This article should be referenced as: Vilaysouk, X., & Babel, S. (2017). Benefits of improved municipal solid waste management on greenhouse gas reduction in Luangprabang, Laos. Environmental Technology, 1-9. doi:10.1080/09593330.2017.1301562 (http://www.tandfonline.com/doi/abs/10.1080/09593330.2017.1301562)

Benefits of Improved Municipal Solid Waste Management on Greenhouse gas Reduction in Luangprabang, Laos

Xaysackda Vilaysouk and Sandhya Babel*

School of Biochemical Engineering and Technology, Sirindhorn International Institute of Technology (SIIT), Thammasat University, Pathum Thani, Thailand

*Corresponding author. Tel: +66 2986 9103 Ext. 2307, Fax: +66 2986 9103 Ext. 2301; Post Address: School of Biochemical Engineering and Technology, Sirindhorn International Institute of Technology, Thammasat University, PO Box 22, Pathum Thani 12121, THAILAND; E-mail: sandhya@siit.tu.ac.th

Accepted Manuscript

Abstract:

Climate change is a consequence of greenhouse gas emissions. The International Panel on Climate Change (IPCC) reported that in 2010, greenhouse gas emissions from the waste sector contribute to 3% of total anthropogenic greenhouse gas emissions. In this study, applicable solutions for municipal solid waste management in Luangprabang, Laos were examined. Material flow analysis of municipal solid waste in Luangprabang was performed to estimate the amount of municipal solid waste generated in 2015. Approximately 29,419 tonnes of municipal solid waste is estimated for 2015. Unmanaged landfilling was the main disposal method, while municipal solid waste open burning was also practiced to some extent. The IPCC 2006 model and the Atmospheric Brown Clouds Emission Inventory Manual (ABC EIM) were used to estimate greenhouse gas emissions from existing municipal solid waste management, and total emissions are 33,889 tonnes/year CO_2-eq. Three scenarios were developed in order to reduce greenhouse gas emissions and environmental problems. Improvement of the municipal solid waste management by expanding municipal solid waste collection services, introducing composting and recycling, and avoiding open burning, can be considered as solutions to overcome the problems for Luangprabang. The lowest greenhouse gas emissions are achieved in the scenario where composting and recycling are proposed, with the total greenhouse gas emissions reduction by 18,264 tonnes/year CO_2-eq. Moreover, results of the study indicate that recycling could also help in reducing the CO_2 emissions and the energy used in production process of virgin materials if the recyclable materials are used instead.

Keywords: greenhouse gas emissions, landfill, open burning, IPCC, ABC EIM

Introduction

Municipal solid waste (MSW) is normally referred to as waste collected and disposed of by local authorities generated from households, commercial places, community facilities, and offices. MSW management is a complex activity that includes controlling MSW generation rate, handling and storage, collection and transportation, treatment processes, and final disposal [1]. The amount of MSW has increased dramatically in accordance with economic and population growth. The higher the economic development and density of urban population, the higher waste generation rate is [2].

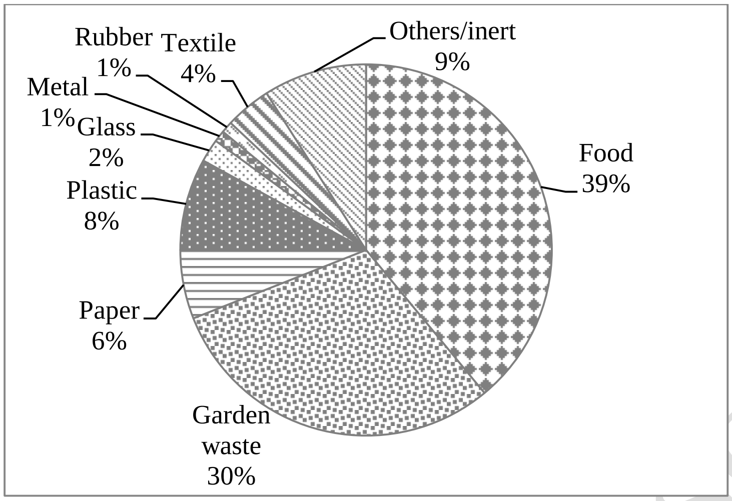
In the least developed and developing countries, MSW landfilling is commonly practiced, as it is cheap and requires less professional skills in operation [2]. MSW open burning is a basic disposal method where MSW collection is unavailable. Recently, global warming is a major concern throughout the world [3]. IPCC [4] reported that GHG emissions from the waste sector contribute to 3% of total GHG globally, and typically, methane (CH4) from landfills is the largest source of GHG in the waste sector [5]. In developing countries, MSW utilization is not well performed due to a lack of budget and public participation [6]. The approach for MSW management keeps changing with time. Brunner and Rechberger [7] suggested the goals of modern waste management as: "to protect human health and environment, to conserve resources such as material, energy, and space, to treat waste before disposal".

In Luang Prabang (LPB), MSW management is at the infant stage. Waste separation and recycling are not commonly practiced. The numbers of studies on MSW management in Laos, especially in LPB, is limited. Thus, it is worth to conduct a study of the current practices of MSW management, and develop scenarios to provide an insight and suggest various options for handling with the increasing amount of waste in LPB. Material flow analysis (MFA) is performed to study the flows of waste in LPB. The appropriate scenarios are developed to reduce the GHG emissions and the environmental problems associated with the MSW management. The GHG and black carbon (BC) emissions are estimated using available models based on the current practices and characteristics of MSW in the case study.

