Evaluation of Household Solid Waste Treatment Alternatives toward GHG Mitigation in Vietnam
ベトナムにおける温室効果ガス削減に向けた家庭系廃棄物の処理手法に関する評価

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ABSTRACT

Rapid urbanization, economic growth, and changing life style have led to a drastic increase in the amount and the variety of municipal solid waste (MSW) in Vietnam. . Household solid waste (HSW) has become a major challenge for waste management authorities in urban areas of developing countries. The total amount of collected municipal solid waste in Vietnam was estimated to be 15.6 million tons as of 2015, of which 71.1% (11.1 million tons) was directly landfilled, and the total solid waste generated in 2020 and 2025 are expected to be approximately 67.6 million tons, and 91 million tons, respectively. To establish sustainable society, the central government and local government in Vietnam have established various kinds of laws and regulations. According to the national strategy to manage waste and discarded material (Decree no. 38/2015/NĐ-CP) issued by Vietnamese central government in 2015, the daily-life solid waste must be sorted and collected separately by three categories: biodegradable organic, reusable and recycled, and other.

To develop a rational strategy of waste management toward sustainable society, it is important to understand the amount of waste generation, the waste composition, the waste stream, and the contribution by each source. However, the reliable data on MSW in Vietnam are limited and not comparable; because of the main categories of waste classification are variety between municipal, region levels and national levels. Some past literatures examined the waste generation from HSW by detailed categories and estimated the total waste amount; but the waste generation rates (WGRs) was described by mean and standard deviation, without mention about the distribution and reliability of data. In addition, waste treatment technologies such as incineration, composting, bio-gasification have been not applied successfully in Vietnam due to lack of technical attention, lack of feasibility study for local waste such as waste generation, characterization, waste practice at source. Implementation of waste separation at source is also a cause of ineffective treatment application. Therefore, the study on HSW characteristic with the influencing factors and the efficiency of waste treatment alternatives is meaningful for waste management authorities. The limited reliable data on HSW generation and characteristics has become a burden for decision makers in waste management. It is important to understand the amount of waste generated, the waste composition, and the waste treatment alternatives as the first step in developing an effective HSW strategy that includes 3R promotion (reduce, reuse, and recycle).

This dissertation focuses on (1) waste generation and characteristic from household in urban areas in Danang, the third largest city in Vietnam, (2) Greenhouse gas (GHG)

emissions and reduction of heat recovery technology in Japan, and (3) GHG emission and reduction of recycling technologies. The author presents the following issues: (i) HSW generation and composition in Danang (physical composition, basis composition, recovery potential by detailed composition, and energy content); (ii) Influence factors for HSW generation(iii) Estimation of total household solid waste generation and recycling potential; (iv) GHG emission and reduction heat recovery technology in Japan and modeling; (v) Scenario analyses on GHG mitigation alternatives by heat recovery and recycling; (vi) Interval estimation and uncertainty analysis of parameters.

First, to understand the characteristics of HSW, the author conducted surveys of 150 households in Danang, Vietnam in December 2016. The target samples were selected by consideration of socioeconomic factors, such as urbanization level, population density, family size and income level. Daily discharged waste from each target was collected and classified into ten physical categories and 66 sub-categories. The compositions of ten physical components were analyzed to identify the moisture content, volatile solid content, and ash content. Meanwhile, the heating values of these components were also examined at laboratory to estimate the energy content in HSW. The recycling and composting potentials were aggregated based on the detail composition by 66 sub-categories. The average HSW generation rate was 231.5 g/cap/day. For ten physical waste compositions, the food waste accounted the highest proportion (68.23%), followed by plastic (10.95%) and paper (9.40%). The composting potential and recycling potential accounted for 72.73% and 13.77%, respectively. The average moisture content, volatile solid content, and ash content were 45.16%, 42.75%, and 12.08%, respectively. The energy content of household solid waste was calculated to be 6,801 kJ/kg, which was acceptable for incineration treatment processes.

Second, the author analyzed the relations between HSW generation rates and influence factors by physical categories and sub-categories by non-parametric methods. The positive correlations between waste generation rates (WGRs) and urbanization level, population density, income level were indicated by rank correlation analysis. On the other hand, the WGRs were negatively correlated with family size. Factors significantly affecting WGRs were also discussed by Kruskal-Wallis H test. Based on the WGRs and population in Danang, the total HSW amount in urban areas was estimated to be 210 tons/day, and the 95% confidence interval was estimated to be 187 – 234 tons/day by non-parametric bootstrap method. Compostable waste, Recyclable waste and Non-recyclable waste were 155 tons/day (131 – 177 tons/day, 95%CI), 29 tons/day (25 – 33 tons/day, 95%CI), and 26 tons/day (21 – 31 tons/day, 95%CI), respectively. The expected revenue from recyclable contained in HSW was estimated to be 79 million VND/day (71 – 89 million VND/day, 95%CI), which was equivalent to 716 labors to be employed by the minimum wage standard. The sensitivity analysis shows that kitchen waste generation rate had highest contribution to the variance of total estimation of waste. Further study should focus on kitchen waste to improve the reliability of estimation.

Third, in order to understand the Waste-to-energy technology, the author aims to estimate the detailed composition of GHG emissions and reductions from the waste incineration facility and their influence factors using two Japanese databases on the operation of incinerators from Japan Ministry of the Environment (1,243 facilities) and Japan Waste Research Foundation (814 facilities). The databases cover detailed data on MSW amount and characteristics, specifications of the facility, annual utility consumption, and annual energy/material recovery. The authors analyze the correlations among them and develop predictive models for the detailed components of GHG emissions and reductions. Japan Ministry of the Environment intended to group small municipalities for replacing small-scale incinerators to large-scale waste-to-energy (WtE) facilities with a higher energy recovery efficiency. Based on the abovementioned data and models, the authors estimate the expected effects of the block formation and major technological alternatives for GHG mitigation by the national level. The current net GHG emission rate from 1,243 operating waste incineration plants in Japan in 2009 was estimated to be 653 kgCO_2e/t. By the block formation based on the master plans collected from 47 prefectures, 1,007 plants were assumed to be closed; 236 kept operating; and 286 facilities would be newly built. The net GHG emission rate could be cut off to 454 kgCO_2e/t by applying the block formation and technological alternatives with a higher energy recovery efficiency (stalker furnace with power generation by extraction condensing turbine providing steam higher than 3MPa and 300 °C). Ash melting caused a larger GHG emission by the increase in energy consumption. The GHG reduction by slag recycling was limited. Furthermore, the net GHG emission rate could be reduced to 242 kgCO2e/t by applying the Best Available Technique (BAT) for combined heat and power plants. When compared with the current status, BAT can reduce 185 kgCO2e/t by improving the power generation efficiency and 187 kgCO2e/t by expanding heat utilization. At present, heat utilization is very limited in Japan, but heat utilization should be more focused and promoted for GHG mitigation decisions.

Finally, the contributions of household solid waste treatment alternatives to mitigate greenhouse gas emissions were investigated by various possible scenarios. The waste treatment alternatives included: (i) landfill without landfill gas recovery; (ii) landfill with landfill gas recovery and power generation; (iii) Composting; (iv) Anaerobic digestion; (v) Incineration; (vi) Material recycling; (vii) Combination of different treatments. For business as usual scenario, the current GHG emission rate was estimated to be 1,242 $kgCO_2e$ per ton of waste (990 – 1,370 $kgCO_2e/t$, 95%CI). The emission could be reduced to 426 $kgCO_2e/t$ (410 – 510 $kgCO_2e/t$, 95%CI) by landfill recovery gas for power generation scenario. By assuming 70% of recyclables and food waste were separately collected for recycling and animal feeding, the GHG emission was estimated to be 274 $kgCO_2e/t$ (120 – 650 $kgCO_2e/t$, 95%CI). Meanwhile, the GHG emission rates of composting and anaerobic digestion scenario were 408 $kgCO_2e/t$ (300 – 800 $kgCO_2e/t$, 95%CI) and 223 $kgCO_2e/t$ (200 – 760 $kgCO_2e/t$, 95%CI), respectively. The incineration is the best waste treatment alternative with 96 $kgCO_2e/t$ (80 – 150 $kgCO_2e/t$, 95%CI). In addition, the results showed that the integrated HSW management considering material recycling, food waste separation for anaerobic digestion and waste-to-energy was the most favorable alternative for GHG mitigation, with GHG emission rate was estimated to be -5 $kgCO_2e/t$ (-50 – 90 $kgCO_2e/t$, 95%CI).

The results of this dissertation suggested the methodology for household solid waste survey, the analysis and evaluation for household solid waste characteristics (waste generation rates based on types, purposes and functions, recovery material and energy contents). For waste to energy incineration, the heat utilization should be improved to enhance the efficiency of facility, as well as cut off the GHG emission. The findings in this study are expected to be useful for decision-makers, planners of 3R programs, authorities of waste management to improve the household solid waste management to achieve the sustainable development.

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1. INTRODUCTION

1.1. Municipal solid waste in Vietnam: current status and challenges

1.1.1. General information

Municipal solid waste (MSW) is commonly regarded as the waste generated from residential, commercial, institutional, and municipal activities that are collected and treated by municipalities (Korner et al., 2006). Rapid economic growth recently has led to the phenomenon of "mass production, mass consumption, and mass disposal" in many major cities (Gu et al., 2017; Qu et al., 2009). The amount of MSW throughout the world has increased dramatically, which poses a potential threat of environmental degradation (McDougall et al., 2001; Pariatamby and Tanaka, 2014). MSW, thus, has been one of the key topics for environmental protection and resource utilization nowadays (Essonanawe et al., 2015; Korner et al., 2006; Thanh et al., 2010).

Population growth, urbanization and improving living standard have led to severe waste management problems in the cities of developing countries like Vietnam. Thanks to the widely used products made of plastic and diversified materials, the compositions of MSW are becoming more complex than ever (Pariatamby and Tanaka, 2014; Thanh et al., 2010).

It requires knowledge of what the wastes are comprised of, and how they need to be collected and treated properly (Kumar, 2016). However, it has been widely observed that the municipalities in Vietnam do not have adequate resources or the technical expertise necessary to deal with current issues. Therefore, the reliable and scientific research on MSW is essential and meaningful for waste management authorities in Vietnam.

1.1.2. Waste generation rate

As a major source of MSW, household solid waste (HSW) is a generated part of daily life activities in urban areas. The household solid waste generation rates (WGRs) per capita per day in major cities in Vietnam have been increased rapidly by years (Byer et al., 2006; Thai, 2009; Thanh et al., 2010). The WGRs are significantly different among area, of which is very high at major cities such as Hanoi, Ho Chi Minh, Da Nang, Hai Phong, Can Tho, and much lower at rural areas. The WGRs range from 0.6 to 1.0 kg/cap/day at urban areas, with the average of 0.814 kg/cap/day. In contrast, the WGRs in rural area are reported to range from 0.6 to 0.8 kg/cap/day with the average of 0.569 kg/cap/day (JICA, 2017)..

