IMPLEMENTATION OF ENVIRONMENTAL LIFE CYCLE ASSESSMENT MODEL IN ORGANIC MUNICIPAL SOLID WASTE MANAGEMENT IN MALAYSIA

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ABSTRACT

Organic Municipal Solid Waste (OMSW) generation in Malaysia is overwhelming and most of the waste generated ended up in the waste stream to be disposed in landfills. However, there has been minimal research on the comprehensive evaluation of the Malaysian OMSW management system from environmental perspective despite priority being given to increase recycling rate and composting of OMSW by the Malaysian government. The main aim of the thesis is to study the environmental benefits of OMSW management. The objectives include: (1) to determine the characteristics and elemental composition of OMSW generated in Malaysia; (2) to provide a comprehensive Life Cycle Inventory (LCI) of medium scale co-composting of OMSW; (3) to evaluate environmental impacts and benefits associated with alternative OMSW management system; and (4) to quantify the total CO_2 equivalent reduction potential from OMSW recycling via composting as compared to landfilling (Business-as-Usual) in Peninsular Malaysia. A comprehensive Life Cycle Inventory (LCI) of medium scale co-composting of OMSW was carried out based on comprehensive field studies. Substance Flow Analysis of C, N, P, K, Cd, Cr, Cu, Ni and Pb were carried out by using STAN 2.5 software. The inputs and outputs of OMSW composting process were also recorded. The life cycle environmental impacts from alternative OMSW management system were evaluated based on ISO 14000 series. The total CO_2 equivalent reduction potential from OMSW recycling via composting as compared to landfilling was assessed through scenarios comparison in accordance to Malaysian municipal solid waste management strategic plan. The LCI of medium-scale co-composting of OMSW in tropical environment was presented. The C/N reduction during the process was in the range of 10-23%. In general, the compost composition was considered to be within the ranges previously reported in literature. Heavy metals were found to remain in the finished compost where the release of heavy metal to atmosphere is insignificant. No

major environmental problems were identified from the OMSE composting process, except for the emissions of GHGs. LCA studies revealed that anaerobic digestion is the most environmentally sound management for OMSW with net environmental gain whereas disposal of OMSW at landfill are generally less environmental favourable. This study also highlights the importance of decomposition emissions control during OMSW composting, particularly CH_4, N_2O and NH_3. OMSW diversion from disposal created significant climate change benefits in term of net GHG emissions reduction. The current study reveals that an additional of 21% GHG emissions reduction including the recycling of OMSW via composting in all sectors, on top of 25.5% GHG emission reduction from Malaysia waste by increasing the recycling rate to 22% as reported by previous study. A knowledge-based goal-oriented OMSW management study is necessary to analyse the state-of-art of OMSW management in Malaysia and direct it towards fulfilling the main goals of waste management. The results provide information of all significant inputs and outputs in the form of elementary flow to and from the environment from OMSW management involved. Based on the experience of SFA in the present study, the emissions quantified are likely to be in agreement with that from previous studies. Hence, author agrees and advocates that SFA is able to be integrated with LCI and eventually LCIA studies upon OMSW management sector in Malaysia.

ABSTRAK

Penghasilan Sisa pepejal perbandaran organik (OMSW) di Malaysia amat merisaukan dan kebanyakan daripada sisa itu dibuang di tapak perlupusan sisa pepejal. Namun demikian, penyelidikan berkenaan penilaian komprehensif atas pengurusan OMSW di Malaysia adalah masih rendah meskipun keutamaan telah diberi kepada peningkatan kadar kitar semula dan pengkomposan OMSW oleh kerajaan Malaysia. Persoalannya, adakah terdapat kaedah penilaian menyeluruh yang telus dan tepat atas sistem pengurusan OMSW? Tujuan utama penyelidikan ini adalah untuk mengkaji kebaikan keseluruhan pengurusan OMSW kepada alam sekitar. Objektif-objektif ini termasuk: (1) untuk menentukan ciri-ciri dan komposisi elemen OMSW yang terhasil di Malaysia; (2) untuk memberikan Inventori Jangka Hayat (LCI) yang menyeluruh pada pengkomposan OMSW berskala sederhana; (3) untuk menilai kesan alam sekitar dan manfaat yang berkaitan dengan system pengurusan alternatif OMSW dan (4) untuk mengukur jumlah potensi pengurangan CO_2 daripada aktiviti kitar semula OMSW melalui pengkomposan berbanding dengan perlupusan di tapak perlupusan sisa pepejal di Semenanjung Malaysia. LCI yang menyeluruh untuk proses pengkomposan OMSW berskala sederhana telah dijalankan berdasarkan kajian lapangan menyeluruh. Analisis aliran bahan (SFA) untuk C, N, P, K, Cd, Cr, Cu, Ni dan Pb telah dijalankan dengan menggunakan perisian STAN 2.5. Input dan output daripada proses pengkomposan OMSW ini juga telah direkodkan. Kitaran hidup kesan alam sekitar (LCIA) daripada pelbagai sistem pengurusan OMSW telah dinilai berdasarkan kaedah siri ISO 14000. Jumlah potensi pengurangan dari kitar semula OMSW melalui pengkomposan berbanding dengan perlupusan di tapak perlupusan sampah telah dinilai melalui scenario perbandingan berpaksikan pelan strategi pengurusan sisa pepejal di Malaysia. LCI untuk pengkomposan OMSW berskala sederhana dalam persekitaran tropika telah dibentangkan. Pengurangan nisbah C/N dalam proses adalah pada kadar 10-23%. Secara

amnya, komposisi kompos dianggarkan pada kadar seperti yang dilaporkan dalam kajian sebelum ini. Logam berat didapati tinggal di dalam kompos di mana kadar perlepasan ke udara adalah tidak ketara. Tiada masalah alam sekitar yang utama dikenalpasti dari proses tersebut kecuali pembebasan gas rumah hijau. Kajian LCIA menunjukkan pengurusan OMSW melalui proses pencernaan tidak beroksigen (anaerobid digestion) adalah paling bermanfaat kepada alam sekitar dan sebaliknya perlupusan OMSW di tapak perlupusan adalah paling tidak berkebaikan. Kajian juga telah menunjukkan kepentingan mengurangkan impak jangka hayat melalui pembebasan hasil daipada proses pencernaan OMSW terutamanya gas CH_4, N_2O dan NH_3. Pengurangan perlupusan OMSW di tapak perlupusan menghasilkan maanfaat yang ketara dari segi pengurangan pembebasan gas rumah hijau. Kajian menyokong pengurangan pembebasan gas rumah hijau sebanyak 21% melalui pengkomposan OMSW dari semua sektor, ditambah atas pencapaipan pengurangan gas rumah hijau sebanyak 25.5% menerusi peningkatan kadar kiatr semula ke 22% seperti yang dibentangkan oleh kajian sebelum ini. Kesimpulannya, kajian tentang pengurusan OMSW yang berpandukan kepada ilmu dan matlamat adalah penting untuk menganalisis pengurusan OMSW di Malaysia. Hasil kajian ini memberikan maklumat tentang input dan output yang berkaitan dari segi aliran elemen atau bahan dalam proses pengurusan OMSW yang terlibat. Berdasarkan pengalaman implementasi SFA dalam kajian ini, pembebasan ke alam sekitar dari proses pengurusan OMSW adalah selaras dengan hasil kajian sebelum ini. Oleh yang demikian, SFA didapati dapat diintegrasikan dalam kaedah penyediaan LCI dan akhirnya kajian LCIA daripada sektor pengurusan OMSW di Malaysia.

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TABLE OF CONTENTS

CHAPTER 2:LITERATURE REVIEW

CHAPTER 4: RESULTS

CHAPTER 5: DISCUSSIONS

LIST OF FIGURES

Chapter 1

Chapter 2

Chapter 3

Chapter 4

LIST OF TABLES

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

AD	:	Anaerobic Digestion
BaU	:	Business as Usual
BMP	:	Best Management Practice
BOD	:	Biochemical Oxygen Demand
C/N	:	Carbon-Nitrogen Ratio
CAPEX	:	Capital Expenses
Cd	:	Cadmium
CDM	:	Clean Development Mechanism
CFC	:	Chlorofluorocarbons
CH_4	:	Methane
CO_2	:	Carbon Dioxide
CO_{2eq}	:	Carbon Dioxide Equivalent
COD	:	Chemical Oxygen Demand
Cr	:	Chromium
CSTR	:	Continuous Stirred Tank Reactor
Cu	:	Copper
DAF	:	Dissolved Air Flotation
DALY	:	Disability Adjusted Life Years
DO	:	Dissolved Oxygen
DOC	:	Degradable Organic Carbon
DOE	:	Department of Environment
FU	:	Functional Unit
FW	:	Food Waste
GDP	:	Gross Domestic Product
GHG	:	Greenhouse gas
GWP	:	Global Warming Potential
H	:	Hydrogen
H_2S	:	Hydrogen Sulphide
HEI	:	Higher Educational Institution
Hg	:	Mercury
IPCC	:	Intergovernmental Panel on Climate Change
ISO	:	International Organization for Standardization
IWM	:	Integrated Waste Management

K	:	Potassium
kwh	:	kilo-watt-hour
LA	:	Local Authority
LCA	:	Life Cycle Assessment
LCI	:	Life Cycle Inventory
LCIA	:	Life Cycle Impact Assessment
LCT	:	Life Cycle Thinking
MBT	:	Mechanical Biological Treatment
MCF	:	Methane Correction Factor
MFA	:	Material Flow Analysis
Mg	:	Magnesium
MHLG	:	Ministry of Housing and Local Government
Mn	:	Manganese
MSW	:	Municipal Solid Waste
Mt	:	Mega-ton
MW	:	Mega-watt
N	:	Nitrogen
N_2O	:	Nitrous Oxide
NGO	:	Non-Governmental Organization
NH_3	:	Ammonia
Ni	:	Nickel
NIMBY	:	Not In My Back Yard
NMVOC	:	non-methane volatile organic compounds
NO_2	:	Nitrogen Dioxide
NSWMD	:	National Solid Waste Management Department
NSWMP	:	National Strategic Plan for Solid Waste Management
OM	:	Organic Matter
OMSW	:	Organic Municipal Solid Waste
OPEX	:	Operational Expenses
OX	:	Oxidation Rate
P	:	Phosphorus
PAH	:	Polycyclic Aromatic Hydrocarbon
Pb	:	Lead
PCB	:	Printed Circuit Board
PDF	:	Potentially Disappeared Fraction

Pt	:	Point
PTE	:	Potentially Toxic Elements
PVC	:	Polyvinyl Chloride
SD	:	Standard Deviation
SFA	:	Substance Flow Analysis
SWPCM	:	Solid Waste and Public Cleansing Management
TC	:	Transfer Coefficient
TKN	:	Total Kjeldahl Nitrogen
TOC	:	Total Organic Carbon
TS	:	Total Solids
UMCC	:	Universiti Malaya Composting Center
UNEP	:	United Nations Environment Program
UNFCCC	:	United Nations Framework Convention on Climate Change
VS	:	Volatile Solids
ww	:	wet weight
YW	:	Yard Waste
Zn	:	Zinc

1. INTRODUCTION

1.1 BACKGROUND OF STUDY

Waste is defined as something that is no longer wanted or valuable. Today, society has recognized that the production of waste is the by-product of social development. Moreover, recyclable materials and energy can be recovered from waste. However, waste recovery is no longer a new idea where recycling programs have been implemented worldwide. However, environmental impacts from waste management is getting more concern by the public with higher awareness on sustainable development for instance; greenhouse gases (GHGs) emissions. Life cycle thinking is being applied in current waste management, recovering waste (e.g. municipal solid waste) for resource to the greatest extent possible.

Organic fraction in Municipal Solid Waste (OMSW) can be a valuable resource for recycling when they are managed reasonably and effectively; in contrast, they affect the environment negatively when not managed properly. OMSW in the present thesis refers to food waste (FW) and yard waste (YW) generated from residential, institutional and commercial areas. FW in particular, is moist and contain protein-rich organics which easily rotten and induce odor problems. They make it difficult to collect and transport food wastes to a disposal site. Furthermore, disposal of FW in landfills or incinerators creates significant adverse impacts on the environment and cost (Kim and Kim, 2010). In view of the negative environmental impacts, OMSW is getting more and more attention from the stakeholders across the world. For instance, Singapore has initiated food waste conversion and material recycling program and achieved up to 30% recycling rate in year 2012 through Singapore Green Plan 2012 (Khoo et al., 2010). Besides, Korean government has shown its initiative in several policies for effective food waste management. These included food waste reduction and separate collection from sources and the prohibition of direct disposal of food waste in landfills.

Pursuant to these policies as mentioned above, FW management in many regions has attracted growing attention in recent years, and it has greatly changed in a short period of time, with a rapid increase of recycling and an decrease of landfilling (Lee et al., 2007). In Malaysia, OMSW accounts for about 50% of total daily Municipal Solid Waste (MSW) generation (JICA, 2006), and its proper management has become one of the most actively debated issues in the last decade. Most OMSW is directly dumped with MSW, but it continuously provoked complaints in association to pollution and odour problems. In line with the great attention on OMSW worldwide, environmental assessments of alternative OMSW management in several areas have been carried out by researchers (Lundie and Peters, 2005; Lee et al., 2007; Lai et al., 2009; Colón et al., 2010; Khoo et al., 2010; Saer et al., 2013). Typical alternative OMSW recovery strategies are composting, energy recovery through anaerobic digestion, incineration and animal feed in order to utilize available resources and at the same time reduce the environmental impact of landfills.

1.2 WASTE MANAGEMENT IN MALAYSIA

MSW management is one of the main challenges in developing countries especially in the urban regions. This challenge applies to Malaysia as well, a developing country in South East Asia. Generally, the main goal of waste management is to remove waste from human settlements and to ensure hygienic environment in shortest duration of time. In order to achieve the above, national goals associated to MSW management is crucial for every country or region (Brunner and Fellner, 2007). The general goals of waste management are: (1) environmental and public health protection; (2) resource conservation; (3) waste management without leaving problems to the future (Brunner and Fellner, 2007).

Federalization of MSW management in Malaysia after passing of the Solid Waste Management and Public Cleansing Act 2007, creates a major resolution to the MSW management sector in the country (Fauziah and Agamuthu, 2012). Rapid increase in annual generation of MSW in Malaysia, results in an urgent need for a more efficient waste management system (MHLG, 2005). The fact that OMSW when disposed in landfills with other waste streams, may create severe and long lasting environmental impacts in term of leachate pollution and GHGs emission, hence defeats the ultimate objective of aftercare-free waste management as remedy and post-closure treatment of landfills has to be carried which is deemed a burden for the future generations. Despite sustainable landfilling practice as provisioned in the national waste regulations, waste minimization through localized recycling programs has been actively introduced by the Federal government of Malaysia to increase the national recycling rate. However, the direct disposal of 95% of total MSW generated has resulted in more than 10 million tons of MSW being disposed in landfills due to the absence of integrated waste management system in large scale. The immense dependency on landfills in Malaysia necessitates that resource recovery has to be improved through various waste which include OMSW and the environmental impacts have to be studied.

1.3 IMRPOVED NATIONAL MSW MANAGEMENT

The National Solid Waste Management and Public Cleansing Act 2007 resulted in significant changes in the government's policy regarding the national waste management strategy. According to National Strategic Plan for Solid Waste management (NSWMP) in Malaysia (MHLG, 2005), a target to achieve 22% recycling rate by year 2020 has been set. Secondly, NSWMP necessitates the conservation of resources (e.g. recycle of food waste into compost) and protection of human health. Hence, the substances and pollutants contained in waste have to be addressed. This is due to the reason of these substances may pose potential negative impacts to environment and human health as hazardous material or may be a useful resource for recycling purpose.

To assess if the specific national waste management goal is achieved, a comprehensive life cycle assessment (LCA) has to be carried out to assess the environmental impacts for the life cycle process from collection to final disposal. The preference of waste management options has been outlined in waste hierarchy which is highly adopted by many countries on how waste management should take place. The hierarchy is outlined as follows: prevent waste generation if possible; reuse or recycle the waste; what cannot be recycled should be energy recovered; and finally, the least favoured option is disposal in landfills (Figure 1.1). However, the waste hierarchy does not consider the technical variables and environmental factors involved and hence can not support decision on specific waste management choices.

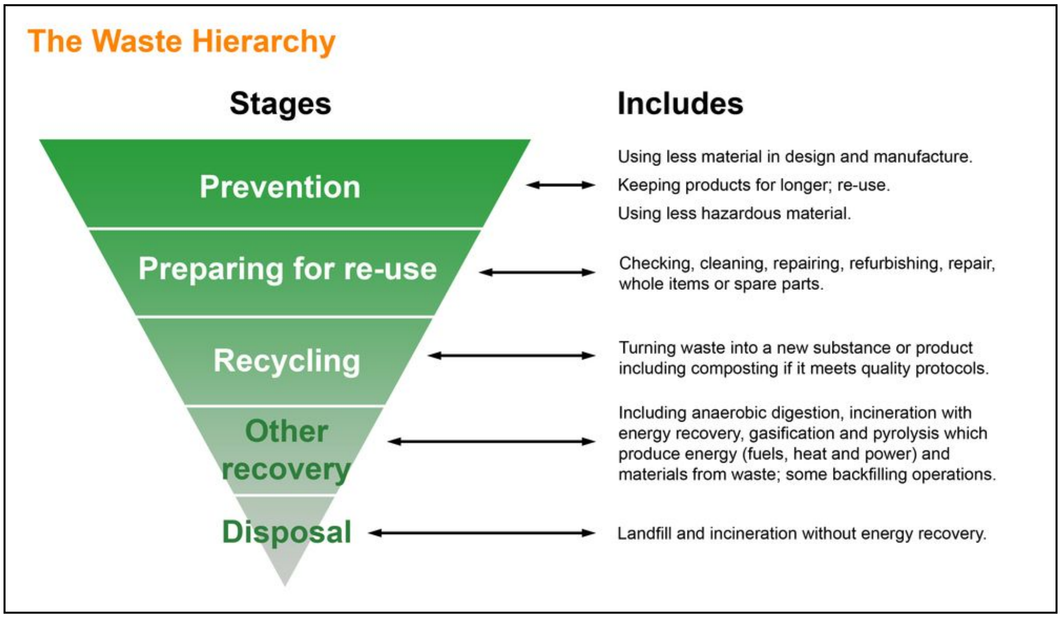

Figure 1.1: Concepts of the Waste Hierarchy (Schmidt et al., 2007)

Waste management planning has become an institutionalized element in public planning efforts in all nations worldwide. Local authorities have been facing increasing demands to deliver a sustainable approach to waste management. Identification of areas in which specific measures should be taken to reduce the environmental impacts of waste management is important. Environmental impacts in addition to evaluation of technical and economic aspects should be considered to evaluate the performance of waste management alternatives in the decision-making process. It is well accepted that LCA concepts and techniques provide an excellent framework to evaluate MSW management strategies.

1.4 ENVIRONMENTAL EVALUATION

1.4.1 LIFE CYCLE ASSESSMENT (LCA)

Life Cycle Assessment (LCA) is a tool to assess the potential environmental impacts and resources used throughout a product's life cycle (ISO, 2006a). The term 'product' includes both goods and services (ISO, 2006a). LCA includes assessment from raw material extraction to manufacturing and consumption by users and followed by disposal or recycled (Finnveden et al., 2009). The difference of he life cycle of waste as compared to that of product is the system boundary of waste is considered from the point of disposal.

LCA has been used in conjunction with various waste streams and the waste management related activities such as collection, landfilling, thermal treatment and biological treatment are modeled. Integrated waste management system can be assessed by LCA through system expansion. For instance, anaerobic digestion is investigated as an waste management sector integrated to energy production sector where energy is recovered from organic waste. Therefore, the assessment of integrated sectors is possible for waste management with LCA.

LCA analysts are interested in forecasting future materials/energy fluxes on regional and global scales, as a function of various economic growth and regulatory scenarios. LCA include not only the indirect inputs to production process, and associated wastes and emissions, but also the disposal fate of any product. The crucial stage in the analysis is quantitative comparisons of material flows and transformations as well as energy fluxes (e.g. fuels, combustion products). However, the data required to accomplish this are not normally available from published sources. Theoretical process descriptions from open sources may not correspond to actual practice. Moreover, so-called 'confidential' data are unverifiable and may well be erroneous (Ayres, 1995). This deficiency can be overcome with the assistance of formal material balance accounting system such as substance flow analysis (SFA).

1.4.2 SUBSTANCE FLOW ANALYSIS (SFA)

Brunner & Rechberger (1986) define the SFA method as "a systematic assessment of flows and stocks of material within a system. It connects the sources, the pathways, intermediate and final sinks of a material". Identification and quantification of environmental loads is possible through balancing the input and output flow of the respective waste flows. Additionally, the SFA allows estimation of the accumulation or depletion of material stocks and some minor changes of those stocks. A distinction between bulk material flow analysis (MFA) and substance flow analysis (SFA) is made where the first considers the total flows of materials, while in SFA the flows of specific substances are studied (e.g. of nitrogen compounds or heavy metals). A couple of waste management model which apply MFA approach such as ORWARE, EASEWASTE and STAN (Dalemo et al., 1997; Eriksson et al., 2002; Christensen et al., 2007; Cencic and Rechberger, 2008).

1.5 PROBLEM STATEMENT

1.5.1 INCREASING WASTE GENERATION

MSW generation is increasing in most developing countries in ASEAN countries. Malaysian waste generation has been increasing drastically over the past 10 years where solid waste generation was estimated to increase to about 15.6 million tons in 2020. Urban community of which made up approximately 70% of total population, generates more waste in the country. In 1980, Malaysian population was 13 million, increased to 27 million in 2010. In overall, the amount of waste generated is growing with population of a region.Besides, it was reported that increase of living standards and changing of spending attitude also lead to increase of waste volume. MSW generation in Kuala Lumpur in relation to population growth is shown in Table 1.1 below.

Table 1.1: MSW generated in Kuala Lumpur for 1998- 2006 (Agamuthu and Victor, 2011)

Year	Kuala Lumpur population	MSW generation (tons/day)
1998	1446803	2257
2000	1787000	3070
2005	2150000	3478

Waste management has to be carried out in sustainable way in view of the projected increase in MSW generation nationwide (Agamuthu and Victor, 2011). The MSW generation in ASEAN countries are illustrated in Figure 1.2.

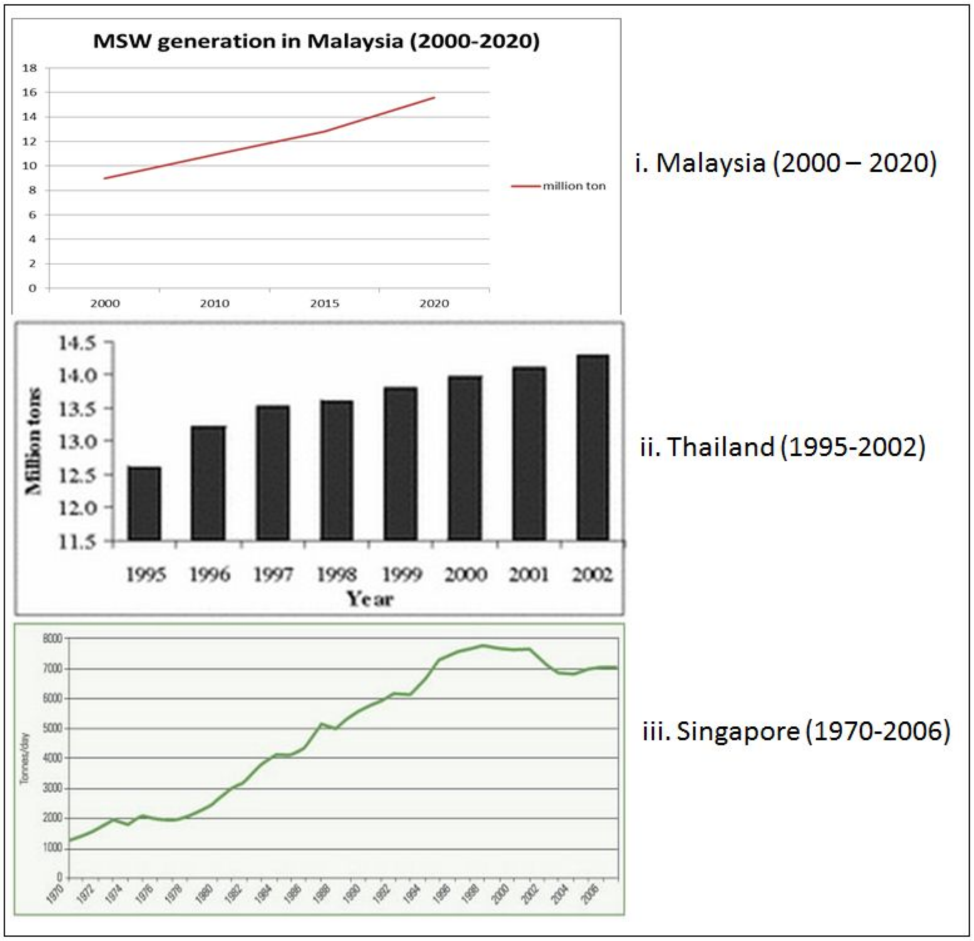

Figure 1.2: MSW generations in Malaysia, Thailand and Singapore; i. (Agamuthu and Victor, 2011); ii. (Chiemchaisri, Juanga et al., 2007); iii. (Bai and Sutanto, 2002)

Prior to the federalization of solid waste management, waste disposal site operations resulted in the problems of surface water pollution, air pollution and the landfill slopes failure were alarming (Fauziah et al., 2004). As a result, national level effort was introduced to improve the management of WSM through the regulation of Refuse Collection & Disposal By-Laws (1983). Moreover, public demand on better waste disposal system has imposed a huge challenge to the existing waste disposal option. Furthermore, the Not-In-My-Backyard (NIMBY) attitude has worsen the situation where replacement of rapidly filling dumping sites further away from the urban areas (waste generated), increased the cost of waste handling, particularly in term of waste transportation (Agamuthu et al., 2009). Hence, measures of waste minimization through implementation recycling programs has to be taken into consideration. FW which accounts for approximately 50% of total waste stream is however not given much attention. If converted for recycling, would bring upon benefits not only to the environment in term of resource conservation, but also to the cost-saving, particularly the waste handling process.

1.5.2 IMPACTS OF INCREASING OMSW GENERATION

OMSW has been dominant in the MSW stream in most ASEAN countries as shown in Figure 1.3. OMSW is known to create problems throughout the life cycle of waste management namely: increase the cost of combustion in incineration process; emission of odorous compounds during collection; water pollution at landfills and so on (Wangyao et al., 2009). The percentage of waste composition (wet weight) in Malaysia is tabulated in Table 1.2 between 1975 and 2005. OMSW generation in Malaysia is overwhelming and most of the waste generated ended up in the waste stream to be disposed in landfills.

Table 1.2: The Waste Composition (wet weight) in Malaysia from 1975 to 2005

Waste Composition	1975	1980	1985	1990	1995	2000	2005
OMSW	70.2	56.2	48.3	48.4	45.7	43.9	51.5
Paper	7.0	8.0	23.6	8.9	9.0	23.7	16.0
Plastics	2.5	0.4	9.4	3.0	3.9	11.2	15.0
Glass	2.5	0.4	4.0	3.0	3.9	3.2	3.0
Metal	6.4	2.2	5.9	4.6	5.1	4.2	3.3
Textiles	1.3	2.2	NA	NA	2.1	1.5	2.8
Others	0.9	0.3	8.8	32.1	4.3	12.3	8.4

OMSW generation with alarming increasing rate recorded is giving numerous burdens to the government in term of disposal as more and more sanitary landfills are required. Despite the effort in upgrading the existing dump sites to landfills in order to minimize water pollution and to protect public health, resource conservation is becoming more important. Waste generated is indeed an useful resource, if recycled, would bring upon great positive impacts to the environment. Recycling of papers, plastics and aluminum has been well established, however, the recycling of OMSW, which make up approximately 50% of the total waste generated in Malaysia, has been given less attention.

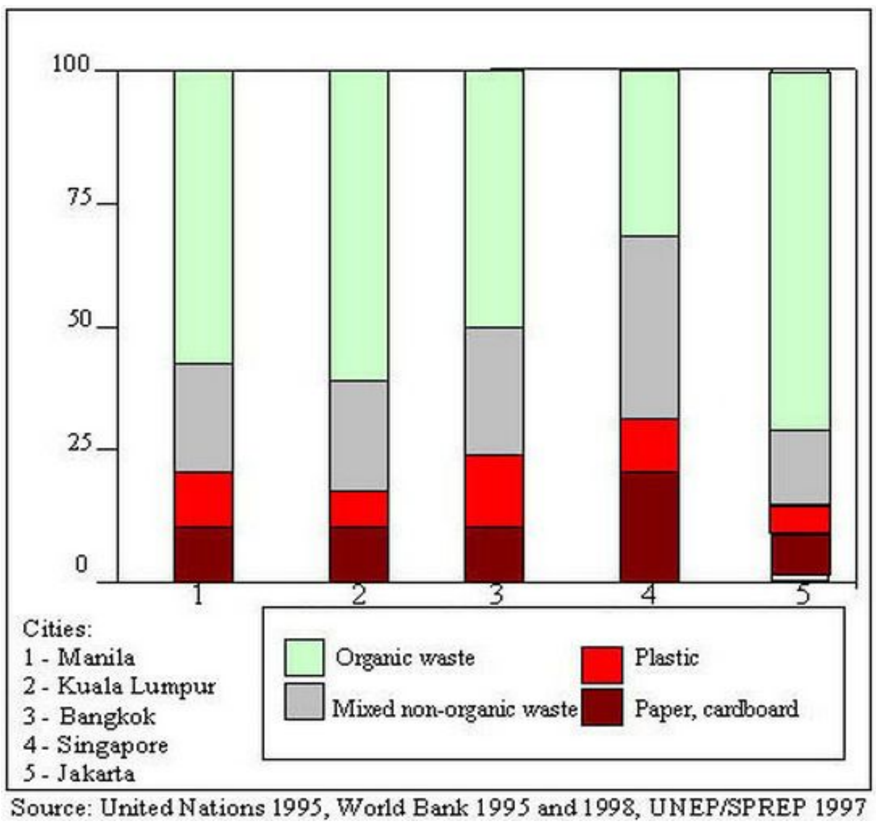

Figure 1.3: Composition of MSW in ASEAN countries in 2001

1.5.3 LACK OF RESEARCH IN COMPREHENSIVE EVALUATION OF TH E MALAYSIAN OMSW MANAGEMENT SYSTEM

There has been little research on the comprehensive evaluation of the Malaysian OMSW management system in the environmental view so far despite the interest in studying individual MSW treatment technologies. A study has been done on Kuala Lumpur MSW and the characteristics of the MSW (in general) are shown in Table 1.3 below. However, no study has been carried out upon the characteristics of OMSW in Malaysia. The data gap has led to the urgency for characteristic study of OMSW which is dominant in MSW stream in most ASEAN countries.

Table 1.3: Characteristics of MSW from Kuala Lumpur (Kathirvale, Muhd Yunus et al. 2004)

Proximate analysis (wet)	**Weight %**
Moisture content	55.01
Volatile matter content	31.36
Fixed carbon content	4.37
Ash content	9.26
Elemental analysis (dry)	**Weight %**
Carbon content	46.11
Hydrogen content	6.86
Nitrogen content	1.26
Oxygen content	28.12
Sulphur content	0.23
Heavy metal (dry)	**ppm**
Chlorine	8.840
Cadmium	0.99
Mercury	0.27
Lead	26.27
Chromium	14.41
Other paramaters	
Bulk density (kg/m^3)	240
Net calorific value (kcal/kg)	2180

Moreover, uncertainty is a fact of life in all matters pertaining to the physical world. All physical measurements are uncertain to some degree, particularly MSW which exhibit great extent of heterogeneity. The uncertainty has to be recognized and taken into account. Despite the LCA framework which have been frequently used for assessment elsewhere, the problem of transparency and reliability of data is still unsolved, particularly the developing countries where lack of background data. Substance-oriented approach can be integrated into LCA to overcome the data deficiency problem. MFA and SFA have been introduced for waste management evaluation in order to provide a transparent and reliable data inventory and fill the data gap for further assessment (Brunner and Fellner, 2007).

The knowledge and information of elemental composition of OMSW and its elemental flow along the process of management are not known. These knowledge is important and necessary for authorities and related stakeholders to plan and make decision in relation to financial and regulatory matters. Information is necessary in order to monitor and control waste management systems as well as to make decisions regarding regulatory, financial and institutional actions.

However, this knowledge gap can be overcome by using Substance Flow Analysis (SFA). The quality of secondary data obtained from literature or previous studies from other continents is doubted and does not reflect the reality of local waste management scenario. Hence, there is an urgency with regards to the basic recent data on the waste components and waste management processes.

1.5.4 GOAL-ORIENTED WASTE MANAGEMENT

Today, many countries have defined far-reaching goals for waste management, and have implemented sophisticated legislative, technological and logistic system to reach these goals (Doberl et al., 2002). Many countries especially the developed ones meet the hygienic requirements so well and they are now focusing on the sustainable MSW perspective, for instance, the after-care free landfilling measures. (Brunner and Fellner, 2007; Mastellone et al., 2009). In Malaysia, however, sustainable MSW development is rather new in view of the recent effort in federalizing MSW management under the provision of SWPCM Act 2007 which was fully enforced since September 2011. In parallel with the increasing public demand, environmental prevention from MSW management activities has become important. This has resulted in development of safe and reliable sanitary landfills. Additionally, the 3R (Reduce, Reuse, Recycle) concept was introduced as a means to replace primary resources as well as reducing the pollution created by raw material extraction and processing activities (NSWMD, 2012a). It is very important to have shared goals as target for comparison between several option. The waste management goal of Malaysia is shown in Table 1.4 below. Priority has been given to increased recycling rate and composting of OMSW. The question is whether there is any evaluation methodology or framework available for a transparent and reliable assessment?

Table 1.4: National Goal in MSW management in Malaysia (Samsudin and Don, 2013)

Treatment Methods	Percentage (%)		
	2002	2006	Target 2020
Recycling	5.0	5.5	22.0
Composting	0.0	1.0	8.0
Incineration	0.0	0.0	16.8
Inert landfill	0.0	3.2	9.1
Sanitary landfill	5.0	30.9	44.1
Other disposal sites	90.0	59.4	0.0
Total	**100.0**	**100.0**	**100.0**

Moreover, Malaysia ratified the United Nations Framework Convention on Climate Change UNFCCC in 1994 and the Kyoto Protocol in 2002 (NC2, 2011). Half of MSW in landfills is FW largely due to the fact that recovery rates for food waste are negligible. Peninsular Malaysia generated 20,500 tons of MSW in 2007 whereas Sabah and Sarawak generated 1,210 tons and 1,988 tons of MSW respectively in 2007. Malaysia's GHG emission was reported 222.99 Mt CO_2eq in 2000 (NC2, 2011). The main contributor of CO_2 is energy industries, followed by landfills and emissions from agricultural. Hence, landfills, energy industries, transport, manufacturing, forest and grassland conversion are among the highest source of GHG emissions. In this particular study, we will focus in landfill where most OMSW is deposited.

In view with the major source of emissions contributed by waste sector, mitigation measures should have been taken. Waste sector mitigation measures were assessed pertaining to landfill of all waste. However, very little study has been carried out upon food waste (make up approximately 50% of the total waste collected).

Comparison between the BAU (Business as Usual) scenario and alternative means to increase the recycling rate to 22% via diversion of OMSW from landfill through biological treatment processes should be carried out. These alternative scenarios are based on the strategic plans as stated in the federal policies on waste management. Furthermore, the application of compost on agriculture land have not been included in the mitigation study, for instance, substitution of nitrogeneous fertilizer with compost reduce the release of N_2O and avoidance of using raw material to produce fertilizer. Hence, national waste management should be enhanced to include diversion of OMSW from landfill through recycling and thus reduce the emission of GHGs from landfill sites, which in line with the target of 40% carbon intensity reduction as one of the commitments towards developed nation.

1.6 HYPOTHESES

Hypothesis proposed: *Recycling of OMSW is more environmentally beneficial, compared to landfill as well as contribute to net carbon emission reduction.*

1.7 OBJECTIVES OF STUDY

The main aim of the thesis is to study the environmental benefits of OMSW management, which in the present thesis refer to FW and YW recycling in Malaysia. Hence, the environmental impacts of the alternative OMSW management/treatment have to be studied. In order to achieve the main goal, the objectives as listed below have to be achieved:

The objectives of the study are:

i. To determine the characteristics and elemental composition of OMSW generated in Malaysia.

ii. To provide a comprehensive Life Cycle Inventory (LCI) of medium scale co-composting of OMSW

iii. To quantify the emissions in relation to OMSW input for alternative management and to evaluate environmental impacts and benefits associated to alternative OMSW management system using an approach of life cycle assessment.

iv. To quantify the total CO_2 equivalent reduction potential from OMSW recycling via composting as compared to landfilling (Business-as-Usual) in Peninsular Malaysia.

1.8 SCOPE OF STUDY

This study focuses on environmental assessment for OMSW management alternatives in Malaysia. The first objective of the study is to identify the characteristics and elemental composition of OMSW generated in Malaysia. The FW samples were collected from various sources which include FW generated from academic buildings, residential hostels, cafeterias, public areas. Yard waste (landscaping and street cleansing) is collected separately from the MSW (academic buildings, residential hostels, commercial areas) and disposed of in separate Ro-Ro containers. The sampling was carried for two complete weeks representing one academic week and one semester-break week. The samples were taken from the ‘intermediate’ collection center in UM campus as it receives MSW generated from all activities carried out at campus.

MSW system model in UM is applicable in Malaysia as waste generated from both institutional and residential sources are rather common where both have high composition of OMSW (40% and 45% respectively). The model studied in the present thesis was based on real OMSW composting project from a higher educational institution in Malaysia which best represent a local government comprising residential and institutional sectors (common socio-economy activities). The model based on institutional OMSW management can be easily applied to a larger scale in local government by having common socio-economy acitivities (residential and institutional). The full LCI creates a basis for environmental modelling and assessments of composting systems for alternative OMSW management. The results of the present study provides information about all significant inputs and outputs in the form of elementary flow to and from the environment from all the unit processes involved.

The comprehensive substance balance study on the OMSW composting has provided information and background data related to the production of compost from FW and YW. The feedstock was obtained from various sources and experiments were carried out in UM composting center with two different runs representing the different size of the composting pile. SFA was carried on both piles to contribute to the LCI data for the composting process. The electricity and energy consumption were recorded throughout the 60-days composting process. Collection and transportation of feedstock as well as the application of compost on land were excluded in the present scope of study.

The environmental impacts from alternative OMSW management were assessed by using LCA methodology. The scope of the study includes data collection of OMSW collection, transportation, treatment (composting and anaerobic digestion), disposal in landfill and use-on-land of compost. The LCI data was partially contributed by the LCI data from first objective in the present thesis. Modelling was carried out with SimaPro LCA software based on Life Cycle Impact Assessment methodology to identify the hotspots in the life cycle of OMSW management.

In the present thesis, total CO_2 equivalent emission from OMSW recycling via composting was assessed as stated in the final objective. The estimate of CO_2 emissions was then compared to existing OMSW management (disposed) in order to calculate the CO_2 emissions reduction potential. This objective of the present study is to assess the total CO_2 equivalent reduction potential from OMSW recycling via composting as compared to landfilling (Business-as-Usual) in Peninsular Malaysia in year 2020 as compared to base year of 2012. The effort of the study is in line with the Malaysian government voluntarily initiative in achieving 40% reduction of carbon emission intensity (tCO_2eq/capita) by 2020.

1.9 FOCUS ON OMSW

The present study focuses on OMSW which make up the largest portion in municipal solid waste (MSW), OMSW management is complex due to its varied composition. Therefore, assessment of the environmental impacts from OMSW management is necessary prior to implementation of policy to mandate separation of OMSW from main waste stream. OMSW was gaining interest in the present study as it is characterized as having high moisture content which increase the combustion cost if incinerated with other MSW. Besides, OMSW is suitable to for composting and anaerobic digestion as compared to other MSW due to its high organic carbon content.

OMSW was decided to be diverted from waste stream before disposal and turned into compost or utilized for biogas production. These alternative will then be compared with current practice in terms of environmental impacts and benefits. The anticipated environmental benefits of anaerobic digestion and co-composting are:

a) Energy recovery

b) Utilization of nutrients for planting.

