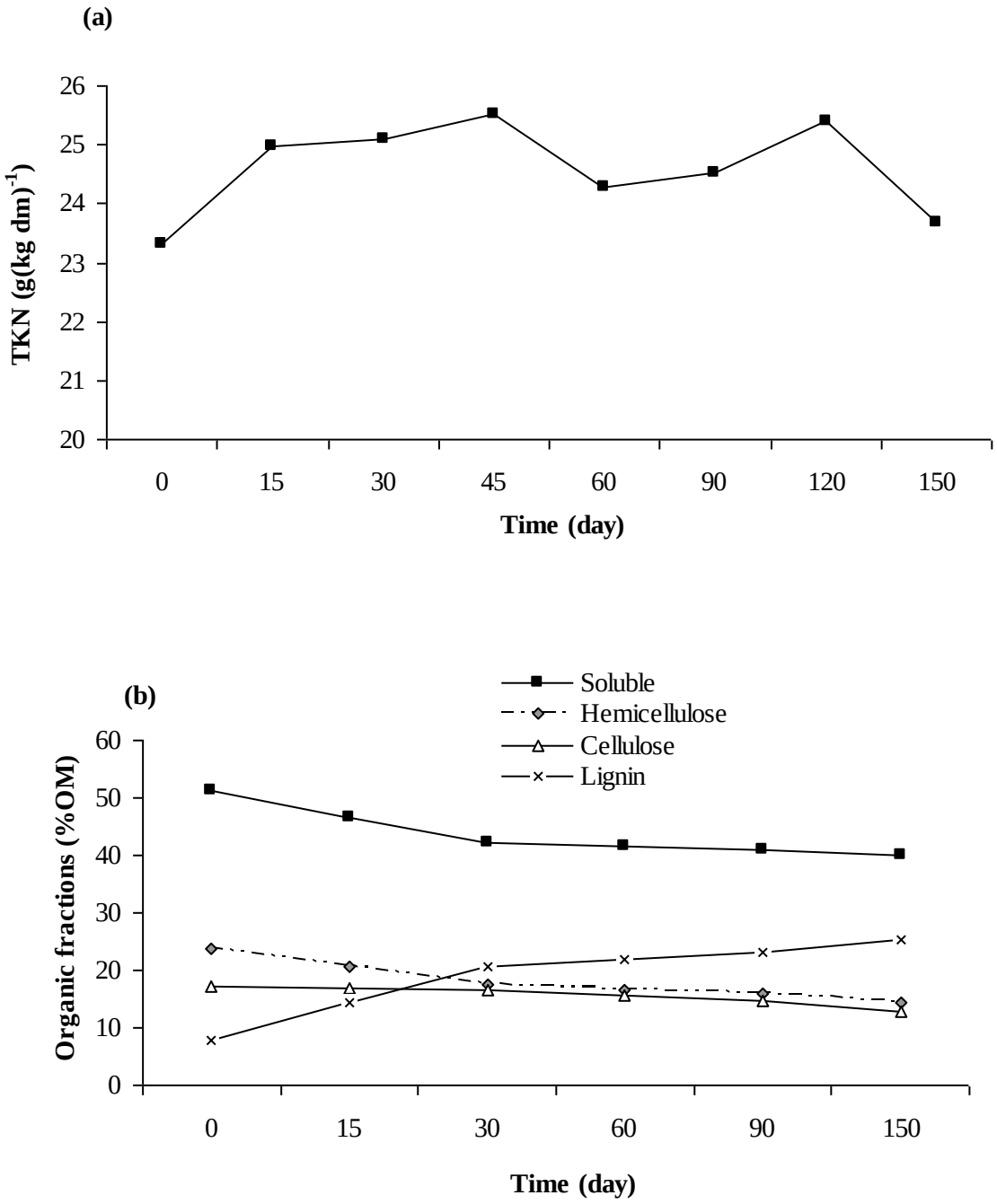


Figure 5.7 Evolution of the TKN and organic fractions for all management practice combinations: (a) TKN; (b) organic fractions.
TKN – total Kjeldahl nitrogen; dm - dry mass; OM – organic matter.
All compost samples were analyzed with BA because of the size of the wood chips.

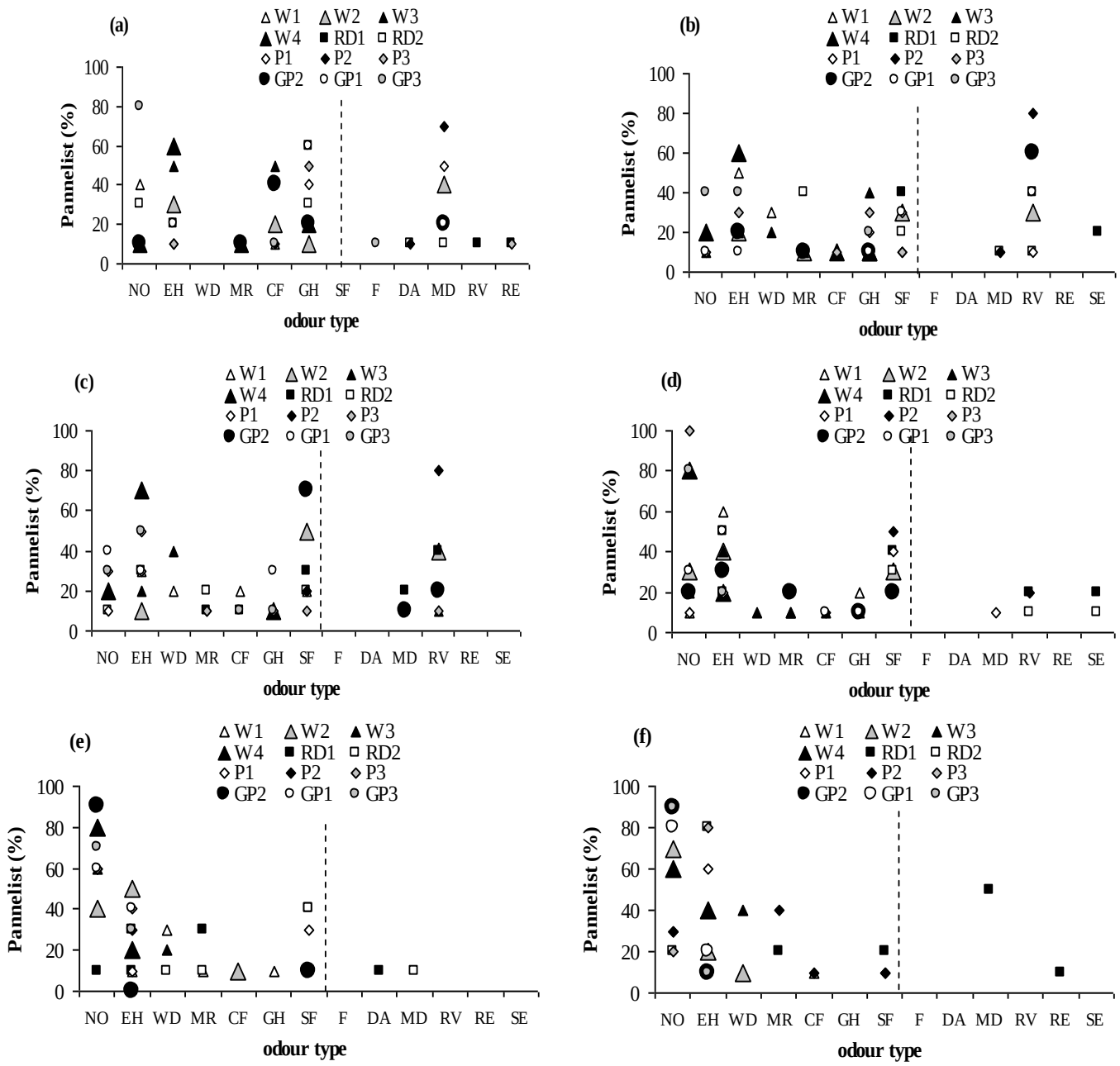


Figure 5.8 Evolution of compost odour characteristics as influenced by management practice combinations for day (a) 15;(b) 30;(c) 60;(d) 90;(e) 120, and;(f) 150. The vertical dotted line separates the acceptable and objectionable smells.

Symbols : NO – no odour, EH-earthy/humus, WD-woody; MR-mushroom, CF-citrus fruits, GH-grassy/hay, SF-soft fermentations, F-fish, DA-dead animals, MD-mouldy, RV-rotten vegetable, RE-rotten eggs, SE-sewage,; W1 – Wood bin with BA, batch fed and mixed; W2 – Wood bin without BA, weekly fed and mixed; W3 – Wood bin with BA, batch fed and not mixed; W4 – Wood bin without BA, batch fed and mixed; RD1 – Rotary Drum without BA, batch fed and mixed; RD2 – Rotary Drum with BA, batch fed and mixed; P1 – Plastic bin without BA, batch fed and not mixed; P2 – Plastic bin without BA, weekly fed and mixed; P3 – Plastic bin without BA, batch fed and mixed; GP1 – Ground Pile without BA, batch fed and not mixed; GP2 – Ground Pile without BA, weekly fed and mixed; GP3 – Ground Pile without BA, batch fed and mixed.

Connecting statement to chapter 6

The previous chapter demonstrated the effect of management practices on the composting process obtained from home composting systems (HC) and their final product quality. This study needs to be further verified from the HC managed by the urban residents. In this context, HC managed by Montreal waste island residents was studied. Chapter 6 examines the compost quality of urban residents managed HC in Montreal West Island.

Chapter 6 is drawn from a manuscript submitted for publication to the Journal of Environmental Technology by the author of the thesis and co-authored by supervisors, Dr. Anne Trémier, Unite GERE, Cemagef, Rennes, France and Prof. Dr. Suzelle Barrington, Department of Bioresource Engineering, McGill University, Montreal, Canada. The format has been changed to be consistent within this thesis.

Chapter 6
Montreal West Island home compost characteristics

Abstract

For organic wastes, home composting eliminates collection, handling and treatment operations at the municipal level. Nevertheless, very few studies have evaluated the quality of the compost produced. Accordingly, a study was conducted to evaluate the influence of management practices on the quality of the compost produced in residential backyards using home composters (HC). The study monitored five HC operated by homeowners of the Montreal West Island area, during 20 weeks spanning June to October 2010. The management practices observed were: the type and backyard location of HC, and; the rate and type of organic waste (OW) fed into the HC. The parameters monitored were: compost temperature and final characteristics including trace metals and pathogens.

For all HC, thermophilic compost temperatures were highly probable within one week of adding more than 10kg of OW composed of equal volumes of food waste and yard trimmings. Top and bottom perforations in HC enhanced convective aeration but concentrated the OW decomposition within the bottom layer. When the HC was fed an equal volume of food waste and yard trimmings, the final compost offered a dry matter and organic matter content over 30% and 50%, respectively. The final compost offered total nitrogen, phosphorous and potassium levels of 2, 1 and 3% on a dry matter basis, representing a good quality soil amendment. As clean OW was fed, the HC compost respected Canadian and European regulations in terms of *E. coli* and Salmonella, irrespective of the active phase temperature regime. In terms of trace metals, regulatory limits may be exceeded when the HC is fed ashes. Homeowners must also be careful when applying pesticides to their lawns and gardens and then feeding the residues to the HC.

Keywords: Home composter, organic waste, aeration perforations, pathogens, trace elements.

6.1 Introduction

In Europe and North America, legislation promotes the landfill diversion of organic waste (CCEM, 1989; EU, 1999) a major constituent of the municipal solid waste (MSW) mainstream (Boldrin and Christensen, 2010; Colón et al., 2010; López et al., 2010). Nevertheless, this diversion offers environmental and economic challenges because recycling treatments generally require either a segregated collection or a complex sorting system, besides their consumption of energy and their requirements for infrastructure (Lundie and Peters, 2005). Composting is recognized as a robust recycling treatment for organic wastes (OW), because of its tolerance for foreign materials (Karnchanawong and Suriyanon, 2011; Domingo and Nadal, 2009). As early as 1929, centralized MSW composting facilities appeared in Holland and, during the 1970s and 1980s, expanded throughout Europe. As a result of full stream MSW operations producing poor quality compost, source-separation was encouraged despite producer reluctance even today (Slater and Frederickson, 2001).

Considering the technical, economical and environmental challenges faced by centralized composting facilities, onsite treatments such as home and community composting become interesting alternatives (Schwalb et al., 2011; Adhikari et al., 2010; Andersen et al., 2010). Canada generated 3.22 million tonnes of OW in 2005, representing 24% of the total mass of MSW (OECD, 2006-2007), and amounting to 100 kg of OW $capita^{-1}yr^{-1}$. Besides reducing equipment and labour costs, home composting of OW eliminates its selective collection and mechanical processing, reducing greenhouse gas generation from fossil fuel consumption. Nevertheless, the successful implementation of onsite composting depends on the active participation of homeowners and the production of a hygienically safe soil amendment (Brändli et al., 2007; Gong, 2007; Stabnikova et al., 2005).

Recent food health incidences have provided an incentive to investigate the hygienic and environmental issues associated with home composting. In West London, Smith and Jasim (2009) studied the effectiveness of 290 L home composters in reaching thermophilic temperatures when fed kitchen waste, paper and yard trimmings. The organic waste in these HC remained mostly at psychrophilic (0-20^{0}C) and mesophilic (20-45°C) temperatures except for a few cases reaching the thermophilic range during summer months as a result of a large input of waste. Nevertheless, the compost obtained was of good quality. In Thailand, Karnchanawong and Suriyanon (2011) evaluated the performance of 6 different polyethylene composting bins with a capacity of 200L, batch fed with food waste and yard trimmings. The study concluded that improved temperature regimes were obtained with bins aerated through bottom and top perforations enhancing convective air displacement.

In the laboratory, Adhikari et al. (2011a) compared the performance of four different types of home composting systems to also conclude that the temperature regime is highly influenced by the design and location of the bin perforations. Furthermore, Adhikari et al. (2011b) observed that batch loading produces thermophilic temperatures, as compared to weekly loading, and that a bulking agent was not necessary when yard trimmings were added along with the food waste.

To validate laboratory results with compost quality actually produced in backyards, and to further examine the influence of home composter (HC) design and management on compost quality, five individual HC were monitored during 20 weeks. Conducted in the West Island area of Montreal, Canada, the project monitored the organic waste (OW) input of five backyard HC, their temperature regime and the final compost quality. Through autoregressive analysis, the project evaluated the

impact of weekly OW loading rate on the compost temperature regime. The final compost was analyzed for dry matter (DM), pH, nutrient levels trace metals and pathogens.

6.2 Material and methods

6.2.1 Experimental home composters and their treated waste

Five homeowners of the Montreal West Island community took part in this study. Two different types of polyethylene HC were used, namely the slatted bin and the top/bottom perforated bin (Figure 6.1). The participating homeowners were selected randomly and coded A, B, C, D and E. The slatted composter of homeowners A, C and E offered a total capacity of 350 L while that with top/bottom perforations of homeowners B and D offered a capacity of 300 L.

The OW produced by the homeowners consisted of kitchen food waste (FW) and yard trimmings (YT), namely grass clippings, garden waste and tree leaves. The fresh OW generated by the participating homeowners was characterized based on that collected at the top of the HC at the end of the study. The OW characteristics observed in this project were compared to those observed for OW produced by restaurant and homeowners of several world cities (Table 6.1).

6.2.2 Methodology

All five homeowners were asked to normally manage their HC (Table 6.2). Home composters A, B, C were shaded by backyard trees while home composter D was exposed to the sun and home composter E was located in a semi-shaded area. Waste log forms were supplied to each homeowner to keep track of type, amount and date of waste loading. A 7.5 L kitchen collection bin (Norseman Plastic Ltd, Canada) and a

22 kg hook scale (Notlegalfortrade, China) were provided to each homeowner to collect and measure the waste added to their HC. As normally done, each homeowner manually loaded their individual HC without compaction. During the experimental 20 week period, the content of the HC was not mixed except for that of homeowner E which was mixed occasionally.

The temperature of the HC content was measured weekly by the researcher on the project using a long-stem thermometer (PTC Instruments, Los Angeles, California, USA, model 8500D-II). This monitoring was conducted throughout the 20 week experimental period of June to October 2010. After 20 weeks, the content of all five HC was removed in 3 separate layers, namely top, middle and bottom, and triplicate samples were collected from each layer for characterization including DM, pH, nutrients, trace metals and pathogens. This characterization verified the compost quality and its suitability as soil amendment (Mato et al., 1994). The temperature regime and compost quality results were analyzed to recommend best management practices for home composting systems.

6.2.3 Analytical procedure

The characterization of all compost samples respected standard laboratory methods (APHA, 2005). Dry matter (DM) was determined gravimetrically by drying at 103°C for 24 h (Scientific John by Sheldon Manufacturing Inc., Cornelius, Oregon, USA). Organic matter (OM) was quantified as volatile solids and determined on the dried samples by burning for 4 h at 550°C in a muffle furnace (Blue M Electric Company, Blue Island, USA). Organic carbon (C) content was determined by dividing the volatile solids by 1.83 (Barrington et al., 2002).

Total nitrogen (TN), phosphorous (TP) and potassium (TK) were quantified after digesting the compost samples with sulphuric acid and hydrogen peroxide (50%) for 15 min at 500 °C. Total Kjeldahl nitrogen (TKN) was quantified by measuring in the digested compost sample, its NH_3-N content at a pH of 13, using a NH_3 sensitive electrode (Orion, Boston, Massachusetts, USA, model BCN). Because of the low compost nitrite and nitrate levels, TN was considered equal to TKN. Total phosphorous and potassium were quantified colorimetrically, at pH 7, using a spectrophotometer (Hach, Model DR 5000, Loveland, Colorado, USA).

The pH was determined using a pH probe connected to an ion meter (Orion, Boston, Massachusetts, USA, model 450) after soaking 10 g of sample for 24 h without shaking at 5°C, in 20 ml of distilled water. After a dichromate digestion at 150°C for 2 h, COD was determined colorimetrically using a spectrophotometer (Hach, Model DR 5000, Loveland, Colorado, USA).

Escherichia coli and fecal *Streptococci* were quantified as colony forming units (CFU) using the Millipore filtration technique according to APHA (2005). The presence of *Salmonella* in 25 g of wet sample was determined using Petri plates with XLD agar (MFHPB-20, 2009). The heavy metals were quantified by Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) after digestion with nitric acid.

6.2.4 Statistical procedure

The PROC ARIMA procedure (SAS Institute Inc.,2008) was used for the autoregressive comparison of temperature profile measured at the centre of the compost mass for all five HC and weekly OW loading. The physico-chemical characteristics of the triplicate samples collected from the top, middle and bottom layers of all five HC were also compared using ANOVA at a 95 % confidence level

for within and between the HC using the General Linerar Model Procedure (PROC GLM) (SAS Institute Inc.,2008).

6.3 Results and discussion

6.3.1 Waste composition and mass input

Table 6.3 and Figure 6.2 present, respectively, the composition and mass of OW loaded into the five HC over the 20 week experimental period. Most HC were loaded with 75 % food waste (FW) and 25 % yard trimmings (YT) including grass clippings, garden residues and tree leaves. Besides FW and YT, home composter A received a large amount of seafood residues in June and some ashes in July, while home composter C regularly received flower stems and soil. Home composter D received generally a lower fraction of FW at 63 % and a higher fraction of YT at 37 %.

All five HC received a mixture of FW and YT with an average DM of 12.5 to 15.9 %, except for home composter D fed a lower FW:YT ratio resulting in a higher DM of 41 %. In general, the C/N ratio of the compost ranged between 20 and 22, except for that of home composters A and D in the lower range of 13 to 14.5, resulting from their fed OW containing no tree leaves. Tree leaves generally offer a C:N ratio in the range of 100-150. For all HC, the fed OW offered a COD level between 990 to 1155 mg $(kg\ dm)^{-1}$.

All five HC were regularly loaded with OW but the amount varied among homeowners and over the experimental period. Home composters B and C received the most OW at an average rate of 8.1 and 8.0 kg $(week)^{-1}$, as compared to home composters A, D and E which received OW at an average rate of 2.4, 4.0 and 1.6 kg $(week)^{-1}$ (Figure 6.2 and Table 6.2), respectively. Home composters B and C received especially high amounts of OW during the first 12 weeks of experimentation.

6.3.2 Home composter management and temperature profile

The compost matrix is influenced by HC selection based on its type and perforation location, and management practices, namely input rate and type of organic waste input, location of HC in the backyard and mixing frequency of the HC content. Such practices influence oxygen availability, compost moisture levels, pH and C/N ratio (Epstein, 1997; Haug, 1993).

Overall, home composter E was loaded with the lowest amount of waste compared to all other HC but exhibited an average temperature profile. On a wet weight basis, home composter E received on the average 1.6 kg $(week)^{-1}$ with a FW:YT ratio of 3:1 and a DM of 15.9 %. The content of home composter E generally exhibited a temperature profile ranging between 1 to 11°C and averaging 4 °C above ambient. This temperature profile exceeded that of home composters A, B and C receiving higher rates of OW, at 2.4, 8.1 and 8.0 kg $(week)^{-1}$, respectively (Figure 6.3). This is explained by the monthly mixing and the partial exposure of the HC to sunshine.

As opposed to home composter E, home composter D exhibited the highest temperature profile ranging between 1 to 36 °C and averaging 8 °C above ambient, for an average loading rate of 4.0 kg $(week)^{-1}$. Peak temperatures were especially observed when the HC received large amounts of OW, such as during weeks 8 and 13. The high temperatures observed for home composter D are associated with its drier OW resulting from a FW:YT ratio of 2:1, the low C:N ratio of its fed OW containing no tree leaves, its location in full sunshine and the bottom/top position of its perforations enhancing convective aeration.

The content of home composter A produced the lowest temperatures, ranging between 0 to 12 °C and averaging 3 °C above ambient. Home composter A received

the second lowest amount of OW, at 2.4 kg $(week)^{-1}$ and was shaded throughout the experiment. It received OW with a FW:YT: ash ratio of 4:1:0.1, and a low C:N ratio of 13 because of the absence of tree leaves in the fed OW. The content of home composter A reached its maximum temperature of 35 °C, 12 °C above ambient, on week 3, after receiving 10.0 kg of OW (Figure 6.3). The lowest temperatures associated with home composter A resulted from its slow loading rate and its low DM content of 12.5 %.