The WGRs are reported to be different among areas, due to the unified waste generation survey methods. The quality of waste generation data is highly affected by the sampling procedure. Solid waste sampling may often involve direct sampling, either at the source (e.g. household). Essonanawe et al., (2015) suggested that collecting waste directly from individual households with a certain household type allow the waste data to be more accurately attributed, reliable and associated to generating sources. Otoma et al., (2013) surveyed 50 households in Da Nang by not considering stratification criteria and reported that each resident generates on average 0.71 kg per day. Meanwhile, Thanh et al., (2010) observed 100 households in Can Tho by considering their respective urbanization levels and the geographical distribution and suggested that the average WGR is 285 g/cap/day.

In order to provide a reliable data on WGR, it is needed to conduct HSW generation survey with adequate sample size by considering stratification criteria such as the type of area, geographic location, and socio-economic differences (European Commission, 2004; Sharma and McBean, 2007). In addition, the uncertainty analysis should be carried out in order to evaluate the reliability of data.

1.1.3. Waste composition

Accurate and reliable data on waste composition are crucial for planning and environmental assessment of waste management as well as for improvement of resource recovery in society. In Vietnam, the absence of national standards for solid waste characterization has led to a variety of sampling and sorting approaches, making difficulties to compare the results between municipalities (Pariatamby and Tanaka, 2014). The MSW composition in Vietnam is reported to be diverse, of which the organic waste is the major component (53.8% – 79.7%), followed by plastic (3.4% – 12.8%), and paper (2.8% – 9.6%) as shown in Table 1.1.

Table 1.1 – MSW composition of typical cities in Vietnam

Waste component	Waste composition shares at typical cities (%)				
	Hanoi	Danang	Cantho	Hue	Pleiku
Organic waste	53.8	66.0	79.7	55.0	60.5
Plastic	3.4	4.0	9.6	5.2	12.8
Paper	4.2	3.1	2.8	4.4	9.6
Metal	1.4	4.9	0.7	7.0	1.2
Glass	1.0	0.9	1.5	1.8	0.1
Inert	28.2	16.4	3.9	21.3	12.6
Rubber & leather	4.9	1.6	1.6	1.5	2.8
Textile	1.7	2.3	1.8	3.0	0.1
Hazardous	1.4	0.8	0.1	0.8	0.4

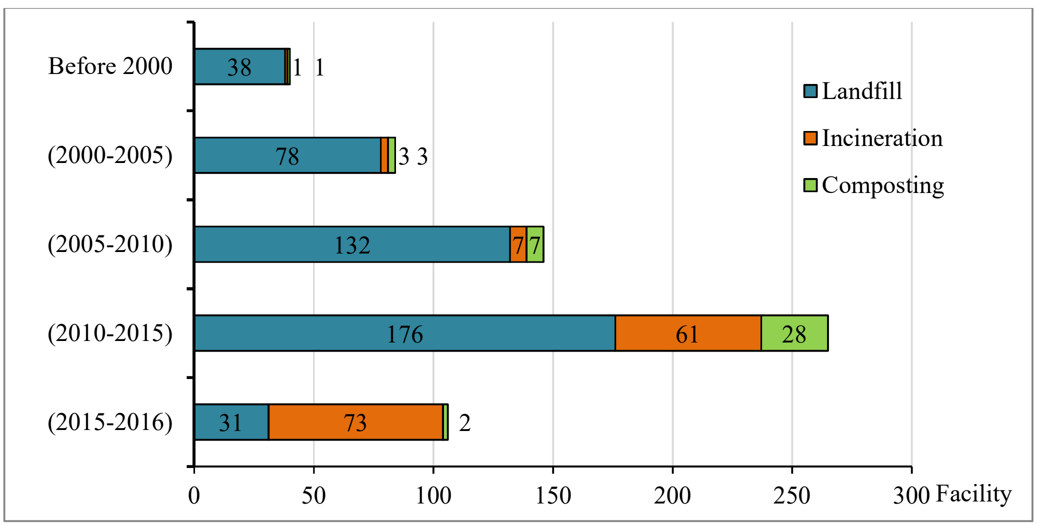
(Source: Pariatamby and Tanaka, (2014))

Inconsistencies among existing solid waste characterization study, e.g. definitions of waste compositions, may cause confusion and limit comparability of waste composition data between studies. While Thanh et al., (2010) published a detailed waste composition for household waste, including 83 waste fractions by considering waste material, function, recycling potential, more transparent and flexible classification for the individual waste material fractions are needed to allow full comparability between studies with carrying numbers of material fractions and sorted objectives. In addition, the basis fraction (combustible, ash and moisture content) with heating value is essential for assessing the potential for energy recovery from waste. However, no scientific research on detailed HSW composition considering recycling potential including energy recovery has been carried out to date. Therefore, scientific HSW generation and composition studies with material/energy recovery potential are fundamental for improving the waste management system.

1.1.4. Waste treatment methods

Vietnam's central government reported that the total amount of collected municipal solid waste in Vietnam was 15.6 million tons as of 2015, of which 28.9% (4.5 million tons) is treated in the intermediate treatment facilities and remaining 71.1% (11.1 million tons) is directly landfilled (JICA, 2017). Regarding a report of Vietnam's Ministry of Construction, there were 641 operating domestic waste treatment facilities in 48 cities/provinces in Vietnam. Figure 1.1 shows the trend of newly constructed waste treatment facilities in Vietnam by year.

The common treatment method for MSW in Vietnam is landfilling. Among hundred operating landfills, there are only 16 sanitary landfill sites, the remaining are open dumping sites or unsanitary landfills (Vietnam Government, 2011). Landfill sites without proper management such as the absence of leachate collection system, poor design of bottom layer, lack of daily cover layer have caused many serious problems to the environment and public health (McDougall et al., 2001). Landfills raise concerns over odor pollution in general, and recently, water pollution by untreated leachate in particular. At the global level, landfills release a large amount of methane gas, which has a high global warming potential. A recent estimation mentioned that the waste sector produced 4.1% of the total greenhouse gas (GHG) emissions from non-Annex I Parties, based on the latest available year (UNFCCC, 2008). Moreover, the disposal of recyclable together with other waste shortens the operating time of landfill as well as wastes society resources. Plastic bag and products can be easily recognized in all dumpsites in Vietnam (Pariatamby and Tanaka, 2014).



Source: (JICA, 2017)

Figure 1.1 – Newly constructed MSW treatment facilities in Vietnam by year

Composting has been recently considered as a cost-effective method for MSW treatment. Composting can recover the organic component in MSW to produce a clean soil conditioner, which reduces the amount of MSW to be buried on a landfill site (Byer et al., 2006). The number of operating composting facilities has been increased about four times, from 11 facilities as of 2015 to 41 as of 2016 (JICA, 2017). However, most of composting facilities in Vietnam are not operating at high efficiency because of the low quality of input material. The input waste is not well separated, and separation is done manually at the treatment facility. (Chi and Long, 2011; Vietnam Government, 2011). The composting of organic waste can be an appropriate technology in Vietnam only if waste can be separated at source properly (Pariatamby and Tanaka, 2014).

Since 2010, the number of waste incineration facilities in Vietnam has been increased rapidly (as shown in Figure 1.1) because of the advantage of this method such as waste volume reduction and energy generation. However, the reliable data of input waste for incineration is lacked due to the insufficient management. (Pariatamby and Tanaka, 2014).

The abovementioned difficulties and environmental impacts relating to MSW could be reduced by efforts both at source and by various techniques like material or energy recovery (Choe and Fraser, 1999). A comprehensive approach to MSW treatment alternatives is obviously needed for Vietnam's government to establish the sustainable development for waste management in the year to come.

1.1.5. National strategy for integrated management of solid waste

To deal with the increasing problems related to MSW, the Government of Vietnam has considered enhancing the SWM through implementing waste separation at source (WSS). According to Decision No. 2149/QD-TTg on the national strategy for integrated management of solid waste up to 2025, with a vision to 2050, 85% of MSW would be recovered by recycling, composting and thermal recovery. Then, until 2025, the total recovery rate is targeted to be 90% (Ministry of Construction and Environment, 2013). In addition, municipalities in Vietnam also need to introduce an integrated solid waste management with waste separation and environmentally friendly waste treatment technology (Chi and Long, 2011; Vietnam Government, 2011).

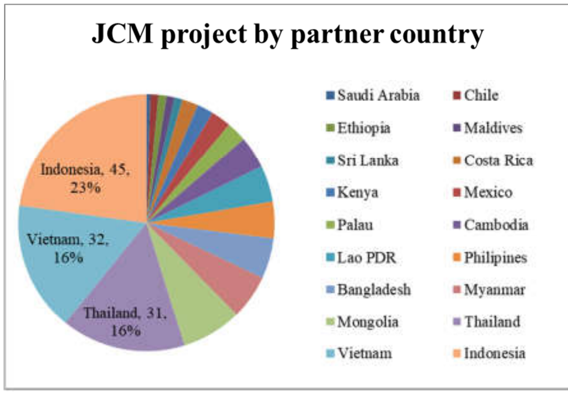
However, even though WSS is regulated, there is no law enforcement and no punishment-rewards system. Furthermore, lacked reliable data on waste characterization has made the target goal achievement challenge. The scientific data on waste composition with recycling potential is essential for municipalities to establish a feasible plan on waste management to fulfill their own target goal.

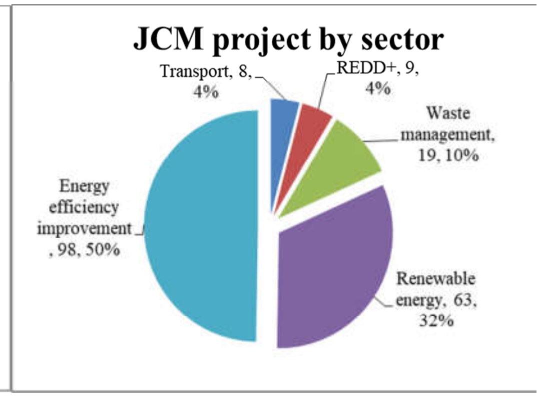
The techniques and management system of the MSW have changed dramatically, shifting from oversimplified procedures, such as collecting unsorted wastes first and then disposing them in landfills, to integrated and sustainable methods that incorporate waste reduction practices, waste separation at source (WSS), material recycling techniques, biological and thermal processes for energy recovery, and landfill disposal (Pariatamby and Tanaka, 2014). Thus, Vietnam's national strategy for integrated management of solid waste also considered that waste-to-energy would be the essential treatment method in the near future in major cities (Ministry of Construction and Environment, 2013). However, there is no scientific study on the energy content of MSW in Vietnam up to date. Therefore, the study on evaluation of self-burning potential of MSW is needed to promote energy recovery techniques for waste treatment in Vietnam.

1.1.6. Waste-to-energy incineration technology under JCM project

Waste-to-energy incineration technology has been widely used in major cities in developed countries thanks to its advantages such as minimizing the buried amount, controlling the sanitary condition, requiring small construction area, as well as energy recovery (Gabor Doka, 2005; Porteous, 2005; Xin-gang et al., 2016). Since the first introduced waste incineration in Japan in 1924, the waste incineration technology has developed and expanded over the years, and there are 1,243 operating incinerators for MSW in Japan as of 2012 ("Japan Ministry of the Environment database 2009 (In Japanese)," n.d.). To control the air pollution from the combustion process, many advanced technologies are applied to waste incineration facility. Consequently, the investment cost is too expensive for developing countries to cover it by themselves(Xin-gang et al., 2016). In order to support the implementation of the advanced low-carbon technologies, Ministry of the Environment, Japan (MOEJ) has established a financing program under JCM (Joint Crediting Mechanism) which covers up to half of the initial cost of projects that reduce GHG emission by utilizing leading low carbon technologies in developing countries. Figure 1.2 shows the summary of JCM projects by partner country and sector since 2013. Vietnam is considered as one of the most attracted partner countries for JCM project, with 32 projects in 198 projects.