1.10 ORGANIZATION OF THESIS

This thesis has been divided into five chapters as follows:

Chapter One covers the current environmental problems associated to MSW management in Malaysia. It also touches on the problems contributed by the rising generation of OMSW and the current national waste management goals in association to the National Waste Management and Public Cleansing Act 2007. The role of HEIs in leading towards good modal in sustainable waste management has been covered. This chapter also presents the problem statements, objectives of the study, significance of the study and briefly touches upon the data deficiency problem in LCA study, particularly in MSW and expresses the lack of comprehensive environmental assessment on food waste management in Malaysia. For better presentation and understanding, each objective is presented in each chapter from chapter three to chapter eight. Every chapter includes the introduction, methodology, results, discussions and conclusions respectively.

Chapter Two presents the literature review that looks at the foundation of this study and sessions related to status of MSW management in Malaysia. The establishment of LCA methodology and future direction are presented. Detailed description of the LCA and the methodology following the ISO 14000 series were included. The description of food waste management modeling followed by a brief review of other similar LCA studies on food waste management in included.

Chapter Three in general describes the methodology used in the study. To fit the standard of ISO 14040 series set by the International Organization for Standardization (ISO), the assessment is conducted thoroughly and each was explained in details. Assumptions and limitations are also described in this chapter.

Chapter Four took into consideration the objective of the study through analysis. Each subtopic in this chapter is based on four specific objectives of the study mentioned in Chapter 1 and finally provides corrective suggestions for identified problems

Chapter Five concludes the findings from this study and provides suggestions for future studies.

2. LITERATURE REVIEW

2.1 OVERVIEW

This chapter provides an insight on the overview of the current MSW management in Asian region, including Malaysia. The section first summarizes the alternative management of MSW in some countries and further elaborates the challenges faced. The high generation of OMSW is highlighted and various management technologies are discussed. Secondly, this features of LCA are explained and the implementation of LCA in solid waste management are further discussed and compared. The chapter is finally ended with examples of LCA models application in bilogical treatment of OMSW.

Asia is characterized by widely varying municipal solid waste management practices. MSW generation is increasing as a result of population growth, urbanization and changing consumer behavior (Agamuthu and Fauziah, 2011). Approximately 60% of local authorities' budget are allocated to MSW management and disposal (JICA, 2006). Integrated approach of MSW management is widely debated (MHLG 2005; JICA, 2006). Many cities have been actively practicing recycling of waste materials. Common recyclable materials include metals, paper, cardboard, plastics, textiles, glass, wood, timber, plastics, waste oil and grease, and construction debris. The management of waste materials requires immediate attention, especially in countries such as China, Malaysia and South Korea due to emerging industrialization. By 2025, approximately 1.8 million tons of waste per day is expected to be generated from Asian region alone. Asian countries are among the main contributors of MSW. Table 2.1 shows the increase of MSW generation from several Asian countries from 1995 to 2025 with Gross National Production (GNP) categories.

Table 2.1: MSW generation in Asian Countries (1995 and 2025)

Country	GNP Per Capita (1995 US$)	GNP Per Capita in 2025 (1995 US$)	Current Urban Population (% of Total)	2025 Urban Population (% of Total)	Current Urban MSW Generation (kg/capita/day)	2025 Urban MSW Generation (kg/capita/day)
Myanmar	240	580	26.2	47.3	0.45	0.6
Vietnam	240	580	20.8	39.0	0.55	0.7
Laos	350	850	21.7	44.5	0.69	0.8
Indonesia	980	2,400	35.4	60.7	0.76	1.0
Philippines	1,050	2,500	54.2	74.3	0.52	0.8
Thailand	2,740	6,650	20.0	39.1	1.10	1.5
Malaysia	3,890	9,400	53.7	72.7	0.81	1.4
Singapore	26,730	36,000	100.0	100.0	1.10	1.1

Source: Adapted from Badgie et.al. (2012)

The MSW are generated from residential, commercial, institutional, industrial, and even tourist activities (Riber, 2007; Taib and Nakagoshi, 2012). As expected, characteristics of MSW vary across cities and seasons. Previous reports revealed that the MSW generated from rural area have higher content of organics but few plastics (Nordtest, 1995; Tanskanen, 2000). In developed countries, MSW is quantified and characterized by municipal authorities at regular intervals (ASTM, 2003; Obersteiner et al. 2007; Slagstad and Brattebø, 2012). Developed cities such as Singapore and Tokyo generate more papers and plastics while cities in China produce MSW with higher ash content due to common use of coal. The recyclable materials content is low in MSW generated from lower income cities due to active informal recycling activities (Gidarakos et al. 2006).

2.1.1 HIGH INCOME COUNTRIES

Reports revealed that waste generation rate is higher in high income countries in comparison to other countries with lower income and the characteristic of MSW varies significantly across cities. Public education on waste reduction, separation at source, and recycling, curbside collection and volume-based collection fees is actively implemented in the economically more advanced urban cities. For instance, South Korea implemented a fee system based on volume of waste disposed since 1995 (World Bank, 1999). Separation of recyclables are compulsory and wastes has to be put in bags where the separated materials are to be collected by local governments. This policy in Korea has resulted in up to 30% reduction of waste disposal (World Bank, 1999).

Japanese cities are now actively promoting various waste reduction strategies. Residents are encouraged to exchange and unwanted clothes or daily necessities within neighborhoods. For instance, Osaka Recycling Monthly to encourage exchanges of furniture and electrical goods as well as the waste education activities promoted by the Hong Kong Productivity Council have resulted in significant reduction in waste disposal. Sophisticated waste trading businesses too play vital role in promoting recycling effort. For instance, approximately more than a quarter of the total Singaporean MSW generated is recycled (Khoo et al., 2012). Moreover, private recycling enterprises are allowed to set up recovery plants on land near to closed dumping grounds.

2.1.2 MIDDLE AND LOW INCOME COUNTRIES

Countries with low income produced 0.64-0.73 kg MSW per capita per day in 1995. Informal recycling of materials have always been dominant in the middle to low income cities. Recyclable materials which are ususally picked out from mixed MSW by the scavengers are paper, plastics, aluminum, electronic waste, metal which are more valuable in recycling market (Kaseva and Gupta, 1996). The main recyclables are purchased by individual recyclable collectors which are then sold to larger dealers and wholesalers, which may exported or processed locally. It is common in cities like Hong Kong, Jakarta and Kuala Lumpur of the existence of large private industries collecting and reselling the recyclable materials (Vesilind, 2002).

It is interesting to note that waste recovery and recycling has been organized at the city level and supported by national ministries in China and Vietnam. There are large recovery companies assigned by municipalities to collect recyclable materials from offices, institutions, and factories. Besides, public has options to sell papers, bottles and clothes at neighborhood collection centers. However, the centers have declined due to competition and hence, more recyclables are disposed of with MSW. However, source-separation of household recyclable materials effort have been continuously implemented in residents complexes (World Bank, 1999).

In conclusion, several cities in developing countries have tried several ways to implement source separation in selected neighborhood but none of them has persisted despite funded under UNEP's Asia-Pacific (UNEP, 2010).

2.2 MUNICIPAL SOLID WASTE MANAGEMENT IN MALAYSIA

Malaysia is a tropical country with land area of 329,847 km^2, separated into two regions by South China Sea. There are 11 states in Peninsular Malaysia while Borneo consists of 2 states. Malaysia is warm and humid throughout the year with temperature ranging between

21 and 32°C and a relative humidity of 80 to 90%. Rainy season hits Malaysia twice a year as result from monsoon wind flow.

Malaysia is a multi-ethnic country which houses 27 million people in 2007, consist of 3 major ethnic group (Malays, Chinese and India) with several other minor ethnic groups. The country is rich in natural resources such as forestry and minerals. The nation's income was contributed by petroleum and agricultural commodities such as rubber, tin, palm oil and timber. The manufacturing industry is emerging for the past 10 years which contribute greatly to the national revenue. The national revenue is greatly contributed by tourism industry as well.

2.2.1 MALAYSIA NATIONAL ENVIRONMENT POLICY

Malaysia has always intended to integrate environmental protection into socio-economy development since the Third Malaysian Plan (1976-80). Furthermore, the National Development Policy of the Second Outline Perspective Plan (1991-2000) categorically states "adequate attention will be given to the protection of the environment and ecology to maintain the long-term sustainability of the country's development." Malaysia's vision 2020 too highlight the importance of conservation of nature resources in the pursuit of economic development.

The Department of Environment (DOE) has played it role in ensuring level of quality of life, health and safety through environmental preservation efforts. DOE is tasked to monitor industrial activities in terms of pollution control and to promote conservation of natural resources. The pollution control strategy is implemented through the enforcement of the Environment Quality Act 1974. The act is the most comprehensive legislation to date for pollution prevention and control as well as for environmental improvement.

The management of non-hazardous waste (MSW) is not included in the jurisdiction of DOE, but lies with local municipalities. The DOE, however, has power to impose pollution controls on waste management facilities, in particular incinerators or landfills through the provision of Environmental Impact Assessment (EIA). This EIA code provides advice to the local municipals on the development of waste management related facilities. DOE however, has not started any massive program related to recycling, even though EQA 1974 provides measures to promote recycling.

2.2.2 DEFERALIZATION OF MSW MANAGEMENT IN MALAYSIA

Prior to 1970s, the government's focus in solid waste management (SWM) was not evident without any policy in place. From 1970s, sanitation related services (SWM and public cleansing) were under the jurisdiction of local authorities (LAs) implemented through the provisions of Local Government Act 1976 (Act 171) and Street, Drainage and Building Act 1976 (Act 133). (Fauziah et al., 2004; Fauziah and Agamuthu, 2012)

State government, as the second tier in Malaysian government administration, shoulders the responsibility to guide and assist LAs in strengthening their institutional and financial capabilities for SWM. At that time, the waste generation back then was as low as 0.5kg/capita/day (Agamuthu et al., 2009). However, Malaysian waste generation is increasing where annual solid waste generation was estimated to reach 15.6 million tons in 2020 (Fauziah et al., 2004). The projected increasing generation of solid waste is anticipated to burden the country's resources and environment in managing this waste in a sustainable manner. (Agamuthu and Victor, 2011). The national program however, did not achieve the desired level of improvement in waste disposal site operations where the problems of surface water pollution, air pollution and the landfill slopes failure were alarming (Fauziah et al., 2004). As a result, national level effort was introduced to improve the improper handling and disposal of municipal and industrial wastes through the regulation of Refuse Collection & Disposal By-Laws (1983). Moreover, public demand on better waste disposal system has imposed a huge challenge to the existing waste disposal option. Furthermore, the Not-In-My-Backyard (NIMBY) attitude has worsen the situation where replacement of rapidly filling dumping sites further away from the urban areas, increased the cost of waste handling, particularly in term of waste transportation. Waste management alone was estimated more than 60% of the annual LA budgets (Agamuthu et al., 2009). In order to satisfy the public needs for efficient waste management system, measures of privatization of MSW management has been undertaken by the national government in September 1995.

MSW management was privatized by some LAs in conjunction with national privatization policy in which to transfer the management and functions from public sector to the private sector. The primary justifications of privatization are the lack of resource (human and financial) by LAs and to prevent further environmental degradation (practice of open dumping) (Fauziah and Agamuthu, 2012). SWM typically accounts for 40% (City Councils) to 60% (District Councils) of the property assessment, which is the main source of income for the LAs (PE-Research, 2008). Privatization was carried out on yearly agreements. Since 1997, solid waste collection and disposal in several LAs in Peninsular Malaysia has been granted to two private operators; Southern Waste Sdn Bhd and Alam Flora Sdn Bhd. The privatization exercise in the northern region by Northern Waste Industries as the designated concessionaire; as well as the exercise in Kelantan, Terengganu, Sarawak and Sabah did not materialize and the LAs continue to undertake the responsibility for collection and transportation of solid waste (Yahaya and Larsen, 2008). However, the landfilling practices were still given less priority unfavourable conditions for the concessionaires, both in term of securing funding from the financial institutions and in term of long term planning (Yahaya and Larsen, 2008; Fauziah and Agamuthu, 2012). Landfill pollution remained as one of the major environmental problems to Malaysia (World Bank, 1999).

After 14 years of interim concessionaire since 1997, federal government decided to continue the privatization scheme in 2011 with a further 22 years concessionaire agreement. To enable the privatization scheme, federal government takes over the executive authority from state government. A draft bill on solid waste management was tabled in 1998 and the contracts of the waste concessionaires were in interim basis. The Solid Waste and Public Cleansing Management Act (SWPCM) 2007 (Act 672) was finally passed by the Parliament in July 2007, which is effective throughout Peninsular Malaysia, Federal Territory of Putrajaya and Labuan. With the gazette of SWPCM Act, federalization of MSW is fully implemented and all related provisions on SWM in the Local Government Act and existing by-laws such as the Refuse Collection, Removal and Disposal By-laws were abolished, while all existing contracts were not terminated.

However, state government has the authority to exempt from the Act 672 and in Peninsular Malaysia; there are three states (Selangor, Perak and Pulau Pinang) that are exempted from the Act. However, some researchers doubted on the ability of the National Solid Waste Management Department (JPSPN) to assume the roles of more than 100 local governments. Consequently, the Solid Waste Management and Public Cleansing Corporation (PPSPPA) was established to manage all MSW operational issues at the Federal, State and Local level, which include the monitoring and enforcement works. The relationships of the respective stakeholder in national MSW management are presented in Figure 2.1.

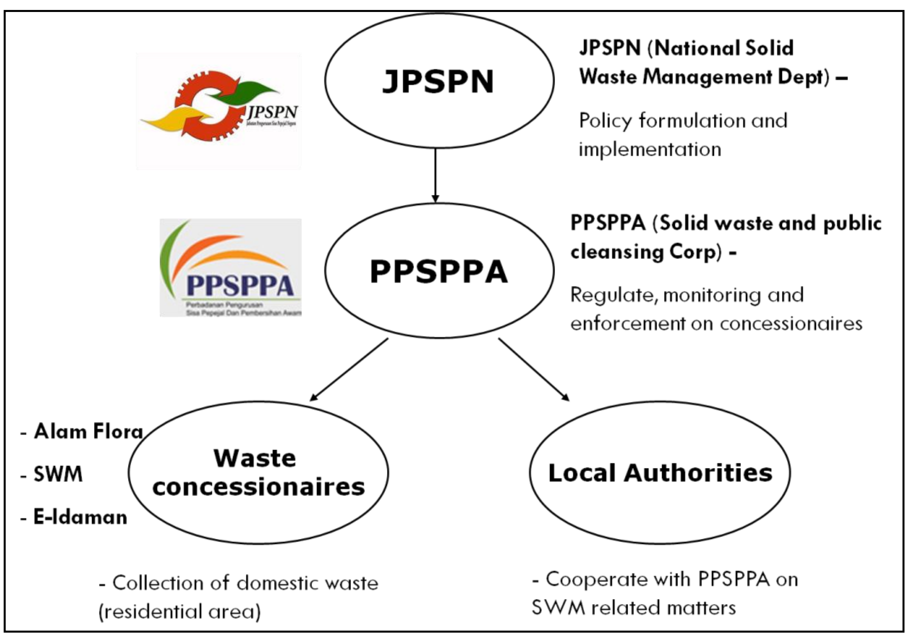

Figure 2.1: Stakeholders of SWM under the New Federal Policy

2.2.3 PERSPECTIVE OF SOLID WASTE GENERATION AND COMPOSITION IN MALAYSIA

Waste generation in Malaysia has increased rapidly over the years by 3% annually due to urban migration, affluence and rapid development. Therefore, early management of solid waste involved very little effort since the waste generated at a manageable level and generally consists of OMSW (food waste, woods and others. Information and data gap for waste characteristics, generation and inventory for waste treatment is still apparent in Malaysia. This data gap leads to inaccurate decision making in term of technology selection, and the operation of facilities.

Daily generation 13,500 ton of domestic and commercial waste was recorded in 1995. This generation has been growing every year. Under the provision of law and regulations, industrial hazardous waste are to be treated separately and are not allowed to be disposed in normal dump sites. Ministry of Housing and Local Government recognized the importance of improving the current solid waste management and adverse impact mitigation due to the rapid increase in waste generation. Table 2.2 shows the waste generation rate from several Malaysian localities from 2000 to 2002.

Table 2.2: Waste Generation in Peninsular Malaysia from 2000 to 2002

States	Population (2000)	Waste generated (tons/day) (2000)	Population (2001)	Waste generated (tons/day) (2001)	Population (2002)	Waste generated (tons/day) (2002)
Johor	2,252,882	1,915	2,309,204	2,002	2,366,934	2,093
Kedah	1,557,259	1,324	1,596,190	1,384	1,636,095	1,447
Kelantan	1,216,769	1,034	1,247,188	1,081	1,278,368	1,131
Melaka	605,361	515	620,495	538	636,007	562
N. Sembilan	890,597	757	912,862	791	935,683	827
Pahang	1,126,000	957	1,154,150	1,001	1,183,004	1,046
Perak	1,126,000	1,527	1,841,489	1,597	1,887,527	1,669
Perlis	230	196	235,75	204	241,644	214
Penang	1,279,470	1,088	1,311,457	1,137	1,344,243	1,189
Selangor	3,325,261	2,826	3,408,393	2,955	3,493,602	3,09
Terengganu	1,038,436	883	1,064,397	923	1,091,007	965
Kuala Lumpur	1,400,000	2,52	1,435,000	2,635	1,470,875	2,755

The latest official study was carried out to assess the MSW generation in Malaysia in 2012. The overall waste generation in Malaysia, including Sabah and Sarawak (household, institutions, commercial and industrial) was about 33,000 ton per day in 2012. On average, the waste generation by urban is relatively higher than that generated in rural area. The housing type group from Medium Cost Landed, High-Medium Cost High-rise an High Cost Landed produce more MSW as compared to Low Cost Landed and Low Cost High-rise. Table 2.3 shows waste generation per capita by region in year 2012. Klang Valley residents produce more waste, 1.35kg/capita/day than the other regions whereas East Coast has the lowest waste generation rate 0.95kg/capita/day.

Table 2.3: Waste Generation in Malaysia by Region in year 2012, Retrieved from JPSPN (2013)

Region	Population	Waste Generation (kg/capita/day)	Total (ton/day)
Northern	6,093,318	1.10	6,724
Klang Valley	7,209,175	1.35	9,702
East Coast	4,076,395	0.95	3,862
Southern	5,190,457	1.28	6,657
Sarawak	2,471,140	1.04	2,571
Sabah	3,293,650	0.98	3,220
Total	28,334,135		32,736

In general, MSW generated contains a high concentration of organic fraction with bulk density above 200 kg/m^3. The characteristics study as shown in Figure 2.2 highlights the main component in Malaysia waste is OMSW (food waste and yard waste), which comprise more than 50% of overall weight. Table 2.4 presents the average generation of household waste generated in 2012. The amount of OMSW (food and garden waste), newspaper, HDPE and noticeably diapers generated by one person was highest in the Klang Valley followed by Southern Zone (which comprises of the states of Negeri Sembilan, Melaka & Johor).

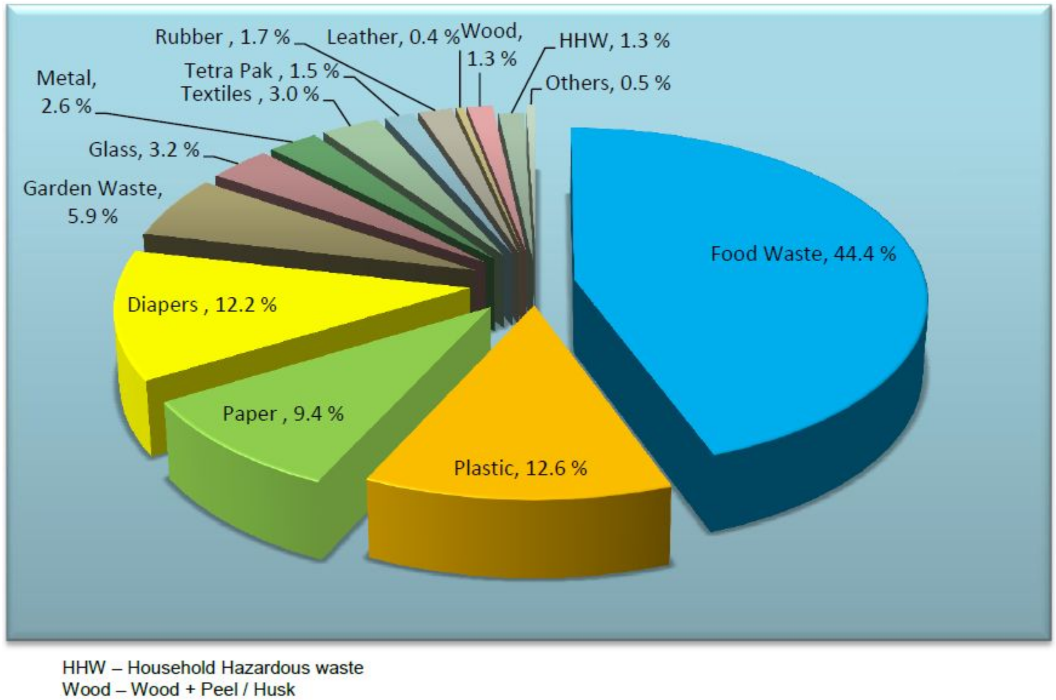

Figure 2.2: Peninsular Malaysia Household Waste Composition (As Generated), retrieved from JPSPN (2013)

Table 2.4: Breakdown of Household Waste Components generated by each person for six Regions, in grams/capita/day

	Waste Components	Northern	Southern	Klang Valley	East Coast	Sarawak	Sabah
Organics	Food Waste	307.51	405.82	416.21	204.27	238.44	225.35
	Garden Waste	40.51	52.06	55.42	29.63	17.57	19.88
	Wood	2.41	2.23	4.71	3.01	5.06	1.52
	Peel / Husk	7.60	6.20	8.01	9.21	6.70	9.10
Paper	Mixed Paper	15.52	13.43	8.69	12.74	10.34	7.53
	Newsprint / Old newspaper	25.41	32.27	41.92	27.02	27.09	22.31
	Cardboard	24.38	30.73	38.03	24.86	31.24	25.01
Plastics	PET	21.29	18.18	19.11	12.70	15.34	19.17
	HDPE	22.38	31.71	33.35	17.32	31.44	28.23
	PVC	4.46	2.07	3.44	3.17	1.47	3.23
	LDPE	27.18	35.85	32.13	24.30	31.82	27.84
	Polypropylene (PP)	9.45	13.79	11.13	7.29	10.87	5.95
	Polystyrene (PS)	12.17	10.02	10.39	10.16	13.26	15.68
	Other Plastics	2.13	0.82	-	-	-	0.48
Glass	Glass Bottle	16.23	27.08	32.64	21.00	31.40	21.97
	Sheet Glass	0.56	0.43	0.29	1.17	0.37	0.16
Metals	Ferrous Metal	14.59	15.44	12.72	13.35	22.21	15.16
	Aluminium	5.18	8.72	7.76	4.68	12.91	6.21
	Other Non-Ferrous Metals	0.41	0.47	0.44	-	0.05	1.14
Household Hazardous Waste	Batteries	0.32	0.39	1.51	0.46	1.46	0.14
	Fluorescent Tube	2.32	2.43	2.48	0.30	1.23	0.42
	E-Waste	0.07	0.54	2.12	1.68	0.32	0.29
	Aerosol Cans	3.12	5.26	7.87	4.59	8.31	3.19
	Paint Container	0.13	1.94	0.54	0.29	-	-
Other Waste Components	Tetra Pak	11.41	12.07	13.52	10.02	10.02	7.94
	Diapers	86.35	113.73	109.93	67.49	57.36	72.59
	Rubber	10.74	10.23	19.73	11.93	13.99	10.61
	Textiles	16.74	16.78	37.01	14.66	26.73	19.15
	Leather	3.91	3.94	2.84	2.04	2.45	0.93
	Porcelain / Ceramic	2.40	2.31	5.47	1.56	4.79	0.35
	Fine	0.62	-	0.03	0.60	-	-

Source: JPSPN (2013)

2.3 INTEGRATED SWM IN SUSTAINABLE DEVELOPMENT AND WASTE MANAGEMENT OPTIONS

Integrated solid waste management (ISWM) can be defined as integration of several technologies and management programs to achieve specific waste management goals. The preference of programs or technologies can be ranked according to the waste problems within the investigated areas by considering the MSW generation data as well as environmental impacts from selected waste management technology through out the life cycle of source reduction, recycling, combustion and landfilling.

2.3.1 SOURCE REDUCTION AND REUSE

Source reduction is the most preferred option in waste management strategy to achieve cleaner environment. It focuses in reduction of the volume and toxicity of waste generated. However, the ideology always contradict with the promotion of products consumption. The benefits of waste disposal reduction are evident. The reasons are listed as below:

a. Decreased landfill life span
b. Strict regulations in constructing new landfills
c. Waste of natural resources
d. Environmental pollution from landfill sites.

Waste reduction can be achieved through several means for instance public education, government policies initiatives, source separation of recyclable and separate collection for recyclables as well as recovery of recyclable materials at the disposal sites.

2.3.2 WASTE SCAVENGER PRACTICE

Some recyclable materials are scavenged from mixed wastes disposed at dump sites. The number of scavengers increases with decrease of recycling programs in local regions as more recyclables reach dump sites. Scavengers are increasing particularly in cities in developing countries despite the attempt to ban scavengers from dump sites to discourage dependence on waste recovery as a livelihood.

Most scavengers are members of poor families migrated from rural areas. They have limited access to formal schooling. The daily incomes of these scavengers are less than USD 3 (World Bank, 1999). Local authorities in Indonesia are controlling the booming amount of scavengers by introducing licenses to the scavengers. This licensing method was successful initially but encountered resistance from the scavengers eventually after several years.

Informally, waste dealers establish materials recovery centers that would sort and process recyclables, in conjunction with source separation programs in surrounding neighborhoods. The separated recyclables materials are purchased and reselled to recycling factories (Agamuthu et al., 2009). There is ongoing argument on the necessity which informal private recycling activities to be included in governmental MSW management: for instance, whether municipalities should enhance the public education to impose separation at source for recyclable materials or whether scavenging should be allowed prior to final disposal.

In conclusion, the practice of recycling of most inorganic materials is essentially market-driven; the price of recycled materials is competitive as replacement with raw resource by recycled materials is expected to be cheaper than using virgin materials for production. However, recycling of OMSW is not common and popular at present. (Kaseva and Gupta 1996; UNEP, 2010).

2.3.3 COLLECTION AND TRANSFER

Cost of MSW management is dominated by collection and transfer activities (Agamuthu et al., 2009). Various common collection methods are employed for MSW collection namely: kerbside collection, indirect collection, with bins placed near common areas which later collected and disposed at landfill sites.

Collection and transfer services in cities of industrialized countries are usually capital-intensive and mechanized with standardized containers to be collected by large vehicles (Baetz and Neebe, 1994). There are regulations governing separated collection of recyclables covering all areas, reaching about 90% (Eriksson and Baky, 2010). Appointed MSW service providers are responsible for the collection and disposal of their solid wastes (Agamuthu et al., 2009).

However, in developing countries, collection and transfer are labor-intensive, although all large cities maintain motorized collection. In multi-story buildings, smaller bins are used for waste collection and transferred to bin centers or collection vehicles. Compactors are often used to collect MSW generated from markets and commercial areas (Agamuthu and Victor, 2011). There no compaction machines fitted on most garbage trucks due to high density of MSW. Cost saving for collection and transportation is greater with the larger size of containers. However, this temporary disposal method encountered several problem including hygienic issues where wastes are thrown surround the bins instead of in the bins. Often, collection crews refused to pick up waste that scattered around the containers as they claimed that this work belongs to street sweepers, hence the container site may remain dirty. MSW collection rates can be lower than 50% in a number of low income cities (Omran et al., 2007). However, collection services cover more than 80% in middle income cities in Asean region. Reports revealed difference in collection service between rich and poor areas (Agamuthu and Fauziah, 2005, Budhiarta et al., 2012).

Decentralized collection is useful for some areas with low population. For instance, the wastes from small villages with low population density are deposited at temporary storage point to be collected by the city service. However, poor communities and the slump areas are not provided with waste collection service by the municipalities due to the reasan that these community do not pay for the collection services and accessibility of the truck to the areas without proper road condition. Morover, lower generation of recyclable materials demotivate the collection crews to serve the area (Marry, 2009).

This practice is becoming common, particularly in developing countries in Asean region (Fauziah et al., 2004). Cost savings to the government becomes the main reason for privatization as the cost of collection is in increasing. Singapore for instance, a private limited company was authorized to take over the MSW collection task since 1996 with private capital fund of US$250 million (World Bank, 1999).

Poor MSW collection and transfer services in the cities in some developing countries are due to the Lack of education and training to the collection crews (JICA, 2006). Besides, collection efficiency is also affected by poor performance of collection trucks, traffic congestion, and lack of public compliance, resulting in low waste collection rates illegal dumping on open land and rivers by irresponsibility collection crews.

The overlapping of responsibility among government agencies with different levels of municipalities also contribute to the problems and has resulted in serious degradation of the environment in terms of hygiene issues, public health and pollution (Fauziah and Agamuthu, 2012)

2.3.4 COMPOSTING

Composting of OMSW is common in countries like Australia, New Zealand and Japan (Colón et al., 2010). The backyard composting is aggressively promoted by providing inexpensive compost bins and training (Liwarska-Bizukojc and Ledakowicz, 2003). OMSW are commonly diverted by the local authorities to reduce MSW for landfilling. However, animal feeding is still in practice to reduce OMSW generation in Asian countries. In cities such as Bangkok, Manila, and Hong Kong, FW are collected separately by pig and poultry farmers for animal feeding.

Besides, pigs and cows are released in waste disposal sites in order to reduce the organic waste, despite the pollution to streams and land resulted from the excreta.

Large mechanized composting plants have been installed in past 10 years in some cities in developing countries, however, most of the are closed due to low efficiency and low utilization (Winkler and Bilitewski, 2007). The reasons given were:

a) high operating and maintenance costs compared to open landfilling;
b) Compost is less acceptable by the farmers as compared to chemical fertilizer;
c) Low quality of compost due to inorganic impurities (e.g. Plastics)
d) Low efficiency of the composting facilities

Open air composting is common in China where the farmers in some cities are instructed to turn waste into compost without separation or pre-treatment. However, this scheme did not last long due to the difficulties for authorities to monitor the farmers' practice. Low quality of compost was increasingly produced due to contamination from plastics and broken glass. However, there is a practice in China and Myanmar where some farmers remove compost from garbage dump site for agricultural activities with the help from authorities in providing sieving machines. Moreover, some authorities in Vietnam allow mining for compost in garbage dump site with a mining fee. However, with recent rapid development and industrialization, these practices will not be effective due to its low efficiency and pollution problem to the environment.

Recently, small-scale neighborhood composting has gained popularity through pilot projects and researches. Some small-medium enterprises have emerged to produce compost from OMSW. Composting process is carried out in box windrow despite some aesthetic and technical problem need to be addressed (Colón et al., 2010; Andersen et al., 2011). When handling composting process, workers are training and knowledge in health and safety. Composting is becoming more common with improvement in knowledge, processes, public education and market for the compost product. However, the production cost for compost is still higher than synthetic fertilizer thus this become a major factor for investors and managers (Lai et al., 2009).

Composting of OMSW can be feasible in smaller cities with intensive agricultural activities (Jasim and Smith, 2003). Technology for composting is provided and shared by international environmental consulting firm through technology transfer initiative. However, the issue of adaptability of technology arises due to the difference in the OMSW characteristics across cities (Marry, 2009). Another biological treatment of OMSW is biogas production through anaerobic digestion.These treatments are well known in rural areas in China, which turn human and animal faeces into biogas and digestate (Lai et al., 2009). The biogas digestors however are not common due to organizational problems and breakup of communes (Ghani and Idris, 2009).

Compost quality guidelines are relatively new. Classification of peats has been comparable to the standard compost in terms of organic soil amendments (Fuchsman, 1980). Compost is a natural products and has been widely used in agriculture industry, however external pressure on the materials and quality of compost has recently emerged (OMRI, 1998). Compost quality has been associated to the definition of contaminat limits and the earliest publication on heavy metal composition in compost was made in the late 70's followed by the concern on degree of maturation and plant-frowth properties of which include the level of allowable heavy metal, physical composition, pathogen content, potential toxic elements and plant growth performance. The compost quality seal in Germany has marked the beginning of the demand for common recognition of compost quality for end-user supply chain. The avaluation of compost quality were evident in Switzerland and the United States, dictated by policies handed down in association to waste management, in particular to the sources of contamination.

Compost grading system has been introduced either mandated by law, or via quality seal program in Europe. For instance, several seal programs were available for compost grading. In 1992, European Commision allowed that a seal of quality to be issued for any qualifing natural soil amendment products, leading to emerging of eco-label within specific product groups. The later was then modified and upgraded for compost application.

Table 2.5: Europe Eco-Label Standards Applicable to Composts

Tested Traits	Limits as Determined by Test Methods 86/278/EEC
Special Metals	If contains industrial or municpal wastes, then test for: Mo, Se, As, F
Constituents	Organic matter > 20%; Moisture < 75%; Total-N less than 2% TS
N-P2O5-K2O application limits	Application rate shall specify not more than: 17g/m2 N - 6g/m2 P2O5 - 12g/m2 K2O
Pathogens	Salmonella non detect in 25g E. Coli < 1000 MPN/g
Other	Contains no offensive odors; no glass, wire or other fragments; No unacceptable weed seeds
Declaration	Must describe recommended use and application rates; All feedstocks > 10% must be reported; Nutrients, organic matter and metals must be reported; No phytotoxic effects.

Source: Official Journal of the European Community

2.3.5 INCINERATION

Incineration processes require huge capital investment and skilled workers. Thus incinerators are more common in industrialized cities due to high maintenance costs and strict environmental pollution control regulations. For instance, there are three incineration plants in Singapore which receive/treat their daily collected MSW. The mixed waste is burned using rotating roller grates. Auxiliary oil burners are used to start up the combustion process self-sustaining with additional of wood waste gradually (Khoo et al., 2012). In general, incineration is feasible due to high combustible fraction in MSW despite the moisture-reducing compaction at transfer stations (Kathirvale et al., 2003). Total electrical energy of 250 to 300 kwh/ton MSW incinerated can be recovered from the plants in Singapore (Papageorgiou et al., 2009; Khoo et al., 2012). The MSW incinerators in Japan, Taiwan and South Korea are common in combustion technology and design.

Incinerators in Hong Kong was closed due to failure in meeting its air pollution standards, but construction of new MSW combustion facilities is planned. Municipalities in South Korea had successfully increased the incinerated portion of the waste to rise from 3% in 1994 to 20% by 1999 by exploring ways to resolve conflicts with public (Lee et al., 2007). There are many incinerators in cities of Japan. MSW undergoes pyrolysis process before combustion at more than $800^{o}C$ in some MSW incineration facilities design. Some incinerators have been transformed into community centers with offices and gardens (World Bank, 1999).

Heat and electricity are recovered from modern MSW incinerators in industrialized cities (Kathirvale et al., 2003; Merrild et al., 2012). Incineration remain popular in cities with land scarcity issue. However, MSW incinerators are not accepted in some countries due to the possibility of GHGs and other gaseous pollutants released during combustion process (Merrild et al., 2012). In some developing countries, incineration processes face challenges and problems: inconsistent temperature control and air pollution controls (Vesilind, 2002). The challenge to incinerators become more apparent with high moisture content in MSW incinerated (Kathirvale et al., 2003).

In order to reduce the volume of waste disposed in landfills, some cities in developing countries practice open burning in landfill sites, in particular the countries with less enforcement in ban for open burning. In remote and rural areas, open burning is common among households during dawn which contributes to toxic pollutants emitted to the atmosphere from uncontrolled burning of plastics waste (Fauziah and Agamuthu, 2012).

2.3.6 LANDFILLING

Landfilling is the most common method of MSW management in all countries (Fauziah et al., 2004). Disposal cost for MSW becomes higher due to exhaustion of suitable land for waste disposal, stricter environmental protection regulations and increase of waste generated particularly in large cities with great population (Fauziah et al., 2004; Fauziah and Agamuthu, 2012). Developed countries have experienced increase in disposal cost for MSW and further increase is anticipated.

Landfills normally accept wider range of wastes. However, the design of landfills for toxic wastes are more stringent. An engineered landfill is a disposal site with several layers of impermeable liners at the bottom and equipped with gas and leachate control systems (Themelis and Ulloa, 2007; Khoo et al., 2012). Leachate collected is treated prior to discharge to river whereas landfill gas collected is combusted for energy recovery (Scheutz et al., 2009; Khoo et al., 2012). Some Japanese municapal (e.g., Kityakushu) reclaim coastal lands with pre-treated and compacted solid wastes. Regulations for landfill design is less stringent in rural areas as MSW contains lesser hazardous compounds as compared to that generated from urban cities (Kowalewski et al., 1999).

Open dumping is however still commonly practiced in developing countries where low-lying land or swamp lands are normally chosen as landfill sites and these lands are expected to be filled up for future development purpose. Malaysia has utilized several old tin mines for MSW disposal. Most modern landfills are equipped with compacted clay liners, but still little consideration is given to the groundwater pollution, and gas migration (Kowalewski et al., 1999). The OMSW, when compacted with other waste, undergoes anaerobic degradation and generates methane gas at dump sites which eventually lead to landfill fire break out (Lou and Nair, 2009; Oonk, 2010). Besides, the uncontrolled dumpsites will create considerable health, safety, and environmental problems (Villanueva and Wenzel, 2007).

It is difficult to standardize the regulations of all nations due to disparities in their allocation of budget in waste disposal sector. Appropriate MSW disposal practices are always anticipated in affordable manner (Matthews and Themelis, 2007; Wangyao et al., 2009). Some cities of developing countries have well designed sanitary landfills (Tonkin and Taylor, 2007). There has been much improvement in landfill design throughout the region.

2.4 MANAGEMENT AND PLANNING

Public's awareness on economics, public health and the quality of the environment determine the development of concepts and technologies for integrated solid waste management in a country (White et al., 1995; Sakawi, 2011). Usually municipal councils are responsible in MSW management while in some countries, the MSW management responsibility is shared between central government and various levels of local councils (Powell, 2000; Saeed et al., 2009).

MSW management in industrialized or developed countries are better than that of developing countries due to the availability of skilled planners, resources and technology. For instance, regulations on governing the pollutant from landfill are implemented and enforced in cities of developed countries such as Japan. Besides, there is regulations on banning some hazardous material from disposed in landfills such as batteries, waste oil and tires. In enforcing this mandate, Japan is constantly enhance the public education on source separation of waste in household level to ease the separate collection process. Similarly, South Korea has passed a law in 1992 to ban disposal of OMSW in landfill which open up opportunities to OMSW treatment process and technology.

There is a lack of planning due to resources constraints and the absence of experienced specialists in waste management sector in developing countries (Brunner and Fellner, 2007; Oh et al., 2010). The common MSWM problems in developing countries (PEMANDU, 2012) of the region are:

a) institutional deficiencies,

b) inadequate legal provisions, and

c) resources constraints

Regulations in respect to MSWM in developing countries (Malaysia) are ineffective in dealing with the complication of managing wastes in populated cities (Onn and Yusoff, 2010). In many cases, the regulations are directly copied from industrialized countries without any serious study of the social and economic conditions, the technology, the level of skill required, and the local administrative structure. As a result, they prove to be unenforceable (Maystre and Viret, 1995). The major problem is the lack of effective enforcement on the existing regulations as reported by previous study (Onn and Yusoff, 2010).

The enforcement and execution of national recycling laws are still week especially among the developing countries despite the community initiative to separate and resell informally and these activities are not normally supported by local government. The monitoring program on MSW management in developing countries are poor, in contrast to MSW management in cities of developed countries where well-structured monitoring programs are available to monitor waste management operation and pollution control (Omran et al., 2007; Machado et al., 2009). Complication and bureaucracy has worsen the decision making process and thus lead to illegal dumping in unauthorized land and rivers (Klang, 2003).

Active international trade on recyclable materials and open communication are keys to waste recycling sector. Technology transfer in terms of foreign experts, installation and operation of waste management technologies are much welcomed with various incentive programs among the developing countries community (Klang, 2003). For instance, reduction in import duties on waste management related equipment and tools is encouraging more advanced technology and knowledge transfer and thus contribute to improvement in waste management (MHLG, 2005).