Methodology

Material flow analysis (MFA) is a powerful tool that is commonly used in various sectors such as environmental and engineering management, industrial ecology, resource management, waste management, and socio-economic. MFA is a systematic tool used to assess flows and stocks of materials within a system defined in space and time [7]. The core concept behind MFA is the first law of thermodynamics on the conservation of matter, which states that "matter is neither created nor destroyed by any physical transformation (production or consumption) process" [8]. By using secondary data of MSW management from JICA [9], MFA is performed to estimate the amount of waste in different scenarios by balancing flows of waste in each process.

Three major GHG gases, CO_2, CH_4, and N_2O, and also BC were estimated in this study. The IPCC 2006 model was used for estimation of CH_4 and N_2O emissions from landfilling and composting. CO_2 emission from landfilling and composting are considered as a biogenic source [5]. Thus, it is neglected from landfill GHG emissions calculations. GHG emissions from open burning were estimated by using ABC EIM [10] to find CH_4, CO_2, and BC. In order to compare different gases, CH_4 and N_2O were converted to carbon dioxide-equivalents (CO_2-eq) using the latest global warming potential factors provided by IPCC [11].



Source: JICA [9]

Figure 1. MSW Composition in Luangprabang (dry weight basis)

Municipal Solid Waste Management in Luangprabang

Luangprabang (LPB) is located in the north of Laos with a total area of 16,875 km2. The total population of LPB municipality was 90,300 people in 2015 [12]. LPB is the centre of economics, education, and trading in northern Laos, and is also well known as one of the most popular destinations for travellers around the world since it was proclaimed as a world heritage city by the United Nations Educational, Scientific and Cultural Organization in 1995. In LPB, the World Heritage office is responsible for the protection of the city landscape as well as the environment, in collaboration with three local government organizations. MSW collection and disposal are handled by the Urban Development Administration Authority of LPB, and local private contractors. JICA reports the total amount of MSW generated in 2011 was 24,820 tonnes. The majority of MSW collected was disposed of in the unmanaged landfill (68% of total MSW). About 3% of MSW generated was recycled. Uncollected waste, which comes from uncovered areas of MSW collection services, was 29%, and the disposal method is unknown.

The MSW generation rate in LPB in 2011 was 0.654 kg/capita/day [9]. The composition of MSW was taken from the JICA report [9] and is similar to other cities in developing countries, consisting mostly of food and garden waste (69% of total MSW generated, see Figure 1). Interestingly, the amount of plastic, paper, and metal (especially packaging materials) presented in the total MSW generated is not influenced by tourism activities, as in other tourism cities. The majority of MSW generated were directly sent to dispose of in a landfill. The landfill has been in operation since 2000. It consists of 4 dumping cells and a simple natural leachate pond with no treatment of collected leachate. The landfill is operated without appropriate management.

IPCC 2006 Model for GHG estimation

The United Nations Framework Convention on Climate Change suggests the use of the IPCC model to

Accepted Manuscript

estimate and report GHG emissions from six major sectors, including the waste sector. IPCC provides three tiers for estimation of GHG emissions from landfills. In this study, based on the availability of the MSW data in the study area, Tier 1 was used. Equation (1) was modified from IPCC 2006 model Tier 1, and was used to estimate the CH_4 generated from the landfill.

$$CH_4 = [(MSW_{LF} \times MCF \times DOC \times DOC_f \times F \times (16/12) - R) \times (1 - OX)] \qquad (1)$$

Where, CH_4 is Methane Emission in Gg/year (1 Gg equal to 10^9 g), MSW_{LF} is total amount of MSW in the landfill (Gg/year), MCF is CH_4 correction factor, DOC is fraction of degradable organic carbon in MSW (Gg C/Gg MSW), DOC_f is the fraction of DOC that can decompose, F is the fraction of CH_4 in generated landfill gas, R is recovered CH_4 (Gg/year), 16/12 is the molecular weight ratio CH_4/C, and OX is the oxidation factor.

The IPCC classifies landfills into five categories as managed – anaerobic, managed – semi anaerobic, unmanaged – deep, unmanaged – shallow, and uncategorized. According to the landfill conditions in LPB, MCF = 0.6 was used in calculations. DOC is the organic carbon in MSW that is decayed by biochemical decomposition processes in landfills. DOC in MSW depends on the MSW composition and is different in each scenario. The actual DOC values on a wet basis were used in GHG emissions calculations. Characteristics of a landfill influence the DOC_f value. Generally, the suggested DOC_f value by IPCC ($DOC_f = 0.77$) is used when a landfill specific value is unavailable. F is 0.5 (default value provided by IPCC). There are no CH_4 collection and recovery systems installed. Thus, R is zero. OX is zero, which is the default value for uncategorized landfills.

Composting, both aerobic and anaerobic, is an effective way to remove biodegradable waste from a waste stream. In the IPCC [5] model, composting refers to aerobic processes that convert degradable organic carbon to CO_2, but CO_2 generated is considered as biogenic carbon. Thus in this study, only CH_4 and N_2O generated are considered as GHG emissions. IPCC [5] provides methods for calculating the CH_4 and N_2O emissions from the composting process using Equation 2.

$$EM = (M \times EF) \times 10^{-3} - R \qquad (2)$$

Where, EM is the GHG emissions from composting (Gg/year), M is the amount of MSW composted (Gg/year), EF is an emission factor (g/kg waste), and R is the amount of methane recovery (Gg/year).