JCM program is a great opportunity for waste management authorities in Vietnam to improve the current waste management system with advanced technologies from Japan. Therefore, a scientific study on GHG emission reduction by waste-to-energy incineration in Japan is needed in order to promote this advanced technology in Vietnam in the year to come.





Source: http://gec.jp/jcm/

Figure 1.2 – Summary of JCM projects by partner country and sector since 2013

1.1.7. Scenario analysis for sustainable waste management

One of the more basic requirements for waste planning, regardless of the type of treatment method to be selected, is that the proposed HSW management be viable. Viability can be evaluated by scenario analysis method with current information on waste generation (Unep, 2009). To evaluate the environmental impact from waste treatment alternatives, a scenario analysis by life cycle assessment (LCA) is widely used by Khoo, (2009); Kim and Kim, (2010); Lou et al., (2015); Ogino et al., (2007); Thanh and Matsui, (2013). LCA is an environmental management tool that attempts to predict the overall environmental burden of a product, service or function, and it can be applied to waste management system (McDougall et al., 2001).

In order to receive the financial support for advanced waste treatment technology transfer from Japan under JCM project, the LCA study on GHG emission from MSW in Vietnam is required. However, the study on GHG emission and reduction from MSW in Vietnam is still limited up to date due to the lack of reliable and scientific on waste data. Thanh and Matsui (2013) conducted a scenario analysis on GHG mitigation of waste treatment alternatives for eight major cities in Vietnam. The authors estimated GHG emission and reduction from severe waste treatment practice with referred waste composition data. However, the uncertainty of input data and the sensitivity analysis were not mentioned and discussed in the previous study. Thus, the scenario analysis on GHG mitigation considering decision factors with reliable waste composition data should be carried out in order to provide more scientific information for waste management authorities.

1.1.8. Challenges of waste management

The remaining issues of solid waste management in major cities in Vietnam can be summarized as follows:

❖ **Environmental issues**

- Improper treatment practices cause a serious impact on the local environment, especially the underground water.
- A large amount of methane gas, having high global warming potential, releases from open dumping site.

❖ **Social issues**

- Unsanitary landfill causes an adverse impact on human health.
- Recycling material is disposed of together with other waste on landfill.

❖ **Technical issues**

- Lack of proper waste treatment practice makes sustain source separation be less effective.
- Lack of advanced treatment technology to control the pollution from secondary emission as well as recover material/energy from waste.

❖ **Political issues**

- Lack of reliable statistic data on waste management. The waste classifications are variety among municipal and national level.
- The local governments are not adequately equipped to provide the proper service due to the lack of reliable information on waste generation and composition.
- Lack of scientific study on evaluation of waste treatment alternatives for authorities, decision-makers and planners.

1.2. Objectives of study

The overall aim of the study is to clarify the pros and cons of municipal solid waste treatment alternatives toward GHG mitigation in major cities in Vietnam. The objectives of the research are to use quantitative and qualitative research methods to gain insight into how much GHG emission can be reduced by advanced technology and by waste management policy. The research aims to: (1) provide reliable and detail information on MSW generation and composition in Da Nang, a representative major city in Vietnam, (2) establish the reliable and basic technological information on W-t-E incineration technology as the most prospected technology in Vietnam based on operation data of Japanese incinerators, and (3) Clarify the pros and cons of MSW treatment alternatives toward GHG mitigation, such as W-t-E incineration, anaerobic digestion to energy, and recycling technologies in consideration of reliable and detail information on characteristics of MSW generation in Da Nang. The main objective and specific objectives are shown in Figure 1.3.

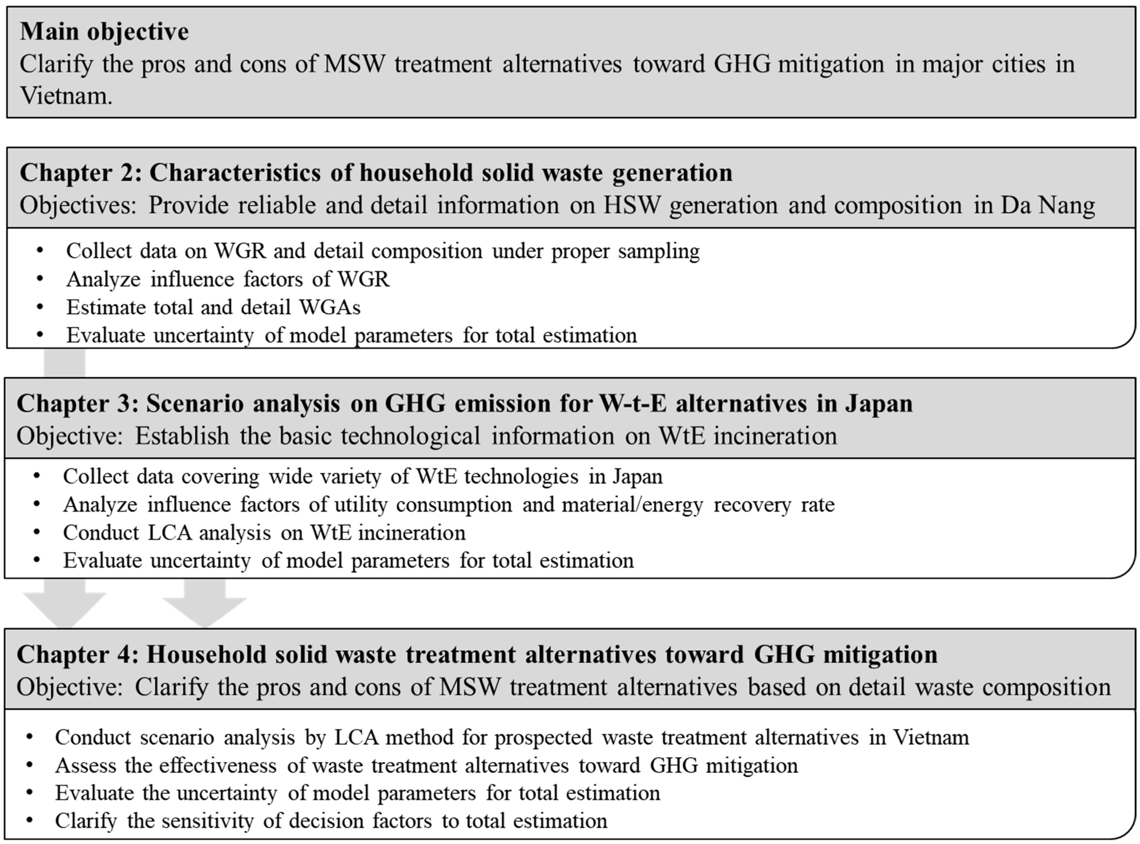


Figure 1.3- Objectives of the study

In order to reach the abovementioned objectives, firstly, the authors conducted HSW surveys at 150 households within six urban districts for ten consecutive days in Da Nang, Viet Nam: 1) the measured survey to identify waste generation, components, and energy content, and 2) the questionnaire survey to determine the relevant factors. Then the authors analyzed the relationship between GWRs and influence factors. Based on WGRs and population, the total HSW in six districts of Da Nang was estimated. The uncertainty analysis was conducted to evaluate the uncertainty of input variables to the total estimation.

Secondly, two Japanese databases on the operation of incineration from

Japan Ministry of the Environment (1,234 incinerators) and Japan Waste Research Foundation (814 incinerators) were examined by considering incinerated amount, the specification of the facility, the annual utility consumption, and annual energy/material recovery. The authors analyzed the correlations among them and developed the predictive models for detail components of GHG emissions and reductions. The effectiveness of technical factors and political factors to GHG reduction from WtE incineration in Japan was evaluated and discussed.

Finally, the scenario analysis by LCA method was conducted for HSW management in Da Nang, Vietnam. The emission factors were selected from past literature and official guideline, which are preferable for Vietnam condition. The LCA mainly focused on the operation process of the treatment facility. The prospective technologies were considered such as landfilling with landfill gas recovery, waste recycling, food waste recycling for animal feeding, composting, anaerobic digestion to energy, and waste-to-energy incineration. The pros and cons of MSW treatment alternatives toward GHG mitigation were assessed and discussed. The research framework is shown in Figure 1.4.

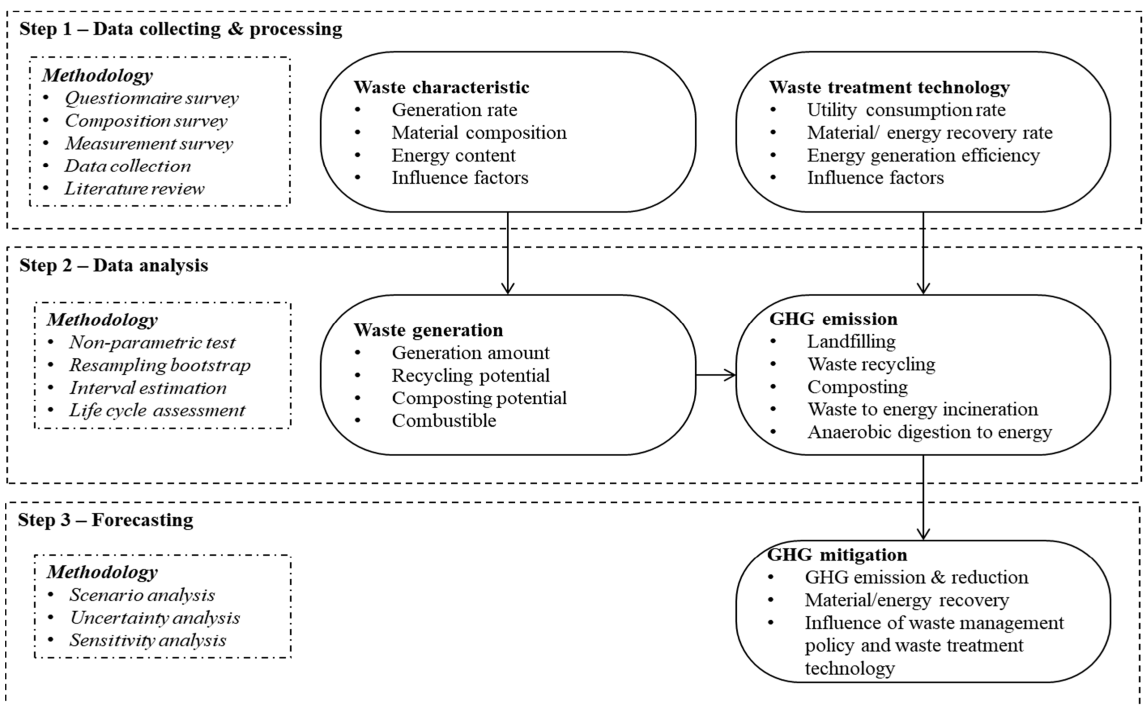


Figure 1.4 – Research framework

1.3. A conceptual outline of the dissertation

This dissertation consists of five sections are shown as follows:

Section 1 introduces the research background, an overview of solid waste management in Vietnam, and the scope as well as the objectives of the study. The outline of the whole study was also presented in this section.