The compost temperature profile of home composter B was generally higher than that of home composter C, although both their ranges were intermediate as opposed to that of home composters A and D. Whereas the temperature profile of home composter B ranged between 1 and 10°C and averaged 6°C above ambient, that of home composter C ranged between 2 and 8°C and averaged 5°C above ambient. Their loading rate was the highest at 8.1 and 8.0 kg of OW $(week)^{-1}$. Home composter B had bottom/top perforations as opposed to home composter C with opening created by slats. Both located in a shady backyard area, home composters B and C respectively received OW at a low DM of 12.5 and 14.5 % with a FW:YT ratio of 6.6:1 and 3.4:1. The slightly better performance of home composter B over home composter C is attributed mainly to its type of perforations, enhancing convective air flow. Nevertheless and despite their heavy OW loading rate, the intermediate temperature regime of both home composters B and C resulted from the low DM content of the fed OW and their shaded location.

For all HC, a large single input of OW exceeding 10 kg, resulted in a temperature increase, as long as the OW offered a DM of at least 15.9 %. Home composter B reached a temperature of 38 °C or 8 °C above ambient, on week 5 following its loading with 16 kg of OW. However, loading 23 kg on week 7 and 20 kg

on week 12 resulted in temperatures of only 35 °C or 5 °C above ambient, and 25 °C or 4 °C above ambient, because FW was the predominant OW. Home composter C reached its maximum temperature of 34 °C on week 6, after receiving 19 kg of OW whereas 26 kg of OW loaded on week 10 only produced 29 °C because the YT contained a lot of soil. Home composter E also reached its maximum temperature of 33 °C or 3 °C above ambient, on week 9 when it was fed 4.5 kg of OW. Home composter D reached 54 °C on week 11 and 60 °C on week 13 when fed over 15 kg of OW composed of FW and YT in equal volumes.

The autoregressive analysis (AR) process was used to confirm the influence of weekly waste input on compost temperature. Using all time series temperature data, the autocorrelation function (ACF) and the partial autocorrelation function (PACF) were estimated (Figure 6.4). For all five HC, the AR analysis indicated a temperature increase especially during the week of feeding (lag of 0). Based on the autoregressive model selection criterion such as significance of model parameter, the AR process was found to be the most suitable to compare timing of temperature response to OW loading. This implies that the amount of OW loaded on a weekly basis into the HC had an immediate influence on the compost temperature profile.

Considering that temperature is an indicator of microbial activity (Diaz et al., 1993), the present observations lead one to believe that thermophilic temperatures can be reached as long as:

1) The HC has bottom/top perforations enhancing convective air circulation;
2) The HC receives a large input of OW, generally over 10 kg and this waste is composed of equal volumes of FW and YT to offer a reasonable DM;

3) Feeding 3 to 5 % tree leaves or wood chips along with the FW will bring the C:N ratio to a reasonable level of 20, whereas in their absence, grass clippings will give a C:N ratio in the range of 12 to 15;
4) The HC content is mixed monthly;
5) The HC is placed in a semi-shaded area and exposed to intermediate climatic conditions (rain and sunshine) as opposed to a shaded or non shaded area.

6.3.3 Compost DM and OM

Figure 6.5 compares the 3 layers of compost, top, middle and bottom, in terms of dry matter (DM) and organic matter (OM) for all HC after 20 weeks of operation. The DM of all 3 layers followed the same trend among HC, with the bottom layer being significantly drier than the middle, which in turn was significantly drier that the top layer ($p < 0.001$). Nevertheless, composter D offered the highest DM value followed by composter E with an intermediate value and then home composters A, B and C with the lowest DM value. The trend in DM content is explained by the fact that composter E was semi exposed to sunshine while composter D was fully exposed, as compared to home composters A, B and C which were shaded. Furthermore, composter D was fed a lower ratio of FW:YT, as opposed to all other HC.

The OM level between layers varied among HC, with the top and middle compost offering a similar level for home composters B and D, as opposed to home composters A, C, and E where the top had a higher OM value than the middle ($p<0.0001$). In all cases, the bottom layer offered a lower OM as compared to the other two layers. For the bottom compost layer, composter C received some soil that

explains its lower OM level as opposed to the other HC. The ash fed to composter A did not impact its OM level.

A lower OM level implies a more active degradation of the volatile solids, leaving behind a material with a higher mineral or ash content. Thus, home composters B and D produced limited decomposition at their top and middle section, as opposed to home composters A, C, and E where their middle layer was active. As opposed to the other HC built out of slats, home composters B and D offered bottom and top perforations enhancing convective aeration. Accordingly, convective aeration tends to concentrate the OW degradation within the bottom layer, as opposed to the slatted HC where degradation is more uniformly distributed over the depth.

6.3.4 Compost nutrients

Figure 6.6 illustrates the stratified variations in pH, TN represented by TKN, TP and TK. Although the bottom and middle layers of all five HC offered a similar pH in the range of 7.2 to 8.0, the top layer demonstrated more variation among HC, with wetter compost demonstrating more acidic conditions. For the top layer compost, home composters A and B offered the lowest pH of 5.0 because of the wet nature of their waste. Home composter C offered an intermediate top layer pH of 5.5 being fed slightly drier OW as compared to home composters A and B, and; home composters D and E offered a pH of 7.2 and 6.8, respectively, because of their drier OW, as a result of sunshine exposure and a lower ratio of FW:YT. Also, the content of home composter E was mixed on a monthly basis.

Figure 6.6 illustrates the variations of TN, TP and TK among layers for all five HC. Except for home composter A, all HC exhibited the same TN level and evolution between layers, with their top and bottom layer offering a similar TN and the middle

layer offering a higher value ($p<0.05$). Home composter A had a higher TN value within its top compost layer because during the last month, the fed OW contained only FW. Home composter E presented a very even TN among its 3 layers because of monthly mixing. Accordingly, HC management seems to have little impact on the final compost TN value.

In terms of TP, the content of all five HC, except for that of A, demonstrated the same value of 1.0% on a dry matter basis. Home composter A demonstrated a TP value of 2.5 % likely because of the higher fraction of ashes and FW fed throughout the summer. In general and for all HC, their 3 layers demonstrated similar TK values averaging 3 % on a dm basis.

All five HC offered bottom compost with a dry matter generally exceeding 30%, nutrient values of 2, 1 and 3 % on a dry matter basis respectively for TN, TP and TK, and an organic matter content of 50%. Accordingly, the compost offers good soil amendment properties (Tognetti et al., 2011; BNQ, 2004; Brinton, 2000; Diaz et al., 1993).

6.3.5 Compost trace metals and pathogens

Table 6.4 presents the trace metals contained in the mixed compost (mixed top, middle and bottom layers) of all five HC after 20 weeks of operation and compares these levels to Canadian and European regulations. In general, the compost from all HC respected even the most stringent regulations, namely that of Germany. Nevertheless, home composter A produced compost with Cr, Cu, Zn and Cd levels approaching these stringent limits, because it was fed ashes which generally concentrate trace metals.

The levels of pathogens found in the mixed compost of home composters A, B, C, D and E are presented in Table 6.5. Despite variations in *Escherichia coli* count, all composts were clean enough to be used on gardens for human consumption without restrictions (MDDEP, 2008). Nevertheless, the level of *Escherichia coli* did not reflect the temperature regime developed within the HC. Whereas home composter D was the only one reaching thermophilic temperatures, *E. coli* levels in the compost of home composter C were just as low. This lack of impact of the thermophilic temperatures developed in home composter D resulted from the fact that the top layer, never reaching thermophilic temperatures, contaminates the bottom layers. All fecal *Streptococci* counts were less than 1000 Colony Forming Units (CFU) $(g\ dm)^{-1}$. Garden waste, grass clippings and tree leaves can introduce *Streptococcus* faecalis into the compost from dog, bird and rodent droppings. *Salmonella* was not detected in any of the composts because of their absence in the original materials.

6.4 Conclusion and recommendations

The home composting of organic waste (OW) is considered to be an interesting recycling alternative with minimal environmental and economic impact. The objectives of the present study were to monitor the composting process of five backyard HC operated by homeowners of the West Island of Montreal, Canada, to compare field and laboratory observations. The temperature regime of the five HC was monitored over 20 weeks, while homeowners recorded their weekly feeding of OW. At the end of the study, the composts were separated into top, middle and bottom layers, and sampled to quantify their solids, pH, nutrients, trace metals and pathogen levels.

In terms of temperature regime, some practices were identified as recommendable to reach thermophilic temperatures on a regular basis:

1) The HC has bottom/top perforations to improve its convective air circulation;
2) The HC receives a large input of OW, generally over 10 kg and this waste is composed of equal volumes of FW and YT to offer an appropriate dry matter content in the range of 40 %;
3) The HC content is mixed at least monthly;
4) The HC is placed in a semi-shaded area to benefit from sunshine without being subjected to extreme climatic conditions.

As for pathogen levels, no impact of the temperature regime was observed, likely because clean organic waste was fed to the HC. In terms of trace metals, homeowners must be careful not to apply herbicides or large amounts of fertilizers on their lawns if grass clippings are to be added to HC. Ashes should be sparingly added to the fed OW, as they may produce high levels of trace elements. When respecting these management practices, the compost produced by HC has a high agronomic value as soil amendment.

6.5 Acknowledgements

This project was funded by the Natural Science and Engineering Research Council of Canada and the Cemagref, Rennes, France. The cooperation from municipalities of Montréal's West Island especially Mr. Ronald Patenaude of Dorval Municipality are highly appreciated. Authors also acknowledge the homeowners who participated in this study.

6.6 References

Adhikari BK, Trémier A, Barrington S and Martinez J (2011a) Home composting of organic waste: Effect of home composter design. This research article is submitted for publication in the International Journal of Environmental Technology and Management (IJETM).

Adhikari BK, Trémier A, Barrington S and Martinez J (2011b) Home composting of organic waste: Effect of management practices. This research article is submitted for publication in the International Journal of Environmental Technology and Management (IJETM).

Adhikari BK, Trémier A, Martinez J and Barrington S (2010) Home and community composting for on-site treatment of urban organic waste: perspective for Europe and Canada. Waste Management & Research 28: 1039-1053.

Adhikari BK, Barrington S, Martinez J and King S (2008) Characterization of food waste and bulking agents for composting. Waste Management 28: 795–804.

AFNOR (2006) NF U44-051 Amendements organiques, Dénominations, spécifications et marquage, Association Française de Normalisation, Paris, France.

Andersen JK, Boldrin A, Christensen TH and Scheutz C (2010) Greenhouse gas emissions from home composting of organic household waste. Waste Management 30: 2475–2482.

APHA (2005) Standard procedures for the Testing of Water and Wastewater, American Public Health Association, Washington, DC, USA.

Barrington S, Choiniere D, Trigui M and Knight W (2002) Effect of carbon source on compost nitrogen and carbon losses. Bioresource Technology 83: 189–194.

BNQ (2004) Organic soil conditioners – composts, Draft Standard P0413-200-5, Bureau de Normalisation du Quebec (BNQ), Quebec, Canada.

Boldrin A and Christensen TH (2010) Seasonal generation and composition of garden waste in Aarhus (Denmark). Waste Management 30: 551–557.

Brändli RC, Bucheli TD, Kupper T, Mayer J, Stadelmann FX and Tarradellas J (2007) Fate of PCBs and PAHs and their source characteristic ratio during composting and digestion of source-separated organic waste in full-scale plants. Environmental Pollution 148: 520-528.

Brinton WF (2000) Compost quality standards & guidelines: an international view, Final reports presented for New York State association of Recyclers. Woods End Laboratories, Inc. Mt Vernon, ME, USA.

CCEM (1989) National Contamination Site Remediation Program, Ottawa, Canada: Environment Canada.

CCME (2005) Guidelines for compost quality, PN 1340, ISBN 1-896997-60-0, Canadian Council of Ministers of the Environment, Winnipeg, Manitoba, Canada.

Chang JI, Tsai JJ and Wu KH (2005) Thermophilic composting of food waste. Bioresource Technology 97: 116–122.

Colón J, Martínez-Blanco J, Gabarrell X, Artola A, Sánchez A, Rieradevall J and Font X (2010) Environmental assessment of home composting. Resources, Conservation and Recycling 54: 893–904.

Diaz LF, Savage GM, Eggerth LL and Golueke CG (1993) Composting and Recycling, Municipal Solid Waste, Lewis Publishers, Boca Raton, USA, pp.175-217.

Domingo JL and Nadal M (2009) Domestic waste composting facilities: A review of

human health risks. Environment International 35: 382–389.

Epstein E (1997) The science of composting, CRC Press LLC, 2000 N.W. Corporate Blvd; Boca Raton, Florida, USA, pp. 19-50.

EU (1999) Landfill directive council directive 1999/31/EC of 26 April 1999 on landfill of waste, official journal of the European Communities, I. 182/1, Official Publications of the European Communities, Luxembourge.

Gong C-M (2007) Microbial safety control of compost material with cow dung by heat treatment. Journal of Environmental Science 19: 1014-1019.

Haug RT (1993) The practical hand book of compost engineering, Lewis Publishers, A CRC Press Company, 2000 N. W. Corporate Blvd; Boca Raton, Florida, USA, pp. 205-258.

Karnchanawong S and Suriyanon N (2011) Household organic waste composting using bins with different types of passive aeration. Resources, Conservation and Recycling 55: 548–553.

López M, Soliva M , Martínez-Farré FX, Bonmatí A and Huerta-Pujol O (2010) An assessment of the characteristics of yard trimmings and re-circulated yard trimmings used in biowaste composting. Bioresource Technology 101: 1399–1405.

Lundie S and Peters GM (2005) Life cycle assessment of food waste management options. Journal of Cleaner Production 13: 275–286.

Mato S, Orto D and Garcia M (1994) Composting of <100 mm fraction of municipal solid waste. Waste Management & Research 12: 315-325.

MDDEP (2008) Guidelines for the beneficial use of fertilizing residuals, Reference criteria and regulatory standard. Ministere du Developpement Durable, de l'Environnement et des Parcs, Quebec.

MFHPB-20 (2009) Isolation and identification of Salmonella from food and environmental samples. Health products and food branch, Ottawa, Government of Canada.

OECD (2006-2007) Environmental Data: Compendium 2006/2007, Waste. Environmental Performance and Information Division OECD, Environmental Directorate, Working Group on Environmental Information and Outlooks, Paris, France.

SAS Institute Inc. (2008) SAS version 9.2, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC, USA.

Schwalb M, Rosewear C, Chin R and Barrington S (2011) Food waste treatment in a community centre. Journal of Waste Management 31: 1570-1575.

Seo JY, Heo JS, Kim TH, Joo WH and Crohn DM (2004) Effect of vermiculite addition on compost produced from Korean food wastes. Waste Management 24: 981–987.

Slater RA and Frederickson J (2001) Composting municipal waste in the UK: some lessons from Europe. Resources, Conservation and Recycling 32: 359–374.

Smith SR and Jasim S (2009) Small-scale home composting of biodegradable household waste: overview of key results from a 3-year research programme in West London. Waste Management & Research 27: 941–950.

Stabnikova O, Ding HB, Tay JH and Wang JH (2005) Biotechnology for aerobic conversion of food waste into organic fertilizer. Waste Management & Research 23: 39 – 47.

Tognetti C, Mazzarino MJ and Laos F (2011) Comprehensive quality assessment of municipal organic waste composts produced by different preparation methods. Waste Management 31:1146-1152.

Table 6.1 Food waste characteristics reported from various world sources

Country	Waste type	Waste producer	pH	DM (%)	TN (%dm)	C (%dm)	C/N	References
France (Rennes)	Food waste	Restaurant	4.7	14.5	2.6	45.0	17.0	Adhikari et al. (2011b)
France (Rennes)	Yard trimmings	Office complex	6.3	56.8	2.0	34.9	17.4	Adhikari et al. (2011b)
Canada (Montreal)	Food waste	Community kitchen and restaurant	4.1	12.2	2.0	47.4	24.0	Adhikari et al. (2008)
Canada (Montreal)	Food waste	Community kitchen, household and restaurant	4.4-5.0	11-17	1.6-2.4	44-48	19.0-30.0	Schwalb et al. (2011)
South Korea	Food waste	household	5.2	20.9	3.7	47.2	12.7	Seo et al. (2004)
Taiwan	Food waste	Kitchen	-	27.5	3.5	51.0	14.6	Chang et al. (2005)
Canada (West Island of Montreal)	Food waste and yard trimmings	residents	4.5-7.0	12-41	2-4	45-50	13-22	This study

DM-dry matter, TN-total nitrogen, C-carbon, C/N-carbon to nitrogen ratio

Table 6.2 Description of experimental home composters

Description	Composter				
	A	B	C	D	E
Composter type	Slatted	Top/bottom perforations	Slatted	Top/bottom perforations	Slatted
Composter installation	Tree shaded	Tree shaded	Tree shaded	Open sky	Semi shaded
Average OW input (kg (week)$^{-1}$)	2.4	8.1	8.0	4.0	1.6
Total capacity (L)	350	300	350	300	350
Mixing	Not mixed	Not mixed	Not mixed	Not mixed	Occasionally mixed

Note: The composter type is illustrated in Figure 6.1.

Table 6.3 Components of the organic waste added in the composters (% total wet mass)

Composter/ Waste components	Month						Input*		
	June	July	August	September	October	Total	DM (%)	COD (g $(kgdm)^{-1}$)	C/N
Composter-A									
Food waste	13.86	8.18	18.42	11.04	20.54	**72.04**			
Grass clippings	20.72	0.00	0.00	0.00	0.00	**20.72**			
Ash	0.00	1.71	0.00	0.00	0.00	**1.71**			
Sea food	5.52	0.00	0.00	0.00	0.00	**5.52**			
Total	**40.11**	**9.89**	**18.42**	**11.04**	**20.54**	**100.00**	12.50	1037	13.0
Composter-B									
Food waste	19.44	27.78	16.98	9.88	12.04	**86.11**			
Tree leaves	0.31	5.86	5.56	0.00	2.16	**13.89**			
Total	**19.75**	**33.64**	**22.53**	**9.88**	**14.20**	**100.00**	12.50	1143	21.6
Composter-C									
Food waste	11.06	20.85	23.06	14.22	8.21	**77.41**			
Grass clippings	0.00	0.00	2.21	0.00	0.95	**3.16**			
Tree leaves	2.05	1.58	0.95	0.00	0.00	**4.58**			
Garden waste (flowers, soil)	9.79	3.16	1.58	0.00	0.32	**14.85**			
Total	**22.91**	**25.59**	**27.80**	**14.22**	**9.48**	**100.00**	14.50	1155	19.8
Composter-D									
Food waste	8.87	15.47	1.07	14.19	23.18	**62.77**			
Grass clippings	2.36	6.85	10.00	0.00	0.00	**19.22**			
Rhubarb leaves	0.00	12.58	0.00	0.00	5.00	**17.58**			
Total	**11.23**	**34.90**	**11.07**	**14.19**	**28.18**	**100.00**	41.10	1056	14.5
Composter-E									
Food waste	15.72	14.15	26.73	6.29	12.58	**75.47**			
Grass clippings	9.75	0.00	0.00	4.72	5.35	**19.81**			
Tree leaves	0.00	0.00	0.00	0.00	4.72	**4.72**			
Total	**25.47**	**14.15**	**26.73**	**11.01**	**22.64**	**100.00**	15.90	987	22.0

*DM, COD, and C/N obtained from the top layer (Figure7.1) of compost mass at the end of the study, which provides an estimate of the initial compost values loaded into the home composters. DM- dry mass, COD-chemical oxygen demand, C/N-carbon to nitrogen ratio.

Table 6.4 Concentration of trace metals in the compost obtained from five home composters and regulatory limits in Canada and EU countries

	Element (mg (kg dm)$^{-1}$)																	
Home composters	**Al**	**V**	**Cr**	**Mn**	**Co**	**Ni**	**Cu**	**Zn**	**Rb**	**Sr**	**Y**	**Cd**	**Ba**	**Ce**	**Ti**	**Pb**	**Fe**	**As**
A	6143	2.92	93	904	1.95	14.10	304	260	34	296	1.49	1.37	343	5.08	0.06	9.13	2415	38.08
std (n=3)	969	0.96	71.74	131	0.39	12.16	37.63	33	1.26	39	0.36	0.12	54	0.71	0.01	0.91	160	7.56
B	3151	5.85	14	143	1.67	7.33	27	98	27	165	2.34	0.39	74	5.20	0.12	12.84	3444	1.43
std (n=3)	420	0.34	2.92	21	0.70	1.64	3.64	11	0.29	10	0.77	0.03	13	1.39	0.09	1.85	522	0.64
C	8337	18.14	150	299	4.96	46.50	28	104	20	122	7.63	0.62	77	17.72	0.18	24.13	12745	2.67
std (n=3)	466	2.73	114.77	54	0.27	26.87	0.94	19	0.77	33	1.64	0.16	3	3.74	0.10	7.90	1805	0.24
D	5592	14.59	20	193	2.93	10.35	25	106	26	115	4.51	0.45	76	14.27	0.14	13.19	6910	2.26
std (n=3)	1019	2.20	2.14	19	0.44	0.82	1.49	7	2.09	11	0.37	0.10	6	1.75	0.14	0.94	1110	0.13
E	2859	6.10	12	198	1.22	7.34	29	68	15	186	1.76	0.41	60	5.80	0.06	4.59	3248	1.01
std (n=3)	192	0.77	2.29	24	0.10	1.24	4.78	7	2.00	41	0.11	0.12	4	1.01	0.01	0.43	188	0.08
Regulatory limits																		
[1]Canada																		
Category-A	-	-	210	-	34	62	400	700	-	-	-	3	-	-	-	150	-	13
Category-B	-	-	1060	-	150	180	757	1850	-	-	-	20	-	-	-	500	-	75
[2]Quebec, Canada																		
Category-C1	-	-	210	-	34	62	400	700	-	-	-	3	-	-	-	150	-	13
Category-C2	-	-	1060	-	150	180	1000	1850	-	-	-	10	-	-	-	300	-	41
[3]Italy	-	-	100	-	-	50	300	500	-	-	-	1.5	-	-	-	140	-	10
[4]France	-	-	120	-	-	60	300	600	-	-	-	3	-	-	-	180	-	18
[3]Germany	-	-	100	-	-	50	100	400	-	-	-	1.5	-	-	-	150	-	-

[1](CCME, 2005), [2](MDDEP, 2008), [3](Brinton, 2000), [4](AFNOR, 2006), dm-dry mass, std-standard deviation, n-number of samples, Al-Aluminum, V-Vanadium, Cr-Chromium, Mn-Manganese, Co-Cobalt, Ni-Nickel, Cu-Copper, Zn-Zinc, Rb-Rubidium, Sr-Strontium, Y-Yttrium, Cd-Cadmium, Ba-Barium, Ce-Cerium, Ti-Titanium, Pb-Lead, Fe-Iron, As-Arsenic.