Slump areas in some countries such as Manila has been transformed into waste recycling centers as part of community improvement programs. NGOs is important in educating the poor and the perspective of waste recycling and simultaneously working closely with waste management authorities on improvement of waste management and recycling. Community participation is the main key to the success and sustainability of the waste management improvement. The traditional way for decision making is changing from top-down to bottom-up, by incorporating inputs and opinions from local communities in order to introduce an efficient waste management and recycling system (Agamuthu and Fauziah, 2005; Brunner and Fellner, 2007). In some places community organizations comprehend in MSW collection service provided by municipal authorities by collecting the MSW themselves and these work well in some cities in Indonesia, Vietnam and South Korea (Kim and Kim, 2010).

2.5 FINANCING

High percentage of municipal budget is located for MSW management activities. For instance, Malaysia local municipalities in average spend 50% of their total budget on MSW collection and disposal activities. However, financial mechanisms vary among cities in terms of sources of fund namely taxes, maintenance fee charged upon public and subsidies received from central government (NSWMD, 2012).

Commonly, MSW management authorities in most countries are seeking cost recovery for waste management activities. There are various methods namely: the deposit-refund system for many recyclables and volume-based fees (World Bank, 1999). There are several forms of levy for waste management services: a) charges based on volume of waste collected; b) taxes and c) service charges for waste collection (JICA, 2006). Mandatory deposit and return scheme is introduced in some countries in order to encourage recycling activities.

This at the same time helps to share the burden of waste disposal and recovery of recyclable materials with manufacturers and retailers (Bandara et al., 2007; Budhiarta et al., 2012). Advance payment of disposal fees are levied on specified products and packages in order to hep sustain cleanup program (Forti et al., 2004; Agamuthu and Victor, 2011).

Private sectors are important in helping the government to overcome problem associated to waste management. Some of the MSW management services are contracted out to private business entities due to resource constraints within the government. For instance, Singapore have privatized most of the waste management related services and facilities since 1996 whereas Malaysia federal government has signed privatization and concession agreements with selected private companies for MSW management services in the country. Some joint-venture between local and foreign waste management companies in order to secure management contract from municipalities with larger financial resources capability and experience (Agamuthu et al., 2009).

There has been great debate that a combination of government and private waste management services would provide the most effective and accountable system of MSW management. Privatization advocates revealed that cost recovery can be achieved through privatization process for MSW management while others have show significant cost recovery with the MSW management run by the governmental sector (Agamuthu and Fauziah, 2005). However, the social implications of such privatization are currently evaluated to reflect the public acceptance towards the MSW management services provided by private concessionaires (Badgie et al., 2012). For instance, privatization of MSW management services will jeopardize the role of scavengers, waste dealers, fees and labour where informal recycling practice is common (Agamuthu et al., 2009). Efficiency may be a significant challenge due to the failure of contractors to fulfill the conditions as stated in contracts. In order to minimize operational cost, private contractors may employ fewer employees to collect and transport more waste per vehicle.

2.6 GENERAL METHODOLOGY OF LCA

Life Cycle Assessment (LCA) is a methodology developed to evaluate the mass balance of inputs and outputs of systems and to organize and convert those inputs and outputs into environmental terms or categories relative to resource use, human health, and ecological areas. Thus LCA is a tool for the analysis of the environmental burden of products at all stages in their life cycle from cradle to grave (Guinee, 2002). The quantification and of inputs and outputs of a system is called a Life Cycle Inventory (LCI). The conversion of these emissions into environmental aspects is Life Cycle Impact Assessment (LCIA) (ISO, 2000a).

LCA is used to quantify the potential environmental impacts and resources consmption throught the entire life cycle of a product, process or system from raw material extraction to disposal and recycling (ISO, 2006). The term 'product' includes both goods and services. LCA considers all attributes or aspects of natural environment, human health and resources.

According to ISO 14040: 2006, the application of LCA can assist in:

i. Identifying opportunities to improve the enviromental performance of products at various points in their life cycle

ii. Informing decision-makers in the industry, government or non-governmental organizations in terms of strategic planning, priority setting, product or processed design or redesign

iii. Selecting the relevant indicators of environmental performance including measurment techniques

iv. Marketing by implementing eco-labelling scheme, making an environmental claim, or producing an environmental product declaration.

Figure 2.3 explains the basic framework of LCA and the order in which it should be carried out. There are four phases in an LCA study namely Goal and Scope Definition, Life Cycle Inventory Analysis, Life Cycle impact Assessment and Interpretation.

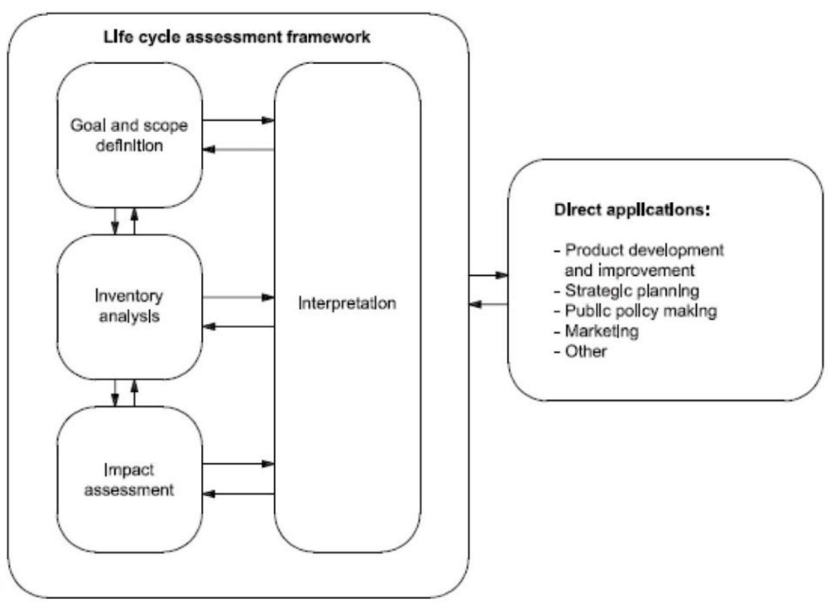

Figure 2.3: ISO 140040 Life Cycle Assessment Frameworks

2.6.1 GOAL AND SCOPE DEFINITION

The very step in LCA is goal and scope definition and it forms the foundation upon which the whole LCA study is laid upon (ISO, 2006). System boundary and functional units are to be defined. The functional unit is a quantitative measure of the goods or services provided within the system boundaries studied. Scope also includes the impact categories selected for the study and the methodology used to carry out the impact assessment (ISO, 2006).

2.6.2 LIFE CYCLE INVENTORY ANALYSIS

The second phase of LCA is inventory analysis, which consists of data collection and calculation procedures to quantify relevant inputs and outputs of a product system. Data gathering is a critical issue in the LCA phase. Data is usually collected from the main producers, suppliers and from LCA databases. According to Green (2002), LCA databases are used for standard inputs such as electricity, water and materials. However, standard inputs found in the database mostly represent the European scenarios, which is not available to other developing countries (Green, 2002). A distinction has to be made between foreground and background data. Foreground data are related specifically to the product system in question. They should be as real as possible, based on actual plant conditions and onsite measurements as possible. Background data are not specifically related to the product system and may consist of average or ranges. In principle, background data on services and utilities should be extracted from the relevant market.

2.6.3 LIFE CYCLE ASSESSMENT

Life Cycle Impact Assessment (LCIA) quantifies and assess the results from the Inventory Analysis in terms of environmental significance (ISO, 2006). Thus, the LCIA should interpret the inventory results into potential impacts towards the environment: human health, natural environment and natural resources (Guinee, 2002).

Impacts on the categories are modelled between interventions in the form of resource extractions, emissions, land and water use, and their impacts in the environment as illustrated in Figure 2.4.

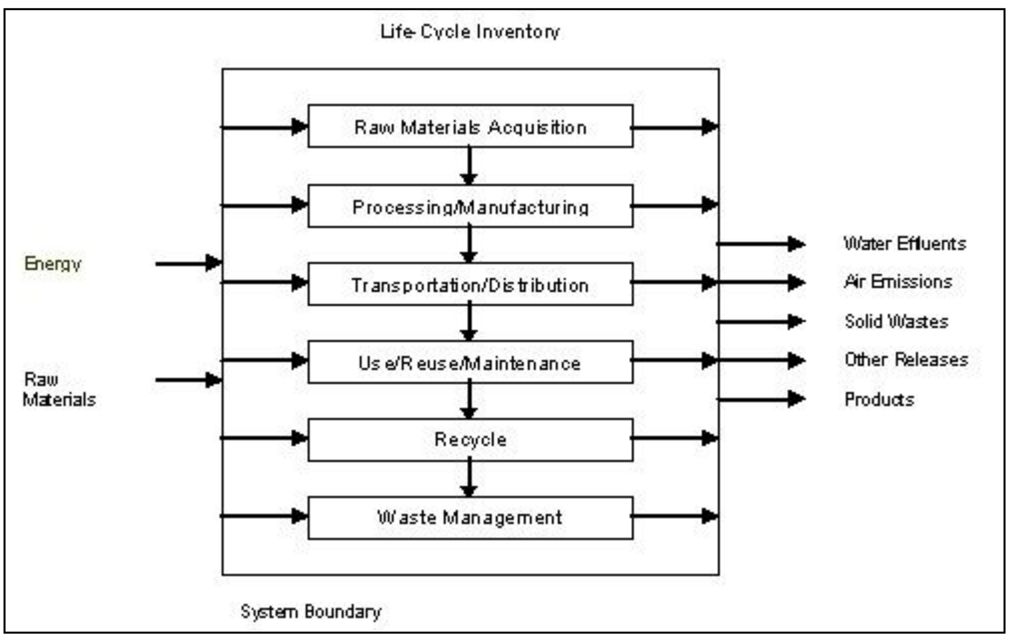

Figure 2.4: Life Cycle Assessment Stages and Boundaries

GHGs in particular CO_2 and CH_4, absorb infrared radiation and thus leads to increase in the atmospheric heat content and temperature, propagating to changes in regional and global climates as well as sea-level rise.

Figure 2.5 shows the difference between midpoint and endpoint, where the later is defined at the level of the areas of protection while midpoint indicators indicate impacts somewhere between the emission and the endpoint (Hauschild and Potting, 2005).

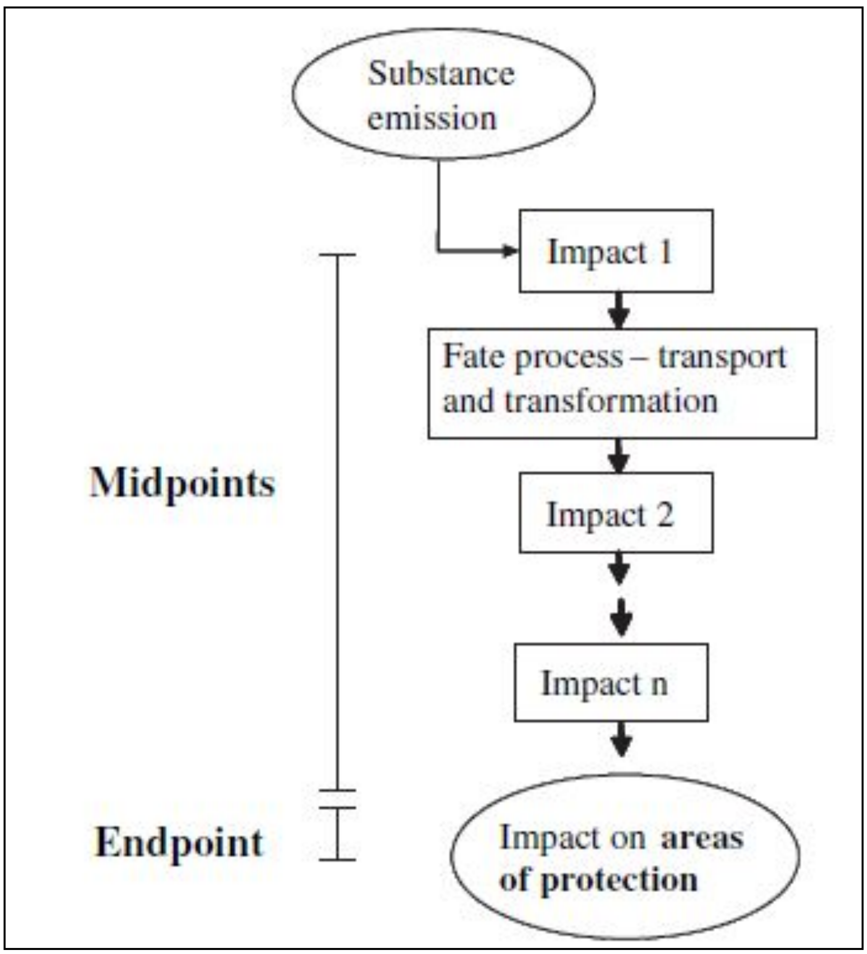

Figure 2.5: Life Cycle Impact Assessment Modelling, adapted from (Curran, 1996).

LCIA models any impact from a product system which creates damages on areas of protection in a holistic perspective. According to the ISO standard on LCA (ISO, 2006), LCIA involves:

i. Selection of impact categories and classification which involves identification of the categories of environmental impacts relevant to the study. The emissions from the inventory are assigned to the selected impact categories based on the contribution of impacting substances to associated environmental problems

ii. Selection of characterization methods and characterization allows summing the contributions from all emissions and resource extractions within each impact category, translating the inventory data into a profile of environmental impact scores.

iii. Normalization where the results from the characterization are related to reference values. Normalization expresses the relative magnitude of the impact scores on a scale which is common to all the categories of impact (typically the background impact from society's total activities) in order to facilitate the interpretation of the results.

iv. The final steps of the Impact Assessment include Grouping or Weighting of the different environmental impact categories and resource consumptions reflecting the relative importance they are assigned in the study.

LCIA include analysis through selection of impact categories, classification and followed by characterization. However, normalization and weighting are not mandatory. Weighting step is subjected to assessor's preference and hence to encouraged to be performed in comparative studies (ISO, 2006).

2.6.4 LIFE CYCLE IMPACT ASSESSMENT METHODOLOGIES

A LCIA methodology is the method that is used in determining the potential impacts. Different methodologies use different approaches but all ultimately give the potential impacts associated to the study. Methods that are common in LCIA are:

i. Eco-Indicator 99	ii. LIME-Life Cycle Impact Assessment Method based on Endpoint modeling
iii. EDIP 97 & EDIP 2003	iv. Swiss Eco-scarcity Method (Ecopoints)
v. EPS 2000	vi. The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI)

In a LCIA, essentially two methods are followed which is either the problem-oriented methods (mid-point) or damaged-oriented methods (end points). problem-oriented method aims at simplifying the complexity of hundreds of flows into a few environmental areas of interest such as climate change, photochemical oxidation, eutrophication and natural resource depletion. The most common methods used for problem-oriented methods are EDIP and CML 2000 methods (Hauschild and Potting, 2005; Winkler and Bilitewski, 2007). The damage-oriented methods classify a system's flows into various environmental themes in terms of damage to human health, ecosystem health or damage to resources. Eco-indicator 99 and LIME are common examples of damage-oriented methods.

2.6.5 LIFE CYCLE INTERPRETATION

The final phase in LCA is interpretation of assessment outcomes. Life cycle interpretation includes communication, to give credibility to the results of other LCA phases (namely the LCI and LCIA), in a form that is both comprehensible and useful to the decision makers (Curran, 1996). It is aimed at identifying the most significant environmental impact category and the life cycle stage. Life cycle interpretation can also be expanded to identify and evaluate eco-efficiency opportunities so that the LCA becomes instrumental in achieving improvements in environmental and economic performance of the product life cycle.

2.7 APPLICATION OF LCA IN SOLID WASTE MANAGEMENT

Solid waste management (SWM) is currently the subject of much topical debate. This has been driven largely by consumer and legislative pressure which seem united in their belief that increasing the levels of recycling of solid waste beyond the present state will provide an environmental solution to solid waste problems. Solid waste management hierarchy is commonly used to provide preference of alternative means over disposal at landfill. In general, waste minimization is preferred over landfilling in terms of environmentally friendliness (As shown in Figure 2.6).

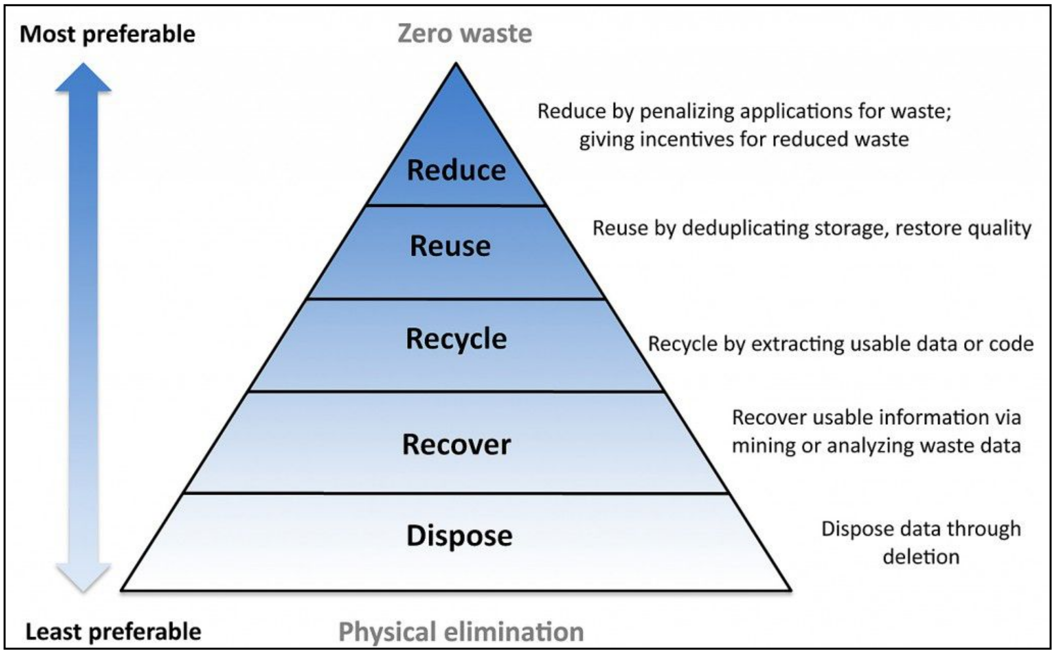

Figure 2.6: Solid Waste Management Hierarchy

However, previous researchers have questioned the applicability of the waste hierarchy. One of the main criticisms of the SWM hierarchy is that it does not reflect directly environmental concerns such as the use of non-renewable reserves, global warming, and destruction of the ozone layer. Instead, it is presented as a means to an end, reflecting varying degrees of environmental preference for the processing of solid waste, with landfill assumed to be the least environmentally preferred solid waste disposal practice. The technique of LCA can be employed in integrating other environmental considerations into the decision making process when it comes to a more holistic approach to SWM. Using this approach, each waste management option can be compared on the basis of its eco-profile for instance, the consumption of energy and raw materials and associated releases to air, water and land necessary to facilitate the process. Collectively, in the context of LCA, inputs and outputs are known as environmental burdens.

2.7.1 INVENTORY ANALYSIS

LCI analysis quantifies the physical exchange between environment and system boundary for all process which include raw material and energy consumption as well as the emissions to the environment. The analysis generates an inventory of the environmental impacts in relation to the functional unit decided in the investigated syste.

Functional unit (FU) is required in order for the results of a comparative study to be valid, comparisons must be made in the basis of equivalent function. In an LCI study, all data will be calculated in the basis of the functional unit. In waste management operations, there are variety of ways to define FU, each of which will depend on the goal and scope of the application. Unlike product LCAs, the FU for waste management scenarios is based on an input to the system rather than an output from the system. In all cases, however, the FU will be expressed in terms of mass although the derivative itself may be in units of mass, volume or even energy. Examples of FU units that might be relevant in the context of waste management are shown in Table 2.5.

Table 2.6: Examples of Mass-derived, Volume-derived and Energy-derived Functional Unit in association to Solid Waste Management

Nature	Examples of Functional Unit
Mass-derived	1000kg of municipal solid waste 1000 household equivalent of solid waste collected That quantity of solid waste collected from a given geographical area
Volume-derived	Volume occupied by the waste collected from a given geographical area, transposed to units of mass, allowing for its density when compacted in landfill
Energy-derived	Amount of fossil fuels (and associated environmental burdens attributable through pre-combustion) displaced by recovering energy generated from that waste collected from a geographical area, allowing for efficiencies of conversion

Another factor which should be considered when one seeks to define a FU is time. The dimension of time in the context of waste management is reflected in two main ways: (1) that time over which data are averaged or normalized and (2) that time period covered by the study, taking into considerations that proportion of environmental burdens associated with start or shutdown procedures or even the building decommissioning of equipment relative to the time specified. For every reference to the mass of solid waste, one must further reflect the composition of that waste (on a mass-by-mass basis) recorded for the given scenario.

2.7.2 SYSTEM AND SYSTEM BOUNDARIES

A system is a collection of connected operations which together perform a defined function. Conventionally, the main life cycle stages included in any LCA are the extraction and processing of raw materials, manufacture of the product, distribution, use, reuse and disposal. Transport operations should be included, where these occur in the primary production sequence. Each of these main life cycle stages can be further broken into down into a series of sub-stages or sub-processes. The level of breakdown will depend on the nature of available data. In general, the greater is the level of breakdown possible, the greater the transparency of the study. Ideally, all material inputs should be traced to the extraction of raw materials from the earth. In practice, however, this is rarely feasible, and the manufacture of many ancillary materials is often excluded from the system.

The system boundary of waste management activities can be extremely complicated. However, the boundaries can be defined from the beginning of the waste management process as for instance, the waste collection. While this approach may be simple enough for the flow of waste into the system boundaries, there are still complications when one considers the outputs from the system. The disposal of all residues on land normally indicates the end of life cycle. However, it becomes more complicated when one considers evaluating material recycling and incineration with energy recovery. The system boundary must be extended to include the benefits of these options. In other words, recycling is viewed as offsetting the environmental burdens associated to with the manufacture, transport and use of virgin materials and fossil fuels.

Waste management LCAs introduce an interesting dimension to the discussion of LCAs is that theoretically one can argue that there is no such thing as life cycle inventory analysis or assessment; but only the application of those techniques to the system defined.

This remark also emphasizes the consistency between the system boundary and the goal and scope of the study. Waste minimization at source and reuse are excluded in system boundaries normally for waste management LCAs. This simply reflects that waste minimization at source and reuse is dealt with more in the context of product-oriented LCAs than waste management LCAs.

2.7.3 INVENTORY COMPILATION

Data collection is carried out according to the system boundaries decided in waste management LCAs. Once these data have been worked through, once can employ the techniques of sensitivity analysis (e.g. examining the difference between alternative data sets) to prioritize one's effort for gathering site-specific, measured data to fine tune a study to the needs of a particular situation. Data quality in LCA is a major topic of debate.

In compiling the inventory, what one actually does is to build up a profile that quantifies the flow of materials through system, with main output from one life cycle stage becoming the main input to the next life cycle stage. At the same time, all other material and energy inputs and outputs occurring as releases to air, water and land are similarly quantified at each life cycle stage. In this way, the total quantity of inputs at one life stage should, by definition, equal the total quantity of outputs occurring at that stage, for example their mass balance. Given the complexity of the LCI methodology, this illustrates the importance of maintaining the transparency of reporting in LCI and LCA work so that all raw data are evident and all elements of the calculation procedures, such as co-product allocation, are transparent.

2.7.4 IMPACT ASSESSMENT

Impact assessment quantifies and convert the inventory data into information which is clearer to audience. In simpler terms, impact assessment serves to transpose the environmental burdens quantified at the inventory analysis stage (e.g. energy consumption, emissions to air and water) to environmental impacts (e.g. depletion of non-renewable fossil fuels, global warming or ozone depletion). The desire to undertake an impact assessment depends on the purpose of the study. Impact assessment is sometimes unnecessary of the results of inventory analysis demonstrate that one waste management system is better than the other across all considerations (e.g. consumes less materials and energy and gives rise to reduced emissions to air and water and solid waste). However, more commonly, one alternative will be better on some considerations but worse on the others. In such case, it is desirable to have an indication of what these results mean when one considers their transposition relative to given environmental concerns, such as impacts on global warming, depletion of resources and ozone depletion. Impact assessment allows the environmental burdens to be translated to potential environmental effects or impacts. Some argue one can take this further by ranking all impacts against each other to generate environmental score. The common approach is a three-stage process: classification and characterization, normalization and valuation.

2.7.4.1 CLASSIFICATION AND CHARACTERIZATION

The data in the inventory are aggregated in accordance to relative environmental concerns. The problem-oriented approach generally incorporates a non-site specific approach which classifies environmental impact on a global level to obtain a general worldwide classification independent of site-specific considerations. Potential impacts are quantified rather than actual impacts. Actual impacts are dependent on the site of production for instance, actual concentrations and the sensitivity of the receiving environment.

The environmental impact categories generally included in an impact assessment are:

i. Nitrification and eutrophication

ii. Ozone layer depletion

iii. Resource depletion

iv. Photochemical oxidant formation

v. Acidification

vi. Greenhouse effect

For each of the chosen environmental impact categories, potential impacts factors (e.g. global warming potentials) are developed. These factors are used to facilitate the aggregation of a number of contributory environmental burdens into a single value.

2.7.4.2 NORMALIZATION

The effect scores defined above which are the result of the classification and characterization step are difficult to interpret because the order of magnitude and units differ. To overcome this problem, a final step in classification and characterization called normalization can be used, which makes the effect scores more meaningful by relating them to the total emissions or extractions over a given period.

2.7.4.3 VALUATION

Valuation is the assessment of the relative importance of the environmental burdens identified in the classification, characterization and normalization stages by assigning weighting factors to them, allowing them to be compared or aggregated. There is increasing pressure to achieve a single value to enable ranking of products and aid in the decision making process.

2.7.5 IMPACT ASSESSMENT IN THE CONTEXT OF SOLID WASTE MANAGEMENT

Similar to product or service system LCAs, solid waste management life cycle inventory data can be classified, characterized and normalized; then if one chooses, one can use weighting factors to yield a single value or score on the results.

2.8 SUBSTANCE FLOW ANALYSIS (SFA)

The SFA is used to assess the metabolisme of anthropegenic and geogenic systems by assessing the flows and stocks of material within a defined system (Brunner and Ernst, 1986). SFA links up the origins, the flows, intermediate and the sinks of a metarial in a system. The input and output flows are quantified and balanced in order to calculate the respective waste flows, environmental loads and their sources. Morover, SFA allows estimation of the material stocks in the system which create flexibility to calculate the minor changes of those stocks which might be insignificant at present but contribute to long-term damage.

Physical units for substance flows defined in period of time can be expressed at different level of space. The analysis applies the concept of law of conservation of mass where the assumption of mass balance for material within an economic system is made (Brunner and Ma, 2009). Material Flow Analysis (MFA) considers the total flows of materials, while in SFA studeis the the flows of specific substances.

2.8.1 MAIN TERMS USED IN SFA

The main terms used in the SFA methodology are presented in Table 2.7 :

Table 2.7: Common terms used in the Substance Flow Analysis

No	Terms in SFA
a)	Substance is any chemical element or compound composed of uniform units
b)	Goods is an economic entity of matter with a positive or negative economic value; made up of one or several substances
c)	Material stands for both substances and goods
d)	Process refers to transformation, transport or storage of materials
e)	Flow (mass flow rate) is a ration of mass per time that flows through a conductor
f)	Import process is a process of origin of a flow or flux that enters the system
g)	Export process is a process of destination of a flow or flux that leaves the system
h)	Transfer coefficient (TC) refers to partitioning of a substance in a process
i)	System is a group of elements, interactions between these elements, boundaries between these and other elements in space and time; the system can be closed or opened (interacting with the surrounding)

Table 2.7 (continued)	
j)	The system is defined in time (temporal boundaries) and space (spatial boundaries)
k)	Activity is a set of all relevant processes, flows and stocks of goods and substances that are necessary to meet and maintain a certain human need.

2.8.2 STEPS OF SFA

Conducting the substance flow analysis consists of the following steps (Table 2.8):

Table 2.8: Summary of methodology for Substance Flow Analaysis

No	Steps in Substance Flow Analysis
a)	Defining problems, goals and the scope of the study
b)	Selecting relevant substances for the evaluation
c)	Defining the system in space and time
d)	Identifying the relevant processes, flows, and stocks
e)	Determining the mass flows, stocks and concentrations
f)	Quantifying the total material flows and stocks
g)	Presentation of the results

2.8.3 APPLICATION OF SFA

The SFA is used for analysis in fields like environmental protection, resource and waste management, and economics. In the field of industrial ecology, SFA is applied to balance industrial input and output to natural ecosystems, to systemize patterns of energy use, control pathways for materials use in industrial processes, or to balance industrial output in the creation of loop-closing industrial practices. In waste management, it is a cost-effective tool for determining waste composition and therefore it helps to make decisions concerning the design of future sustainable waste management systems. Moreover, it is used to investigate substance management of recycling and thermal treatment processes and facilities and thus, it supports the design of new environmental friendly products. The evaluation tools based on SFA enables to assess whether the goals of the investigated system, products and facilities are achieved and which crucial point require more attention or improvement.

2.9 BIOLOGICAL TREATMENT MODULES IN EXISTING WASTE LCA MODELS

Various models for environmental assessment of OMSW management and treatment are available. The section provides a brief introduction of the approaches used, and some strength and weakness of each model (Hansen et al., 2006).

2.9.1 THE IFEU PROJECTS

The model was used to compare alternative treatment options for urban OMSW and the assessment of environmental impacts from biological treatment (Hansen et al., 2006)

The anaerobically digested OMSW is separated into wet fraction which is treated through waste water treatment and dry fraction which is further stabilized through composting process. The biogas produced is used for electricity generation at the power plant. Emission from un-combusted methane during electricity production is available. Detailed mass flow for carbon and nitrogen is included in the assessments. A fraction of carbon is converted into biogas (as in CH_4 and CO_2) or eventually lost to waste water during the digestion process. The rest of the carbon stocked on the digestate is partly lost as emissions to atmosphere (e.g. CO_2 and CH_4) during composting process. A significant amount of the nitrogen contained in the waste water (wet fraction) is lost as ammonia.

Treatment of OMSW by composting is defined as an aerobic degradation process. The mass balances for carbon and nitrogen for are similar to the ones performed by stabilizing digestate from anaerobic digestion.

2.9.2 ORGANIC WASTE RESEARCH: ORWARE

ORWARE is developed by cooperation of different universities and research institutes. The modelling is carried out by using a modular approach and transfer coefficients for determination of the elemental transportation in each system. Anaerobic degradation and composting process are included in the modelling in ORWARE (Dalemo et al., 1997)

Anaerobic digestion is modelled as a one-step mesophilic digestion. Four processes are possible for the pre-treatment: hygienization (70^oC), sterilization (130^oC), maceration and separation of metal and plastic. The degradation rate of organic matter (fat, protein, carbohydrates, etc.) is estimated based on the degradation potential of the substrate and the retention time in the digestion process. The biogas production containing CO_2 and CH_4 is proportional degradation of organic matter. Production of ammonium from organic nitrogen and hydrogen sulphide is proportional to the degradation ratio of proteins contained in the OMSW. 5% of the energy contained in the biogas is assumed to be consumed back for digestion process. Various options for energy recovery are available in biogas modelling. The energy and heat recovery efficiency are assumed for combustion of biogas in a stationary engine.

Three options for composting are available in ORWARE for treatment of OMSW. The model includes energy and material consumption, gas cleaning system and heavy metal removal from OMSW. The model however assumes full aerobic condition without CH_4 emissions and all leachate is recirculate and hence no generation of waste water. The gaseous losses of nitrogen are calculated based on the Kirchmann's equation and distributed into N_2O (2%), N_2 (2%) and NH_3 (96%) (Dalemo et al., 1997). The removal efficiencies in gas cleaning system utilizing condensation unit and bio filter are 90% for NH_3 and N_2O and 50% for CH_4. Moreover, the produced finished product can be further modelled for soil application.

2.9.3 INTEGRATED SOLID WASTE MANAGEMENT- DECISION SUPPORT TOOL (MSW-DST)

The MSW-DST is a model to assess the environmental and economic impact of alternative waste management systems. Similar to others, MSW-DST includes a module for composting of OMSW with contamination reduction (Jambeck et al., 2007; Thorneloe et al., 2007)

There are two windrow composting technologies available in the models namely enclosed composting and outdoor composting. In the first case, the OMSW is shredded and the moisture content is adjusted to 50% (wet weight) by watering. The windrows are turned manually with installation of odour-control system. However, the NH_3 removal and disposal of rejects from composting are excluded. The windrow composting facility in the model treats yard waste only. Water content of the YW is adjusted to 50% if necessary before composting process. The finished compost is then screened through post processing trammel screen to produce fine compost material.

Energy and metarial consumption, as well as emissions from the process are included in the MSW-DST modelling. The model assumes perfect aerobic condition with both composting technologies and hence no CH_4 and nitrogen is emitted to the atmosphere. The leachate generation and control is not included in the model.

Composition of compost product is predefined with three compost quality options namely high quality compost (from sorted household waste), low quality compost (from mixed household waste) and garden waste compost. Thus the compost composition produced in the model is not waste specific (Thorneloe et al., 2007). The model allows user to apply choices of compost as soil amendment and for landscaping purposes whereas low graded compost has to be disposed in landfills.

2.9.4 WASTE AND RESOURCES ASSESSMENT TOOLS FOR THE ENVIRONMENT (WRATE)W

WRATE was developed for assessment of waste management systems in environmental aspect. WRATE includes various technologies modules for OMSW. The default data for various types of biological treatment and MBT plants are available in the model.

The characteristics of the input materials (bio-reacted) is predefined. All direct emissions during the operations are measured or estimated. These waste-specific emissions are in association to the quantity and composition of input materials. The quantity of electricity energy produced is linearly correlated to the quantity of biogenic carbon ifrom the feedstock to anaerobic digestion. All typical fugitive emissions (CH_4, N_2O, NH_3 etc.) are defined for each waste management facility.

The management of rejects can be included in the model through various technologies such as incineration and landfilling. There is flexibility in defining the quantity and composition of waste rejected from a specific process.

2.9.5 INTEGRATED WASTE MANAGEMENT:IWM2

The IWM2 model was developed for both environmental and economic assessment of waste management systems. Specific process data and parameters were used to model different technologies. Biological treatment module includes composting and anaerobic digestion in IWM2 with different pre-treatments options (McDougall et al., 2001).

In anaerobic digestion model, the products (biogas and compost) are in association to the loss organic matter during the process. The total energy consumption and recovery from biogas in the process are estimated in terms of kWh Mg^{-1} wet weight input to the digester. The amount of potential energy production is determined by the methane methane and energy content of the biogas. CO_2 emissions are taken into consideration from the digestion process and combustion of biogas. Digestate with predefined composition is excluded from the model. The residue from screening operation can be further treated or disposed. Default substitution processes for mineral fertilizer by compost is available in the model.

Loss of organic matter determines the amount of compost produced during composting process. Energy consumption in terms of kWh Mg^{-1} ww input is dependent on the technologies used. Similarly, CO_2 emissions are included in the composting model. The composition of compost is predefined in the model. The residue from screening operation can be further treated or disposed.

2.9.6 WISARD

WISARD is life cycle assessment software to evaluate alternative waste management scenarios (Seo et al., 2004). Modules for biological treatment for OMSW are included with case specific parameters.

Process specific data of energy and material consumption are calculated whereas there is flexibility in the model to define the emission factors for different material and processes (e.g. diesel combustion). Reject materials can be treated or disposed at landfills.

The composition of OMSW is predefined with different groups. The compost is used on land and the compounds of several nutrients can be replaced in accordance to the replacement coefficients specific for each nutrient. Nitrate, phosphate and heavy metals are assumed to leach to groundwater during the processes as well as the energy consumption for transportation is accounted for in the model.

Emissions of CH_4, NH_3, N_2O atmosphere and leaching of different compounds (organic matter, heavy metals, Sulphur, phosphorous) are quantified in the module. The anaerobic digestion module includes biogas production calculated based on he amount of organic material and utilization modelling. The composition of biogas in particular CO_2, CH_4, H_2S and hydrocarbons is defined on a mass basis (g kg^{-1} of biogas). The biogas utilization is defined from substituted energy technology of coal, oil and natural gas.

2.9.7 LCA-IWM

LCA-IWM was developed for assessing the environmental sustainability of municipal waste management planning. The model has been described in details by other reports (den Boer et al., 2007).

Anaerobic digestion and composting are the available biological treatments for OMSW in LCA-IWM where both pre-treatments and waste characteristic are defined by the users. Adjustments to the default mass flows of the processes are possible in the model. Anaerobic digestion module is defined with a single stage thermophilic dry process with the outputs of digestate, biogas and wastewater. Digestate and wet fraction compositions are calculated in relation to OMSW compositions. Distribution of several substances between wastewater and digestate is determined by using user-defined leaching coefficients where wastewater further treated in treatment plan in order to remove phosphorous and sludge. Biogas production is determined based on methane potential in waste input (in m^3 Mg^{-1} bio-waste) where the produced biogas is used produce electricity and heat.

Amount and quality of biogas determines the amount of energy generated where the users are able to determine the emissions of several substances in terms of mg m^{-3} of flue gas. The default data available in the software considers the installation of oxidative catalytic air cleaning unit. The digestate from the digestion process is further composted. The stabilization process is assumed to take four weeks and. C and N emissions to air are modeled based on the distribution coefficient of degraded C and N from OMSW into different compounds (CO_2, CH_4, NMVOC, NH_3, N_2O, N_2). The finished compost can be further used as soil conditioner. Energy consumption is summed up throughout the series of processes.

Composting module includes a multiple stages of aerobic degradation and subsequent stabilization phase which require 11 days for degradation process. Emission factors are used to determine the distribution of degraded C and N in to different compounds in water and air emissions. Bio-filter is installed to treat the air captured from both composting and maturation processes. The performance of the bio-filter is assessed using removal efficiency values for selected compounds. The produced compost applied as soil conditioner.

3. METHODOLOGY

3.1 OVERVIEW

In this chapter, the methodologies used to conduct the study are described. The first objective is to determine the characteristics and elemental composition of OMSW generated in Malaysia. To achieve this objective, OMSW (consists of FW and YW) from University of Malaya was collected. Pre-consumer and post-consumer FW was collected from 15 cafeterias and canteens. The FW was assumed to be representative of local Malaysian food waste as the cafeterias and canteens serve mixture of western and local cuisine. All FW was mixed thoroughly before sampling for elemental analysis. YW was collected from landscape in UM. YW consists of mainly leaves, branches, grass clipping, and small trunks. YW was shredded and mixed thoroughly before sampling for elemental analysis. Quartering method was employed for sampling of both FW and YW.

The second objective was to provide a comprehensive Life Cycle Inventory (LCI) of medium scale co-composting of OMSW based on SFA modelling. In order to achieve this objective, mass/substance balance of OMSW composting has to be assessed. The composting experiment was carried out in UM (as in Objective 1). Due to heterogeneity character of OMSW, two composting piles were set up and undergo aerobic degradation process for 60 days. Fresh air was supply constantly during the composting period and leachate generated was collected and weighed. The difference between initial weight and final weight of the feedstock was assessed and recorded. The final product (compost) was sampled by using quartering method and the samples were sent for elemental analysis. Substance Flow Analysis of C, N, P, K, Cd, Cr, Cu, Ni and Pb were carried out by using

STAN 2.5 software. From the model, air emissions of OMSW composting process can be calculated. The waste and energy consumption throughout the composting process was recorded.

The third objective is to evaluate environmental impacts and benefits associated to alternative OMSW management system. In order for fulfillment of the fourth objective, Life Cycle Assessment (LCA) was used as a tool to evaluate the environmental impacts from alternative OMSW management system. Background inventory data was collected from literature and previous studies. Degradation emissions from compositing, anaerobic digestion, landfilling and application of compost on land were calculated via Multi-Inventory Approach, which takes into consideration of the waste composition. This is deemed important as waste composition cannot be projected from one place to another. Hence, degradation emissions have to be modeled based on local waste characteristics. Other background data such as transportation, electricity, fuel consumption emissions and waste water treatment were modeled using Eco-invent database included in the SimaPro software. Life cycle impact assessment studies of OMSW management alternatives were developed using the site specific data and background data. Ultimately the emissions factors for managing 1kg of OMSW were derived.