Section 2 presents the household solid waste generation rates and influence factors by detailed composition considering the recycling/composting potential. In addition, the basic composition (moisture, volatile solids, and ash) and energy content were examined to identify the energy content in HSW. Based on the waste generation rates and population, the total household solid waste amount was estimated. The accuracy of predicted estimation by input waste generation rates and influence factors was also discussed.

Section 3 discusses the scenario analysis on greenhouse gas emission for waste-to-energy alternatives in Japan. Two Japanese databases on the operation of incineration from Japan Ministry of the Environment (1,234 incinerators) and Japan Waste Research Foundation (814 incinerators) were examined by considering incinerated amount, the specification of the facility, the annual utility consumption, and annual energy/material recovery. The authors analyzed the correlations among them and developed the predictive models for detail components of GHG emissions and reductions. A scenario analysis by LCA method is conducted and discussed with seven scenarios considering technical option and waste management policy.

Section 4 shows the investigated contribution of household solid waste treatment alternatives to mitigate greenhouse gas emissions by various possible scenarios. The waste treatment alternatives included: (i) landfill without material/energy recovery; (ii) landfill with landfill gas recovery and power generation; (iii) Composting; (iv) Anaerobic digestion to energy; (v) Incineration; (vi) Material recycling; (vii) food waste recycling. The author conducted the multiple assessments based on different aspects such as GHG emissions and reductions, energy consumption and recovery, land use burden.

Finally, section 5 summarizes the main conclusions of the dissertation and shows the reasonable suggestions for improving and managing municipal solid waste in Vietnamese cities. Additionally, recommendations for future research and the possible development are represented.

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2. CHARACTERISTICS OF HOUSEHOLD SOLID WASTE GENERATION

2.1. Introduction

Household solid waste (HSW) management is considered to be one of the most serious problem confronting local' authorities in developing countries mainly due to the increasing generation of waste, the lack of understanding of factors that affect the different stages of waste management (Grazhdani, 2015). Waste management is a complex process that requires a lot of information from various sources such as reliable data concerning waste generation and composition, influencing factors on waste generation and forecasts of waste quantities, as well as recycling potential rate (Dangi et al., 2008; Eisted and Christensen, 2011; Zhuang et al., 2008).

In general, detail and reliable information about waste generation and composition is required for several purposes from the decision-making concerning waste utilization to the development of local waste management systems and planning information campaigns. Moreover, waste generation and composition studies can be used for landfill design, identifying the sources of component generation, estimating physical, chemical, biological and thermal properties of wastes (Burnley et al., 2007; Shekdar, 2009; United Nations Environment Programme, 2009). In this way, waste composition studies are essential for functional waste management.

There have been a number of scientific studies focusing on HSW generation and composition in major cities in Vietnam. Otoma et al (2013) surveyed 50 households in Da Nang reported that average HSW generation rate is 0.71 kg/cap/day, of which organic waste (food, flowers, leaves, grass) accounts for about 70%, followed by plastic (14%). Dan and Viet (2009) reported that waste generation rate per capita in Ho Chi Minh city is 0.8 kg/cap/day in 2009, of which biodegradable waste, reusable/recyclable waste and other non-recyclable wastes are 60%, 30%, and 10% respectively. Meanwhile, Chi et al (2009) conducted a HSW survey and suggested that average generation rate in Ha Noi is 0.559 kg/cap/day, and waste component are diversified,, decomposed organic counted 47%, recycle plastic 4.66%. Giang et al (2017) conducted a survey in Hoi An to identify the generation rate and composition of household waste from different types of areas of the city. The authors suggested that the mean of HSW generation was 0.223 kg/cap/day, and the composition of HSW was made up of 38% food waste, 19% garden waste, 14% plastic, 15% combustible, and other components constituted less than 5%. The detailed waste composition with recycling potential and specific function was not considered in the previous studies. Thanh et al (2010) conducted a solid waste survey at 100 household in Can Tho by detail waste composition and function, as well as recycling potential. However, the authors did not considered the heating value of HSW and the energy recovery potential of HSW for thermal treatment technologies. The abovementioned studies estimated the total waste generation amount based on the surveyed WGRs; however, the uncertainty of waste composition to the total estimation has not been assessed and discussed.

This section aims to: 1) Provide the basic information on waste generation, characteristics, and its current material flow including informal sector; 2) Clarify the influence factors of waste generation rate and its modelling; 3) Estimate the total waste generation amount and the material flow by breakdown components; 4) Estimate the market value of valuable components contained in HSW; 5) Estimate the confidential intervals of the material flow and the impact of each parameter on confidential intervals.

2.2. Methodology

2.2.1. Research area and target sample

Da Nang (Vietnamese: Đà Nẵng), the fourth largest city in Vietnam in terms of urbanization and economy, is the commercial and educational center of the region. In addition, being located within 100 km of several UNESCO World Heritage Sites (the Imperial City of Hue, the Old Town of Hoi An, and the My Son sanctuary city), it also becomes a famous tourist destination. Da Nang is the fifth most populated city in Vietnam, with an area of 1,285.4 km^2 and a population of 1,046,876 as of 2015 (Da Nang People’s Committee, 2016a). Regarding administrative divisions, Da Nang has 6 districts (Hai Chau, Thanh Khe, Cam Le, Lien Chieu, Son Tra, Ngu Hanh Son) and 2 communes (Hoa Vang, Hoang Sa). They are further subdivided into 45 wards and 14 villages. Da Nang has the highest urbanization ratio among provinces and municipalities in Vietnam with an average annual urban population growth by 3.5% as of 2015, and 87% of the population lived in urban areas (Da Nang People’s Committee, 2018).

The Urban Environment Company of Da Nang (Da Nang URENCO), the formal waste collection and treatment Company in Da Nang, reported that the collected amount of municipal solid waste (MSW) has been increased by 16.7% in five years, from 223,521 tons (2010) to 260,923 tons (2014). In addition, 95% collected amount was from urban areas (248,995 tons). In rural area, the household solid waste (HSW) is dumped or open burned by residences (Da Nang People's Committee, 2016b).

In this study, the author focused on the household solid waste from urban areas considering urbanization levels and geographical distribution. By assuming the population density is the representative indicator of urbanization level, the author defined five levels by accumulated percentile rank on population density, as 10th, 30th, 50th, 70th, and 90th, as levels I, II, III, IV, and V, respectively. The list of wards and accumulated percentile rank is shown in Table 2-1. The research area and the sampling points are shown in Figure 2-1.

For target sample, the author selected 150 households from 15 sampling points, of which three sampling points for each urbanization level and ten households for each sampling points.

Source: Google map

Figure 2.1 – Research area (Da Nang) and sampling points

2.2.2. Outline of survey

The procedure for the waste generation survey followed the methodology presented by Matsui et al., (2015). The authors conducted four surveys for all target facilities: a waste generation survey by actual measurement and a questionnaire survey onsite, a waste detailed composition survey and a basic fraction survey at laboratory. The surveys were conducted from November 21st to December 5th, 2016. The waste generation survey was administered to acquire data on the amount of waste generated for ten consecutive days. The first three days were spent to prepare and practice with surveyors and target facilities; the data of latter seven consecutive days were used for analysis.

At first, a questionnaire survey was conducted by face-to-face interview to collect basic information on demographic and the status of waste storage at each target sample (e.g., place and kinds of containers and bags for storage). This step was aimed to invite target household participating the measurement survey, understand their waste separation habit and to design the proper time for daily measurement. Demographics such as age, family size, occupation, and income level were also surveyed.

Table 2.1 – Characteristic of population density distribution of research area

Ward	Population density (cap/km^2)	% Population density	Accumulated percentile rank (%)	Percentile rank category (%)	Level
Hoaquy	5,058	2.5	2.5	10	I
Hoaxuan	5,255	1.6	4.1	10	I
Hoathotay	8,553	1.8	6.0	10	I
Khuemy *	13,058	1.3	7.3	10	I
Hoaminh *	13,983	1.7	9.0	10	I
naihiendong	14,723	3.1	12.1	10	I
Hoahiepnam *	15,522	1.5	13.7	10	I
Hoaan	16,213	1.5	15.2	10	I
Hoahai	16,567	2.0	17.2	10	I
Hoathodong	16,761	2.5	19.7	10	I
Hoaphat	17,091	2.2	21.9	30	II
Hoahiepbac	19,224	1.4	23.3	30	II
Hoathuantay	20,671	1.6	24.9	30	II
Myan	22,425	2.9	27.8	30	II
Hoacuongbac *	22,743	2.3	30.1	30	II
Thoquang	23,216	1.7	31.8	30	II
Khuetrung *	23,439	1.5	33.3	30	II
Ankhe *	25,145	1.0	34.3	30	II
Hoakhanhnam	25,474	1.2	35.5	30	II
Phuocmy	28,433	1.8	37.2	30	II
Manthai	29,213	2.1	39.3	30	II
Anhaitay *	29,376	5.4	44.7	50	III
Anhaibac *	30,698	3.4	48.1	50	III
Hoacuongnam *	32,500	5.0	53.1	50	III
Hoakhe	37,641	2.8	55.9	50	III
Thanhkhetay	38,174	1.5	57.4	50	III
Thanhkhedong	40,729	1.3	58.8	50	III
Anhaidong	40,775	2.9	61.6	70	IV
Binhthuan	44,266	3.5	65.1	70	IV
Xuanha	45,052	2.1	67.2	70	IV
Thuanphuoc *	46,700	1.5	68.7	70	IV
Chinhgian *	47,753	1.9	70.6	70	IV
Hoakhanhbac *	49,151	2.7	73.3	70	IV
Thachthang	51,206	2.1	75.3	70	IV
Phuocninh	52,528	3.4	78.7	70	IV
Thanhbinh	53,630	2.6	81.3	90	V
Hoathuandong	53,876	2.4	83.7	90	V
Haichau1	55,351	2.1	85.9	90	V
Namduong	59,109	2.1	87.9	90	V
Thacgian *	59,180	1.7	89.6	90	V
Vinhtrung *	60,412	2.3	91.9	90	V
Binhhien *	61,373	1.7	93.6	90	V
Tamthuan	66,484	2.2	95.8	90	V
Tanchinh	69,921	2.0	97.9	90	V
Haichau2	80,023	2.1	100.0	90	V

*: selected sampling points (Source: General Statistics Office, 2015)

For waste generation survey, to avoid the water transition from kitchen waste to other waste categories in composition analysis, the target households were requested to keep and separate their waste basically into three categories; "Recyclables", "Food waste/ kitchen waste", and "General waste". The definition of waste category in the survey was as follows:

- Recyclables: is waste that household keeps for selling to informal sector.
- Food waste/ kitchen waste: is waste that target household keeps for animal feeding (pig/ livestock) or composting.
- General waste: is waste that target discharges (excluding recyclable and food/kitchen waste).