Table 6.5 Levels of organisms in the compost of the five home composters

Organisms	Composter					Legislation	
	A	B	C	D	E	[1]Quebec, Canada	[2]France
Escherichia coli (CFU $(gdm)^{-1}$)	140	24	4.5	4.5	17	$<2x10^6$ MPN $(gdm)^{-1}$ for P2 category compost	-
fecal *Streptococci* (CFU $(gdm)^{-1}$)	<1000	<1000	<1000	<1000	<1000	-	-
Salmonella $(25g)^{-1}$	nd	nd	nd	nd	nd	nd for P1 category compost	ab

[1](MDDEP, 2008), [2](AFNOR, 2006), nd-not detected, ab-absent.

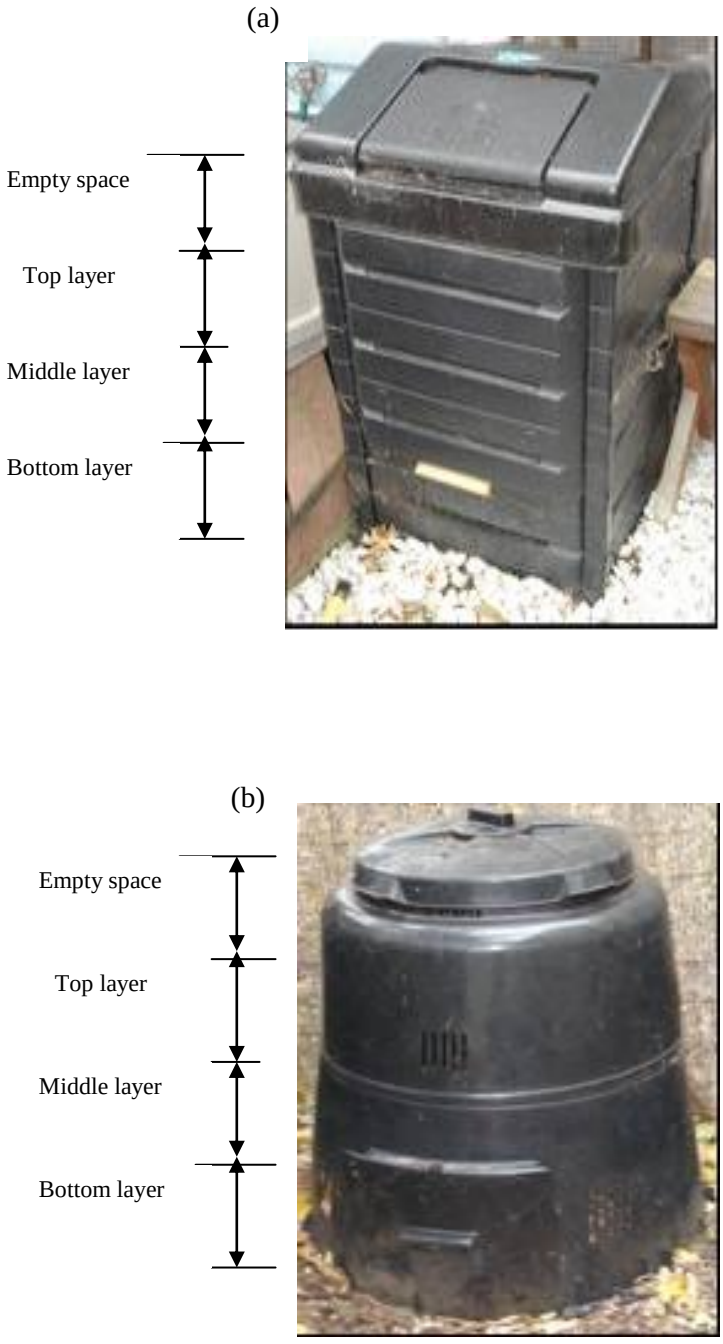


Figure 6.1 Experimental home composters showing the three layer of compost sampled at the end of the 20 week monitoring period: (a) slatted plastic bin, and (b) perforated plastic bin.

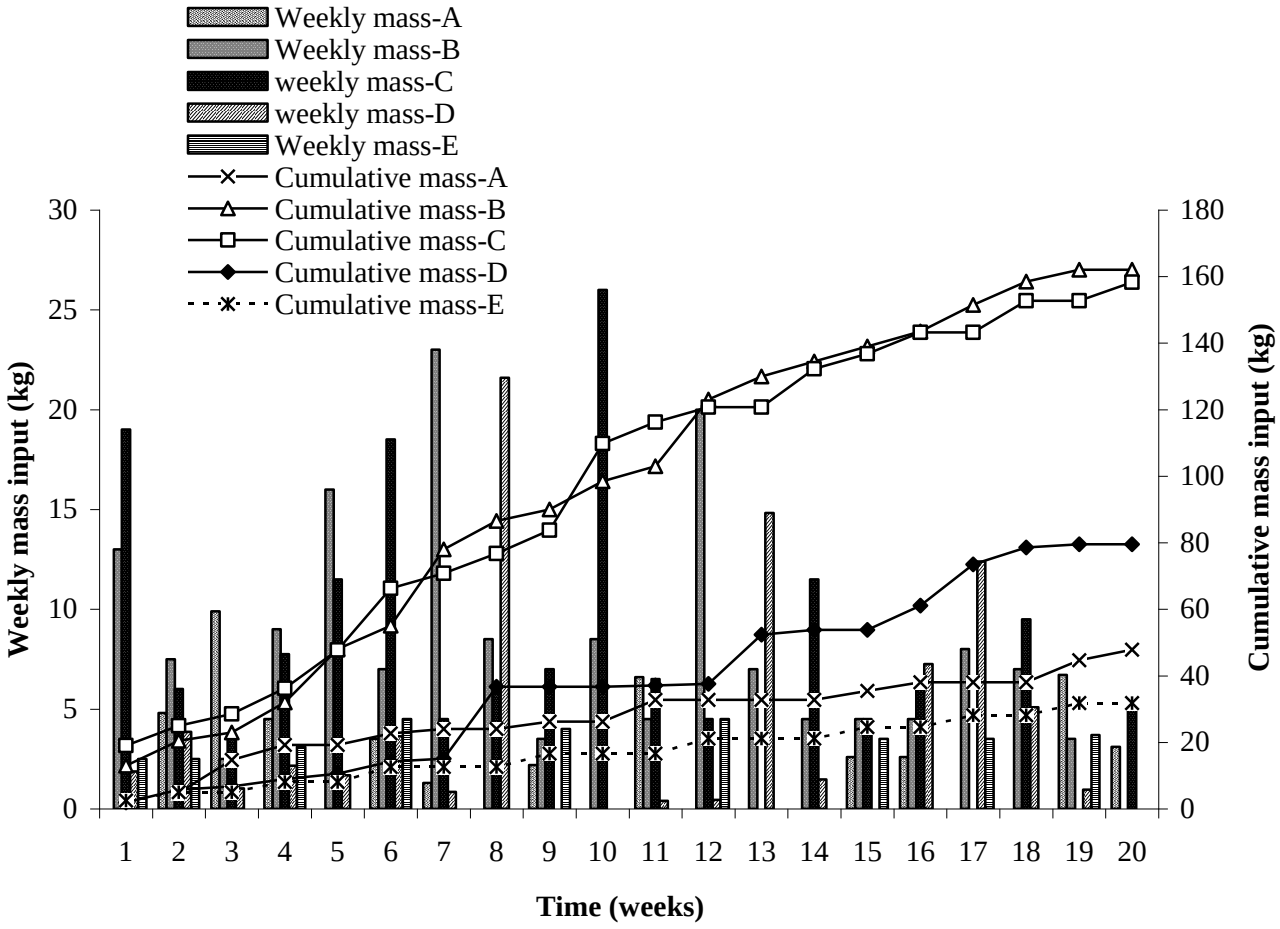


Figure 6.2 Weekly and cumulative organic waste added to the home composters by the individual homeowners over 20 weeks of composting.

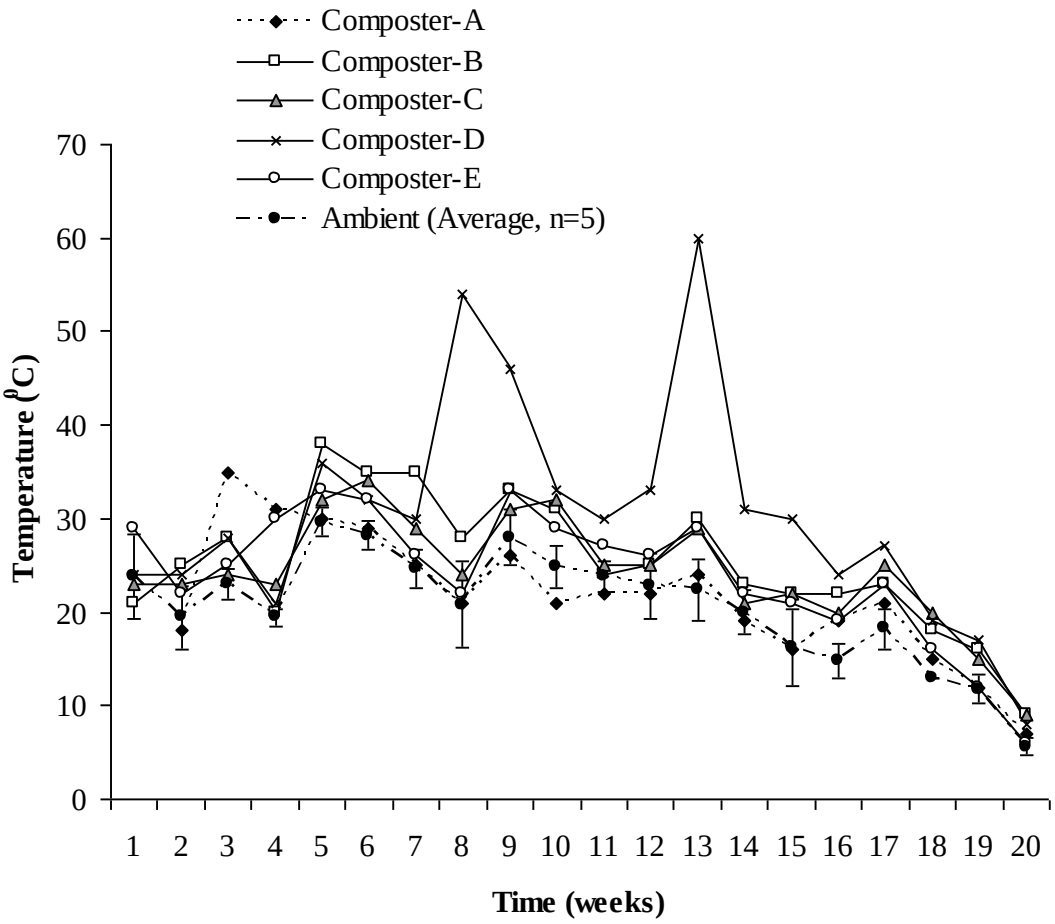


Figure 6.3 For the 20 weeks experimental period, compost temperature profile for the five home composters (compost mass centre) as compared to the average (n=5) weekly ambient temperature. The vertical bars are the standard deviation for the weekly ambient temperature.

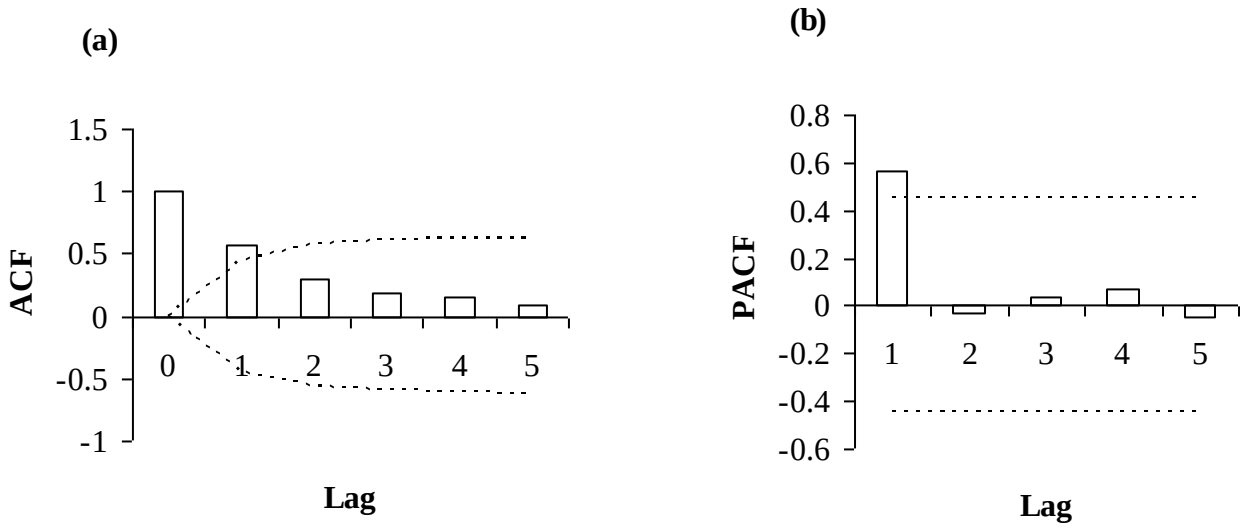


Figure 6.4 For home composter A, autocorrelation function (ACF) and partial autocorrelation function (PACF) illustrated by the bar diagram and limits of standard error (dotted lines) for the temperature data versus the weekly organic waste input: (a) ACF, and (b) PACF. Similar results were obtained for home composters B, C, D and E. The lag represents the effect of temperature in weeks, where for example lag 1 means the effect of organic waste loading on temperature after 1 week.

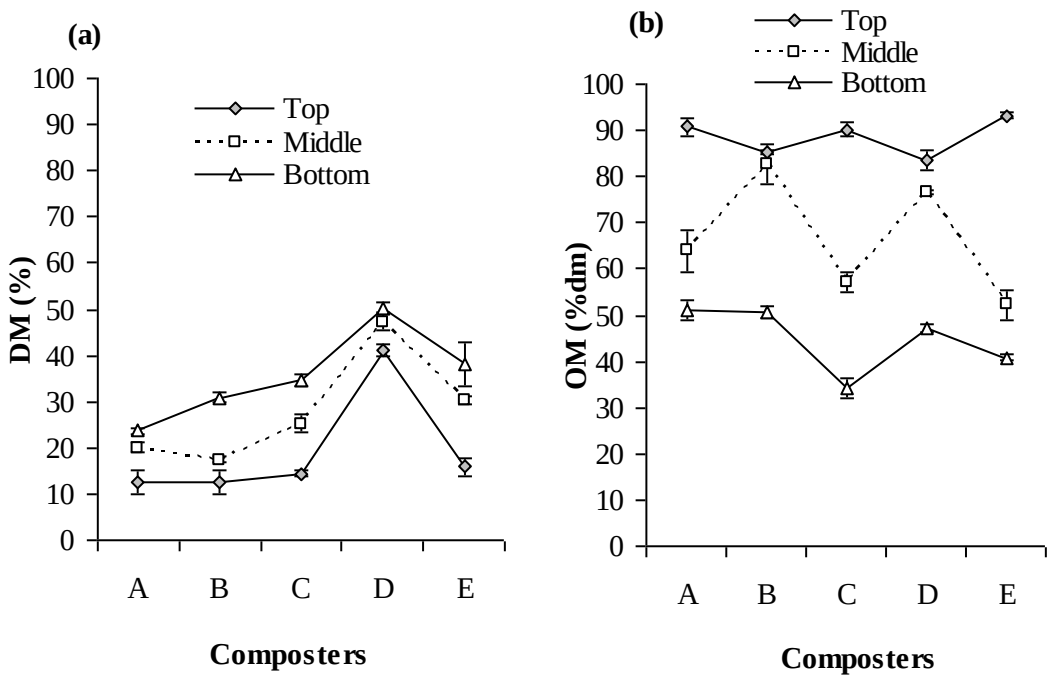


Figure 6.5 Top, middle and bottom layer characteristics for the five home composters after 20 weeks of continuous feeding: (a) dry matter-DM, and (b) organic matter-OM. Vertical bars- standard deviations (n=3).

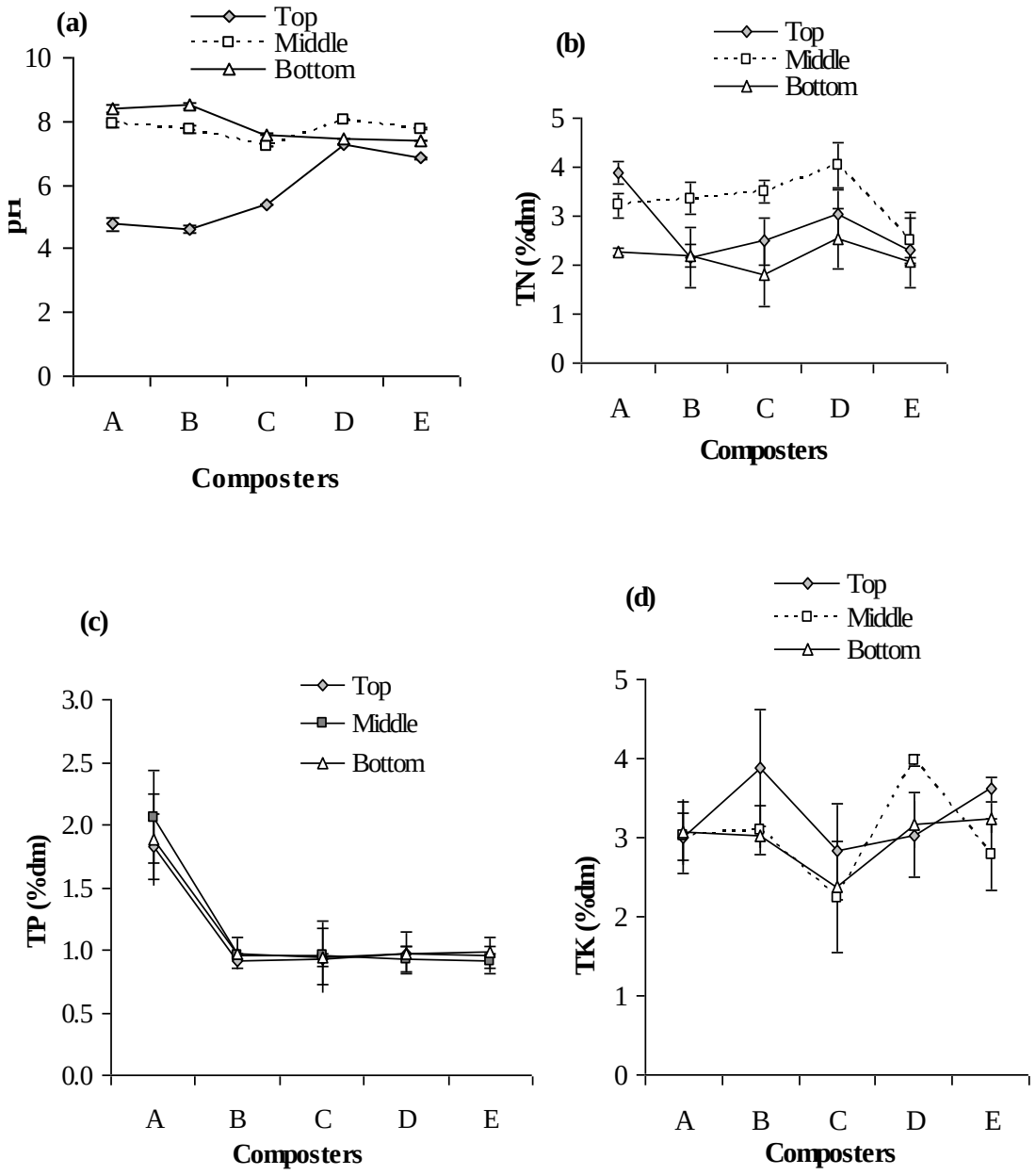


Figure 6.6 Top, middle and bottom layer characteristics for the five home composters after 20 weeks of continuous feeding: (a) pH, (b) total nitrogen-TN, (c) total phosphorus-TP, and (c) total potassium-TK. Vertical bars- standard deviations (n=3).

Connecting statement to chapter 7

Along with the quality of composted product obtained from home composting systems (HC) of organic waste (OW), the greenhouse gas emissions (GGE) during the composting process is a concern for implementation of HC. The effect of HC on GGE needs to be examined. Chapter 7 examines the effect of HC on GGE during composting process of OW.

The chapter 7 is drawn from a manuscript prepared for publication by the author of the thesis and co-authored by supervisors, Dr. Anne Trémier, Cemagef, Rennes, France, Prof. Dr. Suzelle Barrington, Department of Bioresource Engineering, McGill University, Montreal, Canada and Dr. José Martinez, regional director, Cemagef, Rennes, France. The format has been changed to be consistent within this thesis.

Chapter 7

Effect of type of home composting system on greenhouse gas emissions

Abstract

Depending on handling and treatment, organic wastes (OW) generate various amounts of CO_2, CH_4 and N_2O, greenhouse gases contributing to global warming trends. Facilitating the recycling of OW, home composting systems (HC) were monitored for 150 days to compare their greenhouse gas emissions (GGE). Batch fed with restaurant food waste (FW) and yard trimmings (YT), four HC were tested: the wood and plastic bins (WB and PB), the mixed and unmixed ground pile (GPM and GP). Weekly starting on day 15, CO_2, N_2O and CH_4 emissions were measured during 2h sessions using a closed trap placed at the compost surface. Compost characteristics were monitored by sampling weekly and weighing on day 0 and 150. Most GGE consisted of CO_2 and N_2O generated especially between days 0 to 30 and during the maturation phase, respectively. Although not detected except for GP on day 15, future research should focus on CH_4 generation between days 0 to 15. The WB and PB composts produced GGE of 208 and 226 kg CO_2-eq (tonne wet waste treated)$^{-1}$ while that of GP and GPM produced higher values of 255 and 272 kg CO_2-eq (tonne wet waste treated)$^{-1}$, values within the range of that reported for centralized composting facilities averaging 200 kg CO_2-eq (tonne wet waste treated)$^{-1}$. Eliminating GGE for centralized composting facilities resulting from energy required for collection, transportation and treatment at 50 kg CO_2-eq (tonne wet waste treated)$^{-1}$, HC can recycle OW with an important advantage if managed properly.