The final objective was to quantify the total CO_2 equivalent reduction potential from OMSW recycling via composting as compared to landfilling (Business-as-Usual). Life Cycle Assessment (LCA) was carried out to investigate the global warming impacts associated with OMSW composting in Malaysia and its reduction potential as compared to existing disposal practice. The scope of the study includes the entire life cycle of OMSW management, from collection until treatment/disposal. Alternate scenarios were proposed to represent the possible management practice. The emission factors for composting of OMSW derived from previous objective were used to calculate the total CO_2eq reduction potential. Figure 3.1 shows the overall framework of the study.

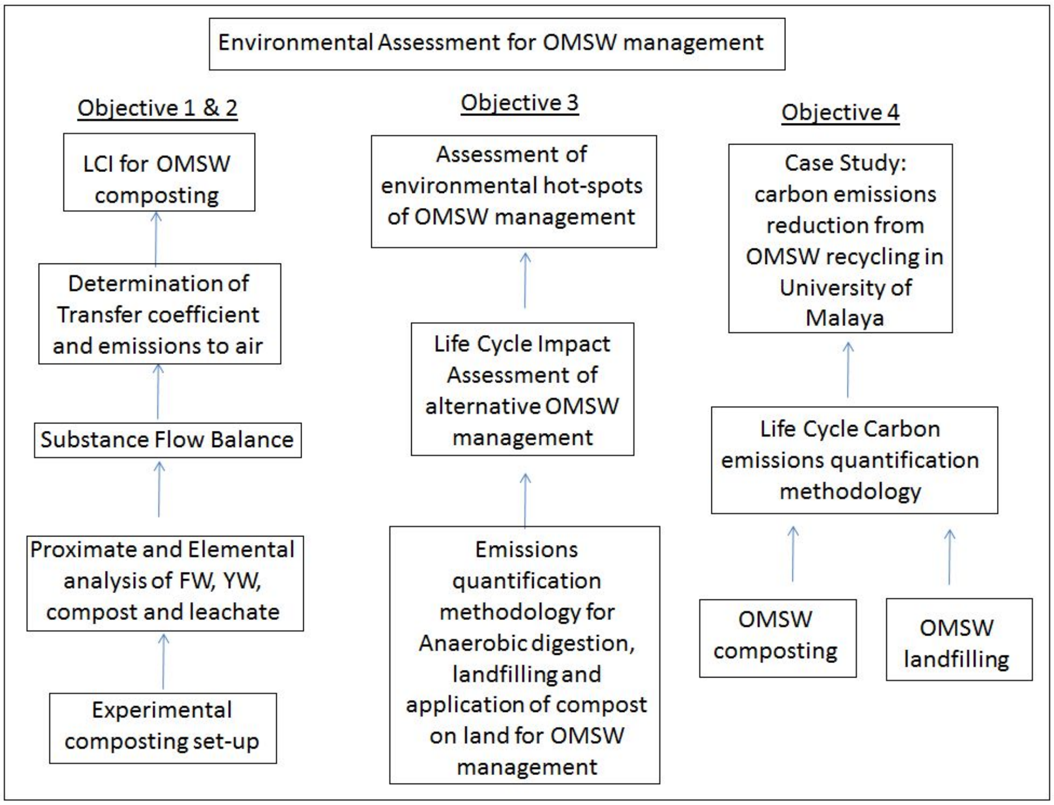

Figure 3.1: Overall Methodological Framework of the Study

3.2 LIFE CYCLE INVENTORY OF CENTRALIZED COMPOSTING OF OMSW IN TROPICAL COUNTRY

LCI of FW and YW composting process was constructed via a series of methodology. The LCI was supported by the comprehensive field work studies which include energy and water consumption during the composting process as well as the process emissions in terms of gaseous and liquid. The data on energy and water consumption was collected during the composting process while the process emissions were estimated using Substance Flow Analysis (SFA) method. Experiment for composting runs was conducted in order to assess the selected substances content of the feedstock, leachate and finished compost. The gaseous and liquid emissions were then estimated. The summary of the methodology was illustrated in Figure 3.2.

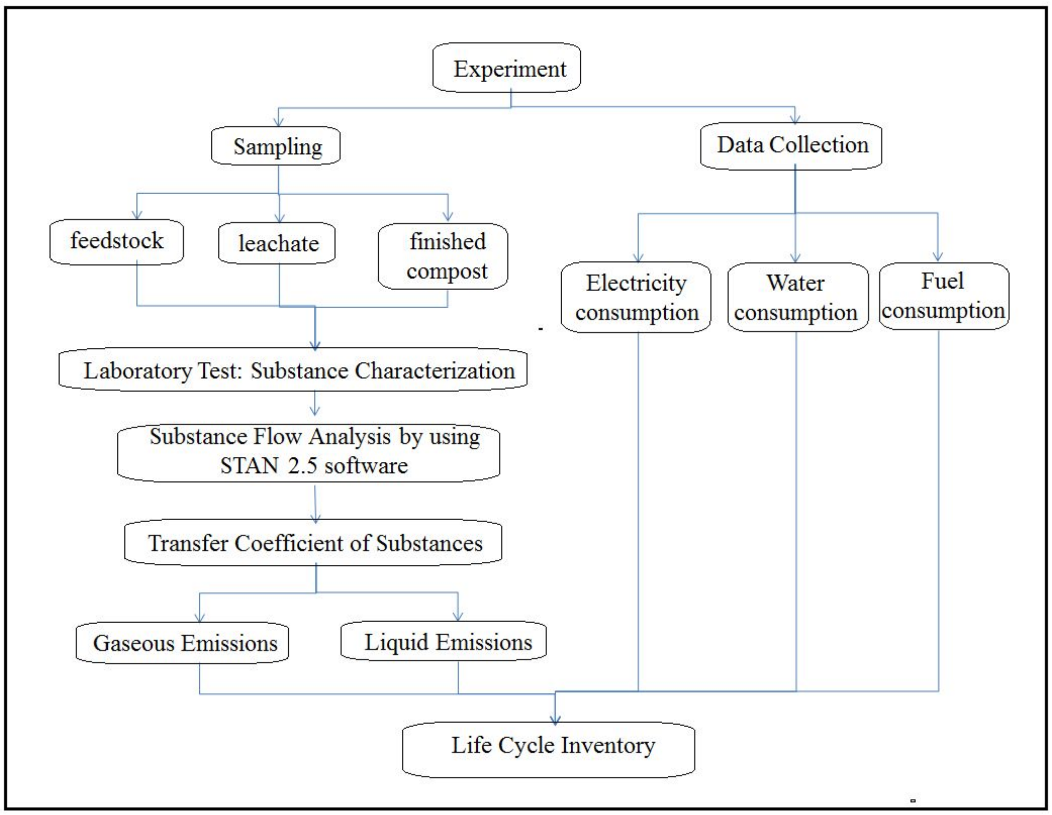

Figure 3.2: The Summary of the Methodology for LCI for OMSW Composting

3.2.1 EXPERIMENT SET-UP

The experiment set-up represents a typical size of compost pile in the composting site of UM. In order to avoid external disturbance such as rain and pets, the compost pile is covered with a cylindrical chamber made from waterproof material (PVC) 3m in diameter and 2.2 m high with a volume of 13 m^3, and installed on a waterproof concrete floor. Fresh air was introduced through a space between the floor and the lower edge of the chamber, and an inverter-controlled blower sucked exhaust gas from the middle of the ceiling. The ventilation rate was fixed to 130m^3/hour (Fukumoto Y. 2003). A plastic sheet was inserted on the inclined platform where the composting pile was placed to collect the leachate. The leachate was collected in a clean plastic container. The design layout of the composting is illustrated in Figure 3.3. Two composting runs were carried out with the intention to showcase the heterogeneity of OMSW and study the effect of windrow size on the performance of the process.

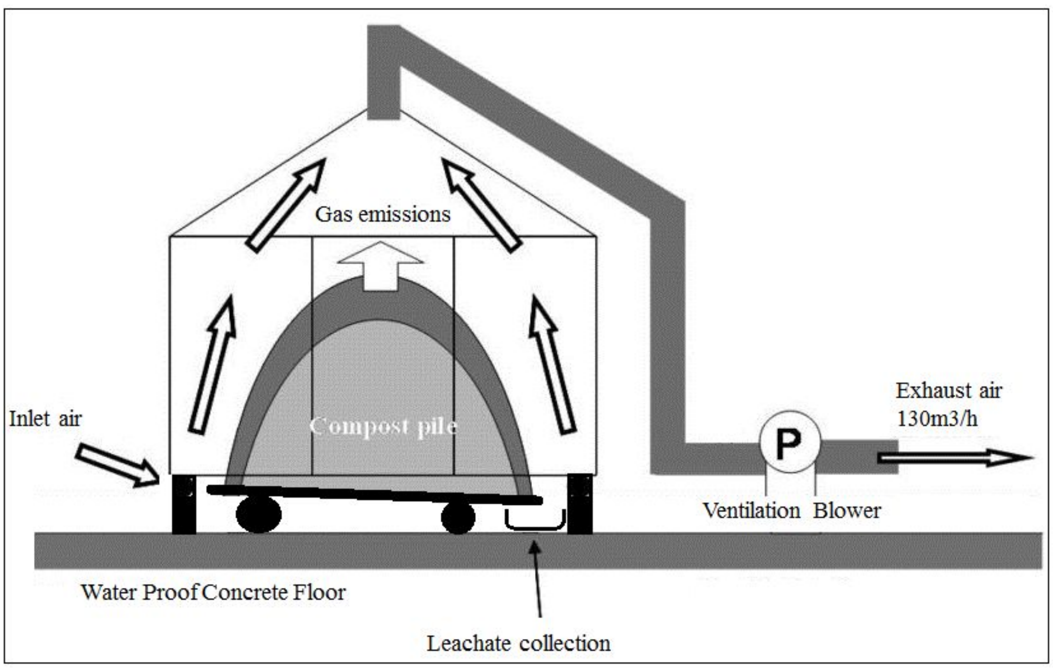

Figure 3.3: Schematic Design of Composting Set-up

3.2.2 EXPERIMENT OUTLINE AND FEEDSTOCK

The experiments represent batch composting in an institutional medium size composting scenario. The OMSW consisted of food waste mixed with grass clippings and dried leaves. Fresh food waste was collected from selected cafeterias in university campus and mixed with grass clippings and dried leaves to adjust the moisture content to approximately 65%. Immediately after the mixing, the mixture was piled up conically inside the chamber. Introduction of small amount of semi-matured compost into the composting pile helped initiate the decomposition of the organic matter in the pile. Each composting run was carried out for duration of 60 days. Initial height of the pile and diameter of the base were about 0.7m and 1.4m. The material was completely turned once in each run. At the end of the composting period, the mixture was weighed.

3.2.3 COLLECTION OF DATA

LCI covers all materials consumption and emissions within the investigated system (ISO, 1998). The gaseous emissions and leachate generation is included in the study. Water, electricity and fuels were used indirectly with the composting process (e.g. cleaning, shredding and grinding). The input and output materials were sampled and characterized in order to quantify the substance balance of the process. Direct decomposition emissions from the composting process were included in the present study. The facility set-up and production of composting tools were not addressed. The provided LCI forms the basis for environmental assessments of OMSW composting at institutional level in future.

3.2.4 SAMPLING OF SOLID MATERIALS

Sampling of the feedstock was performed before and after of every run. Two samples (duplicates), each of 1kg of the OMSW, were collected from composting pile (run). Grab sampling was adopted to be as representatively as possible. The output of the composting after 60 days was weighted and spread on a piece of clean plastic sheet. Sample was obtained from the compost by using quartering method. Finished compost was divided randomly into four sub-groups. Two random apposite sub-groups were mixed up together and further divided into four equal sub-groups. Two random apposite of the sub-groups were mixed again to form four sub-groups. The procedures were repeated until approximately 1 kg of the samples was obtained. The collected samples were oven-dried for keeping the samples solid and brittle before ground into smaller particle by using stone grinder and mass reduction of the sample was performed by quartering method (as described above) to obtain 20g laboratory samples. The samples are then divided into duplicates (10g each) for analysis. The stone grinder was cleaned thoroughly between samples to avoid cross contamination. Average weight of the two samples (10g) was used to determine the flow of material and substances. Total Solids (TS) content of the input and output material was measured by drying the samples at 105^{o}C for about 24 hours (or until constant weight). Volatile Solids (VS) content was measured as mass loss after heating the sample at 550^{o}C for 1 hour. Two replicates per sample were sent for elemental analysis with CHNS analyzer-2400 Series II (for C, N) and ICP-OES (for P, K, Cd, Cr, Cu, Ni and Pb) (PerkinElmer 2012). The analyzed data were used as input parameters in the SFA modelling.

3.2.5 LEACHATE SAMPLING

Leachate generated from the composting process was a contributor to environmental impacts. The experiments were prepared with leachate collection to measure the amount and quality of the leachate collected. A plastic sheet was inserted on the inclined platform where the composting pile was placed to collect the leachate. The leachate was collected in a clean plastic container and weighted. Samples of collected leachate were sent for chemical composition analyses.

3.2.6 SUBSTANCE FLOW BALANCING

SFA was performed by means of the mass balance model STAN 2.5, which perform SFA according to the Austrian standard ONorm 2096 (Cencic and Rechberger, 2008). SFAs have been performed for C, N, K, P, Cd, Cr, Cu, Ni and Pb. The uncertainty of concentrations in the flows was inserted based on the standard deviation of the duplicate samples. Simulations were performed, to compute the gaseous emissions (unknown parameters) based on the known substances content in feedstock, leachate and finished compost. The gaseous emissions to the atmosphere during the composting process were modelled by STAN 2.5 (as shown in Figure 3.4) for all selected substances. CO_2 emissions were assumed as 95%, CH_4 as 4% and CO as 1% of the lost C. NH_3 emissions were made up 0.004% of the total losses of N where N_2O contributes 6.3% of the total loss of N.

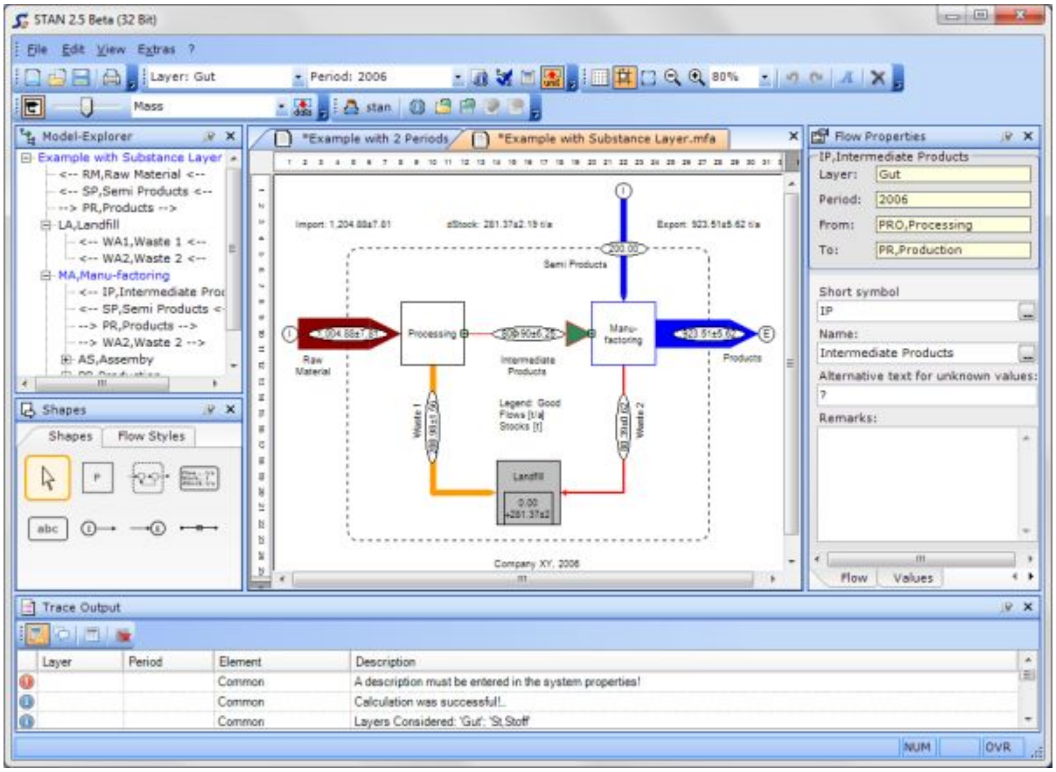

Figure 3.4: Features of STAN 2.5 Software

3.3 QUANTIFICATION OF EMISSIONS FROM ALTERNATIVE OMSW MANAGEMENT

The OMSW management inventoried was based on real OMSW biological treatment project in University of Malaya (UM). Excel-based software tools were created to calculate OMSW management inventories from arbitrary waste compositions. All upstream impacts in the conducted LCA study were assumed to be equal and hence excluded. The life cycle of waste starts when OMSW is disposed of in the trash bin and ends when the waste material is degraded or returned to the technological system through recycling to replace peat and fertilizer. OMSW compositions given as chemical elements such as carbon, nitrogen, phosphorus, potassium, cadmium, chromium, copper, nickel and lead were modeled. The fate of other individual chemical compounds (e.g. hexachlorobenzene, NMVOC, dioxins, PAH etc.) was excluded. Transfer coefficients (TCs) were used to describe the behavior of the OMSW input during treatment process, starting with a given waste composition. The TCs describe what fraction of a pollutant inputted into the treatment process will be emitted through alternative output routes, e.g. emissions to air, water and solid. Pollutants are assessed only as chemical elements. The fate of chemical compounds was excluded due to insufficient individual decomposition data.

Waste composition and TCs were taken from previous work (Ng and Yusoff, 2013). The output routes can be emissions to air or to water, or the generation of by-products like compost and digestate. In order to assess the complete burden of a treatment technology, the generated by-products streams need to be inventoried as well. For example, the compost is applied on land. The concept of waste-specific inventories requires that all by-products streams differ according to the original OMSW input (Christensen et al., 2007). Certain consumptions are not related to the waste composition and are inventoried with average values e.g. energy consumption. These are not waste-specific, but process-specific inventories. These inventory methodology was inspired by EASEWASTE model by Kirkeby et al. (2007) and Christensen et al. (2007).

3.3.1 COMPOSTING

The composting includes emissions to air of nitrogen-compounds and carbon-compounds. The total amount of nitrogen lost (as % of total N) and its distribution among NH_3, N_2O and nitrogen (N_2) is specified. The amount of CH_4 released to the atmosphere, is also estimated. Emissions due to gas cleaning device were not taken into account. The amount of total carbon emitted to the atmosphere during the composting process (kg) is expressed in Equation 1. The amount of CO_2 emitted to atmosphere during the composting process (kg) is expressed in Equation 2. Composting can result in methane emissions due to transient anaerobic conditions in the compost matrix where the amount of methane emitted to atmosphere during composting process (kg) is shown Equation 3. Carbon degradation (and C-release to the atmosphere) is assumed proportional to both the carbon content in the waste and the VS degradation. The degraded carbon is emitted to the atmosphere in different gaseous forms. It is important to note that the equation is based on total carbon. Degradation of C-fossil during the processes under consideration is however considered insignificant where no fossil carbon is degraded during the process. Total N emitted to atmosphere during composting (kg) is expressed in Equation 4. The degradation rate is based on nitrogen balance. The nitrogen is then released to atmosphere in different forms. The amounts of ammonia and nitrous oxide emitted are calculated according to the Equation 5 and 6. In each of them, fractions of degraded N emitted in the specific form are taken into account. The amount of outputs from composting (kg in ww) is shown in Equation 7. Amount of biological carbon in the output from composting (kg) as shown in Equation 8 is calculated based on the amount of biological carbon not degraded during the process and still contained in the output material from composting treatment.

$$Cair_{comp} = Input_{mass} * \Sigma\left(Input_{frac} * TS_{frac} * C_{frac} * Deg_{rate}\right)$$

Equation 1

$$CO2air_{comp} = Cair_{comp} * \left(1 - CH4_{frac}\right) * \frac{Molar_{CO2}}{Molar_{C}}$$

Equation 2

$$CH4air_{comp} = Cair_{comp} * CH4_{frac} * \frac{Molar_{CH4}}{Molar_{C}}$$

Equation 3

$$Nair_{Comp} = Input_{mass} * \Sigma\left(Input_{frac} * TS_{frac} * N_{frac} * N_{\deg}\right)$$

Equation 4

$$NH3air_{comp} = Nair_{Comp} * NH3_{frac} * \frac{Molar_{NH3}}{Molar_{N}}$$

Equation 5

$$N2Oair_{comp} = Nair_{Comp} * N2O_{frac} * \frac{Molar_{N2O}}{Molar_{N}}$$

Equation 6

$$Output_{comp} = \frac{Input_{mass} * \Sigma\left(Input_{frac} * TS_{frac} * \left(Ash_{frac} + (1 - Deg_{rate}) * VS_{frac}\right)\right)}{TS_{output}}$$

Equation 7

$$Coutput_{bio\_comp} = Input_{mass} * \Sigma\left(Input_{frac} * TS_{frac} * Cbio_{frac} * \left(1 - Deg_{rate} * \frac{C_{frac}}{Cbio_{frac}}\right) * TC_{output}\right)$$

Equation 8

3.3.2 ANAEROBIC DIGESTION

The amount of total carbon emitted to the atmosphere during the anaerobic digestion is expressed in Equation 9. The assumption is that the carbon degradation (and C-release to the atmosphere) is proportional to the CH_4 yield. Biogas produced during anaerobic digestion is mainly composed of methane and CO_2. CO_2 and CH_4

emissions to atmosphere are expressed in Equation 10 and 11 respectively. The CO_2 emitted to atmosphere is the sum of the CO_2 contained in biogas and that resulting from combustion of the methane contained in the biogas. The amount of biological carbon in the output from anaerobic digestion is expressed in Equation 14. The equation calculates the amount of biological carbon not degraded during the process and still contained in the output material from anaerobic digestion treatment. Energy content in the methane produced in anaerobic digestion and burned for energy recovery (MJ) is expressed in Equation 12. Substitution of an external process due to energy production is defined by a substitution process and a related percentage expressing the efficiency of the energy recovery process. The amount of nitrogen in the output from anaerobic digestion is expressed in Equation 15 with assumption that no N is lost during the process. The amount of any substance except C and N in the output from both biological treatments is expressed in Equation 17. The equation calculates the amount of substances contained in the output material from a biological treatment, which are not undergoing any degradation (e.g.: heavy metals).

$$Cair_{AD} = Input_{mass} * \Sigma\left(\left(Input_{frac} * TS_{frac} * VS_{frac} * Biogas_{gen} * CH4_{Biogas} * \frac{Molar_C}{Molar_{CH4}}\right) + \left(Input_{frac} * TS_{frac} * VS_{frac} * Biogas_{gen} * CO2_{Biogas} * \frac{Molar_C}{Molar_{CO2}}\right)\right)$$

Equation 9

$$CO2air_{AD} = Input\ mass * \Sigma\Bigg(\bigg(Input_{frac} * TS_{frac} * VS_{frac} * Biogas_{gen} * CO2_{Biogas} * \frac{Molar_{CO2}}{Vol_{ideal}}\bigg) + \bigg(Input_{frac} * TS_{frac} * VS_{frac} * Biogas_{gen} * CH4_{Biogas} * (1 - CH4_{unburned}) * \frac{Molar_{CO2}}{Molar_{CH4}}\bigg)\Bigg)$$

Equation 10

$$CH4_{air_{AD}} = Input_{mass} * \Sigma\bigg(Input_{frac} * TS_{frac} * VS_{frac} * Biogas_{gen} * CH4_{Biogas} * CH4_{unburned} * \frac{Molar_{CH4}}{Vol_{ideal}}\bigg)$$

Equation 11

$$Energy_{process} = Input_{mass} * \Sigma\Big(\big(Input_{frac} * TS_{frac} * VS_{frac} * Biogas_{gen} * CH4_{Biogas} * (1 - CH4_{unburned}) * Energy_{CH4} * Energy_{eff}\big)\Big)$$

Equation 12

$$Output_{AD} = (Input_{mass} * \sum \frac{Input_{frac} * TS_{frac} * \left(Ash_{frac} + VS_{frac} * \left(1 - Bioas_{gen} * \frac{CH4_{Biogas}}{Vol_{ideal}} * Molar_{CH4} * 1.89\right)\right)}{TS_{output}}$$

Equation 13

$$Coutput_{bio\_AD} = Input_{mass} * \Sigma\bigg(Input_{frac} * TS_{frac} * Cbio_{frac} * \bigg(1 - VS_{frac} * Biogas_{gen} * CH4_{Biogas} * \frac{Molar_{C}}{Molar_{CH4}}\bigg) * TC_{output}\bigg)$$

Equation 14

$$Noutput_{AD} = Input_{mass} * \Sigma(Input_{frac} * TS_{frac} * N_{frac} * TC_{output})$$

Equation 15

$$Coutput_{fossil} = Input_{mass} * \Sigma(Input_{frac} * TS_{frac} * Cfossil_{frac} * TC_{output})$$

Equation 16

$$Sub_{output} = Input_{mass} * \Sigma(Input_{frac} * TS_{frac} * Sub_{frac} * TC_{output})$$

Equation 17

$$Coutput_{total} = Coutput_{fossil} + Coutput_{bio}$$ **Equation 18**

$Input_{mass}$ is defined as amount of mass input of OMSW into the composting process (kg); $Input_{frac}$ as ratio of each material fraction in waste generated; TS_{frac} as total solid content in the waste material fraction (ratio); C_{frac} as ratio of carbon in TS in a waste material fraction; Deg_{rate} as ratio of total VS degraded in the composting process; $CH4_{frac}$ as ratio of the emitted C in CH_4 form; N_{frac} as ratio of carbon in TS in a waste material fraction; $N_{\deg}$ as ratio of total Nitrogen degraded in the composting process; $NH3_{frac}$ as ratio of degraded N in NH_3 form; $N2O_{frac}$ as ratio of degraded N in N_2O form; Ash_{frac} as ratio of Ash in TS in a waste material fraction; TS_{output} as total solid content in the output of composting process (ratio); $Cbio_{frac}$ as biological carbon as ratio of TS in a waste material fraction; TC_{output} as transfer coefficient of a substance to outputs (air, water, mass); $Biogas_{gen}$ as experimentally determined maximum methane generation relative to the content of organic matter (VS) in the sample at the beginning of the experiment; $CO2_{Biogas}$ as experimentally determined carbon dioxide content in biogas (ratio); $CH4_{Biogas}$ as experimentally determined carbon dioxide content in biogas (ratio); $CH4_{unburned}$ as ratio of methane not burned and lost to atmosphere; $Energy_{CH4}$ as energy content of methane; $Energy_{eff}$ as substitution process-related production efficiency; $Cfossil_{frac}$ as ratio of fossil carbon in TS of a waste material fraction; Sub_{frac} as ratio of a substance in TS of a waste material fraction.

3.3.3 LANDFILLING

The methane generation of landfilling, Q was modeled by using IPCC zero order model based on degradable material within the waste and methane correction factor as represented in Equation 19. For details of the method see the IPCC Guidelines for National Greenhouse Gas Inventories Volume 5 Chapter 3 (IPCC, 2006). The model employs zero order decay method to estimate methane emissions from landfill sites.

$$Q = \left(MSWT * MSWF * MCF * DOC * DOCF * F * R * \frac{16}{12}\right) * (1 - OX)$$

Equation 19

where, MSWT is total MSW generated, MSWF is fraction of MSW disposed to solid waste disposal sites, MCF is methane correction factor, DOC is degradable organic carbon, DOCF is fraction DOC dissimilated, F is fraction of CH_4 in landfill gas (default is 0.5), R is recovered CH_4 and OX is oxidation factor.

Table 3.1: Assumptions of Landfill Gas Modeling Parameters.

Parameters	Value	Assumption
Methane correction factor (MCF)	0.8	Unmanaged-deep (≥5m waste)
DOC	15% by weight	Food waste
	17% by weight	Garden and park waste and other organic matter (non-food)
OX	0.1	With daily cover

3.3.4 APPLICATION OF COMPOST ON LAND

The use-on-land calculation of compost includes the following processes to account for nutrients lost to the environment: NH_3 volatilization, nitrous oxide formation (N_2O), run-off to surface waters (NO_3^-) and leaching to ground water (NO_3^-). These losses are based on mass balance calculation in association to the N content remain at compost after biological treatment. Temporary binding of carbon will not affect the global warming. In contrast, if the application is considered to contribute to an increase of the carbon level in the soil at the end of the considered time frame, it will represent an actual decrease in CO_2-release thereby contributing (by a saving) to the global warming impact. Carbon sequestration as a percentage of the applied carbon in the waste being permanently bound in the soil is included in the calculation as well. Processed organic waste has certain heavy metal content, as does the commercial fertilizer substituted by the processed organic waste. The difference in input of heavy metals to soil from substitution of commercial fertilizers is included in the model. An increased level of heavy metals and organic pollutants in agricultural soil has a potential toxic impact on humans and ecosystems. Thus, the input of these substances to soil from use of compost influences the environmental impact as Eco toxicity and human toxicity.

The amount of N fertilizer (ammonium nitrate as N) substituted ($Mass_{avoid}$) in kg is expressed in Equation 20. Amount of ammonia ($NH3_{air}$) and nitrous oxide ($N2O_{air}$) emitted to air in kg are expressed in Equation 21 and Equation 22 respectively. Equation 23 describes the amount of nitrate in run-off to surface water after application of compost to soil in kg ($NO3_{runoff}$). Amount of nitrate leaching to ground water in kg ($NO3_{leach}$) is shown in Equation 24. Amount of avoided emissions of CO2 in kg to the atmosphere due to carbon binding to soil (C_{bind}) is expressed in Equation 25 whereas amount of biological CO2 emitted in kg (C_{air}) is shown in Equation 26. $Input_{compost}$ is defined as amount of mass input (kg) of compost resulted from each biological treatment (composting/AD); $TS_{compost}$ as the total solid content of the respective compost; $N_{compost}$ as ration on nitrogen in TS of respective compost; N2O-N as fraction of N in N20 form; NH3-N as fraction of N in NH3 form; NO3-N as fraction of N in NO3 form; $NH3_{evap}$ as the fraction of ammonia evaporated; $Runoff_{eff}$ as the runoff coefficient; $leach_{eff}$ as the leaching coefficient; Ccompost as the ratio of total C in the TS of compost; and C_{fossil} as the ratio of fossil C in the TS of compost.

$$Mass_{avoid} = Output_{treatment} * TS_{compost} * N_{compost}$$ **Equation 20**

$$NH3_{air} = Input_{compost} * TS_{compost} * N_{compost} * NH3 - N * NH3_{evap} * \frac{Molar_{NH3}}{Molar_N}$$

Equation 21

$$N2O_{air} = \Sigma Input_{compost} * TS_{compost} * N_{compost} * N2O - N * \frac{Molar_{N2O}}{MolarN2}$$

Equation 22

$$NO3_{runoff} = Input_{compost} * TS_{compost} * N_{compost} * NO3 - N * Runoff_{eff} * \frac{Molar_{NO3}}{Molar_N}$$

Equation 23

$$NO3_{leach} = Input_{compost} * TS_{compost} * N_{compost} * NO3 - N * leach\_eff * \frac{Molar_{NO3}}{Molar_N}$$

Equation 24

$$CO2_{bind} = Input_{compost} * TS_{compost} * C_{fossil} * \frac{Molar_{CO2}}{Molar_C}$$ **Equation 25**

$$CO2_{air} = Input_{compost} * TS_{compost} * (C_{compost} - C_{fossil}) * \frac{Molar_{CO2}}{Molar_C}$$ **Equation 26**

3.4 LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) was carried out to evaluate the environmental impacts of alternative OMSW management in University of Malaya. Four scenarios were proposed to represent the possible management practice; S1: disposal of OMSW at open dump (current practice), S2: disposal of OMSW at sanitary landfill with landfill gas recovery; S3: composting of OMSW and application of the compost at farm; S4: Biogas recovery of OMSW through anaerobic digestion and application of digestate on land. The system boundary of OMSW disposal life cycle is illustrated in Figure 3.5. This study follows the

ISO 14040 standards (ISO, 1997; ISO, 1998; ISO, 2000a; ISO, 2000b), which defines the LCA phases. SimaPro 7 computer software was used to evaluate alternative OMSW management in respect to impact categories defined by Eco-indicator 99 (H) methodology as shown in Figure 3.5

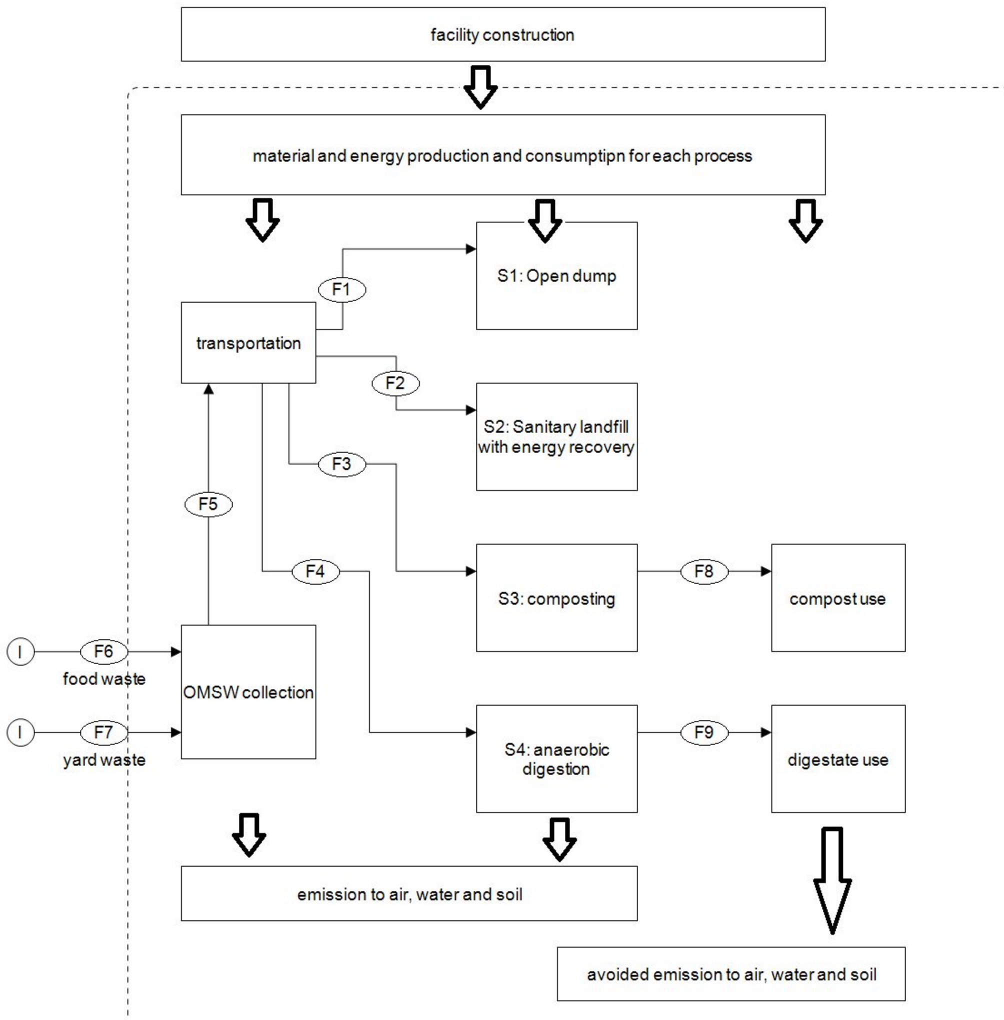

Figure 3.5: System Boundary for the OMSW Disposal Life Cycle

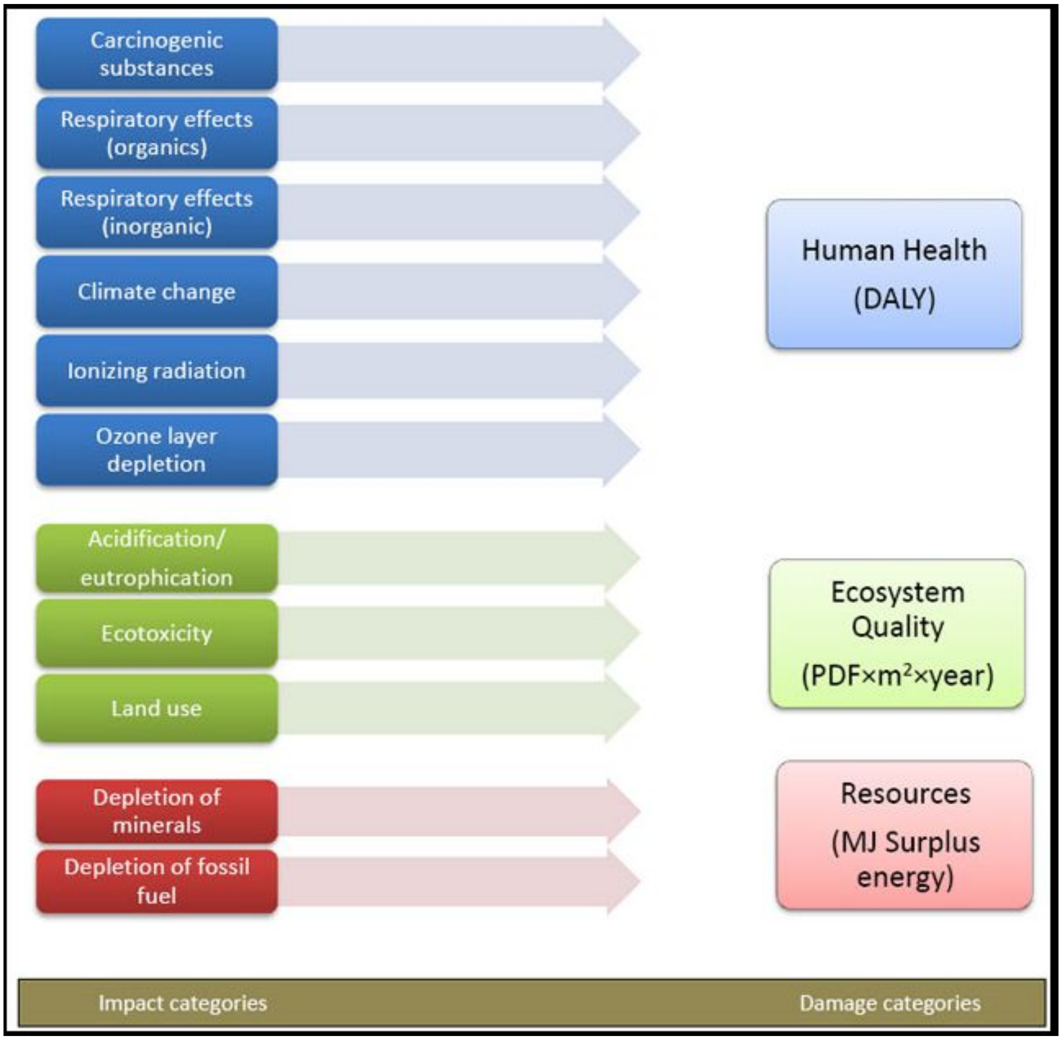

Figure 3.6: Damage Assessment of Eco-indicator 99 Methodology: Categories and Units

The total environmental impact is calculated using Eco-indicator 99 methodology by defining Human Health, Ecosystem Quality and Resources as environmental damages (Goedkoop and Spriensma, 2001). Each damage category consists of a number of impact categories all measured in the same units. The damage assessment of Eco-indicator 99 methodology was summarized in Figure 3.6.

3.4.1 WASTE INPUT

FW generated in UM residential hostels made up the largest fraction of MSW generated daily. Food waste was quantified as 35% consumed and unconsumed rice, 30% vegetables (raw and cooked), 28% protein (raw and cooked) and 7% of fruit peels (Figure 3.7). YW such as fallen leaves, grass and wood chips were added into the feed stock for composting. The waste was separated from the generation point and collected separately by trucks and delivered to the composting facility on daily basis.