For waste composition survey, the waste from each household was collected and delivered to laboratory before classifying into 10 physical categories by material (plastic, paper, food waste, rubber & leather, grass & wood, textile, metal, glass, ceramic, miscellaneous) and 66 sub-categories considering their usage function and purpose, as shown in Table 2-2. The status of recycling potential is defined for each detailed composition, including "recyclable", "compostable", and "non-recoverable" marked as "Re", "Co", and "NRe", respectively.

Because each type of waste has a unique heating value and basis fraction, a further measurement was conducted for each waste component based on ten physical categories to determine the basis fraction and energy content. For basis composition determination, each waste component was cut into small pieces (less than 5mm) before drying in an oven at 105^{o}C to constant mass. The initial weight of each component sample was around 20 gram. After measuring the dry mass, the sample was incinerated in a furnace at 650^{o}C to constant mass.

The basic fraction (moisture, combustible and ash contents) and energy content of HSW were analyzed and calculated based on the standard test method for gross calorific and ash value of waste materials (ASTM, 2014; MOST, 2012). For heating value measurement, the waste components were measured individually in an oxygen bomb calorimeter. In this experiment, inert wastes such as metal, glass, ceramic were excluded because they cannot add or remove heat in incineration process. The energy content in household solid waste was calculated as follows:

$$\mathrm{LHV}_{HSW} = \sum(Proportion_i \times LHV_i) \qquad (2\text{-}1)$$

Where:

LHV_{HSW} (kJ/kg): calculated low heating value of household solid waste

$Proportion_i$ (%): the proportion of waste component i

LHV_i (kJ/kg): measured low heating value of waste component i

Finally, a face-to-face interview survey for informal sector was also conducted to identify the detail categories of recyclable items and their market value.

2.2.3. Analytical procedure

The authors intended to calculate the basic statistics relating to waste generation rates (WGRs) by physical categories and sub-category.

In scientific literature, the statistical procedures including correlation, regression, t tests, and analysis on variance, namely parametric tests, are based on the assumption that the data follows a normal distribution or a Gaussian distribution (Field, 2009). Thode, (2002) mentioned that normality test, such as Kolmogorov-Smirnov test or Shapiro-Wilk test should be conducted to judge whether the data followed normal distribution or not. By Shapiro-Wilk test, the author found that the WGRs of target samples did not follow normal distribution, as shown in Figure 2.2. So, the non-parametric tests were applied for further analysis in this study.

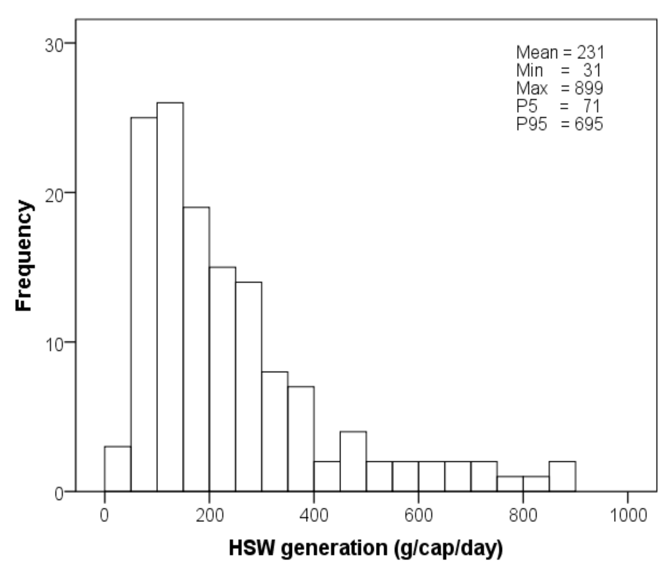

Figure 2.2 – Frequency distribution of HSW in Da Nang (g/cap/day)

The WGRs were presented by mean and 95% confidence interval, which were estimated by non-parametric bootstrap with return (10,000 trials). The authors also assessed the difference of WGRs among business categories by Kruskal-Wallis test. In addition, the relationship between influence factors and WGRs were analyzed. Theodorsson-Norheim, (1986) suggested that the non-parametric tests, such as Kruskal-Wallis test, was proved to perform better than their parametric analogues in the practical research situation, where the data are not normally distributed, contain outliers and the size of the groups is small.

The resampling bootstrap methodology was applied to estimate the confidence interval of total waste generated and the breakdown components, as well as the recyclable waste amount and its revenue. The process was repeated with 10,000 iterations. The authors also conducted the sensitivity analysis to identify the contribution of each variance. The parameters having the greatest effect are considered to be the parameters for which additional data should reduce the amount of overall uncertainty in the results. In this study, the method used for the sensitivity analysis was to square the Spearman Rank Coefficients by each parameter, then sum up and adjust them to 100% (*Crystal Ball User's Guide, 11.1.1.3.00*, 2009; Hammonds et al., 1994). RStudio (R version 3.3.0) was applied for statistical analysis.

2.3. Results and discussions*Waste generation and waste composition*

WGRs by 10 physical compositions are presented in weight (g/capita/day) and percentage as shown in Table 2.2. The average total WGR was 232 g/cap/day with an average of 4.6 residents per household of 150 target samples. Regarding the physical categories, kitchen waste contributed the largest part with 157.9 g/cap/day (68.23%), followed by plastic (25.3 g/cap/day, 10.95%) and paper (19.9 g/cap/day, 9.4%).

Table 2.2 also introduces HSW generation rates and compositions reported in past literatures as reference. The HSW generation rate in this study was similar with those reported in Beijing (230 g/cap/day), Suzhou (280 g/cap/day), Can Tho (283 g/cap/day) and Hue (238 g/cap/day). Regarding the waste composition, kitchen waste accounted for major component of HSW, which is consistent with past studies in developing countries. However, the WGRs in Da Nang are much lower than those in developed countries like Hong Kong (2,250 g/cap/day) and Kyoto (1,098 g/cap/day). In addition, the paper is the major component in HSW in these major cities. It could be explained that developed countries would consume larger amount of paper products and packages. The WGRs, the proportion (%) and the recycling potential by 66 detailed categories are also illustrated in Table 2.3. Table 2.3 shows that compostable waste accounted for the main proportion of the total with 170.7 g/cap/day (approximate 67.9% of total), consisted of food waste, unused food, garden waste, container and packaging by grass, and grass product. Recyclable material also accounted for the high percentage (17.6%) of total HSW generation, which was larger than the amount of the remaining waste (14.5%).

Table 2.2 – HSW generations and compositions in different areas

City, Country	WGR (g/cap/day)	Composition (% wet weight basis) Food	Paper	Plastic	Glass	Metal	Textile	Other
Hong Kong[1]	2,250	38.0	26.0	9.0	3.0	2.0	3.0	9.0
Kyoto, Japan[2]	1,098	39.8	32.2	9.7	0.9	2.0	6.4	-
Beijing, China[3]	230	69.3	10.3	9.8	0.6	0.8	1.3	2.7
Suzhou, China[4]	280	65.7	14.3	8.9	-	-	-	-
Moratuwa, Sri Lanka[5]	504	90.0	5.0	3.0	2.0	1.0	-	-
Kathmandu, Nepal[6]	497	70.1	7.5	12.0	1.3	0.5	0.9	7.7
Can Tho, Vietnam[7]	283	84.2	4.7	6.4	1.0	0.8	0.3	2.6
Hue, Vietnam[8]	238	79.5	4.7	7.3	1.0	0.5	0.5	6.5
Da Nang, Vietnam[9]	710	70.3	5.0	14.0	1.0	0.9	3.5	5.3
Da Nang, Vietnam[10]	232	68.2	8.6	10.9	1.2	0.9	1.3	8.9

[1] (Yau, 2010); [2](Yamada et al., 2017); [3](Qu et al., 2009); [4](Gu et al., 2017); [5](Bandara et al., 2007); [6](Dangi et al., 2011); [7](Thanh et al., 2010); [8](Trang, 2016); [9](Otoma et al., 2013); [10] This study

The detailed compositions of recyclable are presented in Figure 2.3. Regarding plastic waste, shopping plastic was dominant with 12.33 g/cap/day (5.33%). Meanwhile, diapers were the major component in paper waste with 6.88 g/cap/day (1.15%). For kitchen waste, the WGR of unused food was 4.45 g/cap/day (1.92%). The author found that plastic material accounted for the greatest fraction of the total; plastic bag (49.38%), plastic bottle (9.01%), plastic product (1.25%), and other plastic container and packaging (0.5%). The second largest component was paper material, in which newspaper/ magazine accounted for the main part with 8.29% of the total, followed by other paper container and packaging with 6.36%, other paper product (5.9%), photocopy paper (4.05%), cardboard container (2.87%), notebook (0.77%), and book (0.52%). The metal material comprised the main part of aluminum container with 3.09% of the total, followed by metal product (2.42%), and steel container (0.56%). The remaining components were glass container and rubber & leather with 2.8% and 2.2% of the total recyclable waste, respectively.

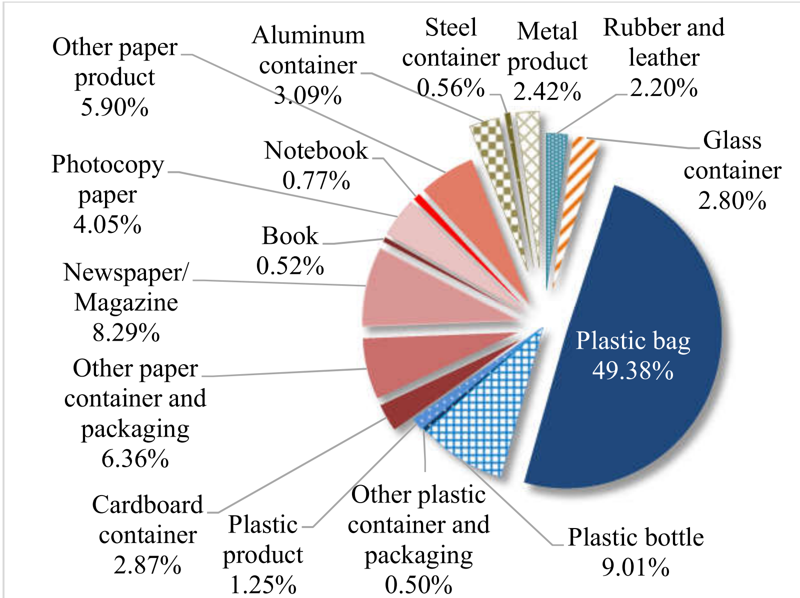

Figure 2.3 – Breakdown components of recyclable waste

The results of basis composition and energy content by ten physical categories are shown in Table 2.4. The moisture content of HSW was 45.16%, which was mainly originated from kitchen waste and grass & wood components. The combustible component and ash content were 42.75% and 12.08%, respectively. For energy content, the plastic component indicated the highest low heating value (LHV) with 24,159 kJ/kg, followed by rubber (18,499 kJ/kg), textile (11,552 kJ/kg), and paper (7,753 kJ/kg). The energy content in kitchen waste was quite low (2,677 kJ/kg) because of its high moisture content. The average LHV of HSW was calculated to be approximate 6,801 kJ/kg, which was higher than self-sustaining combustion (higher than 6000 kJ/kg) and applicable for incineration treatment process (Rand et al., 2000). In addition, the calculated basic fractions of HSW (Figure 2.4) were applicable for self-burning treatment regarding the Tanner triangle (Tanner, 1965).