Emissions generated during composting depend on many factors, such as composition of the waste, composition of supporting materials, temperature, moisture content, and aeration systems. IPCC provides default emission factors for CH_4 and N_2O emission estimation from composting. The values range between 0.03 – 8 g CH_4/kg waste, and 0.06 – 0.6 g N_2O/kg waste, for CH_4 and N_2O, respectively. In this study, EF_{CH_4} = 4 g CH_4/kg waste, and EF_{N_2O} = 0.3 g N_2O/kg waste, were used based on the default data provided by the IPCC 2006 model.

Accepted Manuscript

Atmospheric Brown Clouds Emission Inventory Manual (ABC EIM)

The ABC EIM was developed to provide a user-friendly inventory tool for both developed and developing countries for the estimation of atmospheric brown cloud emission, specifically focusing on Asian countries [10]. The ABC EIM was used for the calculation of CO_2, CH_4 emission, and BC from open burning in this study. The manual provides emission factors for Asian countries, which are more relevant for this study than the factors provided by IPCC. The GHG emissions were estimated by multiplying the open burning amount with emission factors using Equation 3.

$$EM_i = MSW_{OB} \times \delta \times \eta \times 365 \times EF_i \qquad (3)$$

where, EM_i is the emission of pollutant i (tonnes/year), MSW_{OB} is the amount of MSW open burned (Gg/day), δ is the fraction of combustible waste (fraction), η is the burning/oxidation efficiency (fraction), 365 (days/year), and EF_i is the emission factor (Table 1) of pollutant i (tonnes/Gg).

Table 1. Emission factors for MSW Open burning

Gases	Emission factors (tonnes/Gg)	Sources
CO_2	1,453	[10]
CH_4	6.5	[10]
BC*	5.5	[10]

* BC – Black carbon.

Scenario Development

In this study, three scenarios were developed to reduce the GHG emissions as well as to protect the environment. Decreasing waste disposed of in the landfill, introducing composting at source, and recycling, were included in the scenarios. The baseline scenario (S0) represents the current situation of MSW management, which includes unmanaged (uncategorized) landfilling and open burning. Scenario S1 attempts to expand MSW management collection services, and the increased amount of MSW from collection expansion is assumed to be disposed of in the existing unmanaged landfill. Composting is proposed in Scenario S2 to deal with biodegradable waste (food and garden waste). Both composting and recycling are introduced in Scenario S3, to reduce GHG emissions and to extend the lifespan of the landfill.

Results and Discussion

Material Flow Analysis of Municipal Solid Waste Management in Luangprabang

In order to perform MFA, variables and transfer coefficients are required. In this study, there are 7 variables, as shown in Table 3. These variables are calculated based on the MSW data of JICA and the

Accepted Manuscript

latest population data from the Lao Population and Housing Census 2015 (see Table 2). The total amount of waste is allocated to each household category. The waste generation rate in urban and sub-urban areas vary. Thus, waste generated from households is classified into 3 sources, households in urban areas having a waste collection contact (HHW1), households in urban areas that do not have a waste collection contact (HHW2), and households in suburban areas (HHW3). By using JICA's report, waste from other sectors accounts for approximately 29.41% of total waste generated, which is equal to 8,652 tonnes/year.

Table 2. Estimated waste from households in Luangprabang in 2015

Area	Generation Rate (kg/capita-day)*	Population**	Total Waste (tonnes/year)
Urban	0.569	62,307	12,940
HHW1	0.569	56,889	11,815
HHW2	0.569	5,417	1,125
Sub-urban (HHW3)	0.766	27,993	7,827
Total		90,300	20,767

Sources: * JICA [9], ** Lao Statistic Bureau [12]

For recycling, there are two sources, the on-site and off-site recycling. The on-site recycling is practiced at the households. JICA reported that in LPB, on-site recycling rate was 23 g/person/day in urban areas, and 9 g/person/day in suburban areas. Based on this information, total recycling waste is estimated. Total waste recycling from HHW1 is 478 tonnes/year (OnRC.1), and HHW2 is 137 tonnes/year (OnRC.2). Off-site recycling includes the recyclable waste collected by scavengers and sold at recycling shops. Total off-site recyclable waste is estimated to be 203 tonnes/year (OffRC.1). All input parameters are summarized in Table 3. The MFA of MSW in LPB is shown in Figure 2.

Table 3. Summary of MFA input parameters

Flows	Amount (tonne/year)	Description
HHW1	11,815	Household waste from urban areas, collected by municipality authority
HHW2	1,125	Household waste from urban areas, but not collected
HHW3	7,827	Household waste from suburban areas, not collected
Other	8,652	Waste from other sectors
OffRC.1	203	Recycled waste collected by workers and scavengers, received at recycling shop
OnRC.1	478	Recycled waste separated at households in HHW1
OnRC.2	137	Recycled waste separated at households in HHW2, HHW3