Keywords: Greenhouse gas, home composting systems, organic waste.

7.1 Introduction

Greenhouse gas emissions (GGE), namely carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), contribute to global warming trends and their adverse climatic effects (Recycled organic unit, 2011; IPCC, 2006; Friends of the Earth, 2000). Landfilled organic waste (OW) accounts for 13% of the total anthropogenic annual global CH_4 emissions, equivalent to 734 kg CO_2-eq (tonne wet waste treated)$^{-1}$ (Matthews and Themelis, 2007; US EPA, 2006)), whereas composting lowers GGE to values of 0.03 – 8.0 kg CH_4 (tonne wet waste treated)$^{-1}$ and 0.06 – 0.6 kg N_2O (tonne wet waste treated)$^{-1}$, for a total averaging 200 kg CO_2-eq (tonne wet waste treated)$^{-1}$ (Friedrich and Trois, 2011; Hermann et al., 2011; Rogger et al., 2011; Martínez-Blanco et al., 2010; Lou and Nair, 2009; IPCC, 2006). Accordingly, Europe and North America initiated policies for the diversion of the OW fraction from the municipal solid waste stream (Pires et al., 2011; Fenerty-McKibbon and Khare, 2005; Thompson and Tanapat, 2005; Landfill Directive, 1999) and its recycling through either composting or anaerobic digestion.

Composting OW is achieved either at centralized composting facilities or at decentralized systems such as community centres and home composters (Bernstad and Jansen, 2011; Schwalb et al., 2011). Home composting systems (HC) eliminate collection, transportation and processing, thus reducing the investment and energy cost associated with centralized facilities (Boldrin et al., 2011; Andersen et al., 2010). However, CO_2, CH_4 and N_2O emissions from HC can be affected by their configuration and management (Bogner et al., 2008; EPIC, 2002) with a limited number of studies examining their GGE. Using a weekly fed plastic HC, Colón et al.

(2010) report CH_4 and N_2O emissions below their detection threshold. For a bi-weekly fed HC, Andersen et al. (2010) measured CH_4 and N_2O emissions in the range of 0.4 – 4.2 and 0.30 – 0.55 kg (ton wet waste treated)$^{-1}$ respectively, totalling 100 to 239 kg CO_2-eq (ton wet waste treated)$^{-1}$. With a weekly fed and mixed HC, Martínez-Blanco et al. (2010) measured GGE of 0.158 kg CH_4 (tonne wet waste treated)$^{-1}$ and 0.676 kg N_2O (tonne wet waste treated)$^{-1}$. These reported GGE are within the range of those produced by centralized composting facilities (IPCC, 2006), but illustrate variability in GGE from HC, which depend on their configuration and management.

Accordingly, the objective of this study was to compare GGE for four common HC used in Canada and France, namely the wood bin (WB), the plastic bin (PB), the mixed ground pile (GPM) and unmixed ground pile (GP). All four HC were filled at once (batch) with equal wet volumes of food waste (FW) and yard trimmings (YT), to simulate the worst loading scenario and maximise GGE due to self load effect of compost mixture. Emissions of CO_2, N_2O and CH_4 were measured regularly from day 15 to 150. Losses of total carbon (TC) and nitrogen (TN) were compared to measure GGE.

7.2 Material and methods

7.2.1 Composting systems and input organic waste

Greenhouse gas emissions (GGE) from batch fed HC were monitored using four commonly used systems: the slatted wood bin (WB) measuring 0.78 m x 0.65 m by 0.75 m in height; the slatted plastic bin (PB) measuring 0.70 m x 0.70 m by 0.80 m in height, and; the mixed and unmixed ground pile (GPM and GP, respectively), both measuring 0.65 m high and 0.75 m in base diameter (Figures 7.1a, b, c).

The organic waste (OW) composted by the four HC consisted of equal wet volumes of food waste (FW) and yard trimmings (YT). The FW was source separated and supplied by two restaurants in Rennes, France, within 3 days of production. It consisted of vegetable and fruit wastes. The YT were obtained from the green space surrounding the Cemagref research station of Rennes, France, and consisted of a 90 % grass clippings and 10 % tree leaves on wet weight basis. While loading the HC, the initial compost mixture was sampled in triplicate for physico-chemical characterization.

7.2.2 Experimental procedure

The four experimental HC were randomly set-up under an outside tent at the Cemagref Research Centre, Rennes (France), to avoid rainfall and direct sunshine. Equal wet volumes of FW and YT were mixed by hand in a large tub before being loaded without compaction into the HC. All four HC were filled at once on the same day (batch fed) to 80 % of their capacity. While filling the HC, temperature sensors (model DS1921G-F5, Thermochron iButton, Dallas Semiconductor, USA) were installed at their mass center.

While being monitored for 150 days, the HC composts were naturally aerated and manually mixed weekly except for that of GP. During the mixing operation, a compost sample was collected for analysis every 15 days during the first 60 days, and then every 30 days for the rest of the experimental period. The GP treatment was sampled only on days 0 and 150. The temperature sensors were retrieved after 70 days of composting, during one of the mixing and sampling operation.

During the composting process and before the mixing operation, all HC were monitored for GGE, namely carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), starting on day 15. For all gas monitoring sessions, a closed metallic chamber measuring 0.40 m in length x 0.15 m in width by 0.17 m in height was placed over the compost mass (Figure 7.1d). The chamber had a top rubber port to collect air samples using disposable plastic syringes. Each monitoring session was repeated weekly for the first 30 days, every 10 days for days 30 to 60, every 20 days for days 60 to 120, and then on day 150. During each 120 min monitoring session, duplicate air samples were drawn after 0, 10, 20, 40, 60 and 120 min. All air samples were analyzed for CO_2, CH_4, N_2O and O_2 by gas chromatography (GC - HP6890N, Agilent, Santa Clara, USA). The GC was equipped with an electron capture detector (ECD) and a flame ionization detector (FID), and used N_2 as a vector gas.

After 150 days, the compost mass in each HC was weighed and sampled in triplicate for physico-chemical characterization, to compute the loss in DM, total carbon (TC), total nitrogen (TN) and organic matter (OM).

7.2.3 Computation of losses and gaseous emissions

During the 150 days of experiment, the wet compost mass in individual HC could not be measured, although necessary along with concentration values, to compute over time the loss in DM, TC and TN. Based on the principle of fixed solid (non-volatile solid) mass conservation, an equation was developed to predict M_t, the residual mass of wet compost in each HC at time t, where this mass was equated to that of fixed solids, FS_t, plus that of the organic matter OM_t and water:

$M_t = FS_t + M_{(t)} \times OM_t \times DM_t \times 10^{-4} + M_{(t)} \times (1\text{-}DM_t/100)$ (1)

where, M_t is total wet mass at sampling time *t* in kg; FS_t is the fixed solid mass at time *t*, in kg; OM_t is the organic matter concentration in % DM_t, and; DM_t is the dry matter concentration at time *t*, in % of M_t. The values of OM_t and DM_t were measured periodically during the composting process. With the WB, PB, GPM and GP composts losing respectively, 14, 1, 8 and 0 % FS_i as leachate, *FS* was presumed to drop linearly during the entire experimental composting period of 150 days.

Accordingly, Equation (1) can be rearranged to solve for M_t:

$M_t = FS_t / \{1 - (OM_t \times DM_t \times 10^{-4}) - (1 - DM_t/100)\}$ (2)

The mass evolution in total carbon (TC) and nitrogen (TN) could thus be computed using the concentrations measured regularly and the corresponding M_t obtained from Equation (2).

For each GGE session, individual gas production rates were computed from the evolution of their concentration within the closed chamber, during 120 min, neglecting the initial diffusion effect. Emissions in CO_2, CH_4, and N_2O were computed after each GGE session as:

$$Q = \frac{A_r}{OM_i} \times S \times 10^{-6} \times V \times \rho \quad (3)$$

where *Q* is the gas production rate with the assumption of uniform emissions in kg hr^{-1} (kg $OM_i)^{-1}$, A_r is the ratio of the composter to sampler cross sectional area in $m^2\ m^{-2}$ (8.7, 8.3 and 12.5 $m^2\ m^{-2}$ for WB, PB and ground piles respectively), OM_i is the initial mass of organic matter in the composter in kg, S is the rate of gas production equal to the slope of the linear gas concentration regression in ppmv hr^{-1}, *V* is the sampler volume in m^3 and ρ is the gas density in kg m^{-3}. The density used for the gases,

namely CO_2, CH_4 and N_2O were 1.842, 0.668 and 1.826 kg m^{-3} respectively at the standard temperature of 20 °C and pressure of 101.3 kPa (Engineering Toolbox, 2010).

7.2.4 Analytical procedure

Before being analyzed, all triplicate compost samples were dried in an oven (SR 2000, Thermosi, France) at 80 °C until a constant weight was reached and then ground to less than 0.5 mm (ZM model 1000 grinder, Retsch, Germany).

The compost pH was determined by soaking 10 g of wet sample for 24 hours without shaking at 5ºC, in just enough distilled water to use a pH electrode (pH-Electode SenTix41, WTW, Weilhein, Germany). Organic matter (OM) was quantified as volatile solids (VS) and determined by burning at 550 °C for 3 hours (Thermolyne 30400, Furnace, F30420 C-33, Essex, UK), according to AFNOR (1985). Fixed solids concentrations were determined by the ash remaining following the OM procedure. Total carbon (TC) was determined by burning 10 mg samples at 900 °C (Thermo Scientific, FLASH 2000 Series, Organic Elemental Analyser, Courtaboeuf, France) according to AFNOR (2001). According to AFNOR (1995), total Kjeldahl nitrogen (TKN) was determined using an automatic distilling system (VAP 50c, Gehardt automatic distilator, Gehardt, Germany), after digesting 0.5 to 1.0 g of sample with H_2SO_4 (automated Kjeldatherm TZ block digester, Gerhardt, Germany). The TKN value was assumed equal to TN because of negligible amount of nitrite and nitrate in the experimental material.

To correct all analytical results, residual moisture was determined by drying ground compost samples at 105 ºC for 24 hours (SR 1000, Thermosi, France).

7.2.5 Statistical procedure

The experimental HC were filled with the same compost mixtures on the same day and mixed/sampled at the same time, to eliminate all effects except for that of HC type. Gaseous emissions from the different composting systems could therefore be compared with the repeated measures ANOVA procedure, using PROC GLM procedure at 95% confidence level (SAS institute Inc., 2008).

7.3 Results and discussion

7.3.1 Organic waste characteristics and compost temperature regime

Table 7.1 summarizes the initial characteristics of the organic waste mixture fed into all four HC. The initial DM ranged between 23.7 and 24.1 %, with the GP compost being slightly wetter at 22.3 % DM, but not statistically different ($p>0.05$). The TC ranged from 75.2 to 77.0 % and the TN from 22.9 and 23.3 %, for an initial C:N ratio of 17, for all four HC. The pH of all HC compost was at 6.1 initially. These initial properties are considered to be within the range required to support an active aerobic microbial activity for composting (Stabnikova et al., 2005; Haug, 1993; Zucconi and de Bertoldi, 1986).

Figure 7.2 illustrates the temperature of the composts observed during the first 70 days, with that of PB and GPM reaching thermophilic conditions after 2 days, as compared to 3 days for GP and 7 days for WB. Nevertheless and for all HC, the

compost temperature had dropped to close ambient by day 20, with that of WB taking 3 more days to stabilize. During composting, aerobic microbial activity is governed by oxygen supply, and is reflected as heat governing compost temperature (Richard, 2005; Epstein, 1997; Diaz et al., 1993). Since PB and GPM produced very similar high compost temperature regimes, they sustained the same level of high aeration. The GP and WB composts reached thermophilic temperatures 1 and 5 days later, respectively, indicating some initial limitation in generating convective aeration forces. Once thermophilic temperatures are reached, convective air flow rates can be sustained (Barrington et al., 2002). As compared to GPM offering free air flow, the high level of convective aeration obtained with PB can be attributed to its perforations concentrated at its bottom and top (Barrington et al., 2002; Karnechanawong and Suriyanon, 2011).

7.3.2 Emissions in CO_2, N_2O and CH_4

Examples of CO_2, N_2O and CH_4 evolution within the closed chamber, during the GGE measuring sessions, are illustrated in Figure 7.3. Measured compost gaseous concentrations were observed to change linearly, with little initial diffusion effect. Measureable CH_4 concentrations were obtained only for GP on day 15. Most of the gaseous emissions consisted of CO_2, generally reaching levels above 10 000 ppmv after 120 min, with N_2O only reaching levels of 200 to 300 ppmv. Furthermore, the drop in O_2 corresponded to the increase in CO_2, indicating a balance in gas measurement. The gas concentrations observed over time were used to compute GGE rates presented in Figure 7.4 using Equation (3).

The gaseous emission measurements produced different curves depending on the gas monitored. For compost CO_2 emission rates, the highest values observed on day 15 were in the range of 25 to 28 g hr^{-1} (ton wet waste treated)$^{-1}$. These values had dropped to 1.5 g hr^{-1} (ton wet waste treated)$^{-1}$ on day 150. On day 15, CO_2 emission rates were very similar among HC, with some differences appearing later on, such as a peak of 28 and 24 g hr^{-1} (ton wet waste treated)$^{-1}$ for the GPM and GP composts on day 30 and 60, respectively. Compost N_2O emissions rates were at low values of 7 to 105 mg hr^{-1} (ton wet waste treated)$^{-1}$ on day 15, with the PB compost showing the highest value followed by that of WB, GPM and then GP. The N_2O emissions rates increased on day 20, at the end of the thermophilic phase, to peak between 350 and 550 mg hr^{-1} (ton wet waste treated)$^{-1}$ on days 30 and 40 for all HC, except for GP peaking on day 80. Compost CH_4 emissions were below measurement threshold between days 15 to 150, except for GP on day 15.

Gaseous emissions from day 15 to 150 did not reflect the temperature regime developed by the HC composts. On day 15, all HC produced similar CO_2 emission rates, despite the WB compost still at thermophilic temperatures as compared to that of PB, GP and GPM at ambient temperatures. From day 15 to 150, all HC compost demonstrated a very similar CO_2 emission rate, except for a peak at 60 days for the GP composts. This will be explained later by the fact that most CO_2 emissions occurred from day 0 to 15, rather than 15 to 150. For N_2O emissions resulting from ammonia oxidation by ammonia oxidizing bacteria (AOB) under nitrifying conditions (Kim et al., 2010), the WB and GPM composts produced the highest peaks on days 30 and 40, respectively, followed by GP on day 80 and PB on day 30. Nevertheless,

PB produced the least overall N_2O, followed by GP and then GPM and WB at similar levels. The only factor corresponding to this order in N_2O emission is the final compost DM with PB and GP at 66 and 60 %, respectively as compared to GPM and WB at 85 and 81 %.

7.3.3 Evolution of compost characteristics as compared to gas generation

The evolution of all compost characteristics are presented in Table 7.1 and the computed losses in mass are illustrated in Figures 7.5 and 7.6. For all HC similarly, compost organic matter (OM) and total carbon (TC) suffered the highest loss of 45 to 50 % between days 0 and 15, followed from day 15 to 150 by an additional 15 to 20 % loss. As compared to OM and TC, compost total nitrogen (TN) losses was slightly different, dropping by 30 % from day 0 to 15, and then by an additional 25 % between days 15 to 150, as a result of denitrification. Loss in fixed solids mass through leachate amounted to 14 and 8 % for the WB and GPM composts, compared to 0 to 1 % for the PB and GP.

Measured between day 15 and 150, CO_2-C emissions corresponded to TC mass losses. For the WB compost for example, 27 % of the initial mass of 6.8 kg TC was lost between days 15 and 150, amounting to 1.84 kg TC or 25 kg TC (ton wet waste treated)$^{-1}$. For the same period, measured CO_2-C emissions amounted to 23 kg (ton wet waste treated)$^{-1}$. Accordingly and from day 15 to 150 days, all HC composts emitted CO_2-C respecting the following regression equations based on TC losses:

$GGE_{CO2\ from\ WB} = 0.72 \times TC + 1.78$; $R^2 = 0.95$ (4)

$GGE_{CO2\ from\ PB} = 1.55 \times TC + 2.05$; $R^2 = 0.99$ (5)

$GGE_{CO2\ from\ GPM} = 1.08 \times TC + 2.05$; $R^2 = 0.99$ (6)

GGE_{CO2} and TC are the loss of total carbon as measured CO_2 emissions and measured compost TC mass, in kg carbon (ton wet waste treated)$^{-1}$; subscripts WB, PB and GPM correspond to individual HC. Because the compost of the unmixed ground pile (GP) was not characterized regularly, no regression equation could be formulated. Equations (4), (5) and (6) were thus used to compute CO_2 emissions from day 0 to 15, as presented in Table 7.2.

In terms of nitrogen, N_2O emissions occurred at the end of the active composting stage, between days 20 to 50, with the GP compost showing a last peak on day 80. Nitrogen losses as N_2O represented only 4 to 7 % of the final compost TN losses, suggesting that leachate and NH_3-N volatilization were more important. Most of the emissions occurred between 15 to 48 °C at a pH above 8, conditions favouring nitrification and denitrification along with the production of N_2O and NO (Richard, 2005) while during the thermophilic phase, NH_3 volatilization governs nitrogen losses (Pagans et al., 2006; Barton and Atwater, 2002).

Emissions in N_2O were also correlated to TN losses from day 15 and 150. Accordingly, the following regression equations were used to estimate N_2O emissions from day 0 and 15:

$GGE_{N2O\ from\ WB} = 0.08 \times TN + 0.02$; $R^2 = 0.85$ (7)

$GGE_{N2O\ from\ PB} = 0.03 \times TN + 0.0008$; $R^2 = 0.94$ (8)

$GGE_{N2O\ from\ GPM} = 0.11 \times TN + 0.0003$; $R^2 = 0.96$ (9)

where GGE_{N2O} is the compost emission of N as N_2O and TN is the compost loss of nitrogen mass both in kg N (ton wet waste treated)$^{-1}$; the subscripts WB, PB and

GPM correspond to individual HC. Because the compost of the unmixed ground pile (GP) was not characterized regularly, no regression equation could be formulated.

Comparing estimated GGE as presented in Table 7.2, a significant difference was observed ($p<0.01$) for individual gases (CO_2 and N_2O) over time among all four HC. This comparison was performed on estimated CO_2 and N_2O emissions where most CO_2 occurred before initiating GGE monitoring, while most N_2O occurred during GGE monitoring (Table 7.2). Whereas CO_2 emissions were lowest for the driest final compost, namely those of WB and GPM at 81 and 85 % DM, respectively, as compared to the wetter final compost of GP and PB at 50 and 54 % DM, N_2O emissions were lowest for the wetter compost of PB and GP, followed by WB and GPM (Table 7.2). Total GGE values were therefore very similar among all four HC, with the WB and PB composts producing slightly lower values of 226 and 208 kg CO_2-eq (ton wet waste treated)$^{-1}$ as compared to GP and GPM at 255 and 272 kg CO_2-eq (ton wet waste treated)$^{-1}$. More accurate compost GGE monitoring is required in the future, with intensive measurements for the first 15 days especially for CO_2 and CH_4.

7.3.4 Greenhouse gas emissions over time

Whereas Table 7.2 summarizes GGE in terms of individual gas over time, Figure 7.7 illustrated GGE for all HC composts over time, based on kg CO_2-eq emissions (ton wet waste treated)$^{-1}$. The contribution of CH_4 and N_2O, equivalent to 21 and 310 times that of CO_2, is based on 100 years of global warming potential (GWP) (US EPA, 2005; Friends of the Earth 2000). In this calculation, CH_4 is considered to be

minimal, although not monitored from days 0 to 15. This is based on negligible CH_4 emissions from the WB compost on day 15, while still exposed to thermophilic conditions. Nevertheless, future projects should carefully monitor CH_4 emissions especially during the first 2 weeks of active composting.

Overall and from Table 7.2, the PB compost produced the lowest levels GGE at 208 kg CO_2-eq (ton wet waste treated)$^{-1}$, followed by WB at 226, GP at 255 and finally GPM at 272 kg CO_2-eq (ton wet waste treated)$^{-1}$. Emissions of N_2O were just as important as those of CO_2 when considering the overall earth warming potential. Over time, the most GGE occurred between days 20 and 60, except for the GP which lost most of its CO_2 from day 0 to 20 and then most of its N_2O from day 60 and 120. Accordingly, GGE observed for all four tested HC corresponded to that reported for centralized composting facilities of 200 kg CO_2-eq (tonne wet waste treated)$^{-1}$ and were lower than that from landfilled OW at 730 kg CO_2-eq (tonne wet waste treated)$^{-1}$. Since centralized composting facilities are said to spend on the average 25 CO_2-eq (tonne wet waste treated)$^{-1}$ in collecting and transporting OW (Chapter 3, Adhikari et al., 2010), and the same energy can be estimated spent for composting, HC can therefore offer a net GGE advantage of 50 CO_2-eq (tonne wet waste treated)$^{-1}$, if properly managed.

7.4 Conclusion and recommendations

To reduce earth warming trends, lower GGE technologies must be identified for the management of organic wastes (OW). Besides diverting OW from landfill operations, home composting systems (HC) can eliminate the use of fuels required for its

collection, transportation and treatment at centralized facilities. Nevertheless, HC must produce equal if not lower GGE as compared to other treatment alternatives. The objectives of this project were therefore to: measure GGE from OW treated using four common HC, namely the wood and plastic bins (WB and PB) and the mixed and unmixed ground piles (GPM and GP), and; to compare their emissions to centralized composting facilities. Accordingly, all HC were filled at once on the same day to simulate the worst case scenario, and their compost and GGE were monitored regularly during 150 days.