Table 2.3 – Detailed waste composition by sub-category (Sample size N = 150)

Category	Types	Code	Items	WGR (g/cap/day)	Percentage (%)	Recycling potential
Plastic	Container & Packaging	101	PET bottle	1.55 [1.17 – 1.97]	0.67%	RE
		102-1	Other recyclable plastic bottle	1.32 [0.90 – 1.82]	0.57%	RE
		102-2	Non-recyclable plastic bottle	0.02 [0.01 – 0.07]	0.01%	NRE
		103	Foam tray	0.50 [0.31 – 0.74]	0.22%	NRE
		104	Tube	0.12 [0.06 – 0.20]	0.05%	NRE
		105-1	Other recyclable plastic containers	0.16 [0.08 – 0.26]	0.07%	RE
		105-2	Non-recyclable plastic containers	0.47 [0.34 – 0.61]	0.20%	NRE
		106	Shopping plastic bags	12.3 [10.5 – 14.1]	5.33%	RE
		107-1	Other recyclable plastic packaging	3.41 [2.85 – 4.03]	1.47%	RE
		107-2	Non-recyclable plastic packaging	2.67 [2.24 – 3.16]	1.15%	NRE
		108	Non-recyclable plastic containers	0.24 [0.09 – 0.49]	0.10%	NRE
	Plastic product	109	Plastic product	0.26 [0.09 – 0.49]	0.11%	RE
		109a	Non-recyclable plastic product	1.08 [0.71 – 1.57]	0.47%	NRE
		110	Plastic bags for waste	0.14 [0.07 – 0.24]	0.06%	RE
	Other plastics	111	Other non-recyclable plastics waste	1.07 [0.73 – 1.45]	0.46%	NRE
Paper	Container & Packaging	201	Carton	2.72 [1.85 – 3.99]	1.18%	RE
		202	Paper containers	2.03 [1.52 – 2.59]	0.88%	RE
		203	Cardboard	0.92 [0.43 – 1.59]	0.40%	RE
		204-1	Paper packaging	0.06 [0.01 – 0.15]	0.03%	RE
		204-2	Non-recyclable paper packaging	0.26 [0.15 – 0.40]	0.11%	NRE
	Product	206	Newspapers/Advertising/Magazines	2.64 [1.27 – 4.96]	1.14%	RE
		207	Books	0.17 [0.06 – 0.30]	0.07%	RE
		208	Notebooks	0.25 [0.15 – 0.37]	0.11%	RE
		209	Photocopy paper/OA paper	1.29 [0.62 – 2.41]	0.56%	RE
		210	Disposal paper products	2.65 [2.01 – 3.37]	1.15%	NRE
		210a	Nappies/Diapers	6.88 [3.81 – 10.5]	2.97%	NRE
		211	Other paper product	0.45 [0.32 – 0.61]	0.20%	RE
	Other Paper	212	Other type of paper	1.43 [0.73 – 2.53]	0.62%	RE
Kitchen waste (food waste)	Compostable	301-1	Kitchen waste (food waste)	153 [131 – 176]	65.94%	CO
		301-2	Unused food (expired food)	4.45 [2.55 – 6.93]	1.92%	CO
	Non-compostable	302	Large/hard bones of animal or shell	0.84 [0.36 – 1.44]	0.36%	NRE
Rubber and leather	Recyclable	401-1	Recyclable rubber and leather	0.70 [0.18 – 1.39]	0.30%	RE
	Non-recyclable	401-2	Non-recyclable rubber and leather	0.04 [0.01 – 0.07]	0.02%	NRE
Grass and wood	Garden waste	501	Garden waste	8.97 [4.67 – 14.8]	3.87%	CO
	Containers and Packaging	502-1	Containers and packaging by grass	2.30 [1.51 – 3.22]	0.99%	CO
		502-2	Containers and packaging by wood	0.11 [0.01 – 0.29]	0.05%	NRE
	Products and Others	503-1	Grass products and others	0.01 [0.01 – 0.02]	0.00%	CO
		503-2	Wood products and others	2.21 [0.11 – 6.36]	0.96%	NRE
Textile	Textile	601	Textile	3.66 [2.03 – 5.62]	1.58%	NRE
Metal	Aluminum	701-1	Recyclable aluminum containers	0.98 [0.70 – 1.30]	0.42%	RE
		701-2	Non-recyclable aluminum containers	0.05 [0.03 – 0.07]	0.02%	NRE
		702	Durable products	0.06 [0.01 – 0.15]	0.03%	RE
		703	Consumable products and others	0.01 [0.01 – 0.02]	0.00%	NRE
	Steel	704	Containers	0.18 [0.06 – 0.34]	0.08%	RE
		705	Durable Products and others	0.04 [0.01 – 0.10]	0.02%	RE
		706	Consumable products and others	0.02 [0.01 – 0.04]	0.01%	RE
	Stainless	707	Products and others	0.12 [0.02 – 0.29]	0.05%	RE
	Lead	708	Products and others	0.06 [0.01 – 0.15]	0.02%	NRE
	Other metals	709	Other recyclable items	0.40 [0.04 – 1.06]	0.17%	RE
		709a	Non-recyclable items	0.10 [0.01 – 0.25]	0.04%	NRE
		709b	Batteries (small)	0.06 [0.02 – 0.11]	0.02%	NRE
		709c	Accumulator	0.06 [0.01 – 0.16]	0.03%	RE
		709d	E-waste	0.07 [0.02 – 0.15]	0.03%	RE
Glass	Container	801	Returnable bottle	0.89 [0.05 – 2.20]	0.39%	RE
		802	Disposable bottle	0.91 [0.42 – 1.52]	0.39%	NRE
		803	Non-recyclable glass containers	0.55 [0.26 – 0.91]	0.24%	NRE
	Products and others	804	Non-recyclable glass products	0.20 [0.07 – 0.36]	0.09%	NRE
		804a	Thermometers, Fluorescent lamp, broken glass [Hazardous waste]	0.17 [0.03 – 0.36]	0.07%	NRE
Ceramic	Container	901	Containers	0.03 [0.01 – 0.10]	0.02%	NRE
	Products	902	Products	0.51 [0.11 – 1.07]	0.22%	NRE
Miscellaneous		1001	Other combustibles	0.86 [0.32 – 1.67]	0.37%	NRE
		1002	Other liquids	0.53 [0.27 – 0.88]	0.23%	NRE
		1003-1	Other incombustibles (excluding ash)	0.69 [0.26 – 1.26]	0.30%	NRE
		1003-2	Ash	0.50 [0.03 – 1.36]	0.22%	NRE
		1004	Medical care (syringe, needle, ...)	0.03 [0.01 – 0.04]	0.01%	NRE
		1005	Others	0.39 [0.08 – 0.83]	0.17%	NRE
Total				232 [202 – 263]		
Composting potential				168 [145 – 190]	72.3%	CO
Recycling potential				31 [28 – 36]	13.7%	RE
Non-recyclable				32 [28 – 37]	14.0%	NRE

RE: recyclable, CO: compostable, NRE: non-recyclable

Table 2.4 – Basis fraction and energy content by physical component

Component	Proportion (%)	Combustible (%)	Moisture (%)	Ash (%)	LHV (kJ/kg)
Plastic	14.56	67.58	17.09	15.33	24,159
Paper	10.86	47.44	47.10	5.46	7,753
Kitchen waste	64.10	38.08	52.83	9.09	2,677
Rubber	0.56	52.60	15.20	32.20	18,499
Grass & wood	4.51	40.20	55.57	4.23	8,695
Textile	1.53	57.22	37.66	5.12	11,552
Metal	0.83	-	7.12	92.88	-
Glass	1.41	-	1.90	98.10	-
Ceramic	0.22	-	1.98	98.02	-
Miscellaneous	1.42	25.90	30.85	43.24	3,815
Total	100.00	42.75	45.16	12.08	6,801

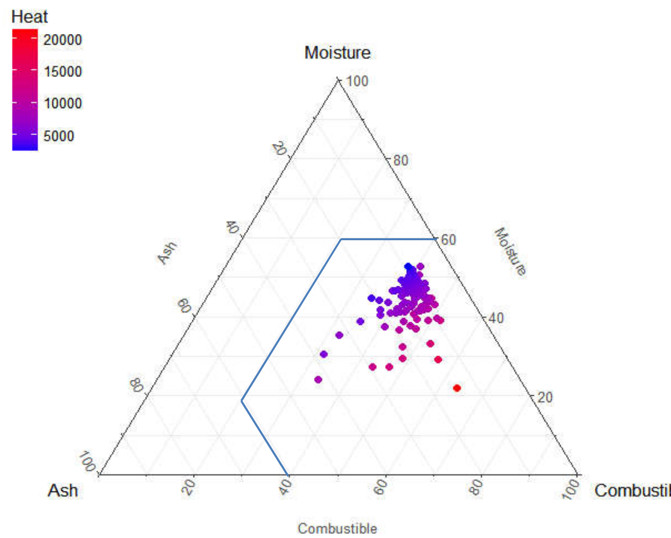

Figure 2.4 – Triangle for determining combustibility of HSW

In this study, the author focused on the most influential 2 components, plastic component (with highest LHV) and kitchen waste component (with high moisture content and lowest LHV), and explored the LHV of HSW by various combinations of separation rates. The calculated energy content of HSW by separation rate is shown in Figure 2.5. Plastic separation decreases the LHV of HSW, and kitchen waste separation increases it. The estimated LHV range varied from 3,844 to 6,801 kJ/kg; and the LHV of HSW is estimated to be less than 6000 kJ/kg if 40% or more of recyclable plastic is removed from HSW for incineration, which is not applicable for self-sustaining combustion (Gray areas in Figure 2.5. On the other hand, the higher the kitchen waste separation rate level, the higher the LHV of HSW value. By increasing the kitchen separation rate, the plastic separation rate can be higher than 40% while LHV of HSW is still suitable for self-sustaining combustion.

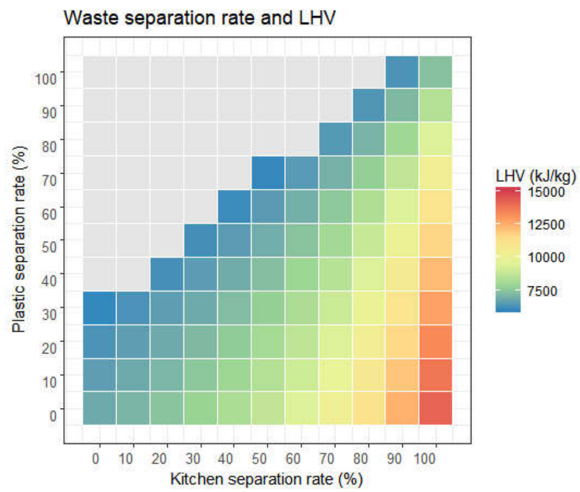

Figure 2.5 – LHV of HSW by different waste separation rate

2.3.2. WGRs and influence factors

The author analyzed the influences of socioeconomic factors such as urbanization level, location, income, household size on WGRs. The results of Kruskal-Wallis test and rank correlation analysis of physical categories, sub-categories by usage and relevant factors are provided in Tables 2.5 and 2.6.