Accepted Manuscript

Scenario S0

This scenario represents the current situation of MSW management in LPB. Approximately 19,786 tonnes/year of waste are disposed of in the unmanaged landfill (Table 4). In the landfill, the waste is just disposed without proper engineering design. As a world heritage city, MSW management is an important agenda for LPB. Hence, the coverage rate of MSW collection services seems to be higher than other cities in Laos. The total amount of recycling in LPB, including on-site recycling and off-site recycling, is 818 tonnes/year. In many developing countries, due to lack of waste collection service or lack of dumping space, MSW is openly burned [13]. Open burning of waste is a significant source of toxic air including polychlorinated dibenzodioxins, dibenzofurans and biphenyls (PCDD/PCDF/PCB), volatile organic compound (VOC), polycyclic aromatic hydrocarbon (PAH) and non-PAH semi-volatile organic compound (SVOC) [14, 15], as well as other GHG such as CO_2, CH_4, NO_2 [5]. From the field observation, it can be seen that open burning is practiced in LPB in the areas where MSW collection services are not provided. Unfortunately, the amount of open burning in LPB was not reported, thus an assumption of open burning amount needs to be made. To accurately quantify the amount of open burning waste is a difficult task. There are a few studies that reported the amount of open burning waste. Damanhuri et al. [16] conducted a study of MSW flow in Bandung metropolitan area in Indonesia. The amount and fraction of MSW open burning in the study area are provided. Permadi and Kim Oanh [17] also performed the assessment of emissions and air pollutions from open burning of biomass, which including MSW open burning, in Indonesia. Even the assumptions were made in these studies to quantify the amount of open burning, but the methodology was not clearly explained. Taking into consideration the previous studies relevant to MSW open burning [13, 16, 17], the government regulations on environmental protection, along with the current situation of MSW management, the open burning amount for LPB was assumed to be 30% of uncollected waste, which is equal to 2,644 tonnes/year (9% of total MSW). The uncollected waste remaining in this scenario is 6,170 tonnes/year.

Accepted Manuscript

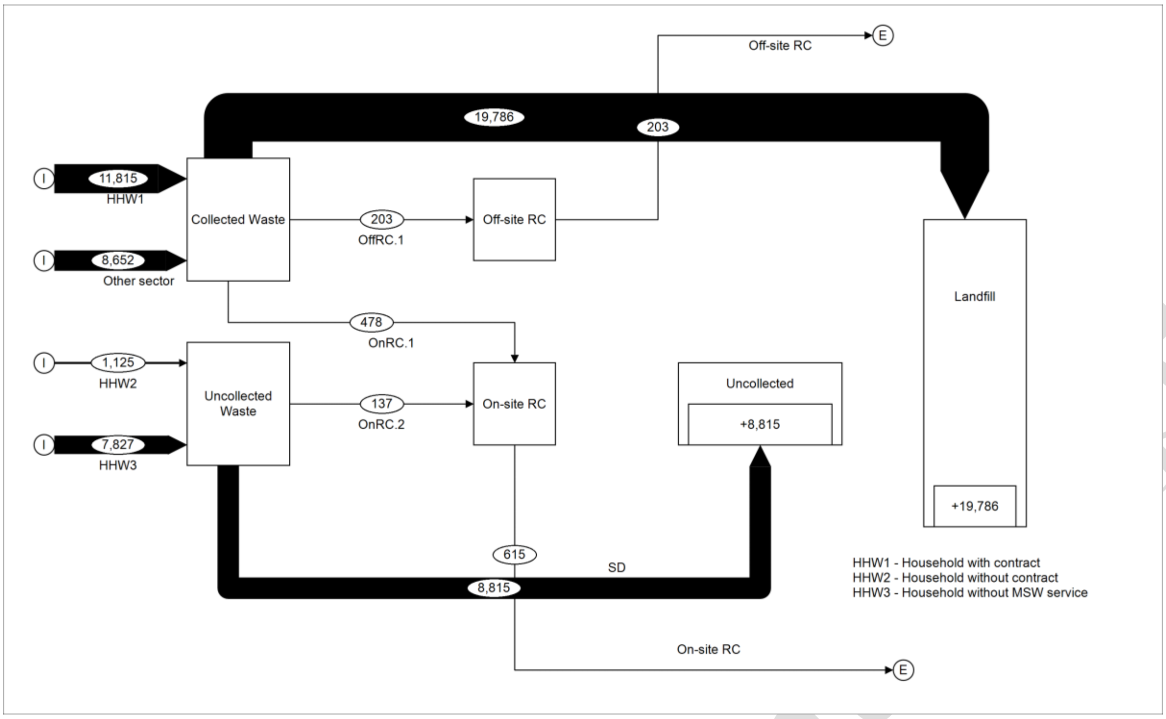


Figure 2. Material flow analysis of MSW in Luangprabang in 2015 (tonnes/year)

Table 4. Summary of MSW amount in scenario development (tonnes/year)

Scenario	MSW Management Methods					Un-CL	Total
	OB	CP	On-RC	Off-RC	LF		MSW
S0	2,644	-	615	203	19,786	6,170	29,419
S1	-	-	615	203	27,719	881	29,419
S2	-	13,075	615	203	14,644	881	29,419
S3	-	13,075	1,487	203	13,772	881	29,419

Remark: OB – open burning; CP – composting; On-RC – On-site recycling; Off-RC – Off-site recycling, LF – landfill; Un-CL – uncollected