Emissions in CO_2 and N_2O were highly correlated to total carbon and total nitrogen losses. Nevertheless, HC producing drier composts lost the most CO_2 and the least N_2O, with thus all four HC releasing similar GGE of 208 to 272 kg CO_2-eq (tonne wet waste treated)$^{-1}$ with the lowest and highest value associated with PB/WB and GP and GPM, respectively. These GGE were quite similar to those reported for centralized composting facilities averaging 200 kg CO_2-eq (tonne wet waste treated)$^{-1}$. Eliminating GGE for centralized composting facilities, in terms of the energy required for collection, transportation and composting estimated at 50 kg CO_2-eq (tonne wet waste treated)$^{-1}$, HC can recycle OW with an advantage in terms of greenhouse gas emissions, if properly managed.

7.5 Acknowledgements

This study is part of a larger project entitled ECCOVAL, conducted in partnership with Rennes Métropole, CRPCC LAUREPS and CIELE, and funded by the regional council of Brittany, France. The authors also acknowledge the financial and logistics

support by the Cemagref of Rennes, France and the Natural Science and Engineering Research Council of Canada. Special thanks to Ms. Mylène Launay, Unit GERE, Cemagref, Rennes, France for her help during sampling and laboratory analysis of the greenhouse gases.

7.6 References

Adhikari BK, Tremier A, Martinez J and Barrington SF (2010) Home and community composting for onsite treatment of urban organic waste: perspective in the EU and Canada. Waste Management & Research 28(11): 1039 – 1053.

AFNOR (2001) NF EN 13137 - Caractérisation des déchets - Dosage du carbone organique total (COT) dans les déchets, boues et sédiments. Association Française de Normalisation, Paris, France.

AFNOR (1995) NF ISO 11261 - Qualité du sol - Dosage de l'azote total - Méthode de Kjeldahl Modifiée. Association Française de Normalisation, Paris, France.

AFNOR (1985) NF U 44-160 - Amendements organiques et supports de culture - Détermination de la matière organique totale - Méthode par calcination. Association Française de Normalisation, Paris, France.

Andersen JK, Boldrin A, Christensen TH and Scheutz C (2010) Greenhouse gas emissions from home composting of organic household waste. Waste Management 30: 2475–2482.

Barrington S, Choinière D, Trigui M and Knight W (2002) Compost convective airflow under Passive aeration. Journal of BioResource Technology 86: 259-266.

Barton PK and Atwater JW (2002) Nitrous oxide emissions and the anthropogenic nitrogen in wastewater and solid waste. Journal of Environmental Engineering 128(2): 137-150.

Beck-Friis B, Pell M, Sonesson U, Jönsson H and Kirchmann H (2000) Formation and emission of N2O and CH4 from compost heaps of organic household waste. Environmental Monitoring and Assessment 62(3): 317-331.

Bernstad A and Jansen J la C (2011) A life cycle approach to the management of

household food waste – A Swedish full-scale case study. Waste Management 31(8) :1879 – 96.

Bogner J (USA), Pipatti R (Finland), Hashimoto S (Japan), Diaz C (Cuba), Mareckova K (Slovakia), Diaz L (USA), Kjeldsen P (Denmark), Monni S (Finland), Faaij A (The Netherlands), Gao Q (China), Zhang T (China), Ahmed MA (Sudan), Sutamihardja RTM (Indonesia) and Gregory R (UK) (2008) Mitigation of global greenhouse gas emissions from waste: conclusions and strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. Working Group III (Mitigation). Waste Management & Research 26: 11–32.

Boldrin A, Andersen JK and Christensen TH (2011) Environmental assessment of garden waste management in the Municipality of Aarhus, Denmark. Waste Management 31: 1560–1569.

Boldrin A, Andersen JK, Møller J and Christensen TH (2009) Composting and compost utilization: accounting of greenhouse gases and global warming contributions. Waste Management & Research 27: 800–812.

Chen T-C and Lin C-F (2008) Greenhouse gases emissions from waste management practices using Life Cycle Inventory model. Journal of Hazardous Materials 155: 23–31.

Colón J, Martínez-Blanco J, Gabarrell X, Artola A, Sánchez A, Rieradevall J and Font X (2010) Environmental assessment of home composting. Resources, Conservation and Recycling 54: 893–904.

Diaz LF, Savage GM, Eggerth LL and Golueke CG (1993) Composting and

Recycling, Municipal Solid Waste. CRC Publishers, Boca Raton, Florida, USA.

Engineering Toolbox (2010) Gas densities – densities and molecular weights of some common gases-acetylene, air, methane, nitrogen, oxygen and others. www.engineeringtoolbox.com/gas-density-d_158.html Accessed 2 October 2010.

EPIC (2002) Opportunities for Reducing greenhouse Gas Emissions through Residential Waste Management. the Environment and Plastics Industry Council (EPIC), a council of the Canadian Plastics Industry Association. 5925 Airport Road, Suite 500, Mississauga, Ontario.

Epstein E (1997) The science of composting. CRS Press LLC, Boca Raton, Florida, USA. pp. 19 – 50, 77-103.

Fenerty-McKibbon B and Khare A (2005) Canada post delivers energy conservation. Energy and Buildings 37: 221–234.

Friedrich E and Trois C (2011) Quantification of greenhouse gas emissions from waste management processes for municipalities – A comparative review focusing on Africa. Waste Management 31: 1585–1596.

Friends of the Earth (2000) Greenhouse Gases and Waste Management Options. Friends of the Earth, 26-28 Underwood Street, LONDON, N1 7JQ.

Haug RT (1993) The practical hand book of compost engineering, Lewis Publishers, A CRC Press Company, 2000 N. W. Corporate Blvd; Boca Raton, Florida, USA, pp. 205-258.

Hermann BG, Debeer L, De Wilde B, Blok K and Patel MK (2011) To compost or

not to compost: Carbon and energy footprints of biodegradable materials' waste treatment. Polymer Degradation and Stability 96: 1159e1171.

IPCC (2006) IPCC guidelines for national greenhouse gas inventories, Volume 5 Waste. Intergovernmental Panel on Climate Change. www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html Accessed 18 May 2011.

Karnchanawong S and Suriyanon N (2011) Household organic waste composting using bins with different types of passive aeration. Resources, Conservation and Recycling 55: 548–553.

Kim S-W, Miyahara M, Fushinobu S, Wakagi T, Shoun H (2010) Nitrous oxide emission from nitrifying activated sludge dependent on denitrification by ammonia-oxidizing bacteria. Bioresource Technology 101: 3958–3963.

Landfill Dirctive (1999) Council directive 1999/31/EC of 26 April 1999 on the landfill of waste. Official Journal of the European Communities, I. 182/1, Office for official publications of the European Communities, 2, rue Mercier, L – 2985 Luxembourg.

Lou XF and Nair J (2009) The impact of landfilling and composting on greenhouse gas emissions – A review. Bioresource Technology 100: 3792–3798.

Lundie S and Peters GM (2005) Life cycle assessment of food waste management options. Journal of Cleaner Production 13: 275–286.

Martínez-Blanco J, Colón J, Gabarrell X, Font X, Sánchez A, Artola A and Rieradevall J (2010) The use of life cycle assessment for the comparison of biowaste composting at home and full scale. Waste Management 30: 983–994.

Matthews E and Themelis NJ (2007) Potential for Reducing Global Methane Emissions From Landfills, 2000-2030. Proceedings Sardinia, Eleventh International Waste Management and Landfill Symposium, S. Margherita di Pula, Cagliari, Italy, 1-5 Oct. 2007, by CISA, Environmental Sanitary Engineering Centre, Italy

Pagans E, Barrena R, Font X and Sánchez A (2006) Ammonia emissions from the composting of different organic wastes. Dependency on process temperature. Chemosphere 62: 1534–1542.

Pires A, Martinho G and Chang N-B (2011) Solid waste management in European countries: A review of systems analysis techniques. Journal of Environmental Management 92: 1033-1050.

Recycled Organics Unit (2001) Greenhouse Gas Emissions from Composting Facilities. Building B11B, he University of New South Wales, UNSW Sydney 2052.

Richard TL (2005) Compost. Iowa State University, Ames, IA, USA.

Richter R de and Caillol S (2011) Fighting global warming: the potential of photocatalysis against CO_2, CH_4, N_2O, CFCs, tropospheric O_3, BC and other major contributors to climate change. Journal of Photochemistry and Photobiology C:Photochemistry Reviews. doi:10.1016/j.jphotochemrev.2011.05.002.

Rogger C Beaurain F and Schmidt TS (2011) Composting projects under the Clean Development Mechanism: Sustainable contribution to mitigate climate change. Waste Management 31: 138–146.

Thompson S and Tanapat S (2005) Modeling Waste Management Options for

Greenhouse Gas Reduction. Journal of Environmental Informatics 6(1): 16-24.

SAS Institute Inc. (2008) SAS version 9.2, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC, USA.

Stabnikova O, Ding HB, Tay JH and Wang JY (2005) Biotechnology for aerobic conversion of food waste into organic fertilizer. Waste Management & Research 23: 39 – 47.

Stevens RJ, Laughlin RJ, Burns LC and Arah JRM (1997) Measuring the contributions of nitrification and denitrification to the flux of nitrous oxide from soil. Soil Biol. Biochem 29(2): 139-151.

Schwalb M, Rosewear C, Chin R and Barrington S (2011) Food waste treatment in a community centre. Journal of Waste Management 31: 1570-1575.

US EPA (2006) Global mitigation of non-CO_2 greenhouse gases. United States Environmental Protection Agency, Office of Atmospheric Programs (6207J), Washington, DC, USA. EPA 430-R-06-005.

US EPA (2005) Emission Facts: metrices for expressing greenhouse gas emission: carbon equivalents and carbon dioxide equivalents, EPA 420-F-05-002. United States Environmental Protection Agency (US EPA), Washington DC, USA: www.epa.gov/oms/climate/420f05002.pdf Accessed 4 June 2011.

Zucconi F and de Bertoldi M (1986) Compost specifications for the production and characterization of compost from municipal solid waste in compost: production, quality and use. In: de Bertoldi M, Ferranti MP, L'Hermite P and Zucconi F (eds): Proceedings of a symposium organized by the commission of the European

communities, Directorate General Science, Research and Development, 17-19 April.Udine Italy.

Table 7.1 Evolution of compost characteristics during the 150 day experiment

Composter/days	*Wet mass (kg)	DM (%)	OM (%dm)	TC (%dm)	TN ($g(kg\ dm)^{-1}$)	C/N ratio	pH
WB							
FW:YT (dm)	0.94:1						
0	72.2	24.1 (1.2)	75.3 (0.2)	39.2 (0.7)	22.9 (0.2)	17.1	6.1 (0.2)
15	49.3	23.0 (0.8)	63.0 (0.1)	32.7 (0.2)	27.0 (0.2)	12.1	8.8 (0.1)
30	37.6	27.0 (2.3)	58.7 (0.2)	30.4 (0.6)	26.3 (0.2)	11.5	8.1 (0.2)
45	33.3	30.0 (0.7)	58.1 (0.1)	29.9 (0.2)	25.8 (0.2)	11.6	8.2 (0.0)
60	27.6	33.0 (1.3)	54.2 (0.1)	29.2 (0.1)	24.9 (0.4)	11.7	8.6 (0.3)
90	17.6	50.4 (0.6)	53.2 (0.3)	28.2 (0.2)	25.2 (0.2)	11.2	8.1 (0.4)
120	13.2	65.9 (0.7)	52.6 (0.2)	27.6 (0.2)	26.4 (0.2)	10.5	7.8 (0.1)
150	9.2	81.0 (0.8)	50.4 (0.3)	26.6 (0.3)	24.6 (0.1)	10.8	7.5 (0.1)
PB							
FW:YT (dm)	0.93:1						
0	75.5	24.1 (1.2)	75.2 (0.2)	39.2 (0.7)	22.9 (0.2)	17.1	6.1 (0.2)
15	50.9	22.0 (3.0)	60.5 (0.3)	31.2 (0.5)	26.6 (0.5)	11.7	8.4 (0.1)
30	44.1	24.0 (3.9)	58.4 (0.2)	30.4 (0.1)	26.2 (0.2)	11.6	8.4 (0.2)
45	38.7	26.0 (0.1)	56.2 (0.1)	29.5 (0.3)	25.0 (0.2)	11.8	8.2 (0.0)
60	34.6	27.0 (1.0)	52.9 (0.2)	28.7 (0.9)	23.3 (0.1)	12.3	8.8 (0.3)
90	24.2	34.5 (0.7)	47.0 (0.2)	25.5 (0.1)	21.3 (1.8)	12.0	8.7 (0.4)
120	16.3	50.9 (2.4)	47.4 (0.3)	25.3 (0.2)	21.4 (0.3)	11.8	8.4 (0.1)
150	12.5	66.0 (1.8)	45.8 (1.0)	24.6 (0.2)	20.6 (0.2)	11.9	7.7 (0.1)
GPM							
FW:YT (dm)	0.96:1						
0	75.0	23.7 (1.2)	75.2 (0.2)	39.4 (0.7)	23.1 (0.2)	17.1	6.1 (0.2)
15	42.9	25.0 (2.1)	59.6 (0.1)	32.1 (0.5)	26.4 (0.2)	12.2	7.9 (0.4)
30	36.4	27.0 (4.1)	56.0 (0.1)	30.1 (0.9)	26.1 (0.1)	11.5	8.5 (0.3)
45	31.4	30.0 (1.8)	54.1 (0.3)	28.7 (0.2)	25.3 (0.1)	11.3	8.2 (0.1)
60	24.3	36.0 (4.1)	50.8 (0.3)	27.6 (0.5)	23.9 (0.4)	11.5	8.9 (0.0)
90	15.7	54.1 (2.5)	49.6 (0.3)	26.2 (0.2)	23.8 (0.3)	11.0	8.3 (0.2)
120	11.2	75.6 (0.7)	49.5 (0.1)	26.1 (0.1)	23.7 (0.4)	11.0	7.8 (0.0)
150	9.4	85.0 (2.2)	49.0 (0.3)	25.1 (0.10	24.5 (0.1)	10.2	7.7 (0.0)
GP							
FW:YT (dm)	1.2:1						
0	63.3	22.3 (2.0)	77.0 (0.2)	39.8 (0.4)	23.3 (0.7)	17.1	6.1 (0.2)
150	11.8	60.0 (3.5)	50.4 (0.8)	25.9 (0.1)	23.2 (0.3)	11.2	7.5 (0.2)

*The total mass was measured on days 0 and 150, otherwise estimated from Equation 2. WB-wood bin; PB-plastic bin; GPM-mixed ground pile; GP-unmixed ground pile; dm-dry mass basis; FW-food waste; YT-yard trimmings; DM-dry matter; TC-total carbon; TN-total nitrogen; OM-organic matter; C/N-carbon to nitrogen ratio. The number in parenthesis represents the standard deviation.

Table 7.2 Total greenhouse gas emission (GGE) for the four home composters

Gas/time interval	Composters (kg (ton wet waste treated)$^{-1}$)			
	WB	PB	GPM	GP
CO_2				
0 to 20 days*	60	108	85	85
20 to 60 days	16	16	19	16
60 to 120 days	7	9	9	19
120 to 150 days	1	1	1	2
Total CO_2 (kg (ton wet waste treated)$^{-1}$)	84	134	114	122
Total CO_2 (CO_2-eq (ton wet waste treated)$^{-1}$)	84	134	114	122
CH_4 (0 to 20 days)	nd	nd	nd	0.002
Total CH_4 (kg CO_2-eq (ton wet waste treated)$^{-1}$)	-	-	-	0.05
N_2O				
0 to 20 days**	0.135	0.065	0.184	0.181
20 to 60 days	0.289	0.150	0.274	0.017
60 to 120 days	0.032	0.022	0.051	0.228
120 to 150 days	0.002	0.001	0.001	0.002
Total N_2O (kg (ton wet waste treated)$^{-1}$)	0.458	0.238	0.510	0.428
Total N_2O (kg CO_2-eq (ton wet waste treated)$^{-1}$)	142	74	158	133
Total GGE (kg CO_2-eq (ton wet waste treated)$^{-1}$)	**226**	**208**	**272**	**255**

WB – wood bin; PB – plastic bin; GPM- mixed ground pile; GP- unmixed ground pile; CO_2 - carbon dioxide; CH_4 –methane; N_2O - nitrous oxide; nd – not detected. The GGE impact of CH_4 and N_2O are assumed to be 21 and 310 times higher than CO_2.

* Values estimated from regression Equations (4, 5, 6); all other values were measured.

** Values estimated from regression Equations (7, 8 and 9); all other values were measured.

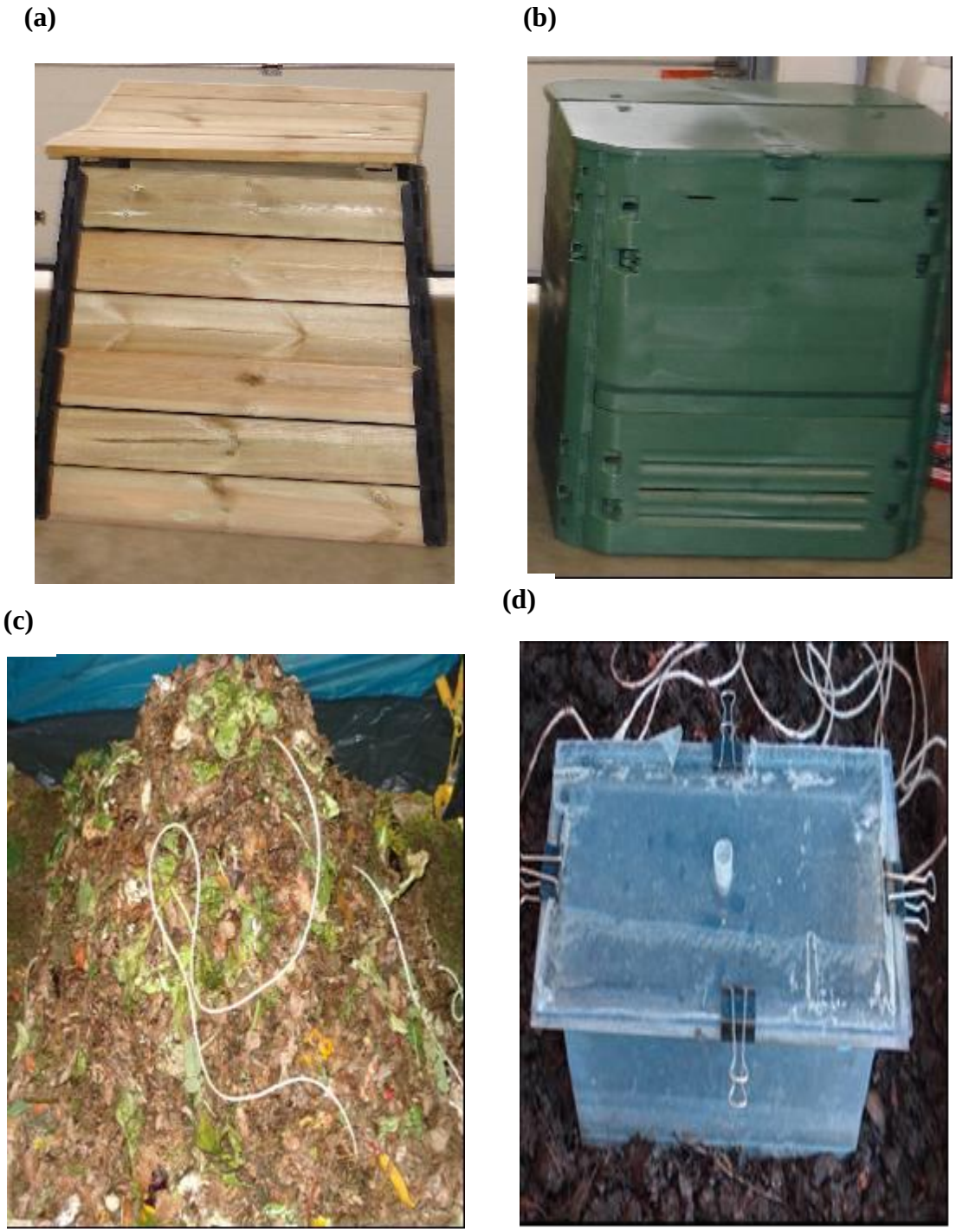


Figure 7.1 Experimental home composting systems (a) wood bin, (b) plastic bin, (c) ground pile. The static gas collection chamber used to measure gaseous emissions (d).

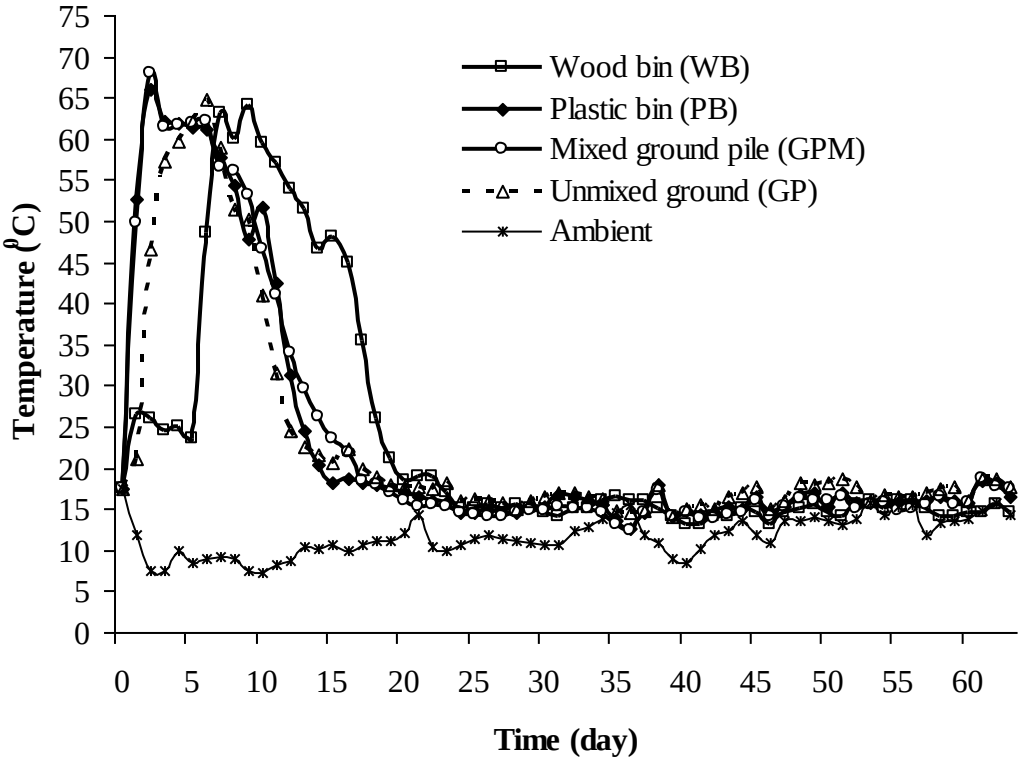


Figure 7.2 Temperature regime at the centre of compost mass for all four experimental home composting systems against ambient temperature. All composters were filled at once (batch fed) and mixed weekly except for the unmixed ground pile (GP).