Regarding urbanization level, the significant mean differences were found for total waste ($p<0.01$), and two physical categories; plastic ($p<0.001$), and food waste ($p<0.01$). For sub-categories of plastic and food waste, the Kruskal-Wallis test results showed the significant differences for the main components such as plastic container & packaging ($p<0.001$), other plastics ($p<0.01$), and compostable food waste ($p<0.01$). The results of rank correlation indicated the positive correlations between urbanization level and waste generation rates of total ($p<0.001$), plastic ($p<0.001$), paper ($p<0.05$), food waste ($p<0.001$), grass & wood ($p<0.01$), and ceramic (($p<0.05$). The significant positive correlations were also found for sub-categories under physical categories mentioned above. This indicated that urbanization level is one of important factor significantly affecting WGRs.

Regarding the Kruskal-Wallis test results for districts, total average waste, plastic, and food waste category differed significantly among districts. The significant differences were also found for the main sub-categories of plastic and food waste; plastic container & packaging ($p<0.01$), compostable food waste ($p<0.05$). The geographical location might affect WGRs in some way. In this study, sample selection, however, was mainly based on urbanization level/ population density of ward, and the number of target wards for each district was different. It would be difficult to conclude the effect of geographic factor from the result of this study.

Regarding income level, the significant differences were found only for total average waste ($p<0.01$), food waste ($p<0.05$), and compostable food waste ($p<0.05$). The results of rank correlation indicated the positive effect of income level on total average waste and three main physical categories; plastic, paper, and food waste. The higher income level resulted in the increasing in per capita waste generation rate.

According to household size, the significant differences among household size were found at total waste ($p<0.001$), plastic ($p<0.01$), paper ($p<0.05$), food waste ($p<0.001$), and grass & wood ($p<0.01$). For sub-categories, the results of Kruskal-Wallis test indicated the mean differences for some sub-categories under the above mentioned physical categories. The negative correlations between household size and waste generation rate were found in total waste ($p<0.001$), plastic ($p<0.001$), food waste ($p<0.001$), and grass & wood ($p<0.001$); and some sub-categories; plastic container & packaging ($p<0.001$), compostable food waste ($p<0.001$), and grass/wood container & packaging ($p<0.05$).

Finding point was that household size would be the important indicator to estimate the waste generation rate. The waste generation rate tended to decrease in the household with higher family size.

Table 2.5 – WGRs (g/cap/day) and influence factors

	10 physical composition	Sample Size	Plastic	Paper	Food waste	Rubber & leather	Grass & wood	Textile	Metal	Glass	Ceramic	Miscellaneous	Total
Urbanization level	Level 1	30	19.16	13.28	117.11	0.52	4.56	1.28	1.43	0.86	0.01	2.68	170.89
	Level 2	30	19.89	17.21	121.51	2.16	6.32	5.03	2.25	3.82	0.39	2.50	172.10
	Level 3	30	20.39	17.56	138.32	0.04	15.5	3.1	3.00	1.18	0.00	1.08	200.17
	Level 4	30	30.19	19.47	214.69	0.87	13.99	4.37	2.29	5.76	2.03	5.15	298.81
	Level 5	30	38.24	32.42	210.6	0.04	29.18	4.58	1.98	1.78	0.19	3.60	322.60
	Kruskal – Wallis[1]		0.017*	0.016*	0.013*	0.784	0.09	0.706	0.295	0.706	0.056	0.230	0.006**
	Spearman[2]		0.189**	0.151**	0.22***	0.09	0.19**	0.12	0.05	0.10	0.15	0.09	0.24***
Districts	Lien Chieu	30	23.13	20.9	130.76	1.3	11.15	1.33	2.88	1.61	0.01	2.59	195.68
	Thanh Khe	30	38.08	26.33	230.4	0.06	16.63	4.56	1.72	3.83	2.06	5.78	329.46
	Hai Chau	50	21.99	20.88	123.5	1.36	12.2	3.76	2.03	4.32	0.13	1.84	192.07
	Cam Le	20	20.55	11.6	168.5	0.04	18.9	2.9	2.77	0.5	0	1.12	226.9
	Son Tra	10	29.36	30.48	160.2	0.21	15.46	11.6	2.17	1.91	1.27	3.23	255.9
	Ngu Hanh Son	10	16.19	27.35	161.8	0.01	5.89	1.65	1.25	0.55	0	5.08	219.7
	Kruskal - Wallis		0.053	0.028*	0.057	0.490	0.227	0.525	0.147	0.110	0.378	0.632	0.051
Income Level	Low	37	20.17	12.65	109.31	0.2	13.06	1.74	2.63	0.92	0	1.17	161.86
	Lower middle	32	16.52	19.72	83.12	0.02	4.77	0.27	2.14	0.55	0	1.01	128.12
	Middle	21	24.01	25.55	136.11	1.72	24.25	2.07	2.61	1.5	1.81	4.99	224.62
	Upper middle	7	27.02	21.27	151.81	0.93	9.55	3.83	2.69	4.34	0.36	2.57	224.38
	High	7	33.67	36.27	257.75	1.93	13.41	7.85	1.23	5.84	0±0	4.56	362.5
	Kruskal – Wallis[1]		0.011*	0.04*	0.047*	0.513	0.788	0.088	0.751	0.187	0.866	0.136	0.046*
	Spearman[2]		0.195**	0.23**	0.20**	0.11	0.04	0.08	-0.09	0.15	0.05	0.15	0.25**
Household size	I (<=3 persons)	21	35.17	26.67	265.48	0.69	33.61	5.07	3.41	2.94	0.59	4.47	378.1
	II (4-5 persons)	93	23.13	15.05	126.46	0.74	8.49	3.73	1.65	2.38	0.76	2.55	184.92
	III (≥ 6 persons)	36	19.88	30.05	112.53	0.8	3.64	2.1	2.05	3.19	0.06	2.44	176.74
	Kruskal – Wallis[1]		0.013*	0.177	0.001**	0.714	0.027*	0.153	0.167	0.946	0.137	0.217	0.001**
	Spearman[2]		-0.24***	-0.04	-0.29***	-0.04	-0.25***	0.04	0.00	-0.02	-0.04	-0.06	-0.29***

*: $p<0.05$, **: $p<0.01$, ***: $p<0.001$
1: Kruskal – Wallis H test (H value)
2: Spearman rank correlation test (ρ value)

Table 2.6 – WGRs (g/cap/day) and influence factors by sub-category

Physical categories		Plastic			Paper			Food waste	
Sub-categories		Container and packaging	Plastic product	Other plastics	Container and packaging	Paper product	Other paper	Compostable	Non-compostable
Urbanization level	Level I	17.64	1.18	0.34	3.75	17.16	2.38	117.11	0.11
	Level II	15.99	1.96	1.95	5.54	10.48	1.18	111.62	0.89
	Level III	18.84	0.66	0.89	4.21	12.22	1.14	137.87	0.45
	Level IV	27.77	1.12	1.3	8.44	10.24	0.78	214.31	0.39
	Level V	34.79	2.63	0.82	8.13	22.59	1.7	207.92	2.68
	Kruskal – Wallis[1]	6.57***	1.29	2.27	1.51	0.99	0.34	3.75**	2.81
	Spearman[2]	0.28***	0.15*	-0.02	0.12*	0.15*	0.154*	0.22***	0.24**
Districts	Lien Chieu	20.91	0.86	1.36	4.37	13.97	2.56	130.36	0.4
	Thanh Khe	35.03	2.82	0.23	10.01	14.8	1.52	229.68	0.72
	Hai Chau	19.08	1.27	1.64	6.29	13.81	0.79	121.92	1.61
	Cam Le	18.76	0.8	0.99	2.18	8	1.42	167.87	0.65
	Son Tra	26.42	1.69	1.25	8.18	20.09	2.2	160.21	0.03
	Ngu Hanh Son	14.62	1.55	0.02	3.22	23.99	0.14	161.79	0.02
	Kruskal – Wallis[1]	4.48**	1.14	2.13	2.19	0.52	0.47	2.41*	0.84
Income Level	Low	17.62	0.7	1.85	4.12	8.3	0.23	109.07	0.24
	Lower middle	15.32	0.54	0.66	5.99	12.45	1.28	83.02	0.1
	Middle	21.43	0.83	1.75	3.59	20.57	1.39	135.14	0.98
	Upper middle	23.96	1.73	1.33	6.27	12.85	2.15	150.79	1.02
	High	31.86	0.7	1.12	7.1	28.15	1.01	257.72	0.02
	Kruskal – Wallis[1]	1.83	0.70	0.45	0.45	0.86	0.21	3.26*	0.81
	Spearman[2]	0.24**	0.09	-0.04	0.10	0.22**	0.17*	0.19**	-0.01
Household size	1 (<=3 persons)	32.12	1.91	1.14	9.35	15.79	1.53	263.49	1.99
	2 (4-5 persons)	20.67	1.43	1.03	4.05	9.38	1.61	126.23	0.22
	3 (≥ 6 persons)	17.66	1.16	1.06	6.44	22.65	0.96	111.62	0.91
	Kruskal – Wallis[1]	7.77**	0.40	0.03	3.88*	2.85	0.16	16.49***	3.45*
	Spearman[2]	-0.25***	0.07	0.06	-0.02	-0.04	-0.08	-0.29***	0.02

*: $p<0.05$, **: $p<0.01$, ***: $p<0.001$

1: Kruskal – Wallis H test (H value)

2: Spearman rank correlation test (ρ value)

Table 2 – 6. WGRs (g/cap/day) and influence factors by sub-category (continue)

Physical categories		Metal					Glass		Ceramic	
Sub-categories		Aluminum	Steel	Stainless	Lead	Other metals	Container	Products and others	Container	Products and others
Urbanization level	Level I	0.84	0.01	0.01	0.2	0.36	0.67	0.19	0	0.01
	Level II	1.55	0.08	0.11	0.07	0.32	3.2	0.62	0	0.39
	Level III	1.69	0.73	0	0	0.25	1.06	0.12	0	0
	Level IV	0.47	0.12	0	0	1.68	4.91	0.84	0.17	1.87
	Level V	0.92	0.25	0.55	0	0.26	1.78	0.01	0	0.19
	Kruskal – Wallis[1]	2.14	2.610*	1.95	0.82	0.86	1.43	2.10	1.03	2.17
	Spearman[2]	0.00	0.12	0.04	-0.11	-0.06	0.16*	-0.03	0.08	0.13
Districts	Lien Chieu	0.64	0.01	0.01	0.2	2.01	1.06	0.55	0	0.01
	Thanh Khe	0.85	0.34	0.37	0	0.15	3.68	0.16	0	2.06
	Hai Chau	1.31	0.19	0.14	0.05	0.3	3.67	0.64	0.11	0.03
	Cam Le	1.4	0.71	0	0	0.22	0.5	0	0	0
	Son Tra	1.67	0.04	0	0	0.06	1.65	0.25	0	1.27
	Ngu Hanh Son	0.95	0.03	0	0	0.27	0.55	0	0	0
	Kruskal – Wallis[1]	0.80	1.49	0.71	0.61	1.14	0.90	1.09	0.45	2.416*
Income Level	Low	0.8	0.11	0.16	0	0.46	0.92	0	0	0
	Lower middle	1.72	0.33	0	0	0.07	0.54	0.01	0	0
	Middle	1.86	0.34	0.15	0	0.25	1.5	0	0	1.81
	Upper middle	0.98	0.21	0.03	0.15	1.24	3.69	0.65	0	0.36
	High	0.51	0.49	0	0	0.23	5.82	0.02	0	0
	Kruskal – Wallis[1]	1.40	0.21	1.33	0.38	0.36	0.79	1.36	0.22	0.94
	Spearman[2]	-0.11	-0.07	-0.18	0.06	0.00	0.11	0.16	0.04	0.04
Household size	1 (<=3 persons)	1.17	0.42	0.29	0	1.5	2.39	0.54	0.01	0.59
	2 (4-5 persons)	0.96	0.21	0.05	0.08	0.29	2.05	0.33	0.07	0.69
	3 (≥ 6 persons)	1.27	0.1	0.11	0.06	0.27	2.92	0.27	0	0.06
	Kruskal – Wallis[1]	0.33	1.03	0.95	0.30	1.52	0.14	0.43	0.46	0.56
	Spearman[2]	0.06	-0.04	0.07	0.08	0.02	0.02	-0.05	-0.08	-0.01