Accepted Manuscript

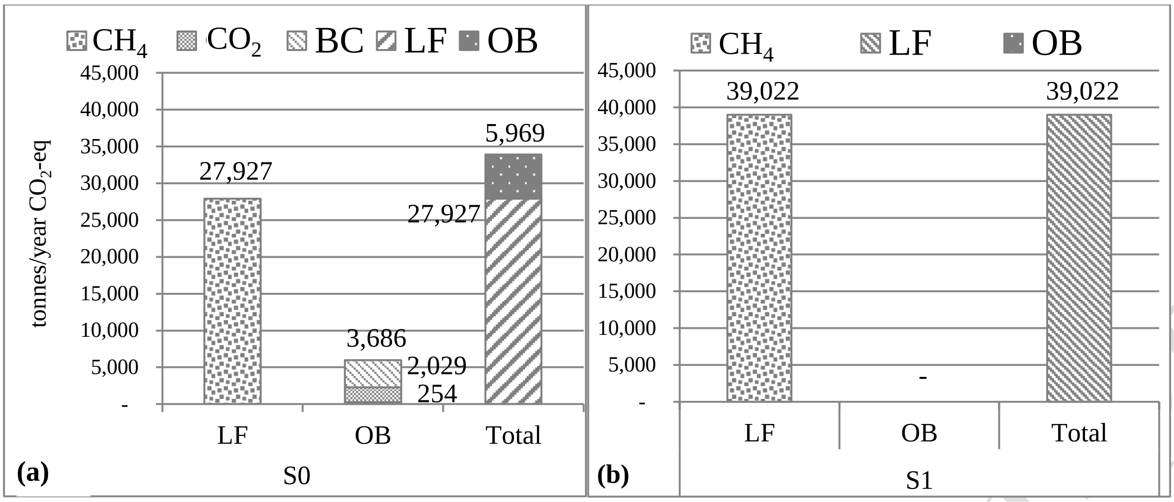


Figure 3 (a) Total GHG emissions in Scenario S0, (b) Total GHG emissions in Scenario S1 (tonnes/year CO_2-eq) (BC - Black Carbon, LF - Landfill, OB - Open burning)

According to the composition of MSW in LPB, which mostly consists of biodegradable materials, total CH_4 emission from the landfill is found to be 27,927 tonnes/year CO_2-eq, accounting for 82% of total GHG emissions in this scenario. For estimation of the CH_4 emission from landfilling using the IPCC [5]'s model, the composition of waste (which indicates DOC value) and classification of landfill type (MCF value), are important parameters that influence CH_4 emission. Dividing total GHG emissions with the total amount of MSW disposed in the landfill, CH_4 emission from landfilling in LPB per unit of waste is 0.050 Gg CH_4/ Gg MSW.

The total GHG emissions from open burning in LPB is 5,969 tonnes/year CO_2-eq. For GHG emissions from open burning, only CO_2 and CH_4 were taken into consideration. Some N_2O is generated from the burning process. The amount observed was marginal in this study, thus, was not considered. CO_2 is a major GHG from open burning in this study. Total CO_2 emission is 2,029 tonnes/year CO_2-eq, and the remaining 254 tonnes/year CO_2-eq is CH_4 (see Figure 3(a)). BC is also a major climate pollutant generated by open burning of MSW. Shrestha et al. [10] stated that atmospheric brown cloud emission, including BC, has reached a critical level. In addition, there has been a 6-fold increase in the BC in South Asia since 1930 [18]. Using the ABC EIM, BC emission from MSW open burning can be estimated. From the amount of open burning in this study, BC emission is 7.68 tonnes/year. By following Permadi and Kim Oanh [17]'s conversion approach, the amount of BC emission from open burning is estimated to be 3,686 tonnes/year CO_2-eq. Considering BC emission, on a CO_2-eq basis, to total GHG emissions from open burning in this study, BC is significantly higher than both CO_2 and CH_4. This indicates that BC is a significant pollutant from MSW open burning that should not be overlooked.

In a view of the total GHG emissions from this scenario, CH_4 emissions from the landfill is found to be the highest, compared to open burning. Disposal of MSW in landfills could reduce some environmental problems. It is better than illegally dumping waste in rivers or canals, open burning, and other improper disposal methods. Therefore, an expansion of MSW collection services is an appropriate option to reduce environmental problems that are caused by improper disposal of uncollected waste.

Accepted Manuscript

Scenario S1

This scenario aims to increase the MSW collection service and reduce MSW open burning. In this scenario, 90% of uncollected MSW is assumed to be collected, and diverted to be disposed of in the existing unmanaged landfill. The total amount of MSW disposed of in the landfill increases to 94% of total MSW generated (27,719 tonnes/year). Recycling accounts for the same amount as the baseline scenario (3%, including on-site and off-site recycling). The remaining MSW, which is uncollected in this scenario, is only 3% and is assumed to be illegal dumping (but not open burning). The amount diverted to landfill plays a significant role in increasing the amount of CH_4 emissions, as compared to the baseline scenario, but environmental problems related to improper disposal methods (including illegal dumping and open burning), can be reduced. GHG emissions from fuel consumption due to expansion of collection service, is not accounted for in this study.

The total GHG emissions estimated in this scenario is mainly based on the amount of waste disposed of in the landfill. CH_4 emission from landfilling in this scenario is 39,022 tonnes/year CO_2-eq (Figure 3(b)). The total GHG emissions in this scenario is increased by 15%, compared to the baseline scenario (Scenario S0). The main driving factor of the GHG increase in this scenario is due to an increase of biodegradable waste.

The type of landfill also plays an important role in CH_4 emission from a landfill. If the existing unmanaged landfill is upgraded to a sanitary landfill (Managed – anaerobic landfill, MCF=1), total GHG emissions are estimated as 65,036 tonnes/year CO_2-eq. This is almost 67% greater than the total GHG emissions from the existing unmanaged landfill. Though, the total amount of CH_4 generated from landfill upgrading may not be economically viable for power generation taking into consideration the amount generated [19]. Taking in to account the high global warming potential of CH_4 (28 times) over CO_2 in the 100 year-time horizon [11], CH_4 flaring could be considered as an alternative option, and is also recommended in the European Union guidelines for landfill gas control [20]. However, to change existing unmanaged landfill to a sanitary landfill, proper engineering design, availability of land at the appropriate location, and proper monitoring, is required. Total GHG emissions from this scenario is used as the reference value for comparison with the other developed scenarios.