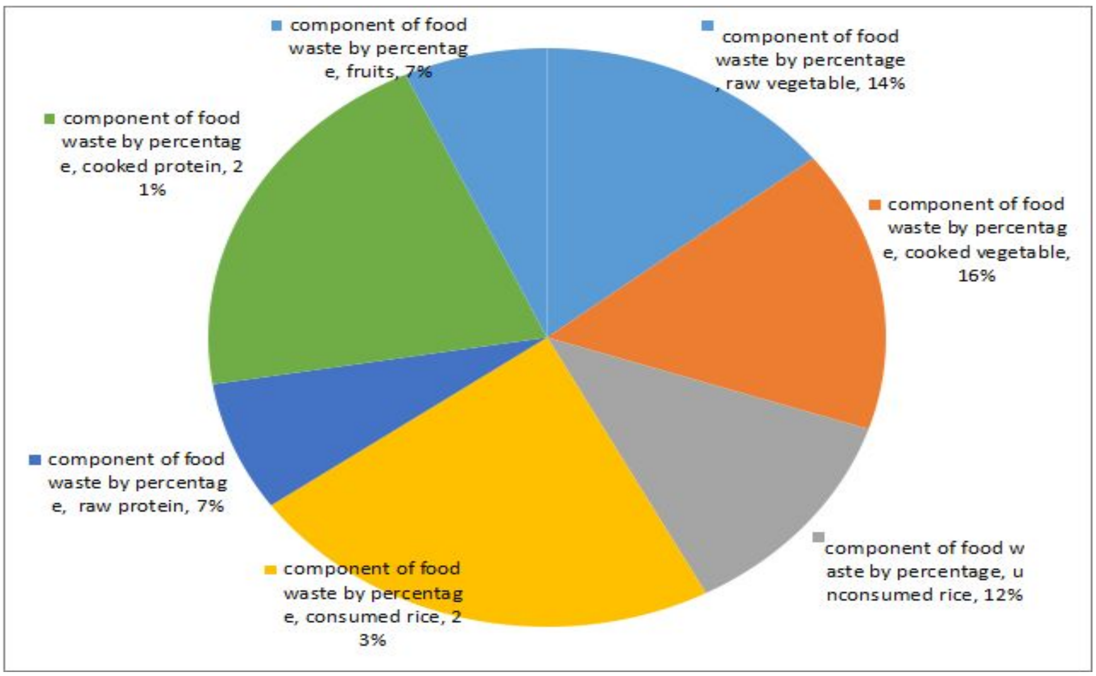

Figure 3.7: Composition of Source-separated Food Waste

3.4.2 SCOPE OF STUDY

The scope of the study includes the entire life cycle of OMSW, from collection until disposal or use-on-land as compost. The application of compost in vegetable farming is compared to alternative end of life products: N-fertilizer as 90% of the compost is used for organic vegetable farming which replaces the use Nitrogen nutrient (Boldrin et al., 2009; Andersen et al., 2012).

3.4.3 FUNCTIONAL UNIT

The functional unit is the reference function to quantify all inputs and outputs of the system. In present study, the functional unit of the investigation systems was defined as the collection, transportation and disposal/treatment and application of one kg of OMSW constituting 0.5kg food waste and 0.5 kg yard waste. All inputs and output flows of the system were gathered from composting and AD operation in UM Zero Waste Center over twelve consecutive months from July 2012 to Jun 2013. The N-fertilizer replacement was also based on the total compost produced from the operation with known N content. Pilot scale composting run revealed that 30% of the initial feedstock weight being transformed into the final compost product.

3.4.4 LIFE CYCLE INVENTORY

Data collection was based on oral interview with Universiti Malaya Composting Center (UMCC) managers which include OMSW physical and chemical characteristics, collection frequency, distance for transportation, fuel and energy consumption, and distances traveled for distribution of final compost. The production and consumption of food and the energy and materials required to gather YW were excluded from the investigation as these processes occur regardless of alternative management of the waste. Impacts associated to the fabrication and set-up of the composting facility were not included as well.

Emissions due to collection of the OMSW to the composting facility were included, as distances may vary in comparing alternative OMSW management scenarios, e.g. between composting center and landfill. Electricity and fuel consumption during the process (shredder and grinder) and decomposition emissions from OMSW in the composting process were included. Additionally, fuel consumption in respect to the distribution of the final compost and the avoided emissions due to fertilizer replacement were taken into consideration. Transportation, energy generation, fuel consumption and waste water treatment were modeled using Eco-invent database included in the SimaPro software. The discharge of waste water treatment plant is assumed to comply with Water Quality Index-Class III.

Table 3.2: OMSW Collection and Transportation

	Feedstock (ton)	Distance (km)	t*km
To composting/AD facility [a]			
food waste	0.001	5	0.005
yard waste	0.001	5	0.005
To landfill [b]			
food waste	0.001	60	0.06
yard waste	0.001	60	0.06

[a] *collection is done by a 3.5 ton lorry*
[b] *transportation by 8 ton lorry*

Distance for transportation of OMSW is shown in Table 3.2. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Particulate emissions comprise exhaust- and abrasions emissions. Heavy metal emissions to soil and water caused by tires abrasion are included as well. Average data for the operation of an average Swiss lorry (fleet average) fully loaded (100%) in the year 2005. Electricity demand for operating a compost plant was included as well as process emissions, infrastructure of the compost plant and transports related to the collection of the biogenic waste. The decomposition began when the food waste was loaded manually on mobile bins, and placed on the shredded yard waste on daily basis. After 60 days, the final compost was screened and ground, where the reject was disposed. The grounded compost was stacked for distribution. LCI data represents the environmental exchanges due to OMSW pretreatment (inclusive the disposal of contaminants). In addition emissions to soil due to the use of compost in agriculture are considered. Transport of compost to farms is taken into account. Process-specific (i.e. independent of waste composition), energy demand and land use of landfill from Eco-invent was taken due to lack of comprehensive date form local landfills.

Diesel consumption of the trucks (for collection of food waste and yard waste) was provided by UM assets department and that of the grinder was provided by UMCC. The collection process of feedstock includes diesel consumption of 41.26E-6 kg diesel/kg food waste and 2.27E-3 kg diesel/kg yard waste. Shredding of yard waste using an electric-powered shredder was estimated to consume 0.00354 kWh/kg yard waste. Grinder in UMCC consumed 8.04E-4kg diesel/kg compost input. Emissions from diesel combustion were calculated using Eco-invent database. Loading of feedstock and turning of windrow was done manually, hence no emissions were taken into account. Finally, the national energy mix of natural gas (46.8%), coal (45.6%), hydroelectric (3.8%) and oil (3.8%) for Malaysia was used to estimate emissions. Emissions were calculated using Eco-invent database on energy generation.

3.5 POTENTIAL GHG EMISSIONS REDUCTION FROM OMSW COMPOSTING AS COMPARED TO LANDFILLING (BUSINESS-AS-USUAL)

3.5.1 METHODOLOGY OF "BACKCASTING"

This study applied backcasting method to achieve a Low-carbon society. The back-casting method involves working backwards from a particular desired objective or goal to the present in order to determine the policy improvement required by considering also the feasibility of implementation. The back-casting approach is divided into two phases namely: desired goal and the means to achieve that goal from present scenario.

As first trial to OMSW management study, this study includes the vision of environmental targets set by the government while maintaining planned development. The environmental targets were identified based on government report, discussions between policy makers and researchers; reduction of CO_2 emissions (-40%) and OMSW final disposal (-50%). The goal of the study should achieve all goals using available counter measures.

3.5.2 MODEL FOR DECISION MAKING

Modeling based on back-casting approach is applied by estimating quantitative future environmental burden in terms of carbon emissions and alternative scenarios or improvements to be implemented to achieve the targets. Firstly, OMSW generation information in the base year (2012) were collected to calculate current emissions. the model estimates the OMSW generation for future projection based on population which. Environmental loads are then calculated with several scenarios (options) and best scenario is identified based on the most carbon emission reduction.

3.5.3 SOCIO-ECONOMIC SCENARIO

The base year for this research is set as 2012 due to the availability of data from Jabatan Pengurusan Sisa Pepejal Negara (JPSPN). The information for base year is obtained mostly from the document on the survey on the current practice of recycling and waste generation information (JPSPN, 2013). As for future projection, some assumptions were made.

As planned nation, population in Malaysia will increase by 2% per annum. The waste generation rate per capita is assumed to be similar as to the base year. Emission intensity waste calculated as emission, as in mass over national per capita Gross Domestic Product (GDP). The per capita GDP growth is assumed to grow approximately at an average of 4.3% per year. The socio-economic assumptions are summarized in Table 3.3.

Table 3.3: Socio-Economic Assumptions

Socio-Eeconomic indicators	2012	2025
Population in Peninsular Malaysia	22,569,345	29,195,854
GDP/capita in Malaysia	USD 17,000	USD 29,000
Average trip distance for OMSW disposal	Trip distance for OMSW disposal will reduce by 50% due to on-site composting activity	

3.5.4 SYSTEM BOUNDARY AND EMISSION SOURCES OF THE STUDY

The system of the study started with the temporary storage of the MSW from generation sources and followed by OMSW diversion process, waste treatment alternative (composting), waste transportation and landfilling of waste. The scope of the study is clearly illustrated in Figure 3.8.

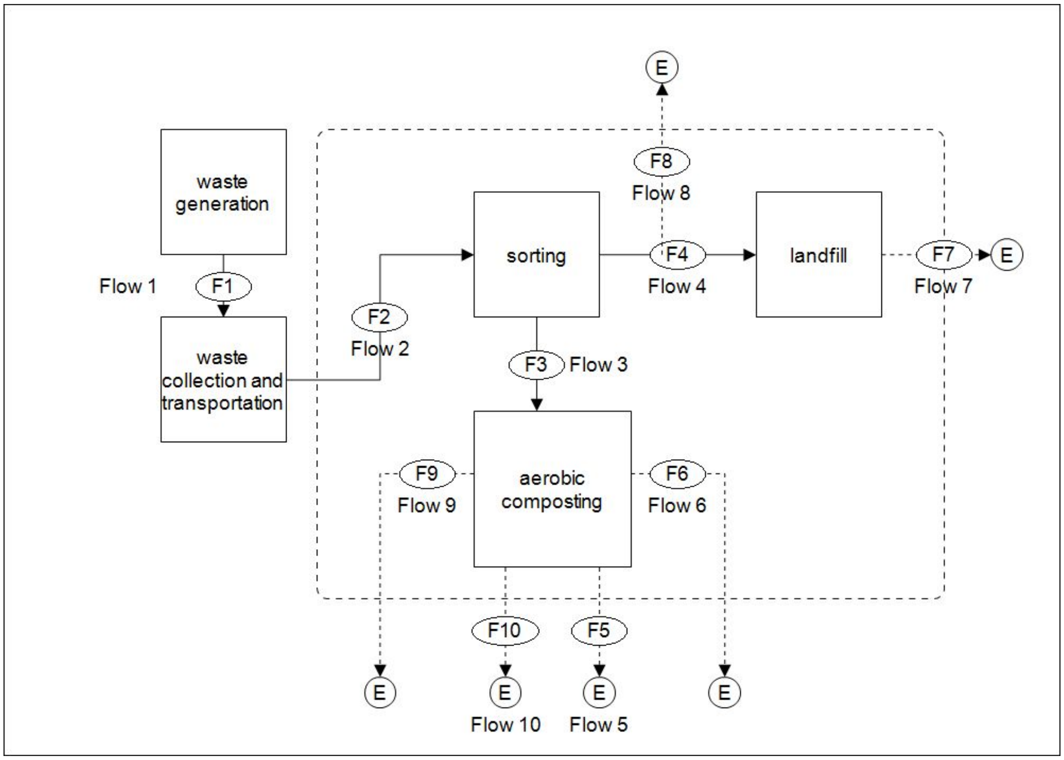

Figure 3.8: System Boundaries of Composting and Landfilling of OMSW, "E" represents substances leaving the system boundary

Components outside the dash dotted lines were not in the boundaries of this study although they were recognized to have some impacts on the environment. The functional unit selected for the study was the management of total waste MSW management generated daily from households, institutional, commercial and industrial for year 2012 and 2025 respectively as shown in Table 3.4.

Table 3.4: OMSW generation from household, institutional, commercial and industrial areas in Peninsular Malaysia for base year (2012) and future (2025).

waste generation (2012)	Households				ICI*			Total
	Northern (‘000)	Southern (‘000)	klang valley (‘000)	east coast (‘000)	Ins	Com	Ind	
Population	6,093	5,190	7,209	4,076				
Total waste generated (mt/day)	18,129				9,673			27,802
FW (g/capita/day)	308	406	416	204	45	106	6	
Table 3.4 continued.								
YW (g/capita/day)	41	52	55	30	9	5	1	
FW (mt/day)	1,874	2,106	3,001	833	1,006	2,382	132	11,333
YW (mt/day)	247	270	400	121	194	106	24	1,361

waste generation (2025)	Households				ICI*			Total
	Northern (‘000)	Southern (‘000)	klang valley (‘000)	east coast (‘000)	Ins	Com	Ind	
Population	7,882	6,714	9,325	5,273				
Total waste generated (mt/day)	23,451.79				12,513.06			35,965
FW (g/capita/day)	308	406	416	204	45	106	6	
YW (g/capita/day)	41	52	55	30	9	5	1	
FW (mt/day)	2,424	2,725	3,882	1,077	1,301	3,081	171	14,661
YW (mt/day)	319	350	517	156	251	137	31	1,761

**ICI consists of Institutional, Commercial and Industrial entities*

The scope of the study included the facilities for composting, on-site electricity consumption, on-site fuel consumption, fuel consumption of waste transportation to landfill, direct emission from composting process and direct emission from landfill. The emissions included in the study are summarized in Table 3.5

Table 3.5: Emissions Included in the Case Study

Carbon emission (tCO_{2e})	**Flow**
Landfilling	Flow 7
Transportation	Flow 8
Composting site electricity consumption	Flow 5
Composting site fuel consumption	Flow 6
N_2O emission from composting	Flow 9
CH_4 emission from composting	Flow 10

The facilities for waste collection and transportation to the composting site were excluded from the study. The application of compost as soil conditioner for landscaping was excluded as well due to its insignificant amount in association to the replacement of chemical fertilizer with compost. The summary of the methodology flow is shown in Figure 3.9.

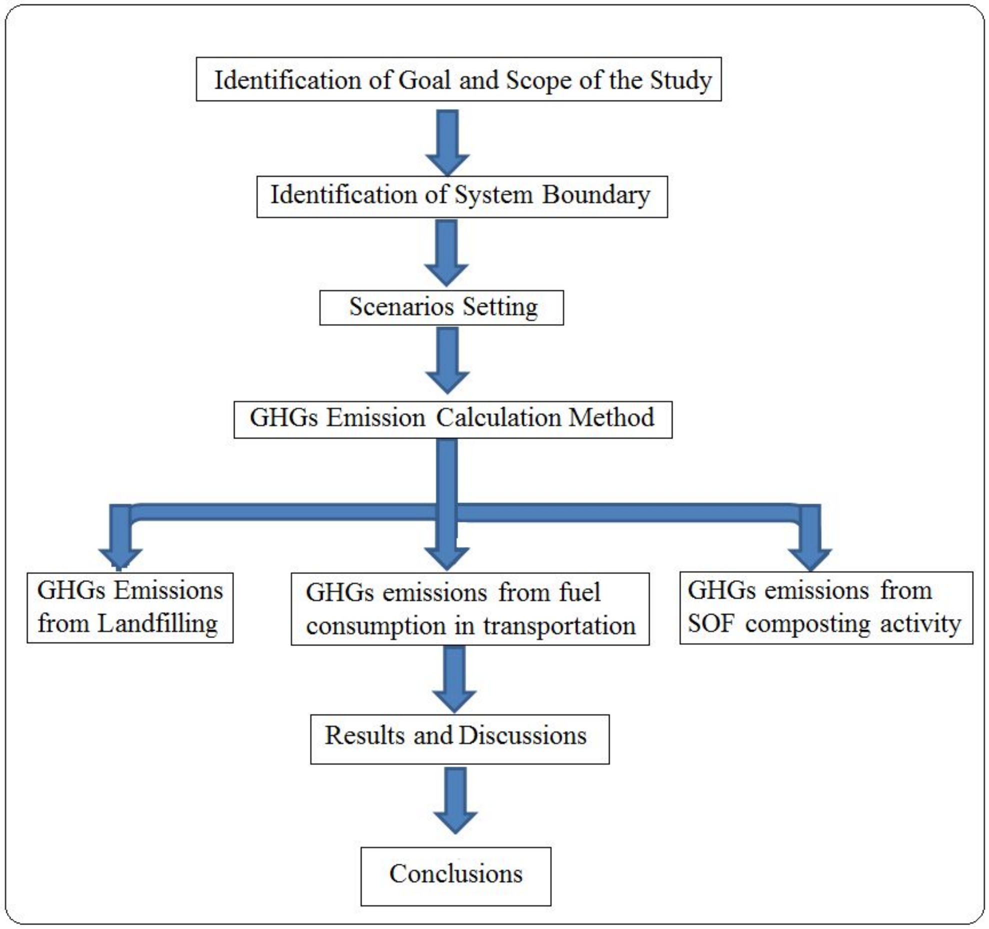

Figure 3.9: The Methodology Flow for GHG Emissions Study

3.5.5 SCENARIO SET-UP

There were six scenarios constructed form comparison. The scenarios were constructed based on the availability of the OMSW from each source of generation. The scenarios are: S0 as the scenario where all wastes were disposed at landfill in the base year of 2012; S1 where total waste as generated is disposed at landfill (Business-As-Usual) in year 2025 (36,000 mt/day); S2 where all OMSW generated from all government and private institutes are sorted from MSW waste stream and composted; S3 where all OMSW generated from institutions and factories are sorted and sent to composting center. S2 and S3 are considered 'low-hanging fruits' with the enforcement of national solid waste management act and private initiatives. S4 is the expansion of S3 which includes all YW collected from commercial areas and 50% FW sorted for composting purpose. S5 has the similar scenario as S4 but includes all YW from residential areas in Peninsular Malaysia diverted to composting centers. S6 is the ultimate scenario which has most OMSW composted which includes the amount in S5 with additional of 22% of FW generated from all households.

Scenarios were proposed as progressive steps towards achieving the national target of recycling rate of 22% of total waste generated. The diversion of OMSW from MSW was expended gradually through S2 (4%), S3 (5%), S4 (10%) S4 (13%) and S6 (19%) by considering the possible immediate diversion of OMSW from institutional, commercial and industrial areas and ultimately residential areas. The summary of the scenario for alternative OMSW management is shown in Table 3.6.

Table 3.6: Scenario Setting for Alternative OMSW Recovery

	To composting center (flow 3)		To landfill (flow 4)		
	Separated YW	Separated FW	YW	FW	Non-OMSW
By weight (t/d)					
S0	-	-	1,360	11,330	15,100
S1	-	-	1,760	14,660	19,540
S2	250	1,300	1,510	13,360	19,540
S3	280	1,400	1,480	13,260	19,540
S4	420	3,000	1,340	11,660	19,540
S5	1,760	3,000	-	11,660	19,540
S6	1,760	5,000	-	9,660	19,540

3.5.6 CARBON EMISSION CALCULATION METHOD

The methodologies used to analyze the GHG emission for this case study are accordance to CDM methodology AM0025 (UNFCCC, 2008), the emission reduction was calculated from the deduction of baseline emissions and project emissions.

3.5.6.1 METHANE EMISSION FROM LANDFILL

A simple mass balance approach was used to estimate the total generation of methane gas from waste disposed in landfill. This method is suggested due to the intention to compare maximum GHG generation potential from different scenarios of FW and YW management. It does not reflect the generation of GHG over time, which is beyond the intention of the present paper. The calculation is expressed in Equation 27. The method assumes that all the potential CH_4 emissions are released during the same year the waste is disposed of. The method is simple and emission calculations require only input of a limited set of parameters. MGF was obtained from Table 4.8 in Chapter 4.

$$\mathbf{Me_{,y}} = \left(\mathbf{MSWt} * \mathbf{MCF} * \mathbf{DOC} * \mathbf{DOCf} * \mathbf{F} * \left(\frac{16}{12}\right) - \mathbf{R}\right) * (1 - \mathbf{OX}) \qquad \textbf{Equation 27}$$

with

$Me_{,y}$: methane emission in year "y" (t/year)

MSW_t : total MSW disposed in year "y" (t/year)

MCF : methane correction factor (fraction)

DOC : degradable organic carbon (fraction) (kg C/kg SW)

DOC_f : fraction DOC dissimilated

F : fraction of CH_4 in landfill gas

16/12 : conversion of C to CH_4

R : recovered CH_4 (t/year)

OX : oxidation factor (fraction)

Electricity consumption was excluded in the assessment as there was no significant reduction of electricity consumption with the diversion of biomass out of landfill. Moreover, we assumed that no landfill gas was collected for flaring or power generation (F = 0), thus emission from thermal energy generation was not included in the assessment as well. CO_2 emission from combustion or decomposition of biomass was not accounted as GHG emissions (IPCC, 2006). The parameters with all the assumed values are shown in Table 3.7. The decay rate of the “other” waste (residual waste) was based on the decay rate of paper and textiles in the Revised 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

Table 3.7: Parameters for Carbon Emission Calculation and Their Values

Parameters	Kitchen waste	Yard waste	Residual waste
Φ	0.9	0.9	0.9
OX	0.1	0.1	0.1
F	0.54	0.54	0.54
DOC_f	0.5	0.5	0.5
MCF	1.0	1.0	1.0
DOC	0.15	0.20	0.4
GWP_{CH4}	21	21	21
GWP_{N20}	310	310	310

3.5.6.2 TRANSPORTATION TO LANDFILL (FUEL CONSUMPTION)

The emission from fuel consumption in transportation of waste from UM to landfill is expressed in Equation 28. The total distance travelled per trip was 120 km and the fuel consumption per distance was 0.25 litre/km (Zamri, 2011). The methodological approach estimated emissions from road transport based on total fuel consumption. The calorific value of diesel was assumed to be 13.495 MJ/kg (Raheman and Phadatare, 2004).The emission factor of diesel was assumed to be 73.9E-06 tCO_2/MJ (Herold 2003) while the density of diesel was taken as 0.832 kg/litre (Alptekin and Canakci, 2008)

$$FEfuel, y = N, i, y * D * VF * CV * \partial * EF \quad \textbf{Equation 28}$$

with

$FEfuel, y$: Total GHG emissions from fuel consumption in transportation in year "y" (tCO_2)

N,i,y : Number of vehicles for transport with similar loading capacity, i in year "y"

D : Average distance travelled by vehicle type i in year "y"

VF : Vehicle fuel consumption in litres per kilometre of vehicle type i (l/km)

CV : Calorific value of fuel (MJ/kg)

∂ : Density of fuel (kg/l)

EF : Emission factor of fuel (tCO_2/MJ)

3.5.6.3 GHG EMISSONS FROM OMSW COMPOSTING ACTIVITY

The OMSW composting emission within the project boundary in year y is expressed in Equation 29 which considered the emission of electricity consumption, fuel consumption, direct emission from composting process in term of N_2O and CH_4.

$$PE,y = PEelec,y + PEfuel,y + PEn20,y + PEch4,y \quad \textbf{Equation 29}$$

with

$PE_{,y}$: Total composting emissions during the year “y” (tCO_2e)

$PE_{elec,y}$: Emissions off-site from the electricity consumption on-site in year “y” (tCO_2e)

$PE_{fuel,y}$: Emissions on-site due to fuel consumption in year “y” (tCO_2e)

$PE_{n2o,y}$: Emissions during the composting process due to N_2O production in year “y” (tCO_2e)

$PE_{ch4,y}$: Emissions during the composting process due to CH_4 production through anaerobic conditions in year “y” (tCO_2e)

The emission from project electricity consumption and project fuel consumption in year y are expressed in Equation 30 and Equation 31 respectively. The composting activity involved on-site electricity consumption which was connected to the national grid. The emission factor from electricity consumption was 0.672 tCO_2/MWh (Rahman Mohamed and Lee, 2006). The yearly electricity consumption for UM composting site was 5564 kWh (UM, 2012). The fuel consumption in the composting project was assumed as 4.63 litre/ton of waste composted (UM, 2011) whereas the net caloric value and the emission factor of diesel were 38.592 MJ/litre and 7.42E-5 tCO_2/MJ respectively (Furuholt, 1995). The fuel (diesel) was only used to power the grinding machine for the production of finished compost.

$$PEelec,y = kWh,y * CEFelec$$ **Equation 30**

with

$kWh_{,y}$: Amount of electricity used for the composting process, measured using an electricity meter (MWh)

CEF_{elec} : The carbon emissions factor for electricity (tCO2/MWh)

$$PEfuel,y = M,y * Fc * NCV * EF$$ **Equation 31**

with

$M_{,y}$: Total waste composted in year y (ton)

Fc : Fuel consumption (l/ton)

NCV : Net caloric value of the fuel (MJ/l)

EF : CO_2 emissions factor of fuel (tCO_2/MJ)

The direct emissions of N_2O and CH_4 from composting activity are presented in Equation 32 and Equation 33 respectively. The emission factor for N_2O emissions from composting process was taken as 4.3E-05 tN_2O/t compost produced (UNFCCC, 2008) whereas the final weight of compost produced is assumed to be 30% of the initial weight of waste input. the emission factor for CH_4 from composting process was assumed as 0.0019 tCH_4/tOM of waste (Fukumoto et al., 2003). The emission factors for both N_2O and CH_4 from composting process were 310 tCO_2/tN_2O and 21 tCO_2/tCH_4 by considering time horizon of 100 years (UNFCCC, 2008).

$$PEn20,y = Mcompost,y * EFn20 * GWPn20$$ **Equation 32**

with

$M_{compost,y}$: Total quantity of compost produced in year y (ton)

$EF_{,n2O}$: Emission factor for N_2O emissions from the composting process (t N_2O/t compost)

GWP_{n2O} : Global Warming Potential of nitrous oxide (tCO_2/tN_2O)

$$PEch4 = EFch4 * GWPch4 * OM,y$$ **Equation 33**

with

OM,y : Organic matter of the waste composted in year "y" (ton)

$EF_{,\,ch4}$: Emission factor for CH_4 emissions from the composting process (t CH_4/t OM)

GWP_{ch4}: Global Warming Potential of methane (tCO_2/tCH_4)

4. RESULTS

4.1 OMSW QUANTITIES AND COMPOSITION

The amount of OMSW added for Run 1 and Run 2 were 212-393 kg (See Figure 4.1; the mixture of FW and YW were given in the inputs to the experiments). The composition of the input material is given in Table 4.1 and Table 4.2 for FW and YW respectively. Sample A was collected from Run 1 whereas Sample B was collected from Run 2 for both FW and YW.

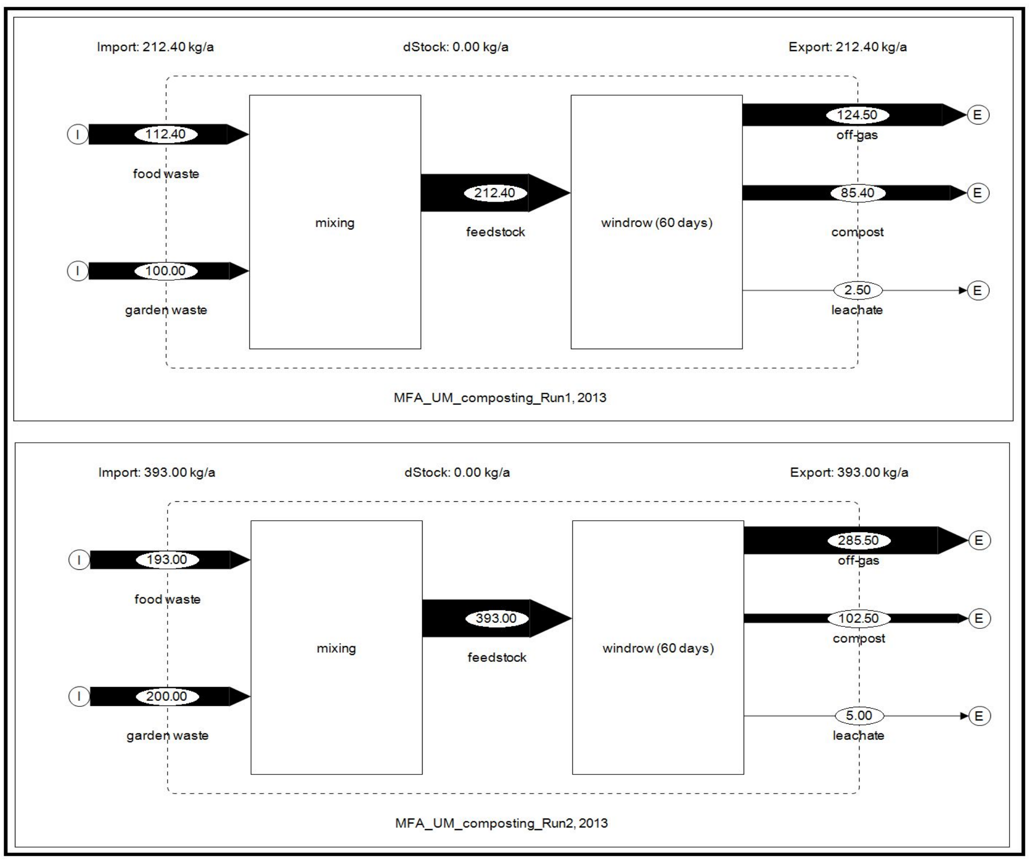

Figure 4.1: Mass Flow of OMSW Composting in kg

4.1.1 ELEMENTAL COMPOSITION OF FOOD WASTE

By considering the mean values, proximate analysis shows that FW constitute moisture, volatile solid (VS) and ash content for Sample A (72.44%ww; 24.53%ww; 3.03%ww) and Sample B (73.84%ww; 17.48%ww; 8.68%ww). The main elements detected in FW for Sample A and Sample B respectively are C (67.25% TS and 66.94% TS), H (8.40% TS and 7.46% TS), N (5.59% TS and 6.22% TS) and Fe (2.58% TS and 2.33% TS). Other elements such as heavy metals and inorganic compounds constitute approximately 13.54% TS and 14.72% TS for Sample A and Sample B respectively. Insignificant amount of trace metals (which contribute approximately 0.02% TS to both runs) were detected in FW.

4.1.2 ELEMENTAL COMPOSITION OF YARD WASTE

The initial weight of YW constitute moisture, VS and ash content in Sample A (39.28%ww; 48.46%ww; 12.26%ww) and Sample B (45.98%ww; 38.89%ww; 15.13%ww). Generally, the moisture content in YW is lower than that in FW whereas the VS and ash content in YW are higher than that in FW. Similarly, the main element detected in YW are C (44.20% TS and 43.70% TS), H (5.34% TS and 5.39% TS), N (2.88% TS and 2.23% TS). The concentration of each element is listed in Table 4.2. The trace metals contribute approximately 0.03%TS to the composition of the YW. The heavy metals and nutrients contents of both materials were in the range provided by previous studies for organic household waste (Riber, 2007).

4.1.3 CHEMICAL COMPOSITION AND QUALITY OF COMPOST

The composition of the compost from both composting runs (Run 1 and Run 2) is presented in Table 4.3. The final weight of compost constitute moisture, VS and ash content from Sample A (20.54%ww; 71.71%ww; 7.75%ww) and Sample B (17.54%ww; 75.30%ww; 7.16%ww). Generally, the moisture content in compost is lower than that in the inputs. Similarly, the main element detected in compost are C (20.96%TS and 23.90%TS), H (7.92%TS and 8.20%TS), N (1.95%TS and 1.64%TS). The concentration of each element is listed in Table 4.3. The trace metals contribute approximately 0.02%TS to the composition of the compost. The heavy metal content was below all threshold limits found by previous researchers. Table 4.4 shows a range of typical heavy metal contents in compost (Brinton, 2000; Hogg et al., 2002).

The characteristics of the final compost was assessed. Apparently, food waste is no longer visible in the compost. Finished compost had dark brown colour and urine smell, indicating leaching of ammonia. A common indicator is the C/N ratio. The decrease of C/N ratio and VS were recorded from both composting runs (Table 4.5).

Table 4.1: Composition and Characteristics of Food Waste Collected as Feedstock to Experiments

	Unit	Sample A							Sample B						
		1	2	3	4	5	Mean	SD	1	2	3	4	5	Mean	SD
Proximate Analysis															
moisture content	% ww	66.40	69.30	75.40	76.90	74.20	72.44	-	71.40	80.60	75.40	69.60	72.20	73.84	-
VS	% ww	30.07	27.45	21.55	20.70	22.88	24.53	-	22.42	13.70	17.05	17.48	16.74	17.48	-
ash	% ww	3.53	3.25	3.05	2.40	2.92	3.03	-	6.18	5.70	7.55	12.92	11.06	8.68	-
Total	% ww	100.00	100.00	100.00	100.00	100.00	100.00	-	100.00	100.00	100.00	100.00	100.00	100.00	-
Elemental Analysis															
C	%TS	65.21	67.23	74.35	59.64	69.82	67.25	5.46	65.40	71.60	68.20	59.30	70.20	66.94	4.86
H	%TS	7.60	8.40	7.90	8.70	9.40	8.40	0.70	8.40	7.60	9.10	5.40	6.80	7.46	1.44
N	%TS	5.60	6.80	5.87	4.32	5.34	5.59	0.90	5.60	7.20	6.80	5.60	5.90	6.22	0.74
S	%TS	0.18	0.13	0.11	0.09	0.16	0.13	0.04	0.12	0.14	0.18	0.16	0.11	0.14	0.03
Ca	%TS	1.06	1.21	0.97	0.89	1.05	1.04	0.12	0.93	0.90	0.87	0.83	0.80	0.87	0.05
Fe	%TS	2.49	2.61	3.01	2.47	2.31	2.58	0.26	2.42	2.38	2.33	2.28	2.23	2.33	0.08
K	%TS	1.27	0.98	1.12	0.84	1.23	1.09	0.18	1.02	1.00	0.98	0.96	0.93	0.98	0.03
Na	%TS	0.23	0.31	0.19	0.22	0.27	0.24	0.05	0.24	0.24	0.24	0.24	0.24	0.24	0.00
P	%TS	0.18	0.23	0.09	0.14	0.08	0.14	0.06	0.06	0.13	0.11	0.12	0.10	0.10	0.03
others	%TS	16.18	12.10	6.39	22.69	10.34	13.54	6.21	15.80	8.81	11.20	25.11	12.69	14.72	6.34
Total	%TS	100.00	100.00	100.00	100.00	100.00	100.00	-	100.00	100.00	100.00	100.00	100.00	100.00	-
Trace metals															
Cd	mg/kg TS	0.90	0.80	0.94	0.73	0.69	0.81	0.11	0.67	0.62	0.57	0.52	0.47	0.57	0.08
Cr	mg/kg TS	12.40	10.70	13.60	9.40	8.60	10.94	2.07	8.27	7.38	6.49	5.60	4.71	6.49	1.41
Cu	mg/kg TS	9.10	13.50	12.90	10.40	9.80	11.14	1.95	10.63	10.46	10.29	10.12	9.95	10.29	0.27

Table 4.1: (Continued)

Mn	mg/kg TS	86.00	80.00	75.00	91.00	73.00	81.00	7.52	76.50	75.00	73.50	72.00	70.50	73.50	2.37
Ni	mg/kg TS	10.80	11.60	12.60	9.80	8.40	10.64	1.62	8.66	8.00	7.34	6.68	6.02	7.34	1.04
Pb	mg/kg TS	5.60	7.10	4.30	6.10	5.90	5.80	1.01	5.68	5.64	5.60	5.56	5.52	5.60	0.06
Zn	mg/kg TS	74.00	69.00	59.00	72.00	84.00	71.60	9.02	78.50	80.80	83.10	85.40	87.70	83.10	3.64
Total	mg/kg TS	198.80	192.70	178.34	199.43	190.39	191.93	8.53	188.91	187.90	186.89	185.88	184.87	186.89	1.60
Total	%TS	0.02	0.02	0.02	0.02	0.02	0.02	-	0.02	0.02	0.02	0.02	0.02	0.02	-

Table 4.2: Composition and Characteristics of Yard Waste Collected from UM as Feedstock to Experiments

		Sample A							Sample B						
		1	2	3	4	5	Mean	SD	1	2	3	4	5	Mean	SD
Proximate Analysis															
moisture content	% ww	33.20	39.20	46.70	41.60	35.70	39.28	-	46.50	46.24	45.98	45.72	45.46	45.98	-
VS	% ww	50.77	48.64	43.71	49.06	50.15	48.46	-	38.73	39.35	39.97	35.17	41.23	38.89	-
Ash	% ww	16.03	12.16	9.59	9.34	14.15	12.26	-	14.77	14.41	14.05	19.11	13.31	15.13	-
Total	% ww	100.00	100.00	100.00	100.00	100.00	100.00	-	100.00	100.00	100.00	100.00	100.00	100.00	-
Elemental Analysis															
C	%TS	43.00	40.00	52.00	47.00	39.00	44.20	5.36	43.90	43.80	43.70	43.60	43.50	43.70	0.16
H	%TS	5.20	5.60	4.80	6.10	5.00	5.34	0.52	5.37	5.38	5.39	5.40	5.41	5.39	0.02
N	%TS	3.60	2.10	4.20	2.60	1.89	2.88	0.99	2.50	2.11	1.72	1.33	3.50	2.23	0.83
S	%TS	0.19	0.21	0.14	0.16	0.22	0.18	0.03	0.19	0.19	0.19	0.19	0.19	0.19	0.00
Ca	%TS	2.11	1.89	1.57	2.34	2.15	2.01	0.29	2.17	2.22	2.28	2.33	2.38	2.28	0.08
Fe	%TS	1.48	1.20	1.07	1.37	1.20	1.26	0.16	1.14	1.19	1.15	1.02	0.97	1.09	0.09
K	%TS	1.27	1.17	0.96	1.34	1.08	1.16	0.15	1.10	1.08	1.06	1.04	1.02	1.06	0.03
Na	%TS	0.09	0.08	0.09	0.12	0.06	0.09	0.02	0.08	0.08	0.08	0.08	0.07	0.08	0.00
P	%TS	0.20	0.21	0.19	0.22	0.19	0.20	0.01	0.20	0.20	0.20	0.20	0.20	0.20	0.00
others	%TS	42.86	47.54	34.98	38.75	49.21	42.67	5.94	43.35	43.75	44.24	44.82	42.75	43.78	0.80
Total	%TS	100.00	100.00	100.00	100.00	100.00	100.00	-	100.00	100.00	100.00	100.00	100.00	100.00	-

Table 4.2: (Continued)

Trace metals															
Cd	mg/kg TS	0.36	0.24	0.18	0.33	0.28	0.28	0.07	0.26	0.25	0.24	0.24	0.23	0.24	0.01
Cr	mg/kg TS	4.50	2.60	3.60	4.80	1.90	3.48	1.23	2.58	2.28	1.98	1.68	1.38	1.98	0.47
Cu	mg/kg TS	20.00	22.00	20.00	25.00	13.00	20.00	4.42	16.70	15.60	14.50	13.40	12.30	14.50	1.74
Mn	mg/kg TS	115.00	120.00	104.00	112.00	103.00	110.80	7.26	101.20	98.00	94.80	91.60	88.40	94.80	5.06
Ni	mg/kg TS	3.20	2.80	4.10	3.90	1.50	3.10	1.04	2.41	2.18	1.95	1.72	1.49	1.95	0.36
Pb	mg/kg TS	24.00	16.00	13.00	9.00	17.00	15.80	5.54	15.00	13.00	20.00	14.00	19.00	16.20	3.11
Zn	mg/kg TS	208.00	156.00	139.00	174.00	194.00	174.20	27.86	171.20	170.20	169.20	168.20	167.20	169.20	1.58
Total	mg/kg TS	375.06	319.64	283.88	329.03	330.68	327.66	32.55	309.35	301.51	302.67	290.84	290.00	298.87	8.28
Total	%TS	0.04	0.03	0.03	0.03	0.03	0.03	0.00	0.03	0.03	0.03	0.03	0.03	0.03	0.00

Table 4.3: Composition and Characteristics of Compost from Experiments

		Run 1							Run 2						
		1	2	3	4	5	Mean	SD	1	2	3	4	5	Mean	SD
Proximate Analysis															
Moisture Content	% ww	18.50	16.30	21.40	25.70	20.80	20.54	-	14.74	16.14	17.54	18.94	20.34	17.54	-
VS	% ww	73.19	76.13	69.48	67.98	71.76	71.71	-	77.50	76.40	75.30	74.20	73.09	75.30	-
Ash	% ww	8.31	7.57	9.12	6.32	7.44	7.75	-	7.76	7.46	7.16	6.86	6.57	7.16	-
Total	% ww	100.00	100.00	100.00	100.00	100.00	100.00	-	100.00	100.00	100.00	100.00	100.00	100.00	-
Elemental Analysis															
C	%TS	23.80	22.40	23.60	18.20	16.80	20.96	3.24	23.50	23.70	23.90	24.10	24.30	23.90	0.32
H	%TS	7.70	6.80	9.40	8.60	7.10	7.92	1.08	8.10	8.16	8.22	8.28	8.34	8.22	0.09
N	%TS	2.50	1.80	1.68	2.00	1.75	1.95	0.33	1.56	1.43	1.90	1.89	1.45	1.64	0.23
S	%TS	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00
Ca	%TS	0.94	0.84	0.88	0.72	0.79	0.83	0.08	0.71	0.67	0.62	0.58	0.54	0.62	0.07
Fe	%TS	1.54	1.46	1.36	1.97	2.19	1.70	0.36	2.24	2.42	2.60	2.79	2.97	2.60	0.29
K	%TS	0.62	0.55	0.48	0.45	0.68	0.56	0.10	0.56	0.56	0.57	0.57	0.57	0.57	0.00
Na	%TS	0.10	0.13	0.09	0.05	0.11	0.10	0.03	0.08	0.07	0.07	0.06	0.05	0.07	0.01
P	%TS	0.02	0.01	0.03	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.00
other	%TS	53.26	53.55	48.43	58.88	60.96	55.01	4.97	48.13	46.34	49.50	48.95	44.99	47.58	1.88
Total	%TS	100.00	100.00	100.00	100.00	100.00	100.00	-	100.00	100.00	100.00	100.00	100.00	100.00	-

Table 4.3: (Continued)

Trace metal															
Cd	mg/kg TS	0.80	0.32	0.47	0.13	0.20	0.38	0.27	0.37	0.23	0.55	0.45	0.47	0.41	0.12
Cr	mg/kg TS	7.00	6.10	4.80	6.40	2.30	5.32	1.87	4.79	3.68	5.40	6.80	4.60	5.05	1.15
Cu	mg/kg TS	17.90	17.20	18.90	18.40	19.10	18.30	0.77	33.40	33.84	34.50	35.60	35.52	34.57	0.98
Mn	mg/kg TS	60.00	65.00	65.00	53.00	57.00	60.00	5.20	54.60	52.80	51.00	49.20	47.40	51.00	2.85
Ni	mg/kg TS	3.60	2.70	3.90	5.10	5.30	4.12	1.08	3.66	4.44	5.22	5.00	5.78	4.82	0.81
Pb	mg/kg TS	7.40	6.90	7.80	6.20	7.60	7.18	0.64	11.09	11.04	11.03	11.00	13.97	11.63	1.31
Zn	mg/kg TS	59.00	52.00	78.00	64.00	38.00	58.20	14.77	49.20	46.20	43.20	40.20	37.20	43.20	4.74
Total	mg/kg TS	155.70	150.22	178.87	153.23	129.50	153.50	17.57	157.11	152.23	150.90	148.25	144.94	150.69	4.55
Total	%TS	0.02	0.02	0.02	0.02	0.01	0.02	0.00	0.02	0.02	0.02	0.01	0.01	0.02	0.00

Table 4.4: Heavy Metal Limit Values (in mg kg^{-1} TS) for Selected EU Countries with Strict Compost Qualities. *The heavy metal content of the home compost, from a composting plant in Denmark, and from other typical compost from green waste as given by previous studies*

	Regulation	Cd	Cr	Cu	Hg	Ni	Pb	Zn	As
Austria	Compost ordinance: quality class A+ (organic farming)	0.7	70	70	0.4	25	45	200	-
	Compost ordinance: quality class A (agric: hobby gardening)	1	70	150	0.7	60	120	500	-
Denmark	Compost after 1/6 2000	0.4	100	1000	0.8	30	120	4000	-
European Commission	Draft W.D. biological treatment of bio-waste (class 1)	0.7	100	100	0.5	50	100	200	-
	"ecolabel": 2001/688/EC	1	100	100	1	50	100	300	10
	"ecoagric": 2092/91EC 1488/98EC	0.7	70	70	0.4	25	45	200	-
Germany	Bio-waste Ordinance	1	70	70	0.7	35	100	300	-
Netherlands	Compost	1	50	60	0.3	20	100	200	15
	Type of compost	Cd	Cr	Cu	Hg	Ni	Pb	Zn	As
Denmark	Home compost (Andersen et al., 2011)	0.2-0.4	17-45	27-60	0.05-0.26	6-8	11-22	77-109	2
	Garden waste compost (Andersen et al., 2010)	0.3	32	28	0.06	7	25	126	-
	Typical compost quality for green waste (Hogg et al., 2002)	1.4	46	51	0.5	22	87	186	-
UK	Green waste compost (Whittle and Dyson, 2002)	1.5	3.7	16	-	-	6.8	108	-
Malaysia	Co-composting of OMSW (this study) Sample A-B (range)	**0.1-0.5**	**3.5-6**	**18-36**	**-**	**3-6**	**5-13**	**44-155**	**-**

Table 4.5: Decrease of C/N ratio and VS in Run 1 and Run 2

	Run 1					Run 2				
	kg	C (kg)	N (kg)	C/N	VS kg	kg	C (kg)	N (kg)	C/N	VS kg
FW	112.40	20.83	1.73	-	27.57	193.00	33.80	3.14	-	33.74
YW	100.00	26.84	1.75	-	48.46	200.00	47.21	2.41	-	77.78
Initial (FW + YW)	212.40	47.67	3.48	13.70	76.03	393.00	81.01	5.55	14.60	111.52
Final (compost)	85.40	14.22	1.32	10.75	61.24	102.50	20.20	1.39	14.57	77.18

4.2 LEACHATE VOLUME AND QUALITY FROM OMSW COMPOSTING PROCESS

The total leachate generations over 60 days are 2.5kg (run 1) and 5.0 kg (run 2). The leachate generation was divided by respective input waste to get a generation of 0.012 kg/kg ww and 0.013 kg/kg ww for both runs respectively (meaning a loss of 1.2-1.3% in wet weight). The composition of leachate for both runs is presented in Table 4.6.