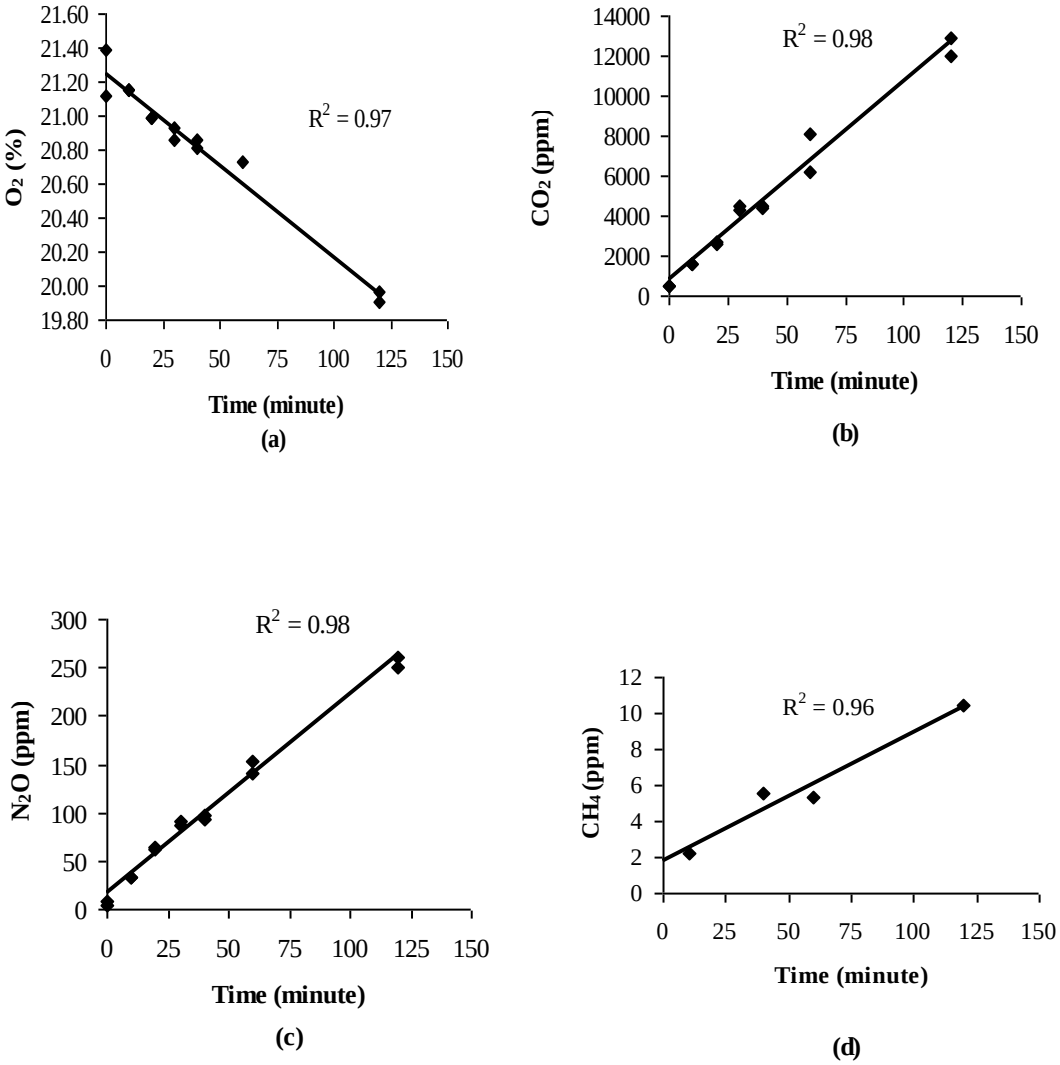
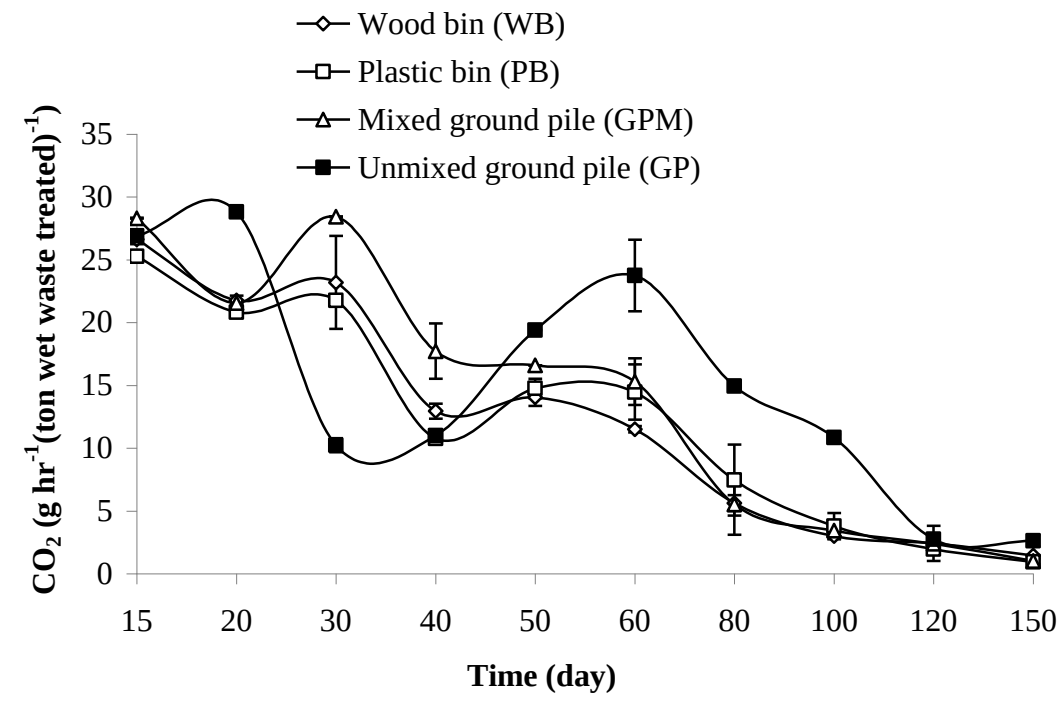
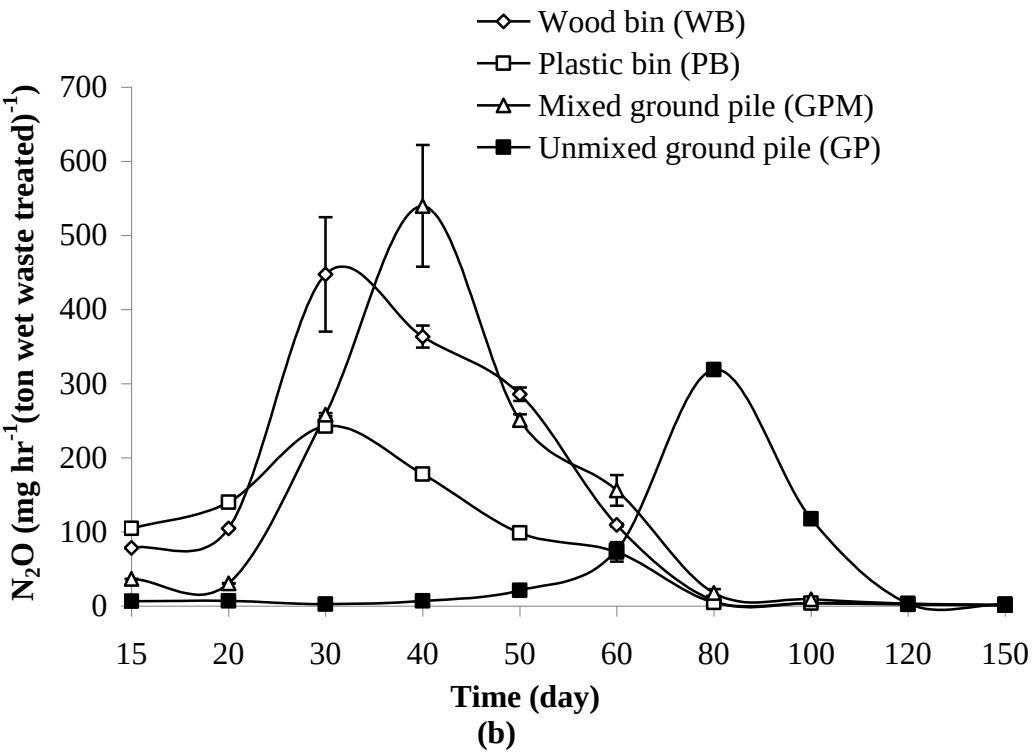


Figure 7.3 Trend of gas concentrations obtained in the closed chamber placed over the compost materials: (a) oxygen for the wood bin at 50 days; (b) carbon dioxide for the wood bin after 50 days; (c) nitrous oxide for the wood bin after 50 days; and (d) methane for the unmixed ground pile on day 15.



(a)



(b)

Figure 7.4 Measured emissions of CO_2 and N_2O from all four experimental home composting systems (HC) over 150 days: (a) carbon dioxide, CO_2; and (b) nitrous oxide, N_2O. Emissions of CH_4 between days 15 to 150 were below the detection threshold. Y-bars indicate the standard deviations (n=2).

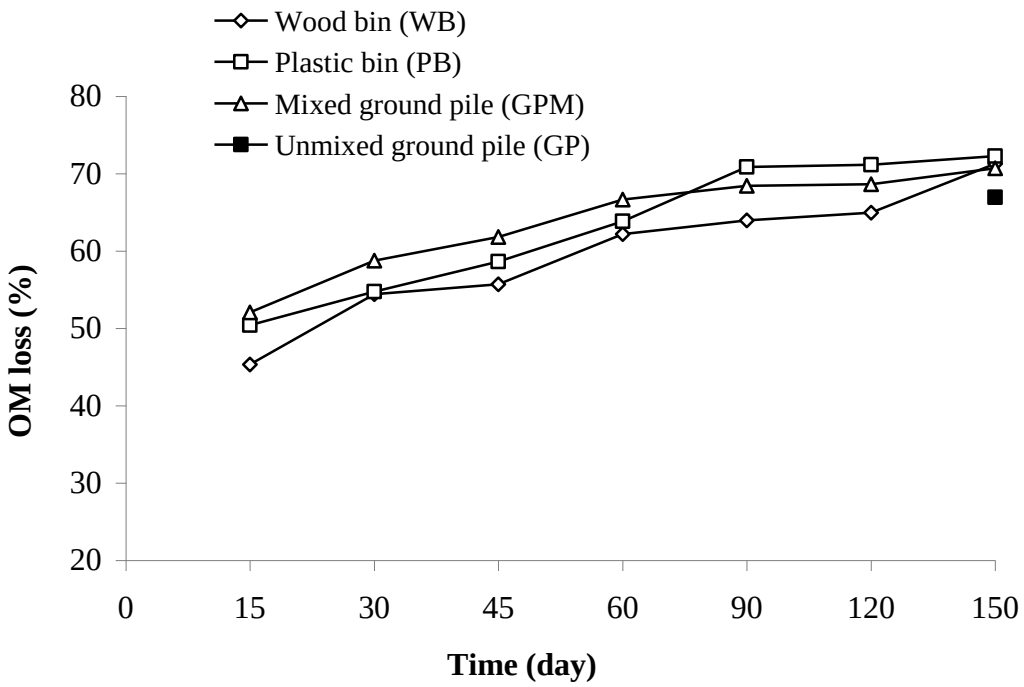
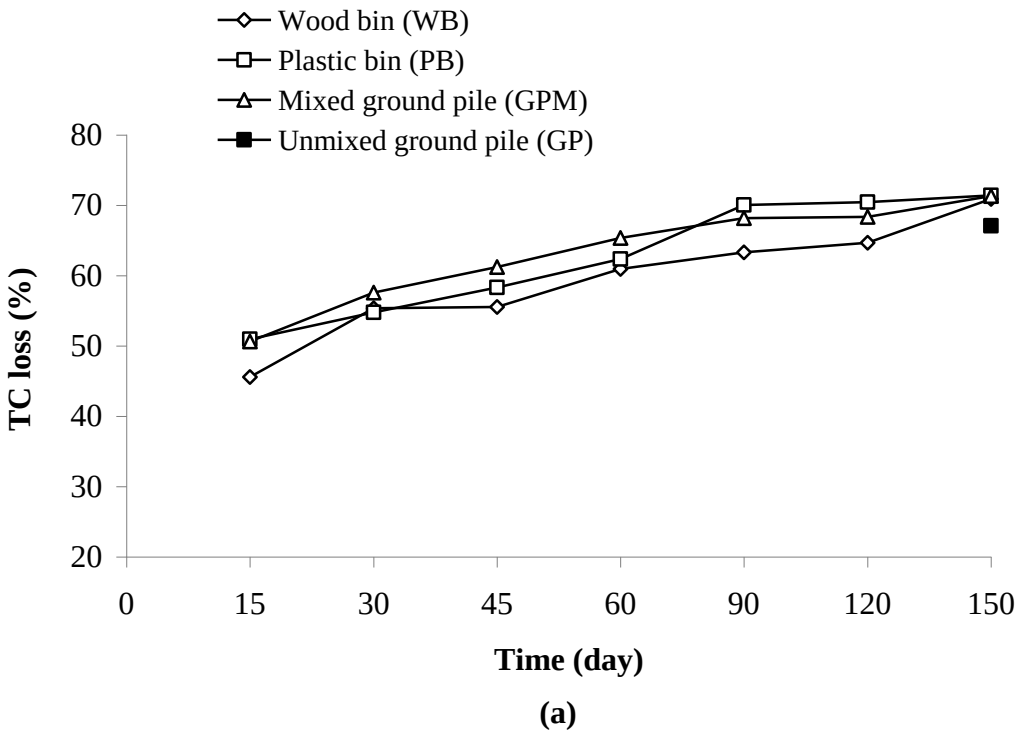
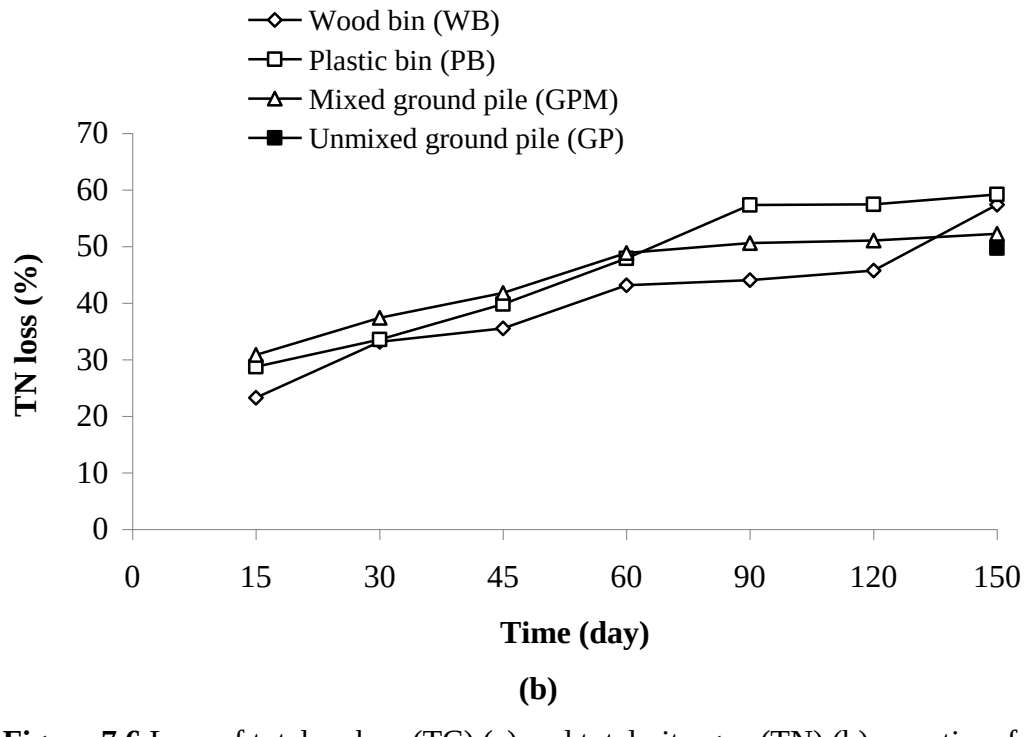


Figure 7.5 Loss of organic matter (OM) over time for the compost of all four home composting systems estimated from Equation (2), based on the initial mass of organic matter (OM_i).



(a)



(b)

Figure 7.6 Loss of total carbon (TC) (a) and total nitrogen (TN) (b) over time for the compost of all four home composting systems estimated using Equation.

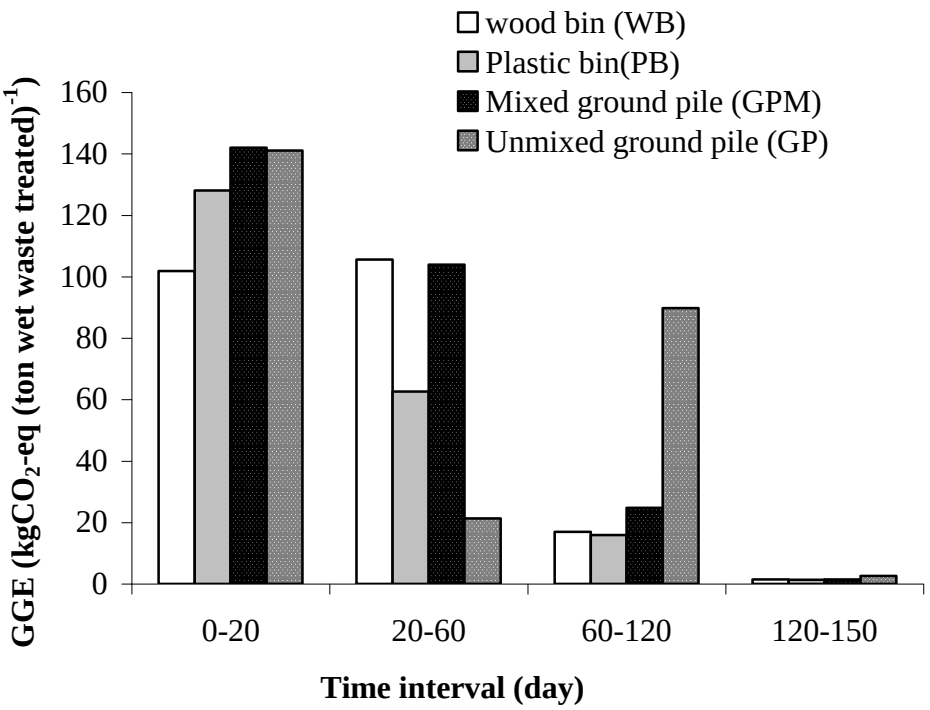


Figure 7.7 Greenhouse gas emissions (GGE) from the compost of all four home composting systems.

Note: The CH_4 and N_2O global warming potential are 21 and 310 times higher than that of CO_2 respectively, based on 100 years of global warming potential (US EPA, 2005; Friends of the l 2000).

Chapter 8

General Conclusion

8.1 General conclusion

The growing urbanization and economic activities create tremendous pressure on municipal solid waste (MSW) management systems by producing remarkable amounts of organic waste (OW) in the urban centres. The OW not properly managed may effect on both environment and human health. The land based disposal systems of MSW along with OW use limited land resources. Therefore, management of MSW along with its organic fraction is a great concern for the modern urban centres.

The economic situation of a country highly influences the growth of urban population and MSW production and its composition. Countries with higher economic activities generate higher amounts of OW as a fraction of the MSW mainstream, with a higher percentage of urban population. Considering environmental, economic and social pressure, the European Union (EU) and Canada have promulgated and implemented legislation for waste management on the concept of hierarchy of reduce, reuse, recycle and landfill as the last option. The EU landfill directive in 1999 set a target of 65% biodegradable waste diversion from landfilling by 2016. The diverted OW needs to be treated and recycled with minimal environmental as well as economic burdens. The onsite treatment (home and community composting) of OW offers the following advantages as compared to landfilling and centralized composting facilities:

(i) onsite treatment of OW rather than disposed in landfills and treating at centralized facilities reduces environmental as well as economic pressure of MSW management systems and saves limited land; and

(ii) onsite treatment of OW can be considered one of the viable options as an alternative to landfilling and centralized composting facilities.

However, the shift of MSW management systems from landfill disposal to resource recovery requires technological input, population participation, compost quality assurance and sufficient urban gardens to divert the mass produced. The composting process and quality of composted product depends on the initial compost mixture formulation, design type and management of home composting systems (HC). The study of commonly used HC design types and management practices suggested that the home composting of OW produces a stable and safe composted product that can be used for soil amendment, as well as eliminating emissions resulting from transportation, with the following conclusions:

(i) batch fed ground pile and plastic bins performed best, quickly producing thermophilic temperatures lasting long enough to sanitize the compost with the lowest level of parasites and pathogens and the least odours;

(ii) The weekly fed composters with larger amounts of waste input produced thermophilic temperatures;

(iii) HC managed by urban residents demonstrated no impact of the temperature regime, likely because clean organic waste was fed to the HC;

(iv) in terms of trace metals, and polycyclic aromatic hydrocarbons (PAHs), homeowners must be careful not to apply herbicides or large amount of fertilizers on their lawns if the grass clippings are to be added to HC; and

(v) the plastic bin demonstrated the lowest level of greenhouse gas emission (GGE) compared to the wood bin and ground piles, because of the top and bottom location of its perforations, enhancing convective aeration;

Finally, the information needs to be disseminated to the stakeholders, because the success of onsite treatment and recycling of OW depend on their awareness and sustained activities.