Scenario S2

Regarding the environmental problems and the public health issues, landfilling is a short term solution. However, for the long term it is not an appropriate solution to deal with biodegradable waste due to the massive amount of CH_4 generated in a landfill, and also the limitation of landfill lifespan and land allocation. Consider the characteristics of MSW in LPB, MSW utilization, such as for composting, could be a better option to deal with the biodegradable materials. Composting is the biochemical process that is commonly used in countries where biodegradable material is a major component of total MSW generated [21]. Taking into consideration the composition of MSW in LPB, as the food and garden waste accounts for 69% of total MSW generated, composting could play an important role in reducing the waste disposed of in the landfill. In this scenario, composting is proposed. Currently, composting in LPB is in the initial state. The JICA pilot project has started off-site composting at the landfill.

Accepted Manuscript

Biodegradable waste is collected from restaurants and hotels in downtown areas but the amount of waste being composted is not reported. By keeping the expansion of MSW collection services as in Scenario S1, assuming that 50% of total biodegradable waste from collected MSW is diverted to composting, the amount of waste treated by composting accounts for 13,075 tonnes/year (44% of total MSW, see Table 4). By introducing the composting technique, the amount of MSW disposed of in the landfill is reduced dramatically, compared to Scenario S1. The total amount of MSW disposed of in the landfill for this scenario is 14,644 tonnes/year (50% of total MSW). The remaining amount of uncollected waste is 3% (881 tonnes/year), compared to 21% as in Scenario S0.

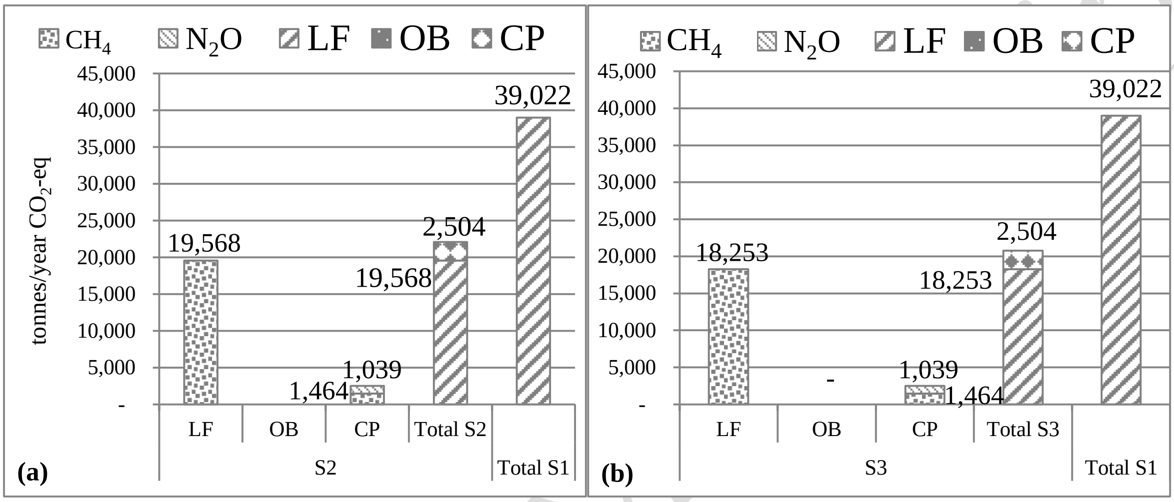
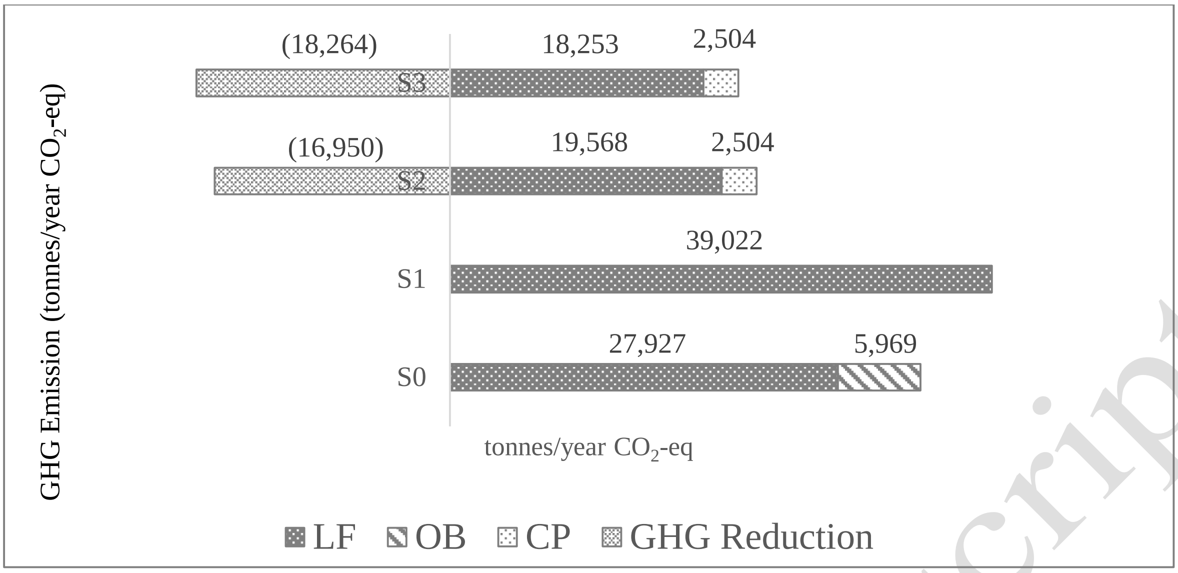