Table 4.6: Composition of Leachate from Co-composting of FW and YW

Parameter	Unit	Run 1*	Run 2*
pH	-	5.26±0.10	6.20±0.10
TOC	mg/l	3250.00±149.14	3122.00±178.87
BOD	mg/l	6576.00±294.40	8400.00±272.88
COD	mg/l	14143.00±555.99	17593.00±487.92
P	mg/l	79.20±5.20	54.00±3.54
K	mg/l	5640.00±900.92	7031.00±1051.77
TKN	mg/l	55.40±8.35	84.90±4.17
Cd	mg/l	0.00±0.00	0.00±0.00
Cr	mg/l	0.02±0.00	0.02±0.00
Cu	mg/l	0.02±0.00	0.02±0.00
Ni	mg/l	0.07±0.02	0.08±0.00
Pb	mg/l	0.10±0.02	0.14±0.01

*values are rounded off to the nearest two decimal places.

4.3 SUBSTANCE FLOW ANALYSIS OF OMSW COMPOSTING

The amount of waste added to each composting run was 210 and 393 kg for Run 1 and Run 2 respectively (see Figure 4.1). It is important to note that the feedstock for compositing in Run 1 and Run 2 were OMSW from Sample A and Sample B respectively. The difference in key parameters of moisture content, VS content and ash content for both composts generated was insignificant, giving 20.54%ww; 71.71%ww; 7.75%ww (Run 1) and 17.54%ww; 75.30%ww; 7.16%ww (Run 2). This is interesting to conclude that quality and composition of compost is independent from the size of the composting pile. The concentration of C and N in the finished compost from both runs were 20.96% TS; 1.95% TS (Run 1) and 23.90% TS; 1.64% TS (Run 2) giving C/N ratio of 10.74 and 14.57 respectively. These parameters are in agreement with the reported range for compost materials except moisture content, which exhibits lower value. The heavy metal contents in composts are in agreement with the range reported by literature (Jasim and Smith, 2003; Papadopoulos et al., 2009; Colón et al., 2010; Martínez-Blanco et al., 2010; Andersen et al., 2011).

Carbon Balance and Nitrogen balance for both composting runs are illustrated in Figure 4.2 and Figure 4.3 respectively. During the composting period, 58-73% of the weight lost to the atmosphere. The C loss to atmosphere was 67-73% and 74-76% for Run 1 and Run 2 respectively. The N loss to atmosphere recorded higher for Run 2 (72-78%) than Run 1 (44-59%). Fraction of heavy metals and the nutrients (P and K) were emitted to the air. The nutrients and heavy metals remained in the leachate was low. The contents of substance remains in the compost are shown in Table 4.3 earlier.

4.4 LIFE CYCLE INVENTORIES OF OMSW COMPOSTING

The full LCI is summarized in Table 4.7. Other gases (such as volatile organic compounds) were excluded in the inventory due to its minor importance.

Table 4.7: LCI Data for Windrow Co-composting of OMSW

	LCI data	Amount		Unit
		min	max	
Input waste	organic household waste	112.4	193.0	kg
	yard waste	100.0	200.0	kg
Energy and materials consumption	electricity	-	-	
	water (direct)	-	-	
	water (cleaning)	5.0	10.0	L
Gaseous emissions (to atmosphere)	Carbon content	0.1464	0.1664	kg/kg ww
	CO2-C (biogenic)	0.1391	0.1581	kg/kg ww
	CH4-C	0.0057	0.0065	kg/kg ww
	CO-C	0.0015	0.0017	kg/kg ww
	Nitrogen Content	0.0052	0.0116	kg/kg ww
	N2O-N	0.0003	0.0007	kg/kg ww
	NH3	0.0000	0.0000	kg/kg ww
	K	0.0027	0.0035	kg/kg ww
	P	0.5240	0.6692	kg/kg ww
	Cd	0.0186	0.1188	mg/Gg ww
	Cr	-	0.6415	mg/Gg ww
	Cu	0.8900	2.0252	mg/Gg ww
	Ni	0.3259	1.3607	mg/Gg ww
	Pb	2.2699	4.0483	mg/Gg ww
Liquid emissions (to groundwater)	Leachate	0.0118	0.0127	kg/kg ww
	N losses	0.3766	1.0687	mg/kg ww
	C losses	36.4977	43.0025	mg/kg ww
	BOD	73.9360	103.4845	mg/kg ww
	COD	159.9263	230.0414	mg/kg ww
	K	55.7801	101.7812	mg/kg ww
	P	641.2214	993.4087	mg/kg ww
	Cd	17.8117	61.2053	mg/Gg ww
	Cr	141.2429	235.4049	mg/Gg ww

Table 4.7 (Continued)

	Cu	211.8644	258.9454	mg/Gg ww
	Ni	612.0527	1,058.5240	mg/Gg ww
	Pb	998.1168	1,804.0710	mg/Gg ww
Finished product	Compost	0.2608	0.4021	kg/kg ww

4.5 LCA OF ALTERNATIVE OMSW MANAGEMENT

4.5.1 EMISSIONS FROM ALTERNATIVE OMSW MANAGEMENT PROCESS

Given the elemental composition of OMSW (as shown in Table 4.1 and Table 4.2), it was determined to calculate the emissions in minimum, average and maximum values. The summary of fugitive emissions of alternative OMSW management is tabulated in Table 4.8. Three decomposition emissions (CH_4, N_2O and NH_3) were taken into consideration. The emission of NH_3 from composting is calculated in the range of 0.38g and 0.81 g NH_3-N. The calculated emission of N_2O was in the range of 0.047g and 0.09 g N_2O-N whereas higher amount of CH_4 is emitted (14.1g-20.8 g CH_4). The emission rate of each gas was calculated based on one kg of T-N in the initial feedstock for NH_3 and N_2O emissions and one kg of organic matter (in volatile solid) in the initial feedstock for CH_4 emission. Therefore, the emission rates of NH_3, N_20 and CH_4 were 38 g NH_3-N/kg T-N, 4.7 g N_2O/kg T-N and 54 g CH_4/kg VS respectively.

The final output as compost is calculated in the range of 201g and 376 g/kg feedstock. Despite the benefits of chemical fertilizer replacement in terms of GHG emission savings, generation of ammonia and nitrous oxide during the application of compost in soil has to be taken into consideration due to their high GWP. 0.002-

0.003 kg NH_3/kg compost and 0.006-0.007 kg N_20/kg compost were evaporated and emitted to the atmosphere. Avoided emission of fossil CO_2 due to carbon binding to the soil of 0.3-0.38 kg CO_2/kg compost, hence provide savings to the global warming impact (credit).

Table 4.8: Summary of Outputs and Impacts from Alternative Management of 1 kg Input of OMSW

Emission	Unit	Food Waste				Yard Waste				Total		
		min	average	max		min	average	max		min	average	max
Composting												
CH4_air	kg	5.64E-03	7.20E-03	8.93E-03		8.45E-03	1.01E-02	1.18E-02		1.41E-02	1.73E-02	2.08E-02
NH3_air	kg	2.18E-04	3.02E-04	3.98E-04		1.62E-04	2.79E-04	4.13E-04		3.80E-04	5.80E-04	8.11E-04
N2O_air	kg	2.69E-05	3.71E-05	4.90E-05		1.99E-05	3.43E-05	5.08E-05		4.68E-05	7.14E-05	9.99E-05
output_mass	kg	4.95E-02	8.83E-02	1.36E-01		1.51E-01	1.93E-01	2.39E-01		2.01E-01	2.81E-01	3.76E-01
Compost use												
NH3_output_air	kg	n/a	n/a	n/a		n/a	n/a	n/a		4.65E-04	7.09E-04	9.92E-04
N2O_output_air	kg	n/a	n/a	n/a		n/a	n/a	n/a		1.20E-03	1.83E-03	2.56E-03
CO2_bind_soil	kg	n/a	n/a	n/a		n/a	n/a	n/a		7.79E-02	9.56E-02	1.15E-01
NO3_runoff	kg	n/a	n/a	n/a		n/a	n/a	n/a		2.64E-04	4.02E-04	5.63E-04
NO3_leach	kg	n/a	n/a	n/a		n/a	n/a	n/a		2.93E-04	4.47E-04	6.25E-04
Anaerobic Digestion												
CH4_air	kg	2.99E-06	4.23E-06	5.69E-06		7.46E-06	8.80E-06	1.03E-05		1.04E-05	1.30E-05	1.59E-05
Energy_process	MJ	9.73E-01	1.38E+00	1.85E+00		2.43E+00	2.87E+00	3.34E+00		3.40E+00	4.24E+00	5.19E+00
Landfill												
CH4_gen (100 years)	kg	9.33E-02	1.01E-01	1.08E-01		6.06E-02	6.59E-02	7.13E-02		1.54E-01	1.67E-01	1.79E-01
COD (100 years)	kg	6.28E+00	6.77E+00	7.27E+00		1.01E+01	1.10E+01	1.20E+01		1.64E+01	1.78E+01	1.92E+01
COD (100 years)	kg	1.26E+00	1.35E+00	1.45E+00		2.03E+00	2.21E+00	2.39E+00		3.28E+00	3.56E+00	3.84E+00

Anaerobic digestion is widely used as a source of renewable energy. The process produces a biogas, consisting of mostly methane and carbon dioxide, with a small amount hydrogen and trace hydrogen sulfide (Machado et al., 2009). Biogas does not contribute to increasing atmospheric carbon dioxide concentrations because the gas is not released directly into the atmosphere and the carbon dioxide is considered biogenic. CH_4 emission is included in the accounting of anaerobic digestion as unburned CH_4, which is determined to contribute great impact in climate change. By considering 90% combustion efficiency of CH_4, the total CH_4 emission to the atmosphere is calculated in the range of 0.01 and 0.016 g CH_4 per kg feedstock. Total energy to be substituted by CH_4 is calculated between 3.4 and 5.19 MJ per kg feedstock. It is assumed that other substances (N and heavy metals) were not degraded and hence remain in the digestate at the end of the anaerobic degradation process.

In present study, sanitary landfill with daily cover and leachate treatment facility was taken into consideration. By assuming 10% oxidation rate of CH_4 by daily cover, total CH_4 emission calculated falls between 0.154 and 0.179 kg CH4 per kg OMSW for a duration of 100 years.

4.5.2 LIFE CYCLE IMPACT ASSESSMENT OF ALTERNATIVE OMSW MANAGEMENT

The life cycle assessment results is presented in Table 4.9 and Figure 4.2. By considering the average decomposition emissions, the net environmental impact (mPt) was highest for S1 (60), followed by S3 (38), S2 (34) and S4 (-21). Negative value in score indicates environmental benefit from Scenario 4. The main category contributing to the net impact score for open dump practice of OMSW (S1) was human health (64%) followed by ecosystem quality (22%) and resource (14%). Due to proper sanitary landfilling practice, S2 exhibits lower impact in human health and ecosystem quality categories, measured at 28 and 15 mPt respectively. Due to energy recovery from landfill gas, the environmental gain was observed in the resources category (-9 mPt). Composting practice of OMSW and application of compost as reflected by S3 contribute highest impact in ecosystem quality category (16 mPt) due to the emission of N_2O, CH_4, NH_3 during the life cycle of OMSW from composting to application on land, followed by human health category (11 mPt). The environmental gain through replacement of fertilizer is however relatively low, resulting in negative environmental impacts in resource category (10 mPt). Anaerobic digestion was determined to be the best way of OMSW management due to its environmental benefit, despite its adverse impact in ecosystem quality (16 mPt). Environmental gain through human health and resources category was measured at -1mPt and -36 mPt respectively.

Table 4.9: Summary of the Characterized, Normalized and Final Single Score for Alternative OMSW Management Scenarios

Impact category	Unit	S1			S2			S3			S4		
		minimum	average	maximum	minimum	average	maximum	minimum	average	maximum	minimum	average	maximum
Characterization													
Carcinogens	DALY	5.97E-08	6.49E-08	6.97E-08	1.08E-08	1.60E-08	2.09E-08	1.04E-09	1.04E-09	1.05E-09	-1.10E-07	-1.39E-07	-1.71E-07
Resp. organics	DALY	2.24E-07	2.42E-07	2.61E-07	1.48E-07	1.61E-07	1.73E-07	3.21E-10	3.60E-10	4.03E-10	2.30E-12	-4.04E-11	-8.94E-11
Resp. inorganics	DALY	7.85E-08	7.85E-08	7.85E-08	-4.07E-08	-4.07E-08	-4.07E-08	8.07E-08	1.15E-07	1.54E-07	-1.64E-07	-1.86E-07	-2.09E-07
Climate change	DALY	6.95E-07	7.53E-07	8.06E-07	6.20E-07	6.77E-07	7.30E-07	1.60E-07	2.17E-07	2.82E-07	1.64E-07	2.88E-07	4.35E-07
Radiation	DALY	1.98E-11	1.98E-11	1.98E-11	-1.10E-11	-1.10E-11	-1.10E-11	3.04E-11	2.75E-11	2.42E-11	-1.57E-10	-2.60E-10	-3.78E-10
Ozone layer	DALY	1.26E-11	1.26E-11	1.26E-11	8.89E-12	8.89E-12	8.89E-12	2.18E-11	2.13E-11	2.07E-11	9.06E-12	4.12E-12	-1.57E-12
Ecotoxicity	PAF*m2yr	1.66E+00	2.13E+00	2.14E+00	1.63E+00	2.10E+00	2.65E+00	1.66E+00	2.14E+00	2.68E+00	1.59E+00	2.05E+00	2.56E+00
Acidification/ Eutrophication	PDF*m2yr	2.93E-03	2.93E-03	2.93E-03	-1.09E-03	-1.09E-03	-1.09E-03	1.32E-02	1.99E-02	2.76E-02	1.73E-02	2.85E-02	4.16E-02
Land use	PDF*m2yr	7.50E-06	7.50E-06	7.50E-06	-1.29E-03	-1.29E-03	-1.29E-03	5.57E-06	5.07E-06	4.49E-06	-2.95E-03	-3.69E-03	-4.53E-03
Minerals	MJ surplus	6.05E-07	6.05E-07	6.05E-07	-1.59E-05	-1.59E-05	-1.59E-05	-3.04E-05	-4.69E-05	-6.60E-05	-1.66E-04	-2.44E-04	-3.32E-04
Fossil fuels	MJ surplus	1.54E-01	1.54E-01	1.54E-01	-2.15E-01	-2.15E-01	-2.15E-01	2.60E-01	2.51E-01	2.41E-01	-6.48E-01	-9.03E-01	-1.19E+00
Normalization													
Carcinogens		6.81E-06	7.40E-06	7.95E-06	1.24E-06	1.82E-06	2.38E-06	1.19E-07	1.19E-07	1.20E-07	-1.26E-05	-1.58E-05	-1.95E-05
Resp. organics		2.55E-05	2.76E-05	2.97E-05	1.69E-05	1.83E-05	1.97E-05	3.66E-08	4.11E-08	4.60E-08	2.62E-10	-4.60E-09	-1.02E-08
Resp. inorganics		8.96E-06	8.96E-06	8.96E-06	-4.64E-06	-4.64E-06	-4.64E-06	9.20E-06	1.31E-05	1.75E-05	-1.87E-05	-2.12E-05	-2.39E-05
Climate change		7.93E-05	8.59E-05	9.19E-05	7.07E-05	7.73E-05	8.33E-05	1.83E-05	2.47E-05	3.21E-05	1.87E-05	3.29E-05	4.97E-05
Radiation		2.26E-09	2.26E-09	2.26E-09	-1.26E-09	-1.26E-09	-1.26E-09	3.47E-09	3.14E-09	2.77E-09	-1.79E-08	-2.97E-08	-4.31E-08
Ozone layer		1.44E-09	1.44E-09	1.44E-09	1.01E-09	1.01E-09	1.01E-09	2.49E-09	2.43E-09	2.36E-09	1.03E-09	4.70E-10	-1.79E-10
Ecotoxicity		2.89E-05	3.73E-05	3.74E-05	2.84E-05	3.68E-05	4.63E-05	2.90E-05	3.73E-05	4.68E-05	2.78E-05	3.57E-05	4.48E-05

Table 4.9 (continued)

Acidification/ Eutrophication		5.12E-07	5.12E-07	5.12E-07		-1.91E-07	-1.91E-07	-1.91E-07		2.31E-06	3.48E-06	4.83E-06		3.02E-06	4.99E-06	7.27E-06
Land use		1.31E-09	1.31E-09	1.31E-09		-2.26E-07	-2.26E-07	-2.26E-07		9.73E-10	8.86E-10	7.84E-10		-5.16E-07	-6.45E-07	-7.91E-07
Minerals		8.01E-11	8.01E-11	8.01E-11		-2.11E-09	-2.11E-09	-2.11E-09		-4.03E-09	-6.21E-09	-8.74E-09		-2.19E-08	-3.23E-08	-4.40E-08
Fossil fuels		2.04E-05	2.04E-05	2.04E-05		-2.85E-05	-2.85E-05	-2.85E-05		3.45E-05	3.33E-05	3.19E-05		-8.58E-05	-1.20E-04	-1.58E-04
Single Score																
Total	Pt	5.41E-02	6.02E-02	6.29E-02		2.79E-02	3.38E-02	4.00E-02		3.11E-02	3.77E-02	4.52E-02		-1.74E-02	-2.11E-02	-2.50E-02
Carcinogens	Pt	2.04E-03	2.22E-03	2.38E-03		3.71E-04	5.47E-04	7.14E-04		3.56E-05	3.56E-05	3.59E-05		-3.77E-03	-4.75E-03	-5.85E-03
Resp. organics	Pt	7.66E-03	8.29E-03	8.92E-03		5.08E-03	5.50E-03	5.92E-03		1.10E-05	1.23E-05	1.38E-05		7.87E-08	-1.38E-06	-3.06E-06
Resp. inorganics	Pt	2.69E-03	2.69E-03	2.69E-03		-1.39E-03	-1.39E-03	-1.39E-03		2.76E-03	3.92E-03	5.26E-03		-5.61E-03	-6.36E-03	-7.16E-03
Climate change	Pt	2.38E-02	2.58E-02	2.76E-02		2.12E-02	2.32E-02	2.50E-02		5.48E-03	7.42E-03	9.64E-03		5.62E-03	9.86E-03	1.49E-02
Radiation	Pt	6.79E-07	6.79E-07	6.79E-07		-3.77E-07	-3.77E-07	-3.77E-07		1.04E-06	9.43E-07	8.30E-07		-5.37E-06	-8.92E-06	-1.29E-05
Ozone layer	Pt	4.32E-07	4.32E-07	4.32E-07		3.04E-07	3.04E-07	3.04E-07		7.48E-07	7.29E-07	7.08E-07		3.10E-07	1.41E-07	-5.36E-08
Ecotoxicity	Pt	1.16E-02	1.49E-02	1.50E-02		1.14E-02	1.47E-02	1.85E-02		1.16E-02	1.49E-02	1.87E-02		1.11E-02	1.43E-02	1.79E-02
Acidification/ Eutrophication	Pt	2.05E-04	2.05E-04	2.05E-04		-7.64E-05	-7.64E-05	-7.64E-05		9.26E-04	1.39E-03	1.93E-03		1.21E-03	2.00E-03	2.91E-03
Land use	Pt	5.24E-07	5.24E-07	5.24E-07		-9.03E-05	-9.03E-05	-9.03E-05		3.89E-07	3.54E-07	3.14E-07		-2.06E-04	-2.58E-04	-3.16E-04
Minerals	Pt	2.40E-08	2.40E-08	2.40E-08		-6.34E-07	-6.34E-07	-6.34E-07		-1.21E-06	-1.86E-06	-2.62E-06		-6.58E-06	-9.68E-06	-1.32E-05
Fossil fuels	Pt	6.13E-03	6.13E-03	6.13E-03		-8.55E-03	-8.55E-03	-8.55E-03		1.03E-02	9.98E-03	9.57E-03		-2.57E-02	-3.59E-02	-4.74E-02
Single Score																
Net environmental impact	Pt	5.41E-02	6.02E-02	6.29E-02		2.79E-02	3.38E-02	4.00E-02		3.11E-02	3.77E-02	4.52E-02		-1.74E-02	-2.11E-02	-2.50E-02
Human Health	Pt	3.62E-02	3.90E-02	4.16E-02		2.53E-02	2.78E-02	3.02E-02		8.29E-03	1.14E-02	1.50E-02		-3.77E-03	-1.25E-03	1.88E-03
Ecosystem Quality	Pt	1.18E-02	1.51E-02	1.52E-02		1.12E-02	1.46E-02	1.84E-02		1.25E-02	1.63E-02	2.06E-02		1.21E-02	1.60E-02	2.05E-02
Resources	Pt	6.13E-03	6.13E-03	6.13E-03		-8.55E-03	-8.55E-03	-8.55E-03		1.03E-02	9.98E-03	9.56E-03		-2.57E-02	-3.59E-02	-4.74E-02

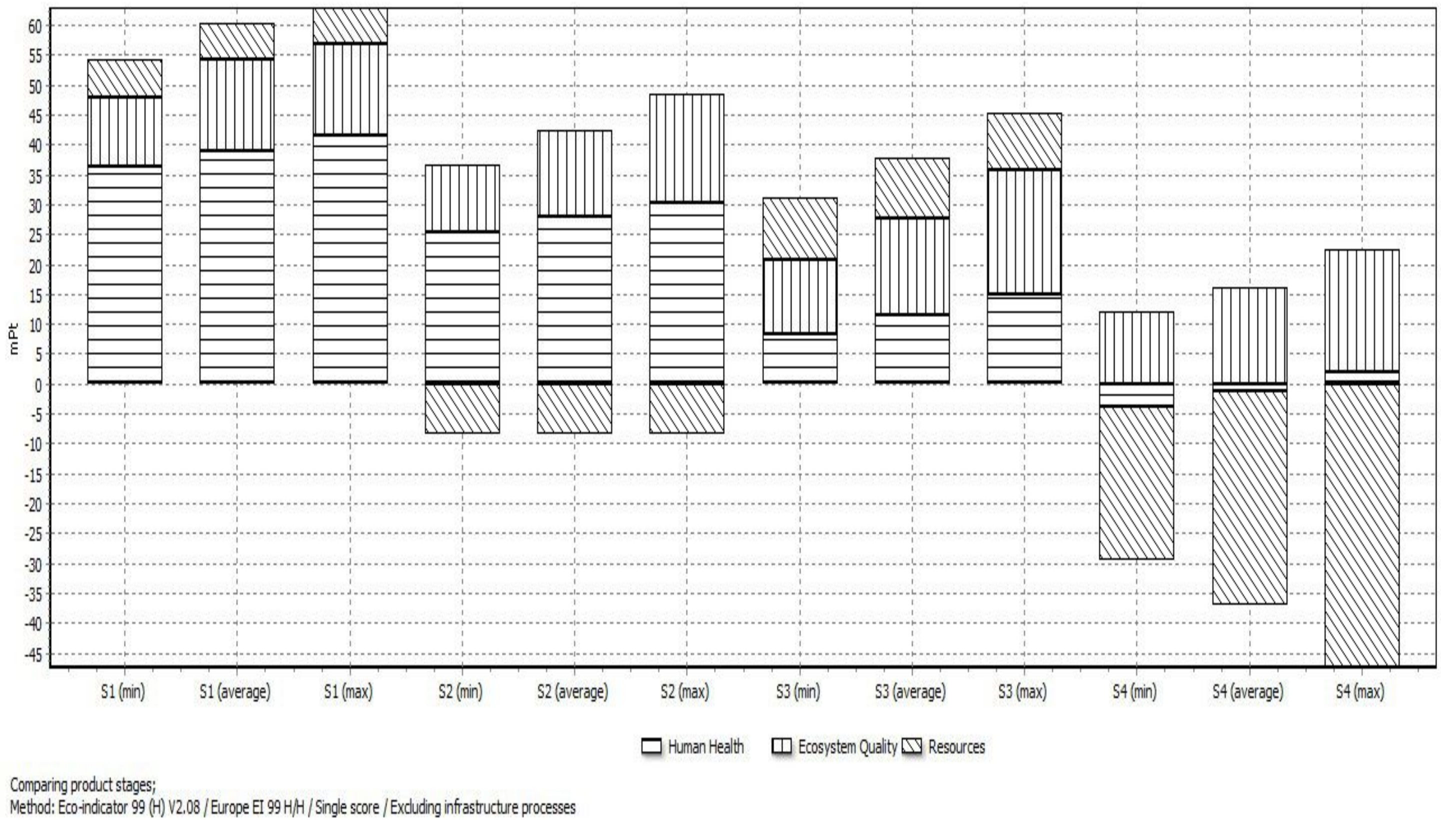

Figure 4.2: Environmental Impact Categories for Alternative OMSW Management

4.5.3 ENVIRONMENTAL IMPACT HOT SPOTS FOR ALTERNATIVE OMSW MANAGEMENT

Landfilling practice of OMSW (Figure 4.3 and Figure 4.4) contribute significantly to climate change and Eco toxicity impact, in term of landfill gas emission, comprising toxic trace gas and the groundwater contamination from leachate emission. Transportation of OMSW to landfill creates relatively high impact in fossil fuel consumption. The environmental gain was observed in fossil fuel category in Figure 4.4 due to the energy substitution by landfill gas recovery, which helps to reduce the net environmental impact significantly.

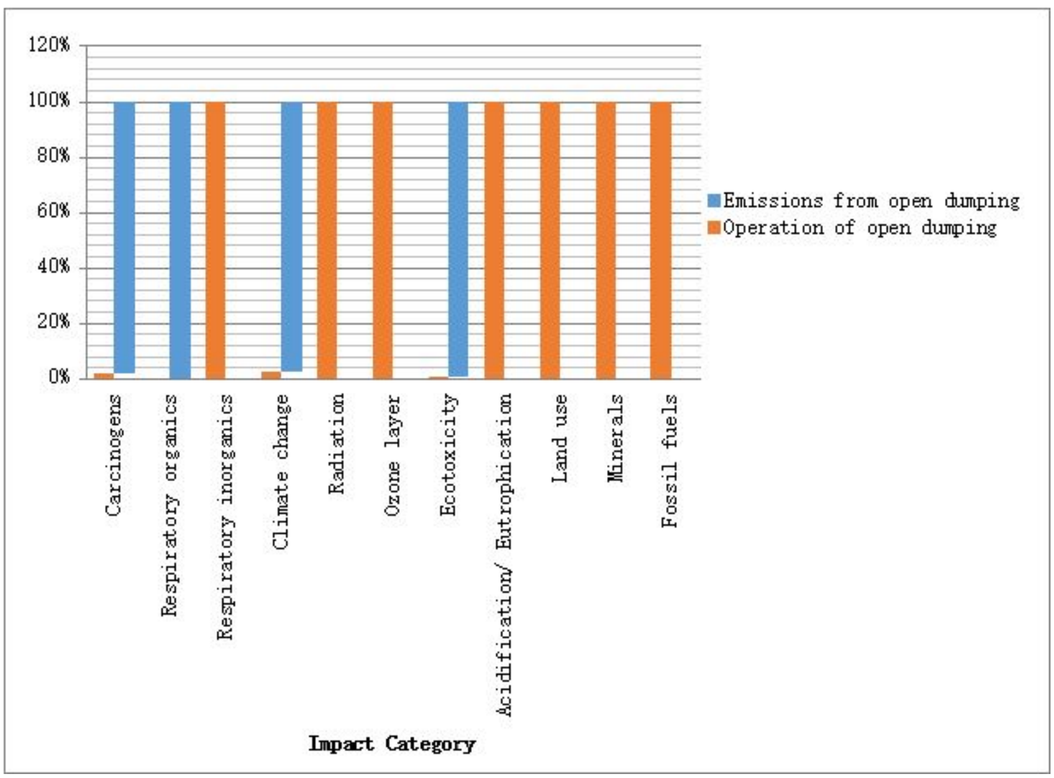

Figure 4.3: Environmental Impacts from Open Dumping of OMSW

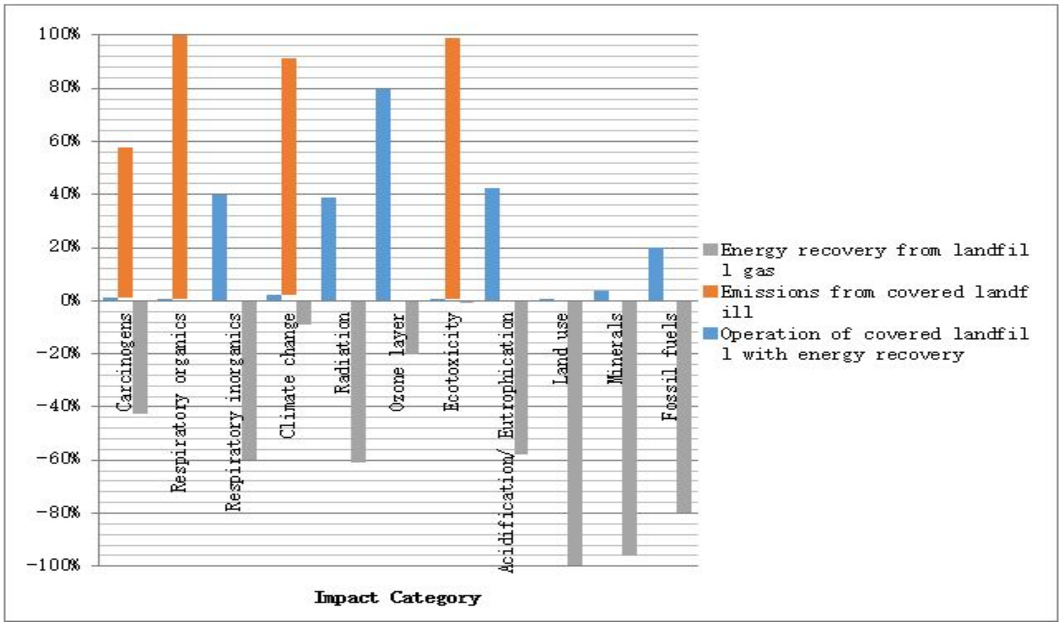

Figure 4.4: Environmental Impacts from Controlled Landfilling of OMSW with Energy Recovery

The major environmental impacts of composting (S3) are illustrated in Figure 4.5. The adverse impacts are in association to climate change, Eco toxicity, respiratory inorganics and fossil fuel, which are resulted from the fugitive emission from the decomposition process, particularly GHG emission to atmosphere and emission of heavy metal to soil during application of compost (heavy metal is not removed in composting process). The high impact categories suggest the need to reduce the emission during composting process particularly the NH_3 and N_2O (respiratory inorganics) and CH_4. The major environmental benefit from composting of OMSW resulted from the synthetic fertilizer substitution, in terms of minerals and fossil fuels consumption as well as land use for fertilizer manufacturing.

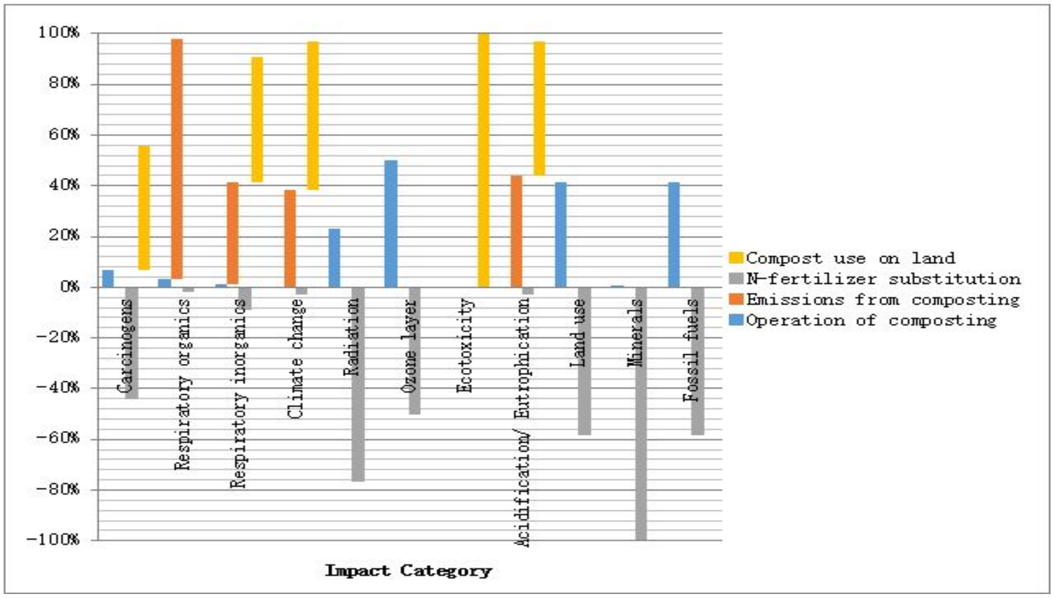

Figure 4.5: Environmental Impacts from Composting of OMSW and Application of Compost on Land

The largest environmental impact modeled in S4 is climate change and Eco toxicity due to the CH_4 emission resulted from unburned biogas and the discharge of digestate to the land. The impacts are however overcome by the environmental gain through energy recovery from CH_4 generation, resulting in high scoring point to fossil fuel category. Due to the significant gain in fossil fuel category, the net environmental gain was observed in S4, indicating an environmental sound management system for OMSW. The environmental impacts from anaerobic digestion of OMSW are illustrated in Figure 4.6

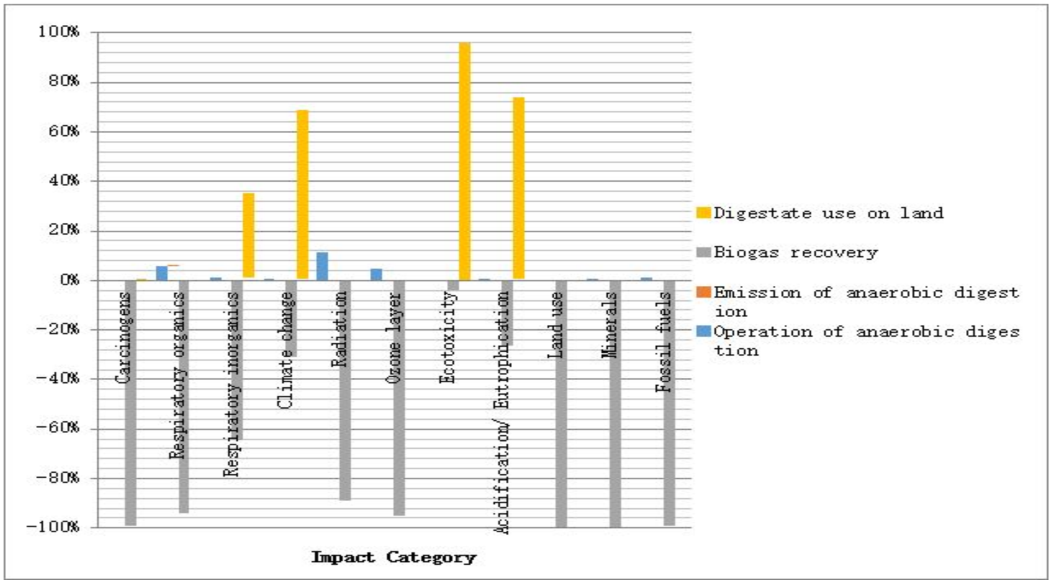

Figure 4.6: Environmental Impacts from Anaerobic Digestion of OMSW and Application of Digestate on Land

In general, environmental impacts increase with the decomposition emission from OMSW management process (as shown in Figure 4.2). This reveals that fugitive emissions from decomposition of OMSW as easily degradable materials have relatively importance in environmental impacts, and hence emission control measures have to be taken in order to reduce the overall environmental impacts regardless of which scenarios to be taken. The summary of contribution of each impact category to alternative OMSW management scenario is tabulated in Table 4.10.