8.2 Contributions to knowledge

Based on the scientific objectives of this project, the research provided the following demonstrations as contributions to knowledge:

(i) home composting systems and community composting centres offer environmental and economic advantages as compared to landfilling and centralized composting facilities;

(ii) the best home composting system has perforations located at its top and bottom, to enhance convective air flow; ground piles can be just as effective as plastic or wooden boxes with perforations providing good convective aeration; under these conditions and their loading of at least 10 kg of organic waste per week, thermophilic temperatures can be reached;

(iii) home composting of source separated OW generally offers a safer composted product, however, in terms of heavy metals and polycyclic aromatic hydrocarbons (PAHs) homeowners must be careful in applying the righ amount of garden herbicides and fertilizers on their lawns if grass clippings are to be added to HC.

(iv) the plastic bin with perforations located at its top and bottom, to enhance convective airflow, produced lowest level of greenhouse gas emissions (GGE).

8.3 Future research direction

The following future research work is recommended:

(i) daily measurement (especially during active composting stage) of greenhouse gas emissions (GGE) from HC is recommended for further verification of GGE factors of home composting systems;

(ii) further study of odorous compounds and ammonia volatilization is suggested;

(iii) leachate production and its possible use as liquid fertilizer need to be studied;

(iv) a study of aspects of community composting centres such as the composting process, the quality of composted product, GGE and leachate production is suggested;

(v) further study of MSW generation, composition, environmental and economic consequences for high, medium and low economic situations with different possible management scenarios is highly recommended for development of effective future MSW management systems; and

(vi) the study of the fate of compost after land application needs to be assessed for a complete picture of environmental issues.

Chapter 9: References

Abu Qdais HA, Hamoda MF and Newham J (1997) Analysis of residential solid waste at generation sites. Waste Management & Research 15: 395- 406.

Adhikari BK, Tremier A, Martinez J and Barrington SF (2010) Home and community composting for onsite treatment of urban organic waste: perspective in the EU and Canada. Waste Management & Research 28(11): 1039 – 1053.

Adhikari BK, Barrington SF and Martinez J (2009a) Urban food waste generation: challenges and opportunities. Int. J. Environment and Waste Management 3(1/2): 4-21.

Adhikari BK, Barrington S, Martineze J and King S (2009b) Effectiveness of three bulking agents for food waste composting. Waste Management 29: 197-203.

Adhikari BK, Barrington S, Martinez J and King S (2008) Characterization of food waste and bulking agents for composting. Waste Management 28: 795–804.

Adhikari BK, Barrington S and Martineze J (2006) Predicted growth of world urban food waste and methane production. Waste Management & Research 24: 421-433.

AFNOR (2006) Amendements organiques, dénominations, spécifications et marquage, NF U44-051. Association Française de Normalisation, Paris, France.

AFNOR (2004) Characterization of sludges - Enumeration and viability of parasite helminth eggs - triple flotation technique, XP X33-017. Association Française de Normalisation, Paris, France.

AFNOR (2002) Organic soil improvers-composts containing substances essential to

agriculture, NF U44-095. Association Française de Normalisation, Paris, France.

AFNOR (2001a) Caractérisation des déchets-Dosage du carbone organique total (COT) dans les déchets, boues et sédiments, NF EN 13137. Association Française de Normalisation, Paris, France.

AFNOR (2001b) Qualité de l'eau-Détermination de la demande chimique en oxygène (DCO), NF T 90-101. Association Française de Normalisation, Paris, France.

AFNOR (2001c) Microbiology of food and animal feeding stuffs-Horizontal method for the enumeration of B-glucuronidase-positive Escherichia coli-Part 2:colony-count technique at 44 °C using 5-bromo-4-chloro-3-indolyl B-D-glucuronate, NF ISO 16649-2. Association Française de Normalisation, Paris, France.

AFNOR (2000) Characterisation of sludges-Determination of polynuclear aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB), XP X33-012. Association Française de Normalisation, Paris, France.

AFNOR (1995) Qualité du sol -Dosage de l'azote total - Méthode de Kjeldahl Modifiée, NF ISO 11261. Association Française de Normalisation, Paris, France.

AFNOR (1985) Amendements organiques et supports de culture-Détermination de la matière organique totale - Méthode par calcination, NF U 44-160. Association Française de Normalisation, Paris, France.

Ahmed K and Jamwal N (2000) Garbage: your problem. Down to Earth 31: 30-45.

Alamgir M and Ahsan A (2007) Municipal solid waste and recovery potential: Bangladesh perspective. Iranian Journal of Environmental Health Science & Engineering 4 (2): 67-76.

Al-Yousfi AB (2003) Environmentally sound technologies (EST) for designing and

operating solid wastes landfills, United Nations Environment Program (UNEPA), Regional Office for West Asia (ROWA), proceedings of international conference on wastes management and pests control, Muscat Municipality-Oman.

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

Andersen JK, Boldrin A, Christensen TH and Scheutz C (2010) Greenhouse gas emissions from home composting of organic household waste. Waste Management 30: 2475–2482.

Antler S (2009) Compost grows stronger. The Compost Council of Canada: www.compost.org/compostinggrowsstronger.html Accessed 3 June 2009.

APHA (2005) Standard procedures for the Testing of Water and Wastewater, American Public Health Association, Washington, DC, USA.

Banegas V, Moreno JL, Moreno JI, Garcia C, Leon G and Hernandez T (2007) Composting anaerobic and aerobic sewage sludges using two proportions of sawdust. Waste Management 27: 1317-1327.

Bank of Canada (1995-2010) Public information, Bank of Canada, Ottawa, Ontario, Canada: www.bankofcanada.ca Accessed 24 January 2010.

Bari QH and Koenig A (2001) Effect of air recirculation and reuse on composting of organic solid waste. Resources, Conservation and Recycling 33: 93-111.

Barrington S, Choiniere D, Trigui M and Knight W (2002) Effect of carbon source on compost nitrogen and carbon losses. Bioresource Technology 83: 189–194.

Barrington S, Choinière D, Trigui M and Knight W (2002) Compost convective airflow under Passive aeration. Journal of Bioresource Technology 86: 259-266.

Barrington S, Choiniere D, Trigui M and Knight W (2002) Compost airflow resistance. Biosystems Engineering 81(4): 433-441.

Barton PK and Atwater JW (2002) Nitrous oxide emissions and the anthropogenic nitrogen in wastewater and solid waste. Journal of Environmental Engineering 128(2): 137-150.

Baumert KA, Herzog T and Pershing J (2005) Navigating the Numbers: Green House Gas Data and international climate policy. World Resources Institute, Washington, D.C., USA.

Beck-Friis B, Pell M, Sonesson U, Jönsson H and Kirchmann H (2000) Formation and emission of N2O and CH4 from compost heaps of organic household waste. Environmental Monitoring and Assessment 62(3): 317-331.

Bergs C.-G (2005) Separate collection of organic waste-how does it work in Germany? BMU, Bonn University, Germany.

Bernstad A and Jansen J la C (2011) A life cycle approach to the management of household food waste – A Swedish full-scale case study. Waste Management 31(8) :1879 – 96.

Berthe L, Druilhe C, Massiani C, Tremier A and de Guardia A (2007) Coupling a respirometer and a pycnometer, to study the biodegradability of solid organic wastes during composting. Biosystems Engineering 97: 75-88.

Bhide AD (1994) Methane emission from landfills. Journal of Indian Association for Environmental Management 21: 1-7.

Biddestone AJ and Gray KR (1985) Composting. In: Moo-Young M (ed.): Comprehensive Biotechnology, vol. 4. Pergamon Press, Oxford, pp. 1059.

Bilitewski B, Hardtle G and Marek K (1994) Waste Management. Springer-Verlag Berlin Heidelberg, Germany, pp. 1-7, 202-209.

BNQ (2004) Organic soil conditioners – composts, Draft Standard P0413-200-5, Bureau de Normalisation du Quebec (BNQ), Quebec, Canada.

Bogner J (USA), Pipatti R (Finland), Hashimoto S (Japan), Diaz C (Cuba), Mareckova K (Slovakia), Diaz L (USA), Kjeldsen P (Denmark), Monni S (Finland), Faaij A (The Netherlands), Gao Q (China), Zhang T (China), Ahmed MA (Sudan), Sutamihardja RTM (Indonesia) and Gregory R (UK) (2008) Mitigation of global greenhouse gas emissions from waste: conclusions and strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. Working Group III (Mitigation). Waste Management & Research 26: 11–32.

Boldrin A, Andersen JK and Christensen TH (2011) Environmental assessment of garden waste management in the Municipality of Aarhus, Denmark. Waste Management 31: 1560–1569.

Boldrin A and Christensen TH (2010) Seasonal generation and composition of garden waste in Aarhus (Denmark). Waste Management 30: 551–557.

Boldrin A, Andersen JK, Møller J and Christensen TH (2009) Composting and compost utilization: accounting of greenhouse gases and global warming contributions. Waste Management & Research 27: 800–812.

Borjesson G and Svenssen BH (1997) Seasonal and diurnal methane emissions from a landfill and their regulation by methane oxidation. Waste Management & Research 15: 33 – 54.

Bou-Zeid M and El-Fadel M (2004) Parametric sensitivity analysis of leachate transport simulations at landfills. Waste Management 24: 681-689.

Brändli RC, Bucheli TD, Kupper T, Mayer J, Stadelmann FX and Tarradellas J (2007) Fate of PCBs and PAHs and their source characteristic ratio during composting and digestion of source-separated organic waste in full-scale plants. Environmental Pollution 148: 520-528.

Brinton WF (2000) Compost quality standards & guidelines: an international view. Final reports presented for New York State association of Recyclers, Woods End Laboratories, Inc. Mt Vernon, ME, USA.

Burnley SJ (2007) A review of municipal solid waste composition in the United Kingdom. Waste Management 27: 1274-1285.

Burnley SJ, Ellis JC, Flowerdew R, Poll AJ and Prosser H (2007) Assessing the composition of municipal solid waste in Wales. Resources, Conservation and Recycling 49: 264–283.

CCC (2010) Composting regulations and guidelines across Canada, Compost Council of Canada (CCC), Toronto, Ontario, Canada: www.compost.org/AboutCompostingindustry.html Accessed 2 Feb 2010.

CCEM (1989) National contamination site remediation program. Environment Canada, Ottawa, Canada.

CCME (2005) Guidelines for compost quality', PN 1340, ISBN 1-896997-60-0.Canadian Council of Ministers of the Environment, Winnipeg, Manitoba, Canada.

CCQC (2001) Compost maturity index. California Compost Quality Council, Nevada City, CA, USA.

CEPA (2002) Compost maturity and nitrogen release characteristics in central coast vegetable production. California Environmental Protection Agency, Integrated Waste Management Board, USA. Publication#442-02-015.

Chang JI, Tsai JJ and Wu KH (2005) Thermophilic composting of food waste. Bioresource Technology 97: 116–122.

Chen T-C and Lin C-F (2008) Greenhouse gases emissions from waste management practices using Life Cycle Inventory model. Journal of Hazardous Materials 155: 23–31.

Chiemchaisri C, Putthamilinprateep P, Promsamai N and Phetcha M (2010) Application of household compost wastes in small communities of Thailand. International Journal of Environment and Waste Management 6(1/2): 117-127.

Chroni C, Kyriacou A, Georgaki I, Manios T, Kotsou M and Lasaridi K (2009) Microbial characterization during composting of biowaste. Waste Management 29(5): 1520-1525.

CIA (2009) The world fact book, Central Intelligence Agency, USA: www.cia.gov/library/publications/the-world-factbook/geos/us.html Accessed 4 February 2009.

CIWMB (2008) Technologies and management options for reducing greenhouse gas emissions from landfills. California Integrated Waste Management Board (CIWMB), publication #200-08-001, California, USA.

Clean Energy (2007) Refuse truck powered by clean-burning natural gas fuel handles trash collection duties at July 7 live earth New York concert event, USA: www.cleanenergyfuels.com/07/07-6-07.html Accessed 13 January 2010.

Coker C (2007) Compost data tracking and analysis. BioCycle 48(7): 26.

Colón J, Martínez-Blanco J, Gabarrell X, Artola A, Sánchez A, Rieradevall J and Font X (2010) Environmental assessment of home composting. Resources, Conservation and Recycling 54: 893–904.

CSC (2003) Environmental Guidelines 318-7, solid waste measurement and management, Correctional Service Canada.

Day M and Shaw K (2001) Compost utilization in horticultural cropping systems. In: Stoffella PJ and Kahn BA (eds.): CRS press, USA, eBook ISBN: 978-1-4200-2622-1. www.crcnetbase.com/doi/pdfp/us/10.1201/9781420026221.ch2 Accessed 8 July 2011.

De Baere I (2000) Anaerobic digestion of solid waste: state-of-the-art. Water Science and Technology 41: 283-290.

de Bertoldi M, Vallini G and Pera A (1983) The Biology of Composting: a Review. Waste Management & Research 1: 157.

de Guardia A, Petiot C and Rogeau D (2008) Influence of aeration rate and biodegradability fractionation on composting kinetics. Waste Management 28: 73-84.

Demographia (2009) Demographia world urban areas & population projections, 5th comprehensive edition, April 2009 revision: http://demographia.com//db-worldua2015.pdf Accessed 5 June 2009.

Déportes I, Benoit-Guyod J-L and Zmirou D (1995) Hazard to man and the environment posed by the use of urban waste compost: a review. The Science of the Total Environmrnt 172: 197-222.

Diaz LF (2008) The search for solutions to maximize waste diversion from landfills. Waste Management 28: 775.

Diaz LF, Savage GM, Eggerth LL and Golueke CG (1993) Composting and Recycling , Municipal Solid Waste. Lewis Publishers, Boca Raton, USA. pp. 121 – 173, 175-217.

Domingo JL and Nadal M (2009) Domestic waste composting facilities: A review of human health risks. Environment International 35: 382–389.

Dunne L, Convery FJ and Gallagher L (2008) An investigation into waste charges in Ireland, with emphasis on public acceptability. Waste Management 28: 2826-2834.

Düring R-A and Gä th S (2002) Utilization of municipal organic wastes in agriculture: where do we stand, where will we go? J. Plant Nutr. Soil Sci 165: 544-556.

EC (2006) Establishing revised ecological criteria and the related assessment and verification requirements for the award of the Community eco-label to growing media. European Commission - notified under document number C(2006) 6962, Official Journal of the European Unio, L32/137, Office for Official Publications of the European Communities, Luxembourg.

EC (2006) European Parliament and Council Directive 2006/12/EC of 5 April 2006 on Waste.

ECN (2009) Country report, The European Compost Network, ECN/ORBIT e.V.,

Postbox 22 29, D-99403 Weimar, Germany. www.compostnetwork.info/index.php?id=36 Accessed 3 June 2009.

Eco-quartier (2009) Personnel conversation with respect to the purchase of a new non-automated composter built of polyethylene tubing, and site preparation and installation costs, Montréal, Canada.

EEA (2009) Diverting waste from landfill, effectiveness of waste-management policies in the European Union, European Environmental Agency, EEA Report NO. 7/2009, ISSN 17259177, Konges, Nytorv 6, 1050 Copenhagen K, Denmark.

EEA (2001) Climate change, European Environmental Agency: www.eea.europa.eu/themes/climate Accessed 18 February 2009.

EEA and ETC-WMF (2002) Biodegradable municipal waste management in Europe. European Environmental Agency (EEA) and European Topic Center on Waste and Material Flows (ETC-WMF), Report Number 15/2001, Copenhagen, Denmark.

Eftoda G and McCartney D (2004) Determining the critical bulking agent requirement for municipal solid waste biosolids composting. Compost Science & Utilization 12(3): 208 – 218.

EG 318-7 (2003) Correctional Service Canada, Environmental Guidelines 318-7 on solid waste measurement and management.

El Asri R and Baxter D (2004) Process control in municipal solid waste incinerators: survey and assessment. Waste Management & Research 22: 177-185.

El-Fadel M, Bou-Zeid E and Chahine W (2003) Landfill evolution and treatability

assessment of high-strengh leachate from MSW with high organic and moisture content. Intern. J. Environ. Studies 60(6): 603–615.

Engineering Toolbox (2010) Gas densities – densities and molecular weights of some common gases-acetylene, air, methane, nitrogen, oxygen and others. www.engineeringtoolbox.com/gas-density-d_158.html Accessed 2 October 2010.

Environment Canada (2009) National inventory report: Greenhouse gas sources and sinks in Canada 1990 – 2007, National Inventory Report. Cat. No.: En81-4/2007E.

EPIC (2002) Opportunities for Reducing greenhouse Gas Emissions through Residential Waste Management. the Environment and Plastics Industry Council (EPIC), a council of the Canadian Plastics Industry Association. 5925 Airport Road, Suite 500, Mississauga, Ontario.

Epstein E (1997) The science of composting. CRS Press LLC, Boca Raton, Florida, USA. pp. 19 – 50, 77-103.

Epstein E, Chaney RL, Henrys C and Logan TJ (1992) Trace elements in municipal solid waste compost. Biomass and Bioenergy 3(3-4): 227-238.

EU directive (2000) Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste. L 332/91, 28.12.2000.

Eunomia (2002) Cost for the municipal waste management in the EU, final report to directorate general environment, The European Commission. The Eunomia research & consulting on behalf of ECOTEC research and consulting: www.edis.sk/ekes/the Eucostwaste.pdf Accessed 26 November 2008.

European Biomass Industry Association (2006) Anaerobic digestion.

http://www.eubia.org/108.0.html Accessed 22 February 2010.

Eurostat (2011) Generation and treatment of municipal waste – issue number 31/2011. http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home Accessed 19 July 2011.

Eurostat (2009) Structural indicators, environment, municipal waste generated and municipal waste by type of treatment, European Commission, Eurostat: http://epp.eurostat.ec.europa.eu/portal/page/portal/structural_indicators/environment Accessed 1Feb. 2010.

Eurostat (2008) New country profile interface, The Euro indicators: http://epp.the Eurostat.ec.the Europa.the EU Accessed 31 October 2008.

Eurostat (2007) Environmental expenditure statistics, general government and specialised producers data collection handbook, Cat.NO.KS-RA-07-012-EN-N.

Fenerty-McKibbon B and Khare A (2005) Canada post delivers energy conservation. Energy and Buildings 37: 221–234.

Fernandes L, Zhan W, Patni NK and Jui PY (1994) Temperature distribution and variation in passively aerated static compost piles. Transactions of the ASAE 48: 257-263.

Finstein MS and Hogan JA (1992) Integration of composting process microbiology facility structure and decision making in science and Engineering of composting, design, environmental microbiological and utilization aspects. In: Hoitink HAJ and Keener HM (eds): Proceedings of an international composting research symposium, 27-29 March 1992. Columbus, OH, USA.

Friedrich E and Trois C (2011) Quantification of greenhouse gas emissions from

waste management processes for municipalities – A comparative review focusing on Africa. Waste Management 31: 1585–1596.

Friends of the Earth (2000) Greenhouse Gases and Waste Management Options. Friends of the Earth, 26-28 Underwood Street, LONDON, N1 7JQ.

Gervais C (2002) An overview of UK waste and resource management policies. Royal Society for Nature Conservation, Forum for the future, London, England.

Gong C-M (2007) Microbial safety control of compost material with cow dung by heat treatment. Journal of Environmental Science 19: 1014-1019.

Groeneveld E and Hébert M (2003) Dioxins, furans, PCBs and PAHs in eastern Canada compost. Quebec Ministry of Environment, Québec, Canada. www.mddep.gouv.qc.ca/matieres/articles/compost-en.pdf Accessed 16 July 2010.

Government of India (2008) Ministry of non-conventional energy sources, energy recovery from wastes, CGO complex, Lodi road, New Delhi – 110 003, India.

Government of Ontario (2008) 60% diversion of blue box waste material specific targets,

municipal bench marks, Waste Diversion Ontario, April 30, 2004.

Guermoud N, Ouadjnia F, Abdelmalek F, Taleb F and addou A (2008) Municipal solid waste in Mostaganem city (Western Africa). Waste Management 29(2): 896-902.

Hamelers HVM (1992) A theoretical model of composting kinetics, Science and engineering of composting, Design, environmental, microbiological and utilization aspects. In: Hoitink HAJ and Keener HM (eds): proceedings of an

international composting research symposium, 27-29 March 1992. Columbus, OH, USA.

Hansen W, Christopher M and Verbuecheln M (2002) EU waste policy and challenges for regional and local authorities. Background paper for the seminar on household waste management "capacity building on European Community's Environmental Policy". Ecologic, Institute for International and European Environmental Policy.

Harjula H, De Tilly S and Stutz J (2001) Waste trends and outlook. In: Zacarias-Farah A and Geyer-Allely E (2003) Household consumption patterns in OECD countries: trends and figures. Journal of Cleaner Production 11: 819-827.

Hargreaves JC, Adl MS and Warman PR (2008) A review of the use of composted municipal solid waste in agriculture. Agriculture, Ecosystems and Environment 123: 1-14.

Harjula H, De Tilly S and Stutz J (2001) Waste trends and outlook. Waste: Chapter 20. OECD Environmental Directorate.

Haug RT (1993) The practical hand book of compost engineering, Lewis Publishers, A CRC Press Company, 2000 N. W. Corporate Blvd; Boca Raton, Florida, USA, pp. 205-258.

Haug RT (1980) Compost engineering, Principles and practice, ANN ARBOR SCIENCE PUBLISHERS, INC. 230 Collingwood, P.O. Box 1425, Ann Arbor, Michigan 48106, USA, pp. 1, 89, 185, 274-275, 347.

Hazra T and Goel S (2009) Solid waste management in Kolkata, India: Practices and challenges. Waste Management 29(1): 470-478.

Hermann BG, Debeer L, De Wilde B, Blok K and Patel MK (2011) To compost or not to compost: Carbon and energy footprints of biodegradable materials' waste treatment. Polymer Degradation and Stability 96: 1159e1171.

Hogg D, Barth J, Favoino E, Centemero M, Caimi V, Amlinger F, Devliegher W, Brinton W and Antler S (2002) Comparison of compost standards within the EU, North America and Australasia. The Waste and Resources Action Programme, The Old Academy, Banbury, Oxon, UK.