*: $p<0.05$, **: $p<0.01$, ***: $p<0.001$

1: Kruskal – Wallis H test (H value)

2: Spearman rank correlation test (ρ value)

2.3.3. Estimation of waste generation

By multiplying the WGR by urbanization level (Table 2.5) with the population by each urbanization level, the total HSW generation was estimated to be 209.6 tons/day. According to Da Nang URENCO, the total collected amount of MSW was reported to be approximately 714 tons/day in 2014, including commercial waste, non-hazardous waste from industrial zones. The estimated amount of HSW accounted for 29.9% of total collected MSW in Da Nang. This result is similar with a study in Hue city, which mentioned that the household without business contributed 32.2% of total MSW (Trang, 2016).

The estimation was also applied for recycling potential with 3 categories; recyclable waste, compostable waste, and non-recoverable waste. Compostable waste accounted for the largest composition with 152.5 tons/day (72.7%), in which, 138.2 tons/day came from food waste. The amount of recyclable waste was 28.9 tons/day (13.8%), with 14.3 tons/day of plastic bag.

The author also estimated the value of recyclable that produced by the household for all 6 districts in Da Nang. The recyclable waste categories and market value of recyclable in Da Nang were updated by the hearing survey of the informal sector. According to the results in Table 2.7, the total value of recyclables was estimated up to 79.3 million VND per day (equal to around 3500 USD). This amount is equivalent to the minimum wage of 716 labors (the minimum wage is 3,320,000 VND/month that was issued in Decree 153/2016/ND-CP). The total amount of plastic bag (all types) was 21.7 million VND/day, that accounted for 27.4% of the total, even though the plastic bag with normal plastic had low prices (1,000 VND/kg).

Table 2.7 – Estimation of recyclable waste and revenue amount

Code	Detail	Price (VND/kg)	Daily Waste generation amount (tons/day)	Revenue (VND/day)
701	Aluminum containers	19,000	0.89	16,936,139
106	Shopping plastic bags (normal plastic)	1000	10.26	10,256,879
106	Shopping plastic bags (soft plastic)	9000	0.84	7,587,018
101	PET bottle (colorless)	5,000	1.41	7,041,000
206	Newspapers/ Magazines (colored paper)	2,700	2.4	6,472,200
102	Other plastic bottle	4,000	1.2	4,784,664
202	Containers (carton paper)	2,500	1.84	4,595,592
209	Photocopy paper/OA paper (white paper)	3,200	1.17	3,749,106
212	Other Paper	2,500	1.29	3,235,883
107	Other plastic packaging	1000	3.1	3,096,184
203	Cardboard	2,500	0.83	2,077,162
401	Rubber and leather	3000	0.64	1,910,542
211	Other paper product	2,500	0.41	1,025,575
702	Aluminum durable Products and others	19,500	0.05	1,008,403
709c	Accumulator	18,000	0.05	984,399
208	Notebooks	4,000	0.22	894,353
106	Shopping plastic bags (crispy plastic)	3500	0.24	825,977
109	Plastic product	3000	0.24	706,489
105	Other shape of containers	4,000	0.15	580,865
207	Books (white paper)	3,200	0.15	485,202
707	Steel products and others	4,200	0.11	472,104
704	Steel containers	1,500	0.16	244,110
705	Steel durable Products and others	4,200	0.03	139,200
110	Plastic bags for waste	1000	0.13	127,171
706	Steel consumable products and others	4,200	0.02	74,477
	Total		28.9 tons/day	79,310,694

To conduct the 95% confidence interval (95% CI) estimation of the total waste generated from household without business from 6 districts in Da Nang, a non-parametric bootstrap with return was applied. The estimation processes followed the Monte-Carlo methodology, which is presented by Matsui et al (2018). The procedure consisted of 5 steps, as follows:

Step 1: One bootstrap sample was created by picking randomly from the original dataset with return. The sampling was completed with replacement, so some of the data will be in the bootstrap sample multiple times, and other data will not appear at all.

Step 2: The calculation of waste generation rates, waste separation participation rates, and waste composition were performed by each business sources with bootstrap sample.

Step 3: The total waste generated, and breakdown components were estimated.

Step 4: Repeat steps 1–3 to create 10,000 bootstrap samples.

Step 5: The approximate relative contribution of each parameter to the variance of the total waste generated amount was analyzed.

The results showed that the range for a 95% CI estimation of total waste generation was 186.9 – 233.5 tons/day as shown in Figure 2.6. The results also showed that the recycling potential and composting potential were estimated to be 131.1 – 177.0 and 25.2 – 32.8 tons/day, respectively.

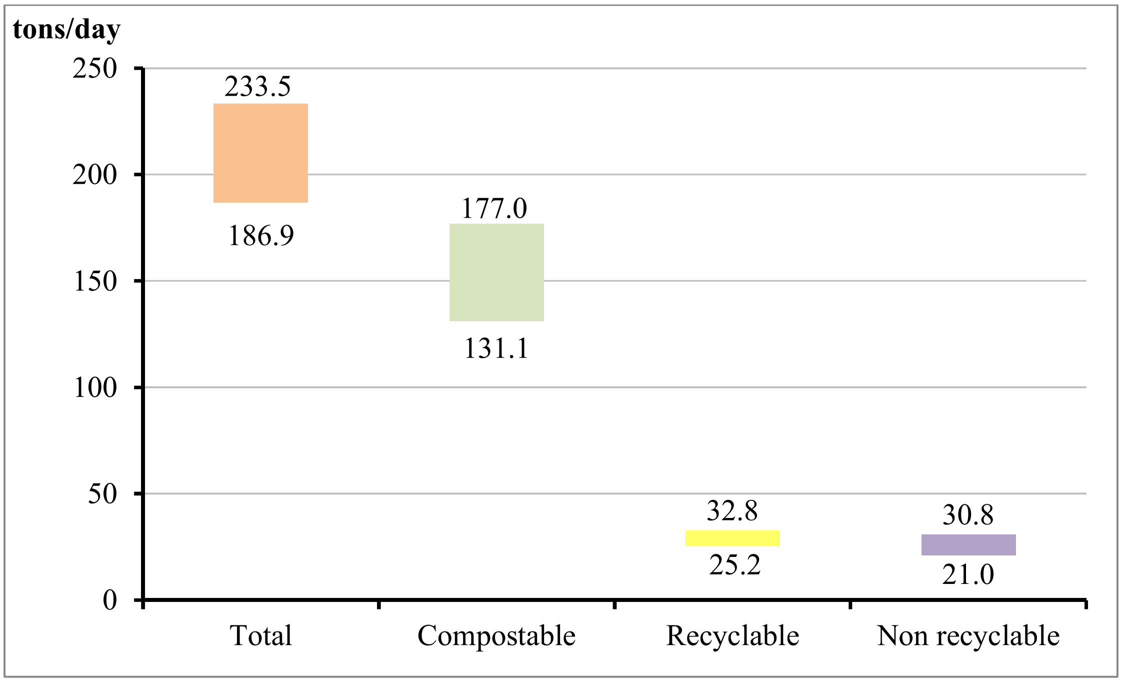

Figure 2.6 –. Total HSW amount and breakdown components

The confidence intervals of recyclable and breakdown components are shown in Figure 2.7. The recyclable plastic was estimated to be 15.08 – 19.83 tons/day, followed by recyclable paper (5.75 – 11.04 tons/day) and recyclable metal (1.51 – 3.66 tons/day). The CI estimation of revenue from recyclable is shown in Figure 2.8. The total revenue was estimated to be 71 to 89 million VND per day.

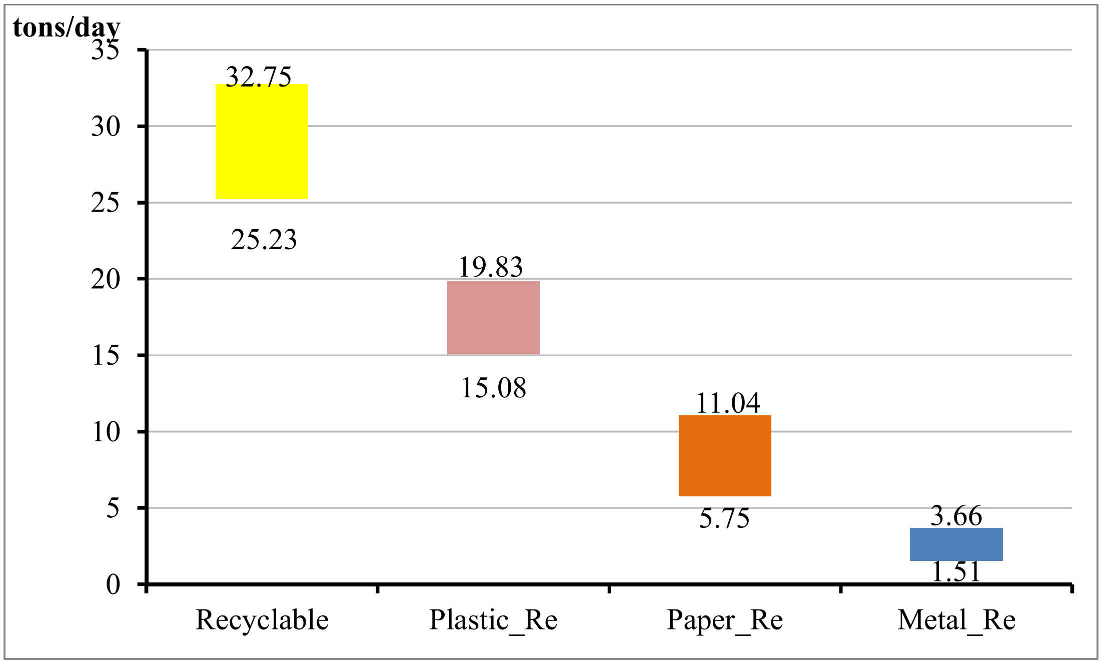

Figure 2.7 – Confidence interval estimation of recyclables