Figure 4 (a) Total GHG emissions in Scenario S2, (b) Total GHG emissions in Scenario S3 (tonnes/year CO_2-eq) (LF - Landfill, OB - Open burning, CP – Composting)

Figure 4(a) shows the total GHG emissions from this scenario. The reduction of GHG emissions from landfilling is due to the diversion of biodegradable waste to composting. CH_4 emissions from landfilling in this scenario is only 19,568 tonnes/year CO_2-eq, which is approximately 50% reduced, compared to Scenario S1. However, CO_2, CH_4, and N_2O are generated during composting. CO_2 is not accounted for as GHG emissions, as it is considered to be from a biogenic source. From the total amount of waste treated by composting, total GHG emissions (CH_4 and N_2O) of 2,504 tonnes/year CO_2-eq are generated, which accounts for only 11% of total emissions in this scenario. From the results of GHG emissions, composting can be considered a suitable solution to deal with the biodegradable waste. Overall, diverting the waste from the landfill to composting could reduce total GHG emissions by 16,950 tonnes/year CO_2-eq (43% reduction), when compared to Scenario S1 (see Figure 5).

Accepted Manuscript



Note: GHG emissions reduction is compared to total GHG emissions of Scenario S1

Figure 5. Summary of GHG emissions in developed scenarios and GHG reduction (tonnes/year CO_2-eq) (LF - Landfill, OB - Open burning, CP – Composting)

Scenario S3

Recycling reduces the amount of raw materials consumption and energy used in production, as well as prevents waste generated from consumer activities. At present, the recycling rate in LPB accounts for only 3% of the total MSW generated, which is equal to only 10% of the total recyclable waste. Only a small amount of waste is being recycled, with little benefit. Recycling also extends the lifespan of landfills and reduces the toxicity from open burning of waste. By strong participation of LPB residents, a recycling campaign could be introduced to decrease the amount of waste going to the landfill. A combination of composting and recycling, are proposed in this scenario. The amounts for each option are presented in Table 4. An increased amount of recycling in this scenario is assumed by increasing the recycling rate at the household level. It is assumed that the recycling rate is increased to 60% of total recyclable waste (packaging materials, including paper, plastic, glass, and metal). The total amount of recycling in this scenario is assumed to be 1,690 tonnes/year. Thus, the total fraction of recycling in this scenario is increased to 6% of the total MSW generated.

Integration of recycling and composting slightly contributes to GHG reduction for MSW management in LPB. The total GHG emissions in this scenario is 20,757 tonnes/year CO_2-eq. The total amount of GHG reduction is 18,264 tonnes/year CO_2-eq, which is reduced by 47%, compared to unmanaged landfill scenario (Scenario S1, see Figure 5). By diverting the amount of the paper disposed of in the landfill to recycling, an additional GHG reduction is observed, as shown in the reduction of GHG emissions from landfill in Figure 4(b), as the DOC value for the paper is higher compared to other wastes (DOC_{paper} = 0.4). For other recyclable materials such as plastic, glass, and metal, if considering GHG reduction in the perspective of Life Cycle Analysis, this might help in the reduction of GHG emissions.

To quantify GHG emissions reduction and energy savings due to recycling of materials instead of using virgin materials, a simple calculation, referring to saving factors provided by

Accepted Manuscript

Lino and Ismail [22], is performed. The amount of each recyclable waste in this scenario is multiplied by these factors to give the total amount of CO_2 and energy savings. A total amount of 3,918 tonnes CO_2 emission and 67,978 GJ/year of energy use, could be saved if a total of 1,215 tonnes/year of recyclable materials (paper, plastic, glass, and metal) would be used instead of virgin materials. Plastic is worth recycling followed by paper, with a contribution of 12,709 GJ/year and 1,207 tonnes CO_2 savings (see Table 5).

Comparisons of GHG emissions in the developed scenarios

Figure 5 shows the comparison of the total GHG emissions and GHG reduction from all scenarios. Scenario S0 represents the current practice of MSW management in LPB. Total GHG emissions in this scenario is 33,896 tonnes/year CO_2-eq, which is mainly from the landfill. The highest GHG emissions is recognised in scenario S1, where approximately 90% of total MSW generated is assumed to be disposed of in the existing landfill. The total GHG emissions from this scenario (S1) is used as the reference value for comparison among other developed scenarios. In scenario S2, where the composting was introduced for dealing with the biodegradable waste, the GHG emissions is reduced to be 22,072 tonnes/year CO_2-eq. In scenario S3, by assuming that 50% organic waste was treated by composting and the recycling rate at household is 6% of total MSW generated, the total GHG emissions in this scenario is reduced to be 20,757 tonnes/year CO_2-eq. Considering the reduction of GHG emissions and the appropriate integration of MSW management options, scenario S3 could be considered as the best scenario for MSW management in LPB.