Table 4.10: Contribution of Each Impact Category to Alternative OMSW Management Scenario in Percentage

Impact category	%[a]							
	S1		S2		S3		S4	
Carcinogens	3.69	(+ve)	1.01	(+ve)	0.09	(+ve)	6.47	(-ve)
Resp. organics	13.77	(+ve)	10.17	(+ve)	0.03	(+ve)	0.00	(-ve)
Resp. inorganics	4.47	(+ve)	2.57	(-ve)	10.40	(+ve)	8.66	(-ve)
Climate change	42.80	(+ve)	42.86	(+ve)	19.68	(+ve)	13.43	(+ve)
Radiation	0.00	(+ve)	0.00	(-ve)	0.00	(+ve)	0.01	(-ve)
Ozone layer	0.00	(+ve)	0.00	(+ve)	0.00	(+ve)	0.00	(+ve)
Ecotoxicity	24.78	(+ve)	27.21	(+ve)	39.61	(+ve)	19.48	(+ve)
Acidification/ Eutrophication	0.34	(+ve)	0.14	(-ve)	3.69	(+ve)	2.72	(+ve)
Land use	0.00	(+ve)	0.17	(-ve)	0.00	(+ve)	0.35	(-ve)
Minerals	0.00	(+ve)	0.00	(-ve)	0.00	(-ve)	0.01	(-ve)
Fossil fuels	10.18	(+ve)	15.80	(-ve)	26.47	(+ve)	48.89	(-ve)
Total	100.00		100.00		100.00		100.00	

[a] +ve values indicate environmental impacts; -ve values indicate environmental gain

4.5.4 COMPARISON OF COMPOSTING AND ANAEROBIC DIGESTION OF OMSW

Previous studies advocated composting as the best option, in view of its lower environmental impacts than landfilling practice. This study suggests that anaerobic digestion is the best mean of OMSW management due to its greater environmental benefit from biogas recovery as compared to composting. Decomposition emission from anaerobic process is lesser than composting due to its closed system. Gaseous emission is trapped and burned before released to the atmosphere. Emission control is more difficult in windrow composting process. Enclosed composting system for instance in-vessel composting, can be employed and gaseous emission can be treated, but conversely, excess electricity consumption air delivery system imposes greater environmental impacts. Emissions from decomposition in composting process have the largest environmental impacts. CH_4 and N_2O are potent GHG and NH_3 deposition on soil and water contributes significantly to eutrophication and acidification. Using different emission factors (minimum, average and maximum) drastically changed the overall impacts of compost processing in terms of climate change, eutrophication, Eco toxicity and respiratory inorganics. Given the importance of composting as an alternative OMSW management scenario in University of Malaya, further investigations into decomposition emissions control from windrow composting are important.

4.6 ASSESSMENT OF GHG EMISSIONS REDUCTION FROM OMSW COMPOSTING AS COMPARED TO LANDFILLING (BAU)

4.6.1 OVERVIEW

The carbon equivalent emission of all scenarios was expressed in tons carbon equivalent (tCO_{2eq}) per day. For the baseline emission in year 2012, all MSW generated was disposed at landfills, which was about 30km from sources of generation. Total distance of 60km was taken into calculation by considering the return trip of the disposal transportation. The emissions for the baseline were basically the methane emission from landfill and the fuel consumption during transportation. For the future project emission in 2025, the emission sources namely the on-site electricity consumption, the on-site fuel consumption and the N_2O and

CH_4 emission from composting itself were identified. Several limitations such as the unknown or data that required further experiment in the analysis were overcome with sufficient references.

4.6.2 BASELINE EMISSION

The baseline emission was referred as the emission arise from disposal of all waste landfills, as well as the emission from transportation of waste. In the baseline calculation, only CH_4 was included as the source of carbon emission. From the baseline scenario (S0), a total of 2.77E+07 tCO_{2eq}/day was generated of which 98% of the total emission was direct emission from landfill whereas the emission from transportation contributed 2.36E+02 tCO_{2eq}/day. Hence, the carbon emission for Peninsular Malaysia in waste management for studied period can be expressed as 9.98E+02 tCO_{2e}/ton waste/day. The amount of methane gas that was released as GHG was determined and the carbon emission equivalent was calculated based on standard conversion. The second source of carbon emission was the transportation to landfill. The combustion of diesel fuel was included as the source of emission for transportation to disposal. The total carbon emission from waste management in year 2012 (S0) is shown in Table 4.11.

Table 4.11: The Summary of Carbon Emission from Different Sources

Emissions (tCO2eq)	S0	S1	S2	S3	S4	S5	S6
Transportation to landfills	2.36E+02	3.06E+02	2.92E+02	2.90E+02	2.76E+02	2.59E+02	1.92E+02
Transportation to composting centres	-	-	5.61E+00	6.34E+00	1.20E+01	1.10E+01	2.66E+01
Disposal of FW in landfills	2.57E+07	3.33E+07	3.03E+07	2.99E+07	2.64E+07	2.64E+07	2.18E+07
Disposal of YW in landfills	2.04E+06	2.64E+06	2.26E+06	2.21E+06	2.01E+06	0.00E+00	0.00E+00
Fuel consumption in composting centres	-	-	2.06E+01	2.33E+01	4.55E+01	6.33E+01	9.01E+01
Electricity consumption in composting centres	-	-	5.91E+01	6.69E+01	1.31E+02	1.82E+02	2.59E+02
N_2O emission in composting centres	-	-	4.81E-02	5.43E-02	1.06E-01	1.48E-01	2.10E-01
CH_4 emission in composting centres	-	-	6.78E-01	7.66E-01	1.50E+00	2.09E+00	2.97E+00
Total CO_{2eq} emission	2.77E+07	3.59E+07	3.26E+07	3.21E+07	2.84E+07	2.64E+07	2.18E+07

4.6.3 EMISSIONS FROM OMSW COMPOSTING ACTIVITY

In OMSW composting activity, there were essentially four sources of carbon emissions: CO_2 from on-site electricity consumption, CO_2 from on-site fuel consumption, and GHGs (N_2O and CH_4) emission from composting process. Besides, the carbon emission from transportation of MSW to landfill disposal was included in the analysis as the non-compostable MSW is disposed of in landfill despite the establishment of on-site composting project. For transportation, the calculation for project was similar with the baseline transportation calculation.

In overall, composting of OMSW exhibits total GHG emission reduction in waste management as compared to BaU in 2025 (S1), as shown in the result presented in Figure 4.7. S6 shows highest net GHG emission reduction (-21%), followed by S5 (-5%). S4, S3 and S2 exhibit net increase of GHG emissions as compared to base year despite its relatively low emissions as compared to S1 (BaU) due to the increase of MSW generation from year 2012 to year 2025.

Net GHG emission for each scenario is mainly contributed by the methane emission from landfills. Methane emission from OMSW disposal in landfill is accounted for over 96% of total emission in waste management as shown in Table 4.11. This results were in accordance with literature (Weitz et al., 2002; Chen and Lin, 2008) which has found out that, the net GHG emissions for a given material was the lowest for source reduction and the highest for landfilling. Hence, the authors wish to present the significance of the methane emission from landfill and thus promote diversion of compostable OMSW from the waste stream. Generally, GHG emission from landfilling decreases with the amount of waste disposed of. S6 (2.18E+07 tCO_{2e}/day) recorded the lowest carbon emission from landfill, followed by S5 (2.64E+07 tCO_{2e}/day) S4 (2.84E+07 tCO_{2e}/day) and S3 (3.21E+07 tCO_{2e}/day) and S2 (3.26E+07 tCO_{2e}/day). S6 exhibits the lowest GHG emission in transportation fuels with the reduction of the number of hauling trips.

The GHG emission from on-site electricity consumption was assumed to increase with the amount of OMSW composted due to increase in floor plan of composting centers. The aeration of composting was done by manual turning. The GHG emission from on-site fuel consumption increases with the amount of OMSW composted as well. The fuel consumption included the diesel or petrol used for the shredding and chipping for yard waste and grinding of finished compost. Emissions of N_2O and CH_4 from composting processes increase with the amount of OMSW fed into composting piles. The emissions are however insignificant as compared to the emissions associated to transportation and disposal of OMSW in landfills (refer to Table 4.11).

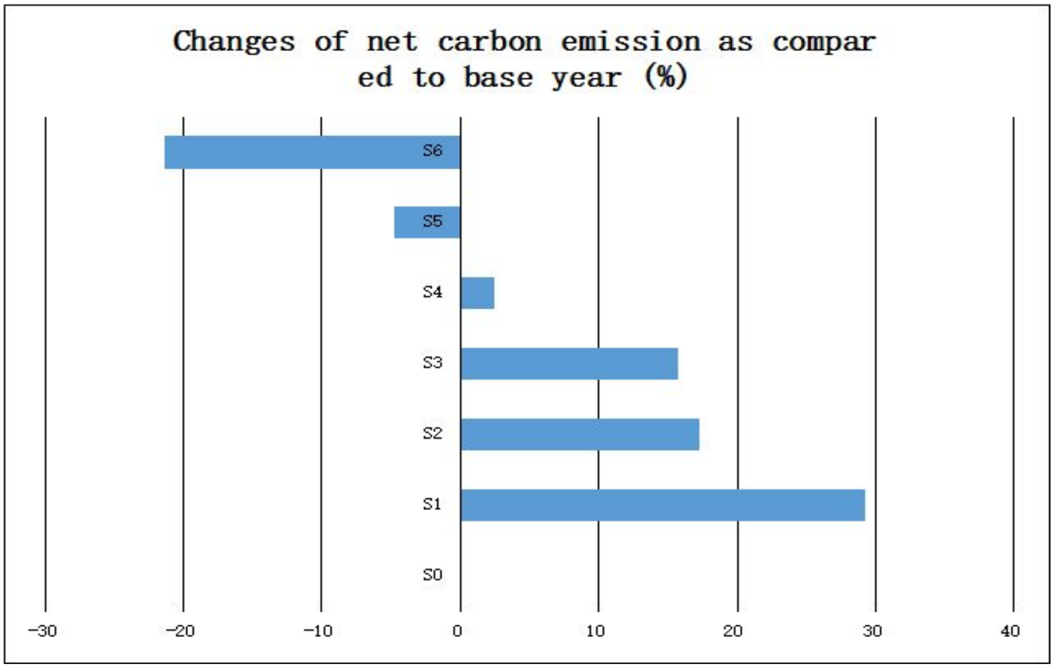

Figure 4.7: The Net Carbon Reduction of each Scenarios as Compared to S0 by Percentage

5. DISCUSSIONS

5.1 LIFE CYCLE INVENTORY OF OMSW COMPOSTING

5.1.1 QUALITY OF COMPOST

The characteristics of the compost produced from both runs were in agreement with the compositions reported by previous studies as shown in Table 4.4 (Chapter 4). The moisture content seems to be very low (17-20%). This may due to the tropical climate where the ambient temperature is averagely high throughout the year. However, moisture content of below 50% is recommended for optimum performance. The VS of the compost is higher as compared to the literature (Colón et al., 2010), which indicates that considerable content of organic matter in the compost output. A longer period of degradation time is needed to reduce the VS content of the compost. However, if the VS content (fraction) is to be multiplied to the total weight of the compost, it shows a reduction of VS of 17-21% (Run 1) and 28-33% (Run 2). VS content reduction is greater in composting pile with larger size (Run 2) with input materials of 193 kg food waste and 200 kg yard waste. This may due to the larger heat retention potential within the pile in order to provide an optimum environment to the aerobic microorganisms. The compost material had a brown colour where some branches are apparent, hence, longer degradation time is required to further degrade the slow-degrading yard waste.

5.1.2 C AND N BALANCE

The loss of C via leachate was insignificant. This means that 24-33% of C in the input material remained in the compost product. The loss of C to atmosphere was higher in Run 2. Result shows that C loss to air is greater from co-composting of food waste and yard waste in larger windrow size. This is in agreement with the greater reduction of VS content in larger composting pile, which indicates higher rate of degradation process.

The total N loss during composting was 44-59% (Run 1) and 72-78% (Run 2). N loss in leachate was insignificant. It is important to note that NH_3 emissions happened in higher temperature as nitrification of ammonium to NO_2^- is inhibited as well as favourable evaporation of NH_3. This could explain the greater emission of N in general in Run 2 (greater windrow size). The N content in the feed stock lost during composting as N_2, which is an environmentally unproblematic compound.

5.1.3 LEACHATE

The volume of leachate collected in Run 1 and Run 2 sampling periods (2.5-5L/composting cycle) were in the range reported elsewhere in the literature. The leachate generation of approximately 3L was recorded in an experiment with daily inputs of 2.5 kg household waste/person/day for 5 weeks (Papadopoulos et al., 2009) whereas another experiment revealed a leachate generation of 43-300 mL/day. The relatively high generation of leachate reflects the high moisture content in food waste. The leachate generation is equivalent to 11.77-12.72 L/Mg ww in the present study, is lower as compared to other similar study with daily inputs (Amlinger et al., 2008).

5.1.4 LIMITATIONS

The difference between the input and output values had caused the negative value in SFA model. This was due to the technique of sampling. The input samples were randomly collected from composting piles with small quantities and this could potentially resulted in great uncertainties, in particular the trace metals which were unevenly distributed in the OMSW. It is suggested that C and N compounds are more representative in grab method. It was reported that FW was considered heterogeneous despite the shredding process due to the relatively great variance in parameters reported by other researchers. Hence, this grab method for FW sampling resulted in limitations to the assessment in term of large uncertainties. However, the uncertainties of the representative samples can be reduced by increasing the number of samples. The sampling of the output was carried out by employing quartering method, which exhibits greater accuracy. Despite the possibility of loss of emissions of heavy metal to the air as calculated by STAN 2.5, it is however considered to be insignificant. The transfer coefficients of selected substances to air, compost and leachate of a co-composting process are shown in Table 5.1.

From the SFA modelling, heavy metals were found to be released to atmosphere (principles of conservation of mass). However, there is limitation within the usage of SFA modelling, e.g. The sampling method. The materials were heterogeneous where the representativeness of the samples were questioned and argued. However, as far as the method and research are concerned, quertering method is the most commonly used approach to sample heterogeneous solid materials and is documented as national standard method within Malaysia' SIRIM. Morover, in order to increase the homogneity, all FW and YW were mixed thoroughly before sampled. The samples were dried in oven for 24 hours at 104 ^{o}C, ground and mixed throughly before sent to lab for elemental tests in order to increase the homogeneity of the samples.

Table 5.1: Transfer coefficients of Selected Substances to off-gas, compost and leachate for Co-composting of OMSW

Substance	Run 1						Run 2					
	TC off gas		TC compost		TC leachate		TC off gas		TC compost		TC leachate	
	min	max	min	max	min	max	min	max	min	max	min	max
carbon	0.67	0.73	0.27	0.33	0.00	0.00	0.74	0.76	0.24	0.26	0.00	0.00
nitrogen	0.44	0.59	0.41	0.56	0.00	0.00	0.72	0.78	0.22	0.28	0.00	0.00
phosphorus	0.85	0.90	0.10	0.14	0.00	0.00	0.92	0.93	0.07	0.08	0.00	0.00
potassium	0.57	0.67	0.31	0.41	0.01	0.02	0.67	0.69	0.28	0.30	0.02	0.02
Cadmium	0.22	0.58	0.42	1.00	0.00	0.00	0.16	0.52	0.48	0.84	0.00	0.00
Chromium	0.00	0.31	0.69	1.00	0.00	0.00	0.10	0.31	0.69	0.90	0.00	0.00
Copper	0.13	0.26	0.74	0.87	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00
Nickel	0.38	0.54	0.46	0.62	0.00	0.00	0.23	0.36	0.64	0.77	0.00	0.00
Lead	0.49	0.65	0.35	0.51	0.00	0.00	0.47	0.56	0.44	0.53	0.00	0.00

5.2 ENVIRONMENTAL IMPACTS OF OMSW ALTERNATIVE MANAGEMENT

The summary of contribution of each impact category to alternative OMSW management scenario is tabulated in Table 4.9 (Chapter 4). Landfilling practice of OMSW (S1 and S2) contribute significantly to climate change and Eco toxicity impact, in term of landfill gas emission, comprising toxic trace gas and the groundwater contamination from leachate emission. Transportation of OMSW to landfill creates relatively high impact in fossil fuel consumption. The environmental gain was observed in fossil fuel category due to the energy substitution by landfill gas recovery, which helps to reduce the net environmental impact significantly. The major environmental impacts of composting (S3) are in association to climate change, Eco toxicity, respiratory inorganics and fossil fuel, which are resulted from the fugitive emission from the decomposition process, particularly GHG emission to atmosphere and deposition of heavy metal to soil during application of compost (heavy metal is not removed in composting process). The high impact categories suggest the need to reduce the emission during composting process particularly the NH_3 and N_2O (respiratory inorganics) and CH_4. The largest environmental impact modeled in S4 is climate change and Eco toxicity due to the CH_4 emission resulted from unburned biogas and the discharge of digestate to the land. The impacts are however overcome by the environmental gain through energy recovery from CH_4 generation, resulting in high scoring point to fossil fuel category. Due to the significant gain in fossil fuel category, the net environmental gain was observed in S4, indicating an environmental sound management system for OMSW. In general, environmental impacts increase with the decomposition emission from OMSW management process (as shown in Figure 4.2). This reveals that fugitive emissions from decomposition of OMSW as easily degradable materials have relatively importance in environmental impacts, and hence emission control measures have to be taken in order to reduce the overall environmental impacts regardless of which scenarios to be taken.

5.2.1 FUGITIVE EMISSIONS OF OMSW MANAGEMENT PROCESS

The emissions from composting of OMSW in this study (as shown in Table 4.8 in Chapter 4) are in agreement with the emissions from literature which shows that average CH_4 emission value was 1.83 g per kg feedstock while emissions of N_20 and NH_3 were 0.075 and 0.406 g per kg feedstock respectively (Saer et al., 2013). The emitted CO_2 resulted from composting of organic matter, is regarded as biogenic CO_2, and hence does not lead to impact on global warming (IPCC, 2006). However, CH_4 emission is significant in emission accounting of composting process due to its high GWP. CH_4 emissions is normally avoided in well-managed compost operation (Lou and Nair, 2009) or oxidized and converted to CO_2 once it reaches the surface from the center of composting pile (USEPA, 2006). However, other authors have included CH_4 emissions in composting systems due to the high GWP of CH_4. N_2O with 298 times GWP of a unit weight of CO_2 can be generated from poorly managed composting process (IPCC, 2006). NH_3 emissions is not compulsory in environmental accounting of composting in LCAs. NH_3 emission is however not included in the emission accounting by IPCC (2006) despite the recognition on the significant impacts of NH_3 emission by previous researchers (Amlinger et al., 2008; Andersen et al., 2010).

Anaerobic digestion is a series of processes in which microorganisms break down biodegradable material in the absence of oxygen (Gray et al., 2008). Biogas may require treatment or 'scrubbing' to refine it for use as a fuel. Hydrogen sulfide, a toxic product formed from sulfates in the feedstock, is released as a trace component of the biogas. Due to insufficient data, hydrogen sulfide is excluded in the present emission accounting. Digestate is the solid remains of the original input material to the digesters that the microbes cannot use. It also consists of the mineralized remains of the dead bacteria from within the digesters (Gray et al., 2008). In general, there are two types of digestate: acidogenic and methanogenic. Besides, it comes in three forms: fibrous, liquor, or a sludge-based combination of the two fractions. The levels of potentially toxic elements (PTEs) depend upon the quality of the original feedstock (Jansen et al., 2004). The liquid digestate typically have elevated levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD), if put directly into watercourses, would cause significant eutrophication impact.

Similarly, OMSW deposited in landfill will generate landfill gas, which constitutes 45-55% of CH_4. Previous researcher had compared modeled CH_4 generation with actual CH_4 generation for landfills which concluded CH_4 generation potential of 0.093 kg per kg of waste was overestimated (Fellner et al., 2003). Another study concluded that a best fit of CH_4 generation potential is 0.08 kg per kg of waste (Wangyao et al., 2009). CH_4 generation potential in waste samples of different age at a Brazilian landfill was measured (Machado et al., 2009), reported about 0.07 kg per ton waste. The difference of CH_4 emission rate between the present study and the literature is argued to be related to both the nature of the waste, in which the author considered source-separated OMSW whereas comingled waste was considered in literature.

5.2.2 COMPARISON OF COMPOSTING AND ANAEROBIC DIGESTION OF OMSW

Previous studies suggested that composting process as the best option for OMSW management, in view of its lower environmental impacts than landfilling practice. This study suggests that anaerobic digestion is the best mean of OMSW management due to its greater environmental benefit from biogas recovery as compared to composting. Decomposition emission from anaerobic process is lesser than composting due to its closed system. Gaseous emission is trapped and burned before being released to the atmosphere. Emission control is more difficult in windrow composting process. Enclosed composting system for instance in-vessel composting, can be employed and gaseous emission can be treated, but conversely, excess electricity consumption air delivery system imposes greater environmental impacts. Emissions from decomposition in composting process have the largest environmental impacts. CH_4 and N_2O are potent GHG and NH_3 deposition contributes significantly to eutrophication and acidification. Emission factors change with the overall impacts of OMSW composting in respect to climate change, eutrophication, eco toxicity and respiratory inorganics impacts. Given the benefits of OMSW composting as an alternative waste management plan in the University of Malaya, further study on the decomposition emissions control from open composting process has to be carried out.

5.2.3 EMISSION CONTROL MEASURES FOR OMSW COMPOSTING

It is very difficult to determine which emission scenarios (minimum, average, maximum) apply to the facility used for the present study, UMCC. However, best management practices (BMPs) can be integrated in order to control the decomposition emissions during the process. For instance, C/N of the initial feedstock can be controlled between 25 and 35 in order to minimize NH_3 and N_20 emissions (Saer et al., 2013). Extreme C/N ratio could result in decomposition limitations. Mature compost can be added into the composting pile to improve the binding efficiency of soluble and volatile carbon and nitrogen sources (Amlinger et al., 2008). Moisture content has to be maintained at 50-60% in order to prevent formation of anaerobic pockets in the pile. In tropical country like Malaysia, it is more advisable to cover the pile with water-proof sheet in order to prevent rainwater absorbing to the pile. Pile has to be turned frequently in order to aerate the inner part of the pile. N_2O emission can be minimized by controlling the temperature in between 40^{o}C and 60^{o}C (Marry, 2009; Levis et al., 2010). Replacing of N-fertilizer with compost also provide important environmental benefits. When subtracting the impacts of fertilizer production, it resulted in environment gain for replacement of fertilizer by compost (Saer et al., 2013). However, due to low N content in compost, amount of N-fertilizer (ammonium nitrate as N) substituted are minimal. Moreover, in the present study, transportation of N-fertilizer (ammonium nitrate as N) from manufacturer to the site is not included, resulting in lower environmental burdens of N-fertilizer.

5.3 GHG EMISSION REDUCTION POTENTIAL FROM OMSW COMPOSTING

5.3.1 EMISSIONS FROM OMSW COMPOSTING ACTIVITY

In OMSW composting activity, there were essentially four sources of carbon emissions: CO_2 from on-site electricity consumption, CO_2 from on-site fuel consumption, and GHGs (N_2O and CH_4) emission from composting process. Besides, the carbon emission from transportation of MSW to landfill disposal was included in the analysis as the non-compostable MSW is disposed of in landfill despite the establishment of on-site composting project. For transportation, the calculation for project was similar with the baseline transportation calculation. The model of OMSW composting in UM was used to study the OMSW composting alternatives in larger national scale. The GHGs emission from composting was in agreement to several studies (Fukumoto et al., 2003; UNFCCC, 2008).

Scenarios were created based on the availability of OMSW from different sources. OMSW collected from institutional and industrial sectors were considered 'low-hanging fruits' due to their availability and relatively homogeneous characteristics. Besides, national waste management policy in Malaysia has mandated institutional and industrial sectors to manage their daily generated waste at their own cost. Moreover, YW generated from these sectors are prohibited to be disposed in any registered municipal landfills and these creates opportunities to YW recycling. With this policy in place, collection of OMSW from industries and institutions such as universities with relatively high purity will be made easy due to increase demand for OMSW disposal from these sectors.

Scenarios have been extended to include OMSW generated from commercial and residential areas (S4, S5 and S6). MSW generated from commercial and residential in Malaysia is heterogeneous with over 40% of OMSW. There was less effort in educating the public to source-separated their MSW prior to the introduction of National Waste Management and Public Cleansing Act 2007. However, the government has taken proactive measures to promote and educate the citizens on source-separation and recycling of OMSW through Takakura home composting program. Besides, the separate curbside collection system has been introduced progressively at selected localities to educate the source-separation of household waste. Taking into consideration of various measures taken by the government to promote source-separation of household and commercial waste, the author has assumed successful source-separation of 20% of FW by the households nationwide in year 2025 and thus included in S6. It is interesting to note that diversion of 20% FW from disposal in landfill has resulted in tremendous reduction of GHG emissions by 16%. Hence, the author would advocate avoidance of FW disposal in landfills by FW recycling methods

There were several FW recycling methods available which include animal feedings, composting and anaerobic digestion with methane gas recovery. However, only composting method was considered in present study due to composting knowledge and technology transfer between Japan and Malaysia. Moreover, composting of

OMSW has been advocated by several researchers to be cost-effective. This is in line with our national commitment to reduce 40% GHG emissions intensity by year 2025 with availability of cost-effective technology and assistance from developed countries. Animal feeding method was not included as not all FW are acceptable for animal feeding due to 'halal' issues in an Islamic country like Malaysia.

OMSW composting model in UM was used to study the national OMSW composting management due to its common socio-economy activities as a township, which consists of residential, commercial, institutional and industrial sectors within a region. The present OMSW composting model can be used to model national GHG emissions reduction strategy, through OMSW composting activities. The present study is significant in showcasing the possibility of GHG emission reduction through OMSW composting and thus contributes to future research in modeling GHG emission reduction from in Malaysia.

5.4 NATIONAL POLICY OF SOLID WASTE MANAGEMENT IN MALAYSIA

Knowledge gap on the GHG emission reduction potential from OMSW recycling hinders the effort from the government to promote OMSW recycling facilities in larger scale. Most of the existing OMSW recycling initiatives in Malaysia are small scale due to . In order to achieve environmental sustainability, the implementation of OMSW recycling with regards to the environment is crucial. The approach between environment and technology/management is very important as technologies are used to help achieving OMSW management goal as well as to conserve the environment.

Despite the lack of expression in monetary terms, there are many important environmental impacts (non-financial) of waste when not properly managed. These are difficult and perhaps impossible to value in a monetary perspective, but they should be given consideration alongside the financial impacts in policy formulation and decision making.

5.4.1 POSITION OF OMSW IN NATIONAL POLICY

It is very important to have shared goals as target for comparison if several options of OMSW management are considered and evaluated for a particular region. The National Solid Waste Management Policy (NSWMP) of Malaysia will be discussed in this section and the Malaysia National Waste Management Objectives are summarized in Table 5.2. The following particulars about these objectives of NSWMP are worth discussed.

Table 5.2: Six Objectives for National Solid Waste Management Policy in Malaysia

Objective	Description
Objective 1	A solid waste management that is integrated and cost effective, which includes collection, transportation, intermediate treatment and disposal
Objective 2	Minimization of solid wastes from the domestic, commercial, industries, institutions community and construction through Reduce, Reuse and Recycling (3R)
Objective 3	Services that are efficient and cost effective through privatization
Objective 4	Selection of technologies that are proven, affordable in terms of Capital Expenses (CAPEX) and Operational Expenses (OPEX), and environmentally friendly
Objective 5	Ensure conservation of the environment and public health
Objective 6	Establish institutional and legal framework for solid waste management

Source: NSWMD (2012a)

First, the Objective 2 stated in Table 5.1 stresses the importance of waste minimization through prevention and recycling. Minimization of OMSW in particular is significant due to its huge generation. The waste hierarchy which emphasizes waste prevention and recycling over waste disposal is often used as the underlying principle for waste management decisions although it could be argued that this principle does not always lead to the most cost-effective waste management system. According to governmental report (MHLG, 2005), a target to achieve 22% recycling rate by year 2020 has been set. The current recycling rate is reported to be approximately 5% (Fauziah et al., 2004; Agamuthu et al., 2009; Agamuthu and Victor, 2011). Even under the Act, materials targeted for recycling based on the current national recycling strategy focus only on paper, plastic, glass and metals. No target has been set for recycling OMSW – hence a discrepancy between the country's new MSW strategy and the national climate mitigation strategy.

Secondly, the Objective 5 in NSWMP highlights the conservation of resources and protection of human health, both depends on the content of certain substances in waste. Waste management and treatment cannot focus only on wastes as products only, instead it is crucial to address the level of substances (chemical elements and chemical compounds) contained in waste. This is due to the reason of these substances may pose potential negative impacts as hazardous material or may be a useful resource for recycling purpose. Thus, it is important to have sufficient information about the composition of waste and to know what happens with waste and its constituents when it undergoes treatment or disposal. Thus, in order to assess if the specific goal is reached by a certain waste management system, a comprehensive substance flow analysis (SFA) could be used to assess the waste flows, chemical composition of waste and transfer coefficient of waste treatment processes (Brunner and Ernst, 1986)

Third, the general aftercare-free waste management objective has severe implications on landfilling and recycling. This aftercare-free objective of sustainable waste management implies that materials in waste are either directed towards clean cycles or that they are eliminated and directed towards safe final sinks. Studies reveal that a landfill requires leachate treatment, landfill gas monitoring and control for several centuries (Belevi and Baccini, 1989). The main reason is the large fraction of biodegradable components in the OMSW resulting in high nitrogen and organic carbon loads of landfill leachate. If the waste is incinerated, this organic fraction is mineralized, yielding hygienic bottom ash that does not contain any degradable organic matter (Mohareb et al., 2008). However, the bottom ash has to be treated prior to landfilling due to the leaching of inorganic salts and metals in order to fulfill the aftercare-free objective. For recycling, the aftercare-free objective requires clean cycle which means any hazardous substances have to be eliminated from cycles when waste is recycled into new products and these eliminated hazardous substances need to be disposed in safe final sinks. However, at the state of the present study, aftercare-free objective is not apparent in NSWMP. Even though Objective 4 in NSWMP implies the selection of environmental friendly technologies for waste management, but it does not clearly identify the guidelines of environmental friendliness. Nevertheless, NSWMD has revealed in their report to safe close 16 illegal dumpsites, upgrade 30 illegal dumpsites to sanitary landfills and construct 9 new sanitary landfills (NSWMD, 2012b). This shows that the waste management authorities are aware of the importance of aftercare-free waste management activity by promoting world class sanitary landfill as in Bukit Tagar sanitary landfill (Tonkin and Taylor, 2007).

Fourth, the other Objectives set in NSWMP underline the significance of institutionalization of solid waste management system in Malaysia and implementation of legal framework. This is crucial in order to have a clear policy on waste management and legislation to realize that policy is imperative. Malaysia is experiencing rapid development and problems associated with increasing waste generation are evident. The SWPCM Act 2007 which was gazatted in 2007 after 10 years delay, is envisaged to have serious consequences in waste management practice in Malaysia. It was found that for countries spending less of its Gross Domestic Product (GDP) for waste management, the waste hierarchy of prevention, recycling and disposal is not an appropriate strategy. In such regions, the improvement of disposal systems (complete collection, upgrading to sanitary landfilling) is the most cost-effective method to reach the general objectives of solid waste management by comparing three cities namely Vienna, Damascus and Dhaka with great difference in their GDP and waste management system. (Brunner and Fellner, 2007).

5.4.2 THE CHALLENGES IN OMSW MANAGEMENT IN MALAYSIA

The MSW collected is mostly landfilled while only small fractions are incinerated. Until June of 2012, there are a total of 165 operating landfills throughout the country, of which only 7 are sanitary landfills. The rest are non-engineered open dumps and a total of 131 dumpsites were closed down up to year 2012. Fauziah and Agamuthu (2012) pointed out that rapid economy development, increase in urban population and improvement of the living of standard resulted in an average MSW generation rate of 1.2kg/capita/day in 2007 and increased to more than 1.5 kg/capita/day. It is estimated that MSW generation in increasing at 3%-5% per annum (Agamuthu and Fauziah, 2005; JICA, 2006; Saeed et al., 2009). MSW is mostly generated from urban areas which accommodate more than 65% of Malaysian total population. More and more sanitary landfills are planned to be constructed in order to meet the ever increasing need of waste disposal in the country. The management of landfills begin to exhibit improvements due to the objectives set in the provision of SWPCM Act 2007. Table 5.3 shows the number of operating landfills and the total number of dumpsites closed for disposal in Malaysia. In RMK 9 and RMK 10, the federal government had spent RM 483 million to safe-close 17 dumpsites (PPSPPA, 2012). Besides, in line with the objectives of environmental protection, the federal government has initiated to: (1) construct 9 new sanitary landfills of level IV, (2) upgrade 21 dumpsites to sanitary landfills of level III and (3) upgrade 11 dumpsites to sanitary landfills of level IV (PPSPPA, 2012). The classification of sanitary landfills is summarized in Table 5.4.

However, relying alone on landfill practice alone is not sustainable and effective as more loads are required in the future to accommodate the continuous increasing generation of MSW. The rapid increasing of MSW, without material recovery practice, will fill up the disposal sites in alarming speed, resulting in premature closure of many of the disposal sites. Moreover, it is not cost effective in long term as the remediation and the monitoring after closure of the sites are high. It is advisable to incinerate the MSW before disposal in order to achieve massive volume reduction of MSW and energy recovery (Belevi and Baccini, 1989; Lai et al., 2009;

Bernstad and la Cour Jansen, 2011; Chua et al., 2011). The federal and state government had constructed 5 incinerators at Langkawi, Labuan, Tioman, Pangkor and Cameron Highland respectively. As discussed earlier, incineration has the potential to solve the problem of rapid landfill fill-ups as the original volume and weight of MSW may be reduced tremendously. This helps to prolong the life span of landfill sites.

Table 5.3: Number of Operating and Closed Landfills in Malaysia in 2012

State	Operating landfills	Closed landfills	Total
Johor	14	23	37
Kedah	8	7	15
Kelantan	13	6	19
Melaka	2	5	7
Negeri Sembilan	7	11	18
Pahang	16	16	32
Perak	17	12	29
Perlis	1	1	2
Pulau Pinang	2	1	3
Sabah	19	2	21
Sarawak	49	14	63
Selangor	8	14	22
Terengganu	8	12	20
Kuala Lumpur	0	7	7
Labuan	1	0	1
Total	**165**	**131**	**296**

Source: NSWMD (2012b)

Table 5.4: Classification of Landfills in Malaysia

Sanitary landfill class	Available facilities	Pollution impact
I	Minimum infrastructure such as fencing and drains	High
II	Class I facilities, in addition to gas removal system, separate unloading and working area, daily cover and enclosing bund, elimination of scavenging and provision of environmental protection facilities	Moderate
III	Class II facilities, in addition to leachate recirculation system allowing the collection, recirculation and monitoring of landfill leachate	Moderate
IV	Class III facilities, in addition to a leachate treatment system	Low

5.4.3 ENVIRONMENTAL GUIDELINES OF MSW

Malaysian effort in environmental protection has been evident since Third Malaysia Plan (1976-1980), followed by adoption of the sustainable development concept. In line with the vision to control pollution, Department of Environment (DOE) is formed to contribute towards better level of health, safety and quality of life through conservation and promotion of wise use of natural resources despite national development. The pollution control and monitoring are implemented under the provision of the Environmental Quality Act 1974 (Badgie et al., 2012) In relation to waste management system, scheduled wastes is controlled and regulated by the DOE while the MSW rests with the local government. Inadequate collection, transport or improper disposal of MSW can have adverse impacts on: (1) air pollution and unpleasant odour; (2) potential health hazards from accumulation of polluted water; (3) loss of productive land due to the presence of non-biodegradable items; (4) contamination of soil, ground and surface waters by leachate; (5) contamination of the marine environment through direct or indirect discharge of waste. MSW consists of wide spectrum of materials handled by individuals before being discarded. Care needs to be exercised over such materials soon after disposal as hazardous substances may be present in small quantities. The presence of biodegradable constituents in MSW demands care in the recovery treatment and disposal. Until the pathogens present in the waste have been destroyed, there is always the possibility a threat to human health (toxicity) and the environment (Eco toxicity) (UNEP, 2000). Besides the technical guidelines by Base Convention, the pollution control guidelines by DOE in term of river water, ground water, air and climate change can serve as a clear guideline for remedial approach of MSW management as presented in Table 5.5

Table 5.5: Relevant Guidelines for Pollution Control in relation to MSW Management

Parameter	Guidelines
River water	The Water Quality Index
Ground water	National Guidelines for Raw Drinking Water Quality
Air	Malaysian Ambient Air Quality Standard
Climate Change	Malaysia Second National Communication submitted to UNFCCC

Source: DOE (2009)

5.5 USE OF COMPOSTED ORGANIC WASTE AS ALTERNATIVE TO SYNTHETIC FERTILIZER

Land application of composted material as a fertilizer source not only provides essential nutrients to plants, it also improves soil quality and effectively disposes of wastes. One of the major problems of agricultural soils in the tropical region is the low organic matter content. Composted organic waste is being applied on agricultural fields as an amendment to provide nutrients and also to enhance the organic matter content and improve the physical and chemical properties of the cultivated soils (Atiyeh, et. al., 2001; Atiyeh, et. al., 2000; Soumare, 2003). Composted organic waste contains essential nutrients for plant growth, especially N and P (Beltran et al., 2002). A study was carried out to evaluate the use of composted organic waste as an alternative to synthetic fertilizers (Golabi, 2004). The preliminary findings clearly indicated that productivity can be improved by proper use of composted organic materials and the environment also benefits through the reuse of organic wastes that otherwise would be buried in the land field. A number of reports have shown that composted organic waste are able to protect plants against biotic stresses caused by pathogenic factors (Courtney and Mullen, 2008; Chen, 2006; Atiyeh, et. al., 2001; Atiyeh, et. al., 2000; Soumare, 2003). Stimulatory effects of composted organic waste on plant growth and productivity have been previously less investigated although, lately, they are receiving great attention. Field trials by Pane (2104) indicated the potential of this organic formulate to induce bio-stimulation effects by enhancing productivity of the plants. They may determine a more efficient growth of the plants, reducing dependence from external inputs, such as pesticides and fertilizers. Soumare (2003) and Berjón (1997) claimed that compost appeared to be a good supplier of nutrients for tropical soil. Compost and mineral fertilization significantly increased dry matter production, soil organic carbon, available P, Fe, Mn, Zn, Cu, K and pH. Golabi (2014) stated that application of organic materials increased organic status of the soil and nutrient content. However, the effectiveness on improving the productivity of the soil varied across compost produced from different materials. Developing a suitable nutrient management system that integrates use of compost from OMSW may be a challenge to reach the goal of sustainable agriculture; however much research is still needed. Therefore, advances on this topic could increase the potential for diffusion and practical applications of these organic formulates. However, since the topic is beyond the scope of the present study, which focuses mainly on the environemntal assessment of alternative management of OMSW, further studies on the use of compost to enhance plant producticity, improve plant health, expand resistance to insects and diseases as well as improved nutritional qualities of plant growth.

6. CONCLUSIONS

6.1 LIFE CYCLE INVENTORY OF OMSW COMPOSTING

For the first time, a life cycle inventory was made for medium scaled co-composting of food waste and yard waste in tropical environment. An experiment set-up with two composting windrows for different size (212.4kg and 393kg respectively) was performed for duration of 60 days the environmental impacts were assessed.