Hong Y, Pan S, Shoa Q, Liu F and Duo Y (1996) A study to define a standard health protection zone for sanitary landfill in Fu Shan City. Waste Management & Research 14: 505 – 510.

Hughes EG (1980) The composting of municipal wastes. In: Bewick MWM (ed): Handbook of organic waste conversion. Chapter 4, Published by Van Nostrand Reinhold Company, 135 West 50th Street, New York, N.Y. 10020, USA, pp. 108-134.

IPCC (2006) Biological treatment of solid waste, volume 5: waste. Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories.

IPCC (2006) IPCC guidelines for national greenhouse gas inventories, Volume 5 Waste. Intergovernmental Panel on Climate Change. www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html Accessed 18 May 2011.

Iwegbue CMA, Emuh FN, Isirimah NO and Egun AC (2007) Fractionation, characterization and speciation of heavy metals in composts and compost-amended soils. African Journal of Biotechnology 6(2): 067-078.

Karnchanawong S and Suriyanon N (2011) Household organic waste composting using

bins with different types of passive aeration, Resources, Conservation and Recycling 55: 548–553.

Kanbour F (1997) General status on urban waste management in west Asia, paper delivered at the United Nations Environment Programme (UNEP) regional workshop on urban waste management in west Asia, Bahrain, 23 – 27 November.

Kanat G, Demir A, Ozkaya B and Bilgili MS (2006) Addressing the operational problems in a composting and recycling plant. Waste Management 26: 1384-1391.

Kelleher M (2007) Anaerobic digestion outlook for MSW streams. BioCycle 48(8): 51.

Kim MH and Kim JW (2010) Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery. Science of the Total Environment 408(19): 3998 – 4006.

Kim S-W, Miyahara M, Fushinobu S, Wakagi T, Shoun H (2010) Nitrous oxide emission from nitrifying activated sludge dependent on denitrification by ammonia-oxidizing bacteria. Bioresource Technology 101: 3958–3963.

Kollikkathara N, Feng H and Stern E (2009) A purview of waste management evolution: special emphasis on USA. Waste Management 29: 974-985.

Körner I, Saborit-Sánchez I and Aguilera-Corrales Y (2008) Proposal for the integration of decentralised composting of the organic fraction of municipal solid waste into the waste management system of Cuba. Waste Management 28: 64–72.

Kumar S, Bhattacharya JK, Vaidya AN, Chakrabarti T, Devotta S and Akolkar AB

(2009) Assessment of the status of municipal solid waste management in metro cities, state cities, class I cities, and class II towns in India: An insight. Waste Management 29(2): 883-895.

Landfill Dirctive (1999) Council directive 1999/31/EC of 26 April 1999 on the landfill of waste. Official Journal of the European Communities, I. 182/1, Office for official publications of the European Communities, 2, rue Mercier, L – 2985 Luxembourg.

LAP (2003) The national waste management plan (LAP), Part 1 Policy framework: www.vrom.nl/docs/internationaal/National%20Waste%20Management%20Plan.pdf Accessed 1 February 2010.

Legg BJ (1990) Farm & food waste: Utilization without pollution. Agricultural and food processing wastes. Proceedings of the sixth international symposium on agricultural and food processing wastes. 17-18 December 1990, pp. xi-xxi. ASAE publication 05-90.

López M, Soliva M, Martínez-Farré FX, Bonmatí A and Huerta-Pujol O (2010) An assessment of the characteristics of yard trimmings and recirculated yard trimmings used in biowaste composting. Bioresource Technology 101: 1399–1405.

Lou XF and Nair J (2009) The impact of landfilling and composting on greenhouse gas emissions – A review. Bioresource Technology 100: 3792–3798.

Lundie S and Peters GM (2005) Life cycle assessment of food waste management options. Journal of Cleaner Production 13: 275–286.

Machado SL, Carvalho MF, Gourc JP, Vilar OM, and do Nascimento JCF (2009)

Methane generation in tropical landfills: simplified methods and field results. Waste Management 29(1): 153-161.

Mato S, Orto D and Garcia M (1994) Composting of <100 mm fraction of municipal solid waste. Waste Management & Research 12 (4): 315-325.

MEEDDM (2009) La politique des dechets 2009-2012. Ministere de l'Ecologie,de l'Energie, du Developpement durable et de la Mer, Paris, France.

Marchettini N, Ridolfi R and Rustici M (2007) An environmental analysis for comparing waste management options and strategies. Waste Management 27: 562-571.

Marmo L (2008) EU strategies and policies on soil and waste management to offset greenhouse gas emissions. Waste Management 28: 685-689.

Martínez-Blanco J, Colón J, Gabarrell X, Font X, Sánchez A, Artola A and Rieradevall J (2010) The use of life cycle assessment for the comparison of biowaste composting at home and full scale. Waste Management 30: 983–994.

Marton C and Alwast H (2002) Report: Operational experiences and legal aspects of co-combustion in Germany. Waste Management & Research 20: 476-483.

Mato S, Orto D and Garcia M (1994) Composting of <100 mm fraction of municipal solid waste. Waste Management & Research 12 (4): 315-325.

Matthews E and Themelis NJ (2007) Potential for Reducing Global Methane Emissions From Landfills, 2000-2030. Proceedings Sardinia, Eleventh International Waste Management and Landfill Symposium, S. Margherita di Pula, Cagliari, Italy, 1-5 Oct. 2007, by CISA, Environmental Sanitary Engineering Centre, Italy

MDDEP (2008) Guidelines for the beneficial use of fertilizing residuals, Reference criteria and regulatory standard. Ministere du Developpement Durable, de l'Environnement et des Parcs, Quebec.

Messineo A and Panno D (2008) Municipal waste management in Sicily: Practices and challenges. Waste Management 28: 1201- 1208.

Meunchang S, Panichsakpatana S and Weaver RW (2005) C0-composting of filter cake and bagasse; by-products from a sugar mill. Bioresource Technology 96: 437-442.

MFHPB-20 (2009) Isolation and identification of Salmonella from food and environmental samples. Health products and food branch, Ottawa, Government of Canada.

Mitaftsi O and Smith SR (2006) Quantifying household waste diversion from landfill disposal by home composting and kerbside collection. Final report, Centre for environmental control and waste management, department of civil and environmental engineering, Imperial College, London UK.

Moghadam MR, Mokhtarani N and Mokhtarani B (2009) Municipal solid waste management in Rasht City, Iran. Waste Management 29(1): 485-489.

Montejo C, Ramos P, Costa C and Márquez MC (2010) Analysis of the presence of improper materials in the composting process performed in ten MBT plants. Bioresource Technology 101(21): 8267-8272.

Nakasaki K, Nag K and Karita S (2005) Microbial succession associated with organic matter decomposition during thermophilic composting of organic waste. Waste Manage and Research 23: 48–56.

Nakasaki K, Kuratomi H, Wakizaka H, Hiyama R and Akakura N (1998) Quantitative analysis of ammonia and odorous sulphur compounds evolved during thermophilic composting. Waste Management & Research 16(6): 514-524.

Nakasaki K, Yaguchi H, Sasaki Y and Kubota H (1993) Effects of pH Control on composting of garbage. Waste Management & Research 11: 117.

Nash C (1992) Backyard composting: the first step in organic waste management. Resource Recycling, May 1992.

Nas SS and Bayram A (2008) Municipal solid waste characteristics and management in Gumushane, Turkey. Waste Management 28(12): 2435- 2442.

NB ELG (2001) Waste Reduction division & an action plan for New Brunswick. New Brunswick Environment and Local Government: www.gnb.ca/elg-egl Accessed 18 February 2009.

Nickolas J and Young HK (2002) Material and energy balances in a large scale aerobic bioconversion cell. Waste Management and Research 20: 234-242.

NSDOE (2000) Status report 2000 of solid waste resource management in Nova Scotia, Nova Scotia, Too Good To Waste. Nova Scotia Department of the Environment: www.gov.ns.ca/envi/wasteman Accessed 18 February 2009.

NS EAL (2004) Status report 2004 of solid waste-resource management in Nova Scotia, Nova Scotia, A World Leader in Recycling. Nova Scotia Environment and Labour: www.gov.ns.ca/enla/emc/wasteman Accessed 18 February 2009.

OECD (2006-2007) OECD Environmental Data; Compendium 2006/2007, Waste.

Environmental Performance and Information Division OECD, Environmental Directorate. Working Group on Environmental Information and outlooks, Paris, France.

Official Journal (2006) Regulation (EC) No 1013/2006 of the European Parliament and of the council of 14 June 2006 on shipments of waste, 12.7.2006, L190/1.

Official Journal (2000) Commission Decision 2000/738/EC of 17 November 2000 concerning a questionnaire for member states reports on the implementation of Directive 1999/31/EC on the landfill of waste, 25.11.2000, L298/24. Office for official publications of the European Communities, 2, rue Mercier, L – 2985 Luxembourg.

Official Journal (2000) Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste. L 332/91, 28.12.2000.

Otegbeye M, Abdel-Malek L, Hsieh HN and Meegoda JN (2009) On achieving the state's household recycling target: A case study of North New Jersey, USA. Waste Management 29(2): 647- 654.

Otten L (2001) Wet-dry composting of organic municipal solid waste: Current Status in Canada. Can. J. Civil Eng. 28(Suppl.1): 124-130.

Pace MG, Miller BE and Farrell- Poe KL (1995) The composting process. Utah state University, Extension, October 1995.

Pagans E, Barrena R, Font X and Sa´nchez A (2006) Ammonia emissions from the composting of different organic wastes. Dependency on process temperature. Chemosphere 62: 1534–1542.

Papadopoulos AE, Stylianou MA, Michalopoulos CP, Moustakas KG and

Hapeshis KM (2009) Performance of a new household composter during in-home testing. Waste Management 29(1): 204-213.

Parrot L, Sotamenou J, and Dia BK (2009) Municipal solid waste management in Africa: strategies and livelihoods in Yaounde, Cameroon. Waste Management 29(2): 986-995.

Pawelczyk A (2005) EU policy and legislation on recycling of organic wastes to agriculture. ISAH- Warsa, Poland, Vol 1. Wroclaw University of Technology, Institute of Inorganic Technology and Mineral Fertilizers, Wroclaw, Poland.

Peavy HS, Rowe DR and Tchobanoglous G (1985) Environmental Engineering McGraw-Hill, Inc. USA. pp 640-644.

Pettus A (2009) Methane: Tapping the untapped potential, Clean Air Task Force, 18 Tremont Street, Boston, USA.

Picci et al (1978) In: Ferrari G (1986): Oxygen, water and temperature in the decomposition process of an organic substance during composting in compost: production, quality and use. In: Bertoldi M De, Ferranti MP, L'Hermite P and Zucconi F (eds). Proceedings of a symposium organized by the commission of the European communities, Directorate General Science, Research and Development,17-19 April. Udine Italy.

Petiot C and de Guardia A (2004) Composting in a Laboratory Reactor: A Review. Compost Science & Utilization 12(1): 69-79.

Pires A, Martinho G and Chang N-B (2011) Solid waste management in European countries: A review of systems analysis techniques. Journal of Environmental Management 92: 1033-1050.

Pokhrel D and Viraraghavan T (2005) Municipal solid waste management in Nepal: practices and challenges. Waste Management 25: 555–562.

QRMMP (2008) Quebec residual materials management policy, 1998-2008.

Rasapoor M, Nasrabadi T, Kamali M and Hoveidi H (2009) The effects of aeration rate on generated compost quality, using aerated static pile method. Waste Management 29(2): 570-573.

Recycled Organics Unit (2001) Greenhouse Gas Emissions from Composting Facilities. Building B11B, he University of New South Wales, UNSW Sydney 2052.

Recyc-Québec (2006) Odour related preoccupations during the composting or organic wastes. Quebec, Canada.

Recycle Works Ltd (2010) Compost bins and composting, Unit 1, Bee Mill, RIBCHESTER, UK: www.recycleworks.co.uk Accessed 28 January 2010.

Renkow M and Rubin AR (1996) Municipal solid waste composting: does it makes economic sense? AREP 96-3 October 1996: http://www.bae.ncsu.edu/bae/programs/extension/publicat/arep/2arep963.html Accessed 18 February 2009.

Richard TL (2005) Compost. Iowa State University, Ames, IA, USA.

Richter R de and Caillol S (2011) Fighting global warming: the potential of photocatalysis against CO_2, CH_4, N_2O, CFCs, tropospheric O_3, BC and other major contributors to climate change. Journal of Photochemistry and Photobiology C:Photochemistry Reviews. doi:10.1016/j.jphotochemrev.2011.05.002.

Rogger C Beaurain F and Schmidt TS (2011) Composting projects under the Clean

Development Mechanism: Sustainable contribution to mitigate climate change. Waste Management 31: 138–146.

Rosenfeld PE, Clark JJJ, Hensley AR and Suffet IH (2007) The use of an odour wheel classification for the evaluation of human health risk criteria for compost facilities. Water Science & Technology 55(5): 345–357.

Saha JK, Panwar N and Singh MV (2010) An assessment of municipal solid waste compost quality produced in different cities of India in the perspective of developing quality control indices. Waste Management 30:192–201.

Sakai S, Sawell SE, Chandler AJ, Eighmy TT, Kosson DS, Vehlow J, van der Sloot HA, Hartlen J and Hjelmar O (1996) World trends in municipal solid waste management. Waste Management 16(5/6): 341-350.

Sartaj M, Fernandes L and Patni NK (1997) Performance of forced, passive and natural aeration methods for composting manure slurries. Transactions of the ASAE 40(2): 457-463.

SAS Institute Inc. (2008) SAS version 9.2, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC, USA.

Sawell SE, Hetherington SA and Chandler AJ (1996) An overview of municipal solid waste management in Canada. Waste Management 16(5/6): 351-359.

Schnurer HL (2000) Regulation on waste management- the situation in Germany. Federal Ministry of the Environment, Nature Conservation and Nuclear Safety, Bonn, Germany.

Schwalb M, Rosewear C, Chin R and Barrington S (2011) Food waste treatment in a community centre. Journal of Waste Management 31: 1570-1575.

Seo JY, Heo JS, Kim TH, Joo WH and Crohn DM (2004) Effect of vermiculite addition on compost produced from Korean food wastes. Waste Management 24: 981–987.

Shaw PJ and Maynard SJ (2008) The potential of financial incentives to enhance householder's kerbside recycling behaviour. Waste Management 28: 1732-1741.

Shin HS, Han SK, Song YC and Lee CY (2001) Performance of UASB reactor treating leachate from acidogenic fermenter in two-phase anaerobic digestion of food waste. PII: S0043-1354(01)00041-0.

SITA Australia Pty Ltd. (2008) Methane captured for greenhouse neutrality, prepared by Hyder consulting Pty Ltd., North Sydney, Australia, Report no. NS04054-R01-04.

Slater RA and Frederickson J (2001) Composting municipal waste in the UK: some lessons from Europe. Resources, conservation and Recycling 32: 359-374.

Smith SR (2009) A critical review of the bioavailability and impacts of heavy metals in municipal solid waste composts compared to sewage sludge. Environment International 35: 142–156.

Smith SR and Jasim S (2009) Small-scale home composting of biodegradable household waste: overview of key results from a 3-year research program in West London. Waste Management & Research 27 (10): 941-950.

Solid waste landfill guidance (1999) Landfill gas monitoring and mitigation, technical section, division of solid waste management program, Tennessee Division of Solid Waste Management, 3 March.

Stabnikova O, Ding HB, Tay JH and Wang JY (2005) Biotechnology for aerobic conversion of food waste into organic fertilizer. Waste Management & Research 23: 39 – 47.

Statistics Canada (2008) Waste management industry survey: Business and government sectors 2006. Catalogue no. 16F0023X: www.statcan.gc.ca/pub/16f0023x/16f0023x2006001-eng.pdf Accessed 1 February 2010.

Stevens RJ, Laughlin RJ, Burns LC and Arah JRM (1997) Measuring the contributions of nitrification and denitrification to the flux of nitrous oxide from soil. Soil Biol. Biochem 29(2): 139-151.

Sufian MA and Bala BK (2007) Modeling of urban solid waste management system: The case of Dhaka city. Waste Management 27: 858-868.

The water planet company (2010) Nitrification and denitrification. The Water Planet Company, Connecticut, USA.

Thompson S and Tanapat S (2005) Modeling Waste Management Options for Greenhouse Gas Reduction. Journal of Environmental Informatics 6(1): 16-24.

Tognetti C, Mazzarino MJ and Laos F (2011) Comprehensive quality assessment of municipal organic waste composts produced by different preparation methods. Waste Management 31:1146-1152.

Tremier A, de Guardia A, Massianic C, Paul E and Martel JL (2005) A respirometric method for characterising the organic composition and biodegradation kinetics and the temperature influence on the biodegradation

kinetics, for a mixture of sludge and bulking agent to be co-composted. Bioresource Technology 96: 169-180.

Troschinetz AM and Mihelcic JR (2009) Sustainable recycling of municipal solid waste in developing countries. Waste Management 29 (2): 915-923.

Turan NG, Coruh S, Akdemir A and Ergun ON (2009) Municipal solid waste management strategies in Turkey. Waste Management 29(1): 465-469.

UN (2010) World Urbanization Prospects: The 2009 Revision. Director, Population Division, Department of Economic and Social Affairs, United Nations, New York, USA: http://esa.un.org/unpd/wup/Documents/WUP2009_Wallchart_Urban-Rural_Final.pdf Accessed 6 July 2011.

UN (2007) Urban population development and the environment, United Nations, Department of Economic and Social Affairs, population Division: www.unpopulation.org Accessed 23 May 2008.

UNPD (2007) World urbanization prospects: The 2007 revision population database, department of economics and social affairs, United Nations Population Division: www.unpopulation.org Accessed 21 January 2009.

UNSD (2008) Department of economic and social affairs, United Nations Statics Division: http://unstats.un.org/unsd/snaama/SelectionCountry.asp Accessed 21 January 2009.

US CESLG (2008) Landfill methane utilization, United States Clean Energy Strategies for Local Government . USA.

US EPA (2006) Global mitigation of non-CO_2 greenhouse gases. United States Environmental Protection Agency, Office of Atmospheric Programs (6207J), Washington, DC, USA. EPA 430-R-06-005.

US EPA (2005) Emission Facts: metrices for expressing greenhouse gas emission: carbon equivalents and carbon dioxide equivalents, EPA 420-F-05-002. United States Environmental Protection Agency (US EPA), Washington DC, USA: www.epa.gov/oms/climate/420f05002.pdf Accessed 4 June 2011.

US EPA (2005) Tribal composting nourishes land and tradition. United States Environmental Protection agency. Tribal Waste Journal, Issue 4, EPA530-N-05-001.

US EPA (2003) Inventory of US greenhouse gas emissions and sinks 1990-2001, final version, April 2003, EPA 430-R-03-004.

US EPA (1999) Waste wise update. United States Environmental Protection Agency, solid waste and emergency response (5306W), EPA530-N-99-007: www.epa.gov/wastewise (16 October 2008).

US EPA (1998) An analysis of composting as an environmental remediation technology. United States Environmental Protection Agency, solid waste and emergency response (5306W), EPA530-R-98-008.

US EPA (1994) Composting yard trimmings and municipal solid waste. United States Environmental Protection Agency, Solid Waste and Emergency Response (530S), EPA530-R-94-003.

US EPA (1993) Markets for compost. United States Environmental Protection Agency, solid waste and emergency response (5306), EPA/530-SW-90-073A.

Van der Sloot HA (1996) Present status of waste management in The Netherlands. Waste Management 16 (5/6): 375-383.

Van Soest PJ (1963) Use of detergents in the analysis of fibrous feeds. I. Preparation of fibre residues of low nitrogen content. Journal of the Association of Official Agricultural Chemists 46: 825–829.

Vehlow J, Bergfeldt B and Visser R (2007) European union waste management strategy and the importance of biogenic waste. J Mater Cycles Waste Manag 9: 130-139.

Wagner T and Arnold P (2008) A new model for solid waste management: an analysis of the Nova Scotia MSW strategy. Journal of Cleaner Production 16: 410-421.

Wang Y, Odle WS, Eleazer WE and Barlaz (1997) Methane potential of food waste and anaerobic toxicity of leachate produced during food waste decomposition. Waste Management & Research 15: 149- 167.

WHO (1995) Solid waste management in some countries – environmental dimensions of waste disposal, World Health Organization regional center for environmental health activities (CEHA), P.O. Box 926967, Amman 111 90, Jordan.

Wiley and Pierce (1955) In: Epstein E. (1997) The science of composting. CRS Press LLC, Boca Raton, Florida, USA, pp. 20.

Willson GB (1993) In: Day M and Shaw K (2001) Compost utilization in horticultural cropping systems. In: Stoffella PJ and Kahn BA (eds.): CRS press, USA, eBook ISBN: 978-1-4200-2622-1.

www.crcnetbase.com/doi/pdfp/us/10.1201/9781420026221.ch2 Accessed 8 July 2011.

Wolkowski R (2003) Nitrogen management considerations for land spreading municipal solid waste compost. J. Environ. Qual. 32: 1844-1850.

World Resources (1998 – 99) A Guide to the Global Urban Environment, city level, 1993. Data table 9.3, pp. 278.

World Population prospects (2007) United Nations Population Division: http://esa.un.org/unpp Accessed 6 July 2008.

Zacarias-Farah A and Geyer-Allely E (2003) Household consumption patterns in OECD countries: trends and figures. Journal of Cleaner Production 11: 819-827.

Zhang D, Keat TS and Gersberg RM (2010) A comparison of municipal solid waste management in Berlin and Singapore. Waste Management 30(5): 921 – 933.

Zsigraiová Z, Tavares G, Semião V and Carvalho MG (2005) Municipal solid waste incineration- contribution to sustainable development of energy and environment. Acta Metallurgica Slovaca 11(4): 450-459.

Zucconi F and de Bertoldi M (1986) Compost specifications for the production and characterization of compost from municipal solid waste in compost: production, quality and use. In: de Bertoldi M, Ferranti MP, L'Hermite P and Zucconi F (eds): Proceedings of a symposium organized by the commission of the European communities, Directorate General Science, Research and Development, 17-19 April.Udine Italy.