Table 5. Energy and CO_2 emission savings from recycling

Waste Component	Amount (tonnes/year)	Saved energy factor (GJ/tonne)*	Avoided CO_2 emission factor (tonnes CO_2/ tonne waste)*	Total saved energy (GJ/year)	Total avoided CO_2 (tonnes CO_2/year)
Paper	398	31.9	3.03	12,709	1,207
Plastic	622	86.1	4.1	53,591	2,552
Glass	115	2.5	0.089	289	10
Metal	79	17.6	1.88	1,389	148
Total	1,215			67,978	3,918

Sources: * Lino and Ismail [22]

Conclusions

MSW management is a challenge for developing countries. In LPB, the unmanaged landfill is the primary disposal method, and open burning is also practised in some areas. Based on the current practices, the total GHG emissions of 33,896 tonnes/year CO_2-eq was generated. Expansion of MSW collection services and upgrading the existing landfill to sanitary landfill could be considered as an option, but this will lead to increased GHG emissions as the amount of methane generated is not enough to generate electricity. A combination of composting and

Accepted Manuscript

recycling (scenario S3) could be considered as the best practice for the MSW management in LPB. This could result in the reduction of the total GHG emissions by 18,264 tonnes/year CO_2-eq.Regarding the substitution of virgin materials by recyclable materials, this can reduce GHG emissions and energy used in the production process. Even various alternative options for MSW management in LPB, and GHG emissions from each option could be examined, though there are some limitations and uncertainties in the study due to the availability of the data. The higher Tier of GHG estimation model could be employed to reduce the uncertainty of the results if the enough data is available.

References

[1] S.T. Tan, C.T. Lee, H. Hashim, W.S. Ho, J.S. Lim. Optimal process network for municipal solid waste management in Iskandar Malaysia. Journal of Cleaner Production. 2014;71:48-58.

[2] U.N. Ngoc, H. Schnitzer. Sustainable solutions for solid waste management in Southeast Asian countries. Waste Management. 2009;29:1982-95.

[3] S. Kumar, S.A. Gaikwad, A.V. Shekdar, P.S. Kshirsagar, R.N. Singh. Estimation method for national methane emission from solid waste landfills. Atmospheric Environment. 2004;38:3481-7.

[4] IPCC. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edenhofer O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, J.C.Minx, editors. Cambridge, United Kingdom: Cambridge University Press; 2014.

[5] IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. Eggleston H.S., Buendia L., Miwa K., Ngara T., Tanabe K., editors. IGES, Japan: the National Greenhouse Gas Inventories Programme; 2006.

[6] N. Stanisavljevic, P.H. Brunner. Combination of material flow analysis and substance flow analysis: A powerful approach for decision support in waste management. Waste Management & Research. 2014;32:733-44.

[7] P.H. Brunner, H. Rechberger. Practical Handbook of Material Flow Analysis: CRC Press; 2003.

[8] Eurostat. Economy-wide Material Flow Accounts and derived indicators: A methodological guide 2001.

[9] JICA. Laos Pilot Program for Narrowing the Development Gap toward ASEAN Integration, Progress Report 1: Supplement 2 (Luangprabang). Vientiane, Laos2012.

[10] R.M. Shrestha, N.T. Kim Oanh, R.P. Shrestha, M. Rupakheti, S. Rajbhandari, D.A. Permadi, T. Kanabkaew, M. Iyngararasan. Atmospheric Brown Clouds (ABC) Emission Inventory Manual. United Nations Environment Programme, Nairobi, Kenya2013.

[11] IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, Pachauri RK, Meyer LA, editors. Geneva, Switzerland2014.

Accepted Manuscript

[12] Lao Statistics Bureau. Lao Population and Housing Census 2015: Provisional Report. Vientiane, Lao PDR: Lao Statistics Bureau; 2015.

[13] T. Karak, R.M. Bhagat, P. Bhattacharyya. Municipal Solid Waste Generation, Composition, and Management: The World Scenario. Critical Reviews in Environmental Science and Technology. 2011;42:1509-630.

[14] G. Solorzano-Ochoa, D.A. de la Rosa, P. Maiz-Larralde, B.K. Gullett, D.G. Tabor, A. Touati, B. Wyrzykowska-Ceradini, H. Fiedler, T. Abel, W.F. Carroll Jr. Open burning of household waste: Effect of experimental condition on combustion quality and emission of PCDD, PCDF and PCB. Chemosphere. 2012;87:1003-8.

[15] P.M. Lemieux, C.C. Lutes, D.A. Santoianni. Emissions of organic air toxics from open burning: a comprehensive review. Progress in Energy and Combustion Science. 2004;30:1-32.

[16] E. Damanhuri, I.M. Wahyu, R. Ramang, T. Padmi. Evaluation of municipal solid waste flow in the Bandung metropolitan area, Indonesia. J Mater Cycles Waste Manag. 2009;11:270-6.

[17] D.A. Permadi, N.T. Kim Oanh. Assessment of biomass open burning emissions in Indonesia and potential climate forcing impact. Atmospheric Environment. 2013;78:250-8.

[18] V. Ramanathan, C. Chung, D. Kim, T. Bettge, L. Buja, J.T. Kiehl, W.M. Washington, Q. Fu, D.R. Sikka, M. Wild. Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle. Proceedings of the National Academy of Sciences of the United States of America. 2005;102:5326-33.

[19] Z.Z. Noor, R.O. Yusuf, A.H. Abba, M.A. Abu Hassan, M.F. Mohd Din. An overview for energy recovery from municipal solid wastes (MSW) in Malaysia scenario. Renewable and Sustainable Energy Reviews. 2013;20:378-84.

[20] European Union. Landfill Gas Control - Guidance on the landfill gas control requirements of the Landfill Directive. 2014.

[21] A.M. Troschinetz, J.R. Mihelcic. Sustainable recycling of municipal solid waste in developing countries. Waste Management. 2009;29:915-23.

[22] F.A.M. Lino, K.A.R. Ismail. Analysis of the potential of municipal solid waste in Brazil. Environmental Development. 2012;4:105-13.

Accepted Manuscript