The C loss during composting was recorded in the range of 0.146-0.166 kg/kg ww. C losses via leachate were insignificant (0.02% of the total input C). The total N loss during the process was 0.005-0.012 kg/kg ww. Due to unavailability of gas measuring equipment with suitable detection range, the emission of CO_2, CH_4, CO, NH_3 and N_2O were not measured. However, the emissions of these gas compounds were estimated via SFA. The leachate generation was measured as 0.012-0.013 kg/kg ww. The flows of selected heavy metals were assessed. Heavy metals were of minor significance due to low concentrations in the inputs (food waste and yard waste). Heavy metals were found to be released to the atmosphere. However, most heavy metals remained in the compost. The C/N reduction during the process was in the range of 10-23%. In general, the compost composition was in agreement with the ranges previously reported in literature and thus ready to be used as soil conditioner.

The LCI provided in the present study can be useful for environmental modelling and assessments of medium-scale co-composting of food waste and yard waste in tropical environment. No significant environmental impacts were identified from the process, except for the emissions of GHGs. The emissions of GHGs can be decreased by frequent mixing of the composting pile to avoid anaerobic condition in within the pile.

6.2 LIFE CYCLE IMPACT ASSESSMENT FOR ALTERNATIVE OMSW MANAGEMENT

The objectives of this study are twofold: (1) to calculate waste-specific fugitive emissions for OMSW in alternative treatment/disposal processes and (2) to evaluate environmental impacts and benefits associated to alternative OMSW management system using an approach of life cycle assessment. Prior to analysis, the main methodological issues in modelling waste management were addressed. The present study highlights the importance of data source from modelling against empirical data. Multi-input inventory approach were used to calculate the waste-specific fugitive emissions from alternative OMSW biological treatment process, including landfilling, composting, anaerobic digestion and application of compost on land. CH_4, N_2O and NH_3 emissions were considered whereas other substances/compounds were assumed remain in the compost/digestate after treatment. Several LCAs of OMSW management alternatives have been carried out, including the compost use, replacing N-fertilizer, particularly in Malaysia. The calculated emissions of these gases were in agreement with those reported from previous studies. The present study has compared alternative OMSW management process generated by using LCA methodology. We have shown that when accounting for the resource utilization, OMSW anaerobic digestion system has a net environmental gain. Hence, anaerobic digestion is proposed as the most environmental sound management for OMSW. For all scenarios, disposal of OMSW at landfill are generally less environmental favourable. This study also highlight the importance of decomposition emissions control, particularly CH_4, N_2O and NH_3. In addition, further studies on emission reduction and emission control are needed.

6.3 IMPLEMENTATION OF LIFE CYCLE ASSESSMENT IN OMSW MANAGEMENT IN MALAYSIA

Current MSW management is a challenge that must be addressed and improved. Extra attention has to be put on OMSW which make up more than 50% of the total MSW generated. Strategies to reduce the OMSW generation are among the best and most environmental friendly methods. Separation of OMSW reduces the total MSW sent to landfills tremendously, not to mention the environmental pollution resulted from anaerobic degradation of OMSW in uncontrolled landfill sites. Reduction of OMSW can be achieved through composting and anaerobic digestion. The attainment of the above recycling process could be a difficult task with regards to the knowledge about the heterogeneous nature of OMSW and the recycling process. Therefore information and knowledge about the content and characteristics of OMSW as well as the substance flow within the recycling/treatment process is important to facilitate good decision making.

In Malaysia, OMSW analysis and data have not been well documented. Several studies was carried out on waste sampling, but none of them was on OMSW in specific. In that regards, the life cycle inventory for OMSW composting is deemed important in understanding the impacts of a composting process to anticipate the implementation of massive OMSW recycling effort nationwide. Successful OMSW recycling depends on reliable information about the process and inventory. In other words, comprehensive life cycle information about the recycling/treatment process is crucial towards achieving significant weight and volume reduction as well as environment enhancement. The study provides baseline data for waste management goals and objectives formulation and assessing whether these objectives are achieved as well as for the further studies within the OMSW management sector in the country.

6.4 CARBON EMISSION REDUCTION FROM OMSW COMPOSTING AS COMPARED TO BAU

According to Malaysia Second National Communication to UNFCCC, the efforts to reduce GHG emission are outlined in the National Strategic Plan through various means to improve on solid waste management. The present waste management systems are not directly quantifiable in terms of climate change impact. Waste prevention was considered as one of the critical success factors in integrated waste management hierarchy. However, waste prevention on OMSW is still insufficient. The study on GHG mitigation through OMSW recycling is hence timely and crucial to assess the benefit to the environment. This study presented the climate change benefits from waste prevention strategies through OMSW composting case study in Peninsular Malaysia. The study shows that potential GHG mitigation can be achieved by increasing the recycling rate targets for OMSW through acquiring cheapest and easiest method (Static Pile Composting). In conclusion, OMSW diversion from disposal created climate change benefits in term of net GHG emissions reduction derived from life cycle of waste management. The current GHG emission in association to waste management in is 9.98E+02 tCO_{2e}/ton waste/day. Scenario comparison was carried out in line with the target to achieve 22 % recycling rate by 2025.

From the baseline scenario (S0), a potential of 2.77E+07 tCO_{2e}/day was anticipated by MSW generated in year 2012 of which 98 percent of the total emission was direct emission from landfill whereas the emission from transportation contributed 2.36E+02 tCO_{2e}/day. The net GHG emission for S1, S2, S3, S4, S5 and S6 in tCO_{2e}/day were 3.59E+07, 3.26E+07, 3.21E+07, 2.84E+07, 2.64E+07 and 2.18E+07 respectively. In general, waste diversion for composting proved a significant net GHG emission reduction as compared to BaU in year 2025 (S2). However, only S5 and S6 achieve net GHG reduction of 5% and 21% to the base year of 2012. Despite the emission due to direct on-site activity, the significant reduction in methane generation at landfill has reduced the net GHG emission. The emission source of each scenario was studied and analyzed. Study showed that landfill methane gas emission contributed to the largest share of emission among all scenarios. The second largest emission contributor was the emission from transportation of waste to disposal (1%~1.2%) followed by the emission diesel consumption in composting site (3%~9%). Direct emission of N_2O and CH_4 from composting process is accounted for less than 5% of total GHG emissions in all scenarios.

A GHG mitigation assessment has been reported by National Second Communication to UNFCCC. The assessment estimated 2,000 Gg of CH_4 will be emitted from Malaysia in specific year 2020, in the absence of mitigation strategies. Two scenarios were compared: Scenario 1 and Scenario 2. Scenario 1 represented the achievement of 22% material recycling rate through separate collection and buy-back service as desired by the government whereas Scenario 2 supplements the earlier with several material recovery facilities (MRFs) and incineration plants. In both instances, methane recovery facilities with an anticipated 25% recovery rate is available in the landfill model where all residue waste eventually end up. Scenario 2 showed a potential CH_4 emissions reduction of 57.7 percent. However, this assessment focused only on inorganic materials such as papers, aluminum, plastics and metals and was based on projections for Peninsular Malaysia only. OMSW recycling was however excluded from the assessment.

The mandatory source separation as stipulated in the new Solid Waste and Public Cleansing Management Act 2007 could favour OMSW collection and further treated via composting. The present OMSW recovery facilities have great potential to be expanded if further support is provided such as incentives on GHG mitigation potential. Some of these efforts are:

a) Composting of OMSW from hawker centres by using in-vessel composting technology with treatment capacity of 500kg/day.
b) Windrow composting of OMSW with effective microorganisms with treatment capacity of 1.7 ton/day in commercial areas.
c) Composting of OMSW with treatment capacity of 40kg/day in wet markets.
d) Home composting of househlod kitchen waste within residential areas.
e) Self-initiatives effort from several hotels in recycling OMSW for animal feed.

Diversion of OMSW from disposal at landfill was reported to provide substantial benefits to both community and environment. Integration of OMSW recovery in comprehensive waste management as well as enhancing public education would contribute to greater GHG emission reduction potential. Chua et al (2011) in their another study advocates that GHG emission can be reduced by 25.5% from Malaysia waste by increasing the recycling rate to 22% for inorganic materials only. The current study supports an additional of 21% GHG emissions reduction by including the recycling of OMSW via composting in all sectors. This is help to achieve the target committed by the Malaysian government, which is to reduce its GHG emission by 40% in year 2020. The study advocates that GHG emissions per unit GDP reductions can be further enhanced by including OMSW recycling.

6.5 CONTRIBUTION TO NATIONAL WASTE MANAGEMENT POLICY

Previous studies focused mainly on waste management in Peninsular Malaysia. Source separation of OMSW is mandatory in the present and hence it is mixed with other waste streams and thus hinders the effectiveness of implementing OMSW recovery. Furthermore, OMSW is always excluded from the recycling targets. Knowledge gap on the GHG emission reduction potential from OMSW recycling hinders the effort from the government to promote OMSW recycling facilities in larger scale. Most of the existing OMSW recycling initiatives in Malaysia are small scale due to . In order to achieve environmental sustainability, the implementation of OMSW recycling with regards to the environment is crucial. The approach between environment and technology/management is very important as technologies are used to help achieving OMSW management goal as well as to conserve the environment. Despite the lack of expression in monetary terms, there are many important environmental impacts (non-financial) of waste when not properly managed. These are difficult and perhaps impossible to value in a monetary perspective, but they should be given consideration alongside the financial impacts in policy formulation and decision making.

The federalization of MSW management in Malaysia has created a big interest in sustainable OMSW management. The problems and challenges associated with the OMSW management implementation are highlighted. The challenges are summarized as: (1) life cycle thinking of waste management; (2) Environmental impacts from increasing OMSW generation; (3) Data deficiency problem; (4) lack of research in Malaysian OMSW management and; (5) Low carbon initiative. The federalization policy is already at its implementation phase to craft an effective policy trajectory toward the development of the SWM sector. Current practices reflect concrete improvements through gradual replacement of open dumps with sanitary landfills that incorporate at least some environmental protection measures. Federal government as the highest governmental level plays an important role to introduce new policy to development SWM in the country and provide necessary assistance to state and local governments. However, the improvement strategies should not focus only on upgrading the landfills but the implementation challenges discussed earlier have to be taken into account. In addition to that, extra attention has to be given to OMSW which make up the main component in Malaysian MSW. A knowledge-based goal-oriented OMSW management study is necessary to analyze the state-of-art of OMSW management in Malaysia and direct it towards fulfilling the main goals of waste management: the protection of the human being and the environment, the conservation of resources and aftercare-free landfills. Finally, the appropriate evaluation of the current situation of OMSW management in Malaysia with regards to the set goals, supported by the experience from other countries, should effectively aid the future decision processes regarding the development of a proper OMSW management system in Malaysia.

6.6 METHODOLOGICAL CHOICES

There are three major activities in the present studies namely: (1) construction of the LCI; (2) LCIA of alternative OMSW management and (3) construction of model for carbon emission reduction through OMSW composting. Of all these activities, data collection is the most time consuming and cost-intensive activity in the studies. The data collection becomes more challenging when dealing with quantification of emissions to air and water, particularly from an open process such as composting. In particular the modeling of direct emissions requires a large amount of parameters. (E.g. aerobic condition, moisture content, windrow size, climatic condition etc.) An efficient solution in the frame of composting life cycle assessment is required. Some adaptions are necessary according to the goal and scope of the study. To minimize the time consumption of direct measurement, an alternative methodology such as SFA could be employed in the future. Based on the experience of SFA in the present study, the emissions quantified are likely to be in agreement with that from previous studies. SFA will be able to integrate a wide portfolio of LCI and eventually LCIA projects from the OMSW management sector.

6.7 FUTURE STUDIES

The full LCI creates a basis for environmental modelling and assessments of composting systems for alternative OMSW management. The results of the present study provides information about all significant inputs and outputs in the form of elementary flow to and from the environment from all the unit processes involved. The information is essential for Life Cycle Assessment (LCA) for OMSW management strategies. The Inventory analysis is followed by impact assessment to evaluate the significance of potential environmental impacts based on the LCI flow results from the present study.

REFERENCES

Agamuthu, P. and S. Fauziah (2011). Challenges and issues in moving towards sustainable landfilling in a transitory country - Malaysia. *Waste Management & Research,* 29(1): 13-19.

Agamuthu, P. and S. H. Fauziah (2005). MSW management in Malaysia: Current Scenario and Future Planning. *Warmer Bulletin*, 98: 20-22.

Agamthu, P., Hamid, F. S., & Khidzir, K. (2009). Evolution of solid waste management in Malaysia: impacts and implications of the solid waste bill, 2007. *Journal of material cycles and waste management*, 11(2): 96-103.

Agamuthu, P., Khidzir, K. M., & Hamid, F. S. (2009). Drivers of sustainable waste management in Asia. *Waste Management & Research*, 27(7): 625-633.

Agamuthu, P. and D. Victor (2011). Policy trends of extended producer responsibility in Malaysia. *Waste Management & Research*, 29(9): 945-953.

Alptekin, E. and M. Canakci (2008). Determination of the density and the viscosities of biodiesel–diesel fuel blends. *Renewable Energy*, 33(12): 2623-2630.

Amlinger, F., Peyr, S., & Cuhls, C. (2008). Green house gas emissions from composting and mechanical biological treatment. *Waste Management & Research*, 26(1): 47-60.

Amutenya, N., Shackleton, C. M., & Whittington-Jones, K. (2009). Paper recycling patterns and potential interventions in the education sector: A case study of paper streams at Rhodes University, South Africa. *Resources, Conservation and Recycling*, 53(5): 237-242.

Andersen, J. K., Boldrin, A., Christensen, T. H., & Scheutz, C. (2010). Mass balances and life-cycle inventory for a garden waste windrow composting plant (Aarhus, Denmark). *Waste Management & Research*, 28(11): 1010-1020.

Andersen, J. K., Boldrin, A., Christensen, T. H., & Scheutz, C. (2011). Mass balances and life cycle inventory of home composting of organic waste. *Waste management*, 31(9):1934-1942.

Andersen, J. K., Boldrin, A., Christensen, T. H., & Scheutz, C. (2012). Home composting as an alternative treatment option for organic household waste in Denmark: an environmental assessment using life cycle assessment-modelling. *Waste management*, 32(1): 31-40.

Andersen, J. K., Boldrin, A., Samuelsson, J., Christensen, T. H., & Scheutz, C. (2010). Quantification of greenhouse gas emissions from windrow composting of garden waste. *Journal of environmental quality*, 39(2): 713-724.

ASTM (2003). Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste. *American Society of Testing and Materials*, 5232-5292.

Atiyeh, R. M., Edwards, C. A., Subler, S., & Metzger, J. D. (2001). Pig manure vermicompost as a component of a horticultural bedding plant medium: effects on physicochemical properties and plant growth. *Bioresource Technology*, *78*(1): 11-20.

Atiyeh, R. M., Subler, S., Edwards, C. A., Bachman, G., Metzger, J. D., & Shuster, W. (2000). Effects of vermicomposts and composts on plant growth in horticultural container media and soil. *Pedobiologia*, *44*(5), 579-590.

Ayres, R. U. (1995). Life cycle analysis: A critique. *Resources, Conservation and Recycling*, 14: 199-223.

Badgie, D., Samah, M. A., Manaf, L. A., & Muda, A. B. (2012). Assessment of municipal solid waste composition in Malaysia: Management, practice and challenges. *Polish Journal of Environmental Studies*, 21(3): 539-547.

Baetz, B. W., & Neebe, A. W. (1994). A planning model for the development of waste material recycling programmes. *Journal of the Operational Research Society*, 45(12): 1374-1384.

Bai, R., & Sutanto, M. (2002). The practice and challenges of solid waste management in Singapore. *Waste management*, 22(5): 557-567.

Bandara, N. J., Hettiaratchi, J. P. A., Wirasinghe, S. C., & Pilapiiya, S. (2007). Relation of waste generation and composition to socio-economic factors: a case study. *Environmental Monitoring and Assessment*, 135(1-3): 31-39.

Belevi, H., & Baccini, P. (1989). Long-term behavior of municipal solid waste landfills. *Waste Management & Research*, 7(1): 43-56.

Berjón, M. A., Morato, M. C., Revuelta, P. A., & Simon, A. C. (1997). The influence of solid urban waste compost and nitrogen‐mineral fertilizer on growth and productivity in potatoes. *Communications in Soil Science & Plant Analysis*, *28*(17-18): 1653-1661.

Bernstad, A., & la Cour Jansen, J. (2011). A life cycle approach to the management of household food waste–a Swedish full-scale case study.*Waste management*, 31(8): 1879-1896.

Boldrin, A., Andersen, J. K., Møller, J., Favoino, E., & Christensen, T. H. (2009). Composting and compost utilization: accounting of greenhouse gases and global warming contributions. *Waste Management & Research*, 27(8): 800-812.

Brinton, W. F. (2000). Compost quality standards and guidelines: an international view. *New York State Association of Recyclers*: New York: Wood End Research Laboratory, 15-72.

Brunner, P. H., & Ernst, W. R. (1986). Alternative methods for the analysis of municipal solid waste. *Waste Management & Research*, 4(2): 147-160.

Brunner, P. H., & Fellner, J. (2007). Setting priorities for waste management strategies in developing countries. *Waste Management & Research*, 25(3): 234-240.

Brunner, P. H., & Ma, H. W. (2009). Substance flow analysis. *Journal of Industrial Ecology*, 13(1): 11-14.

Budhiarta, I., Siwar, C., & Basri, H. (2012). Current status of municipal solid waste generation in Malaysia. *International Journal on Advanced Science, Engineering and Information Technology*, 2(2): 129-134.

Cencic, O., & Rechberger, H. (2008). Material flow analysis with software STAN. *Journal of Environmental Engineering and Management*, 18(1): 3.

Chen, J. H. (2006, October). The combined use of chemical and organic fertilizers and/or biofertilizer for crop growth and soil fertility. In *International Workshop on Sustained Management of the soil-rhizosphere system for efficient crop production and fertilizer use* (Vol. 16, p. 20). Land Development Department Bangkok, Thailand.

Chen, T. C., & Lin, C. F. (2008). Greenhouse gases emissions from waste management practices using Life Cycle Inventory model. *Journal of Hazardous Materials*, 155(1): 23-31.

Chiemchaisri, C., Juanga, J. P., & Visvanathan, C. (2007). Municipal solid waste management in Thailand and disposal emission inventory.*Environmental monitoring and assessment*, 135(1-3): 13-20.

Christensen, T. H., Bhander, G., Lindvall, H., Larsen, A. W., Fruergaard, T., Damgaard, A., ... & Hauschild, M. (2007). Experience with the use of LCA-modelling (EASEWASTE) in waste management. *Waste Management & Research*, 25(3): 257-262.

Chua, K. H., Sahid, E. J. M., & Leong, Y. P. (2011). Sustainable municipal solid waste management and GHG abatement in Malaysia. ST-4: Green & Energy Management, 4(02).

Colon, J., Martínez-Blanco, J., Gabarrell, X., Artola, A., Sánchez, A., Rieradevall, J., & Font, X. (2010). Environmental assessment of home composting. *Resources, Conservation and Recycling*, 54(11): 893-904.

Courtney, R. G., & Mullen, G. J. (2008). Soil quality and barley growth as influenced by the land application of two compost types. *Bioresource Technology*, *99*(8): 2913-2918.

Curran, M. A. (1996). Environmental life-cycle assessment. *The International Journal of Life Cycle Assessment*, 1(3): 179-179.

Dalemo, M., Sonesson, U., Björklund, A., Mingarini, K., Frostell, B., Jönsson, H., ... & Thyselius, L. (1997). ORWARE–A simulation model for organic waste handling systems. Part 1: Model description. *Resources, Conservation and recycling*, 21(1): 17-37.

Den Boer, J., Den Boer, E., & Jager, J. (2007). LCA-IWM: a decision support tool for sustainability assessment of waste management systems. *Waste management*, 27(8): 1032-1045.

Döberl, G., Huber, R., Brunner, P. H., Eder, M., Pierrard, R., Schönbäck, W., ... & Hutterer, H. (2002). Long-term assessment of waste management options-a new, integrated and goal-oriented approach. *Waste Management & Research*, 20(4): 311-327.

DOE (2009). Environmental Quality Report. Department of Environment Malaysia, Putrajaya, Ministry of Natural Resources and Environment.

Eriksson, O., & Baky, A. (2010). Identification and testing of potential key parameters in system analysis of municipal solid waste management.*Resources, Conservation and Recycling*, 54(12): 1095-1099.

Eriksson, O., Frostell, B., Björklund, A., Assefa, G., Sundqvist, J. O., Granath, J., ... & Thyselius, L. (2002). ORWARE—a simulation tool for waste management. *Resources, Conservation and Recycling*, 36(4): 287-307.

Fauziah, S. H., & Agamuthu, P. (2012). Trends in sustainable landfilling in Malaysia, a developing country. *Waste Management & Research,* 30(7): 656-663.

Fauziah, S. H., Simon, C., & Agamuthu, P. (2004). Municipal solid waste management in Malaysia-Possibility of improvement?. *Malaysian Journal of Science*, 23(2): 89-101.

Fellner, J., Schöngrundner, P., & Brunner, P. H. (2003). Methanemissionen aus Deponien Bewertung von Messdaten (METHMES). Wien, im November.

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., ... & Suh, S. (2009). Recent developments in life cycle assessment. *Journal of environmental management*, 91(1): 1-21.

Forti, M., Hansen, S. B., Kirkeby, J. T., Agamuthu, P., & Christensen, T. H. (2004). Environmental assessment of household waste disposal in Kuala Lumpur. *Malaysian Journal of Science*. Series A: Life Sciences, 23: 115-123.

Fukumoto, Y., Osada, T., Hanajima, D., & Haga, K. (2003). Patterns and quantities of NH 3, N 2 O and CH 4 emissions during swine manure composting without forced aeration—effect of compost pile scale.*Bioresource Technology*, 89(2): 109-114.

Furuholt, E. (1995). Life cycle assessment of gasoline and diesel.*Resources, Conservation and recycling*, 14(3): 251-263.

Ghani, W., & Idris, A. (2009). Preliminary study on biogas production of biogas from municipal solid waste (MSW) leachate. *Journal of Engineering Science and Technology*, 4(4): 374-380.

Gidarakos, E., Havas, G., & Ntzamilis, P. (2006). Municipal solid waste composition determination supporting the integrated solid waste management system in the island of Crete. *Waste management*, 26(6): 668-679.

Goedkoop, M., & Spriensma, R. (2001). The eco-indicator99: A damage oriented method for life cycle impact assessment: Methodology report.

Golabi, M. H., Denney, M. J., & Iyekar, C. (2004, July). Use of composted organic wastes as alternative to synthetic fertilizers for enhancing crop productivity and agricultural sustainability on the tropical island of Guam. In *Proceedings of the 13th International Soil Conservation Organisation Conference* (Vol. 234, pp. 1-6).

Gray, D., Suto, P., & Peck, C. (2008). Anaerobic digestion of food waste.East Bay Municipal Utility District Report.

Green, A., Ed. (2002). Life Cycle Impact Assessment: Striving towards Best Practice. United States, Society of Environmental Toxicology and Chemistry (SETAC).

Griffin, M., Sobal, J., & Lyson, T. A. (2009). An analysis of a community food waste stream. Agriculture and Human Values, 26(1-2), 67-81.

Guinee, J., Ed. (2002). Handbook on Life Cycle Assessment-operational Guide to the ISO Standards (Vol 7), Netherlands: Kluwer Academic Publisher.

Hansen, T. L., Christensen, T. H., & Schmidt, S. (2006). Environmental modelling of use of treated organic waste on agricultural land: a comparison of existing models for life cycle assessment of waste systems. *Waste management & research*, 24(2): 141-152.

Hauschild, M., & Potting, J. (2005). Spatial differentiation in Life Cycle impact assessment-The EDIP2003 methodology. Environmental news, (80).

Herold, A. (2003). Comparison of CO2 emission factors for fuels used in Greenhouse Gas Inventories and consequences for monitoring and reporting under the EC emissions trading scheme. ETC/ACC technical paper, 10, 2003.

Hogg, D., Barth, J., Favoino, E., Centermoero, M., Caimi, V., Amlinfer, F., ... & Antler, S. (2002). Comparison of compost standards within the EU. Review of Compost Standards in Ireland, Oxon.

Homedes, N. (1996). The disability-adjusted life year (DALY) definition, measurement and potential use. World Bank.

Hoornweg, D., & Thomas, L. (1999). What a waste: solid waste management in Asia. The World Bank.

IPCC. (2006). IPCC guidelines for national greenhouse gas inventories. IPCC WGI Technical Support Unit.

ISO (1997). Environmental Management-Life Cycle Assessment-Principles and Framework (ISO 140040:1997). International Standard Organization, Geneva.

ISO (1998). Environmental management- Life Cycle Assessment- Goal and Scope Definition and Inventory Analysis (ISO:14041), International Standards Organization, Geneva.

ISO (2000a). Environmental Management- Life Cycle Assessment- Life Cycle Impact Assessment (ISO14042:2000), International Standards Organization, Geneva.

ISO (2000b). Environmental Management- Life Cycle Assessment- Life Cycle Intrepretation (ISO 14043:2000), International Standards Organization, Geneva.

ISO (2006). Environmental Management-Life Cycle Assessment-Principles and Framework (ISO 140040:1997). International Standard Organization, Geneva.

Jambeck, J., Weitz, K., Solo-Gabriele, H., Townsend, T., & Thorneloe, S. (2007). CCA-treated wood disposed in landfills and life-cycle trade-offs with waste-to-energy and MSW landfill disposal. *Waste Management*, 27(8): S21-S28.

La Cour Jansen, J., Spliid, H., Hansen, T. L., Svärd, Å., & Christensen, T. H. (2004). Assessment of sampling and chemical analysis of source-separated organic household waste. *Waste Management*, 24(6): 541-549.

Jasim, S. (2003). The practicability of home composting for the management of biodegradable domestic solid waste (Doctoral dissertation, Imperial College London (University of London)).

JICA (2006). The Study on National Waste Minimization in Malaysia. Malaysia, Ministry of Housing and Local Government Malaysia.

JPSPN (2013). Survey on Solid Waste Composition, Characteristics & Existing Practice of Solid Waste Recycling in Malaysia. Putrajaya, Kementerian Kesejahteraan Bandar, Perumahan dan Kerajaan Tempatan.

Kaseva, M. E., & Gupta, S. K. (1996). Recycling—an environmentally friendly and income generating activity towards sustainable solid waste management. Case study—Dar es Salaam City, Tanzania. *Resources, Conservation and Recycling*, 17(4), 299-309.

Kathirvale, S., Yunus, M. N. M., Sopian, K., & Samsuddin, A. H. (2004). Energy potential from municipal solid waste in Malaysia. *Renewable energy*,29(4), 559-567.

Khoo, H. H., Lim, T. Z., & Tan, R. B. (2010). Food waste conversion options in Singapore: environmental impacts based on an LCA perspective. *Science of the total environment*, 408(6): 1367-1373.

Khoo, H. H., Tan, L. L., & Tan, R. B. (2012). Projecting the environmental profile of Singapore's landfill activities: Comparisons of present and future scenarios based on LCA. *Waste management*, 32(5): 890-900.

Kirkeby, J. T., Birgisdottir, H., Hansen, T. L., Christensen, T. H., Bhander, G. S., & Hauschild, M. (2006). Environmental assessment of solid waste systems and technologies: EASEWASTE. *Waste Management & Research*,24(1): 3-15.

Kim, M. H., & Kim, J. W. (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.

Klang, A., Vikman, P. Å., & Brattebø, H. (2003). Sustainable management of demolition waste—an integrated model for the evaluation of environmental, economic and social aspects. *Resources, Conservation and Recycling*,38(4): 317-334.

Kowalewski, R., Lea, W. R., & Tittlebaum, M. E. (1999). Standardized data reporting methodology for long-term integrated municipal solid waste management- a case study. *Journal of solid waste technology and management*, 26(1): 26-35.

Lai, C. M., Ke, G. R., & Chung, M. Y. (2009). Potentials of food wastes for power generation and energy conservation in Taiwan. *Renewable Energy*,34(8): 1913-1915.

Lee, S. H., Choi, K. I., Osako, M., & Dong, J. I. (2007). Evaluation of environmental burdens caused by changes of food waste management systems in Seoul, Korea. *Science of the Total Environment*, 387(1): 42-53.

Levis, J. W., Barlaz, M. A., Themelis, N. J., & Ulloa, P. (2010). Assessment of the state of food waste treatment in the United States and Canada. *Waste Management*, 30(8): 1486-1494.

Liwarska-Bizukojc, E., & Ledakowicz, S. (2003). Stoichiometry of the aerobic biodegradation of the organic fraction of municipal solid waste (MSW). *Biodegradation*, 14(1): 51-56.

Lou, X. F., & Nair, J. (2009). The impact of landfilling and composting on greenhouse gas emissions–a review. *Bioresource technology*, 100(16): 3792-3798.

Lundie, S., & Peters, G. M. (2005). Life cycle assessment of food waste management options. *Journal of Cleaner Production*, 13(3): 275-286.

Machado, S. L., Carvalho, M. F., Gourc, J. P., Vilar, O. M., & do Nascimento, J. C. (2009). Methane generation in tropical landfills: Simplified methods and field results. *Waste Management*, 29(1): 153-161.

Martínez-Blanco, J., Colón, J., Gabarrell, X., Font, X., Sánchez, A., Artola, A., & Rieradevall, J. (2010). The use of life cycle assessment for the comparison of biowaste composting at home and full scale. *Waste Management*, 30(6): 983-994.

Mastellone, M. L., Brunner, P. H., & Arena, U. (2009). Scenarios of waste management for a waste emergency area. *Journal of Industrial Ecology*,13(5): 735-757.

Matthews, E., & Themelis, N. J. (2007, October). Potential for reducing global methane emissions from landfills, 2000-2030. In Proceedings of International Landfill Symposium, Sardinia, Italy.

Maystre, L. Y., & Viret, F. (1995). A goal-oriented characterization of urban waste. *Waste management & research*, 13(3): 207-218.

Mbuligwe, S. E. (2002). Institutional solid waste management practices in developing countries: a case study of three academic institutions in Tanzania. *Resources, Conservation and Recycling*, 35(3): 131-146.

McDougall, F. R., White, P. R., Franke, M., & Hindle, P. (2008). Integrated solid waste management: a life cycle inventory. John Wiley & Sons.

Merrild, H., Larsen, A. W., & Christensen, T. H. (2012). Assessing recycling versus incineration of key materials in municipal waste: the importance of efficient energy recovery and transport distances. *Waste management*,32(5): 1009-1018.

MHLG (2005). National Strategic Plan for Solid Waste Management. Local Government Department, Local Government Department, Ministry of Housing and Local Government Malaysia.

Mohamed, A. R., & Lee, K. T. (2006). Energy for sustainable development in Malaysia: Energy policy and alternative energy. *Energy policy*, 34(15): 2388-2397.

Mohareb, A. K., Warith, M. A., & Diaz, R. (2008). Modelling greenhouse gas emissions for municipal solid waste management strategies in Ottawa, Ontario, Canada. *Resources, Conservation and Recycling*, 52(11): 1241-1251.

NC2 (2011). Malaysia's Second National Communication submitted to the United Nations Framework Convention on Climate Change, Ministry of Natural Resources and Environment Malaysia.

Ng, C. G., & Yusoff, S. (2015). Life Cycle Inventory of Institutional Medium-scaled Co-composting of Food Waste and Yard Waste in Tropical Country.*Sains Malaysiana*, 44(4): 517-527.

Nordtest (1995). Solid waste, municipal: sampling and characterization. Nordtest Method NT ENVIR 001, Nordtest, Espoo, FInland.

NSWMD (2012, 15/4/2012). "National Solid Waste Management Policy." Retrieved 7/12/2012, 2012, from http://www.kpkt.gov.my/jpspn_en/main.php?Content=vertsections&SubVertSectionID=29&VertSectionID=1&CurLocation=4&IID=.

NSWMD (2012(a), 15/4/2012). "National Solid Waste Management Policy." Retrieved 7/12/2012, 2012, from http://www.kpkt.gov.my/jpspn_en/main.php?Content=vertsections&SubVertSectionID=29&VertSectionID=1&CurLocation=4&IID=.

NSWMD (2012(b), 1/10/2012). "Summary of Disposal Sites Projects." Retrieved 10/12/2012, 2012, from http://www.kpkt.gov.my/jpspn/main.php?Content=articles&ArticleID=65&IID=.

Obersteiner, G., Binner, E., Mostbauer, P., & Salhofer, S. (2007). Landfill modelling in LCA–a contribution based on empirical data. *Waste management*, 27(8): 58-74.

Oh, T. H., Pang, S. Y., & Chua, S. C. (2010). Energy policy and alternative energy in Malaysia: issues and challenges for sustainable growth.*Renewable and Sustainable Energy Reviews*, 14(4): 1241-1252.

Omran, A., Mahmood, A., & Aziz, H. A. (2007). CURRENT PRACTICE OF SOLID WASTE MANAGEMENT IN MALAYSIA AND ITS DISPOSAL.*Environmental Engineering & Management Journal* (EEMJ), 6(4): 295-300.

Onn, C. C., & Yusoff, S. (2010). The formulation of life cycle impact assessment framework for Malaysia using Eco-indicator. *The International Journal of Life Cycle Assessment*, 15(9): 985-993.

Oonk, H. (2010). Literature Review: Methane From Landfills Methods To Quantify Generation, Oxidation, and Emission. Innovations in Environmental Technology.

Pane, C., Palese, A. M., Celano, G., & Zaccardelli, M. (2014). Effects of compost tea treatments on productivity of lettuce and kohlrabi systems under organic cropping management. *Italian Journal of Agronomy*, *9*(3), 153-156.

Papadopoulos, A. E., Stylianou, M. A., Michalopoulos, C. P., Moustakas, K. G., Hapeshis, K. M., Vogiatzidaki, E. E. I., & Loizidou, M. D. (2009). Performance of a new household composter during in-home testing. *Waste Management*, 29(1): 204-213.

Papageorgiou, A., Barton, J. R., & Karagiannidis, A. (2009). Assessment of the greenhouse effect impact of technologies used for energy recovery from municipal waste: a case for England. *Journal of environmental management*,90(10): 2999-3012.

PE-Research (2008). The cost of solid waste management and public cleansing in Peninsular Malaysia: Current experience of 3 local authorities, Department of National Solid Waste Management/DANIDA Environmental Planning and Strategy Component 2008.

PEMANDU (2012). Chapter 5: Developing Greater Kuala Lumpur/Klang Valley as an Engine of Economic Growth. Economic Transformation Program: A Roadmap for Malaysia. Putrajaya, Ministry of Prime Minister, Malaysia.

PerkinElmer (2012). "Technologies for Mass Spectrometry." from http://www.perkinelmer.com/default.xhtml.

Powell, J. (2000). The potential for using life cycle inventory analysis in local authority waste management decision making. *Journal of Environmental Planning and Management*, 43(3): 351-367.

PPSPPA (2012). Annual Report of 2011. Putrajaya, Malaysia Ministry of Housing and Local Government.

Raheman, H., & Phadatare, A. G. (2004). Diesel engine emissions and performance from blends of karanja methyl ester and diesel. *Biomass and Bioenergy*, 27(4): 393-397.

Riber, C., Rodushkin, I., Spliid, H., & Christensen, T. H. (2007). Method for fractional solid-waste sampling and chemical analysis. *International Journal of Environmental and Analytical Chemistry*, 87(5): 321-335.

Saeed, M. O., Hassan, M. N., & Mujeebu, M. A. (2009). Assessment of municipal solid waste generation and recyclable materials potential in Kuala Lumpur, Malaysia. *Waste management*, 29(7): 2209-2213.

Saer, A., Lansing, S., Davitt, N. H., & Graves, R. E. (2013). Life cycle assessment of a food waste composting system: environmental impact hotspots. *Journal of Cleaner Production*, 52: 234-244.

Sakawi, Z. (2011). Municipal solid waste management in Malaysia: solution for sustainable waste management. *Journal of Applied Sciences in Environmental Sanitation*, 6(1): 29-38.

Samsudin, M. D. M., & Don, M. M. (2013). Municipal solid waste management in Malaysia: current practices, challenges and prospects.*Jurnal Teknologi*, 62(1).

Scheutz, C., Kjeldsen, P., & Gentil, E. (2009). Greenhouse gases, radiative forcing, global warming potential and waste management—an introduction.*Waste Management & Research*, 27(8): 716-723.

Schmidt, J. H., Holm, P., Merrild, A., & Christensen, P. (2007). Life cycle assessment of the waste hierarchy–A Danish case study on waste paper.*Waste Management*, 27(11): 1519-1530.

Seo, S., Aramaki, T., Hwang, Y., & Hanaki, K. (2004). Environmental impact of solid waste treatment methods in Korea. *Journal of Environmental Engineering*, 130(1): 81-89.

Slagstad, H., & Brattebø, H. (2012). LCA for household waste management when planning a new urban settlement. *Waste management*, 32(7): 1482-1490.

Soumare, M., Tack, F. M. G., & Verloo, M. G. (2003). Effects of a municipal solid waste compost and mineral fertilization on plant growth in two tropical agricultural soils of Mali. *Bioresource technology*, *86*(1), 15-20.

Taib, S., & Nakagoshi, N. (2012). Climate Benefit of Recovering Biodegradable Municipal Solid Waste: A Case Study in Kuala Lumpur, Malaysia. *Environmental Research Journal*, 6(1): 32-38.

Tanskanen, J. H. (2000). Strategic planning of municipal solid waste management. *Resources, conservation and recycling*, 30(2): 111-133.

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

Themelis, N. J., & Ulloa, P. A. (2007). Methane generation in landfills.*Renewable Energy*, 32(7): 1243-1257.

Thorneloe, S. A., Weitz, K., & Jambeck, J. (2007). Application of the US decision support tool for materials and waste management. *Waste Managemen*t, 27(8): 1006-1020.

Tonkin and Taylor (2007). Bukit Tagar Landfill. KUB-Berjaya Enviro Sdn Bhd. MHLG. Kuala Lumpur. PT158.11.06.07.

UM (2011). "The University of Malaya official website." Retrieved 14 November 2011, from www.um.edu.my.

UM (2012). Final report of zero trash campaign in University of Malaya in yer 2012. University of Malaya, Kuala Lumpur.

UNEP (2000). Technical guidlines on waste collected from households. Basel convention on the control of transboundary movements on hazardous wastes and their disposal. B. C. s. S. N. 02/08, Secretariat of the Basel Convention.

UNEP (2010). Waste and Climate Change: Global trends and strategy framework.

UNFCCC (2008). Approved baseline and monitoring methodology AM0025 "Avoided emissions from organic waste through alternative waste treatment processes". AM0025/Version 11 Sectoral Scope: 01 and 13 EB 44. 28 November 2008.

USEPA (2006). Solid waste management and greenhouse gases- A life-cycle assessment of emissions and sinks.

Vesilind, P. A., Worrell, W. A., & Reinhart, D. R. (2002). Solid waste engineering. Brooks/Cole Publishing Company.

Villanueva, A., & Wenzel, H. (2007). Paper waste–recycling, incineration or landfilling? A review of existing life cycle assessments. *Waste manageme*nt,27(8): 29-46.

Wangyao, K., Yamada, M., Endo, K., Ishigaki, T., Naruoka, T., Towprayoon, S., ... & Sutthasil, N. (2010). Methane generation rate constant in tropical landfill. *Journal of Sustainable Energy & Environment*, 1(4).

Weitz, K. A., Thorneloe, S. A., Nishtala, S. R., Yarkosky, S., & Zannes, M. (2002). The impact of municipal solid waste management on greenhouse gas emissions in the United States. *Journal of the Air & Waste Management Association*, 52(9): 1000-1011.

White, P., Dranke, M., & Hindle, P. (2012). Integrated solid waste management: a lifecycle inventory. Springer Science & Business Media.

Whittle, A. J., & Dyson, A. J. (2002). The fate of heavy metals in green waste composting. *Environmentalist*, 22(1): 13-21.

Winkler, J., & Bilitewski, B. (2007). Comparative evaluation of life cycle assessment models for solid waste management. *Waste management*,27(8): 1021-1031.

Yahaya, N., & Larsen, I. (2008). Federalising solid waste management in peninsular Malaysia. In Proceeding of International Solid Waste Association (ISWA) World Congress, Singapore.

Zamri, M. (2011). Taman Beringin Transfer Station. Site visit to Taman Beringin Transfer Station.

Zhang, N., Williams, I. D., Kemp, S., & Smith, N. F. (2011). Greening academia: Developing sustainable waste management at Higher Education Institutions. *Waste management*, 31(7): 1606-1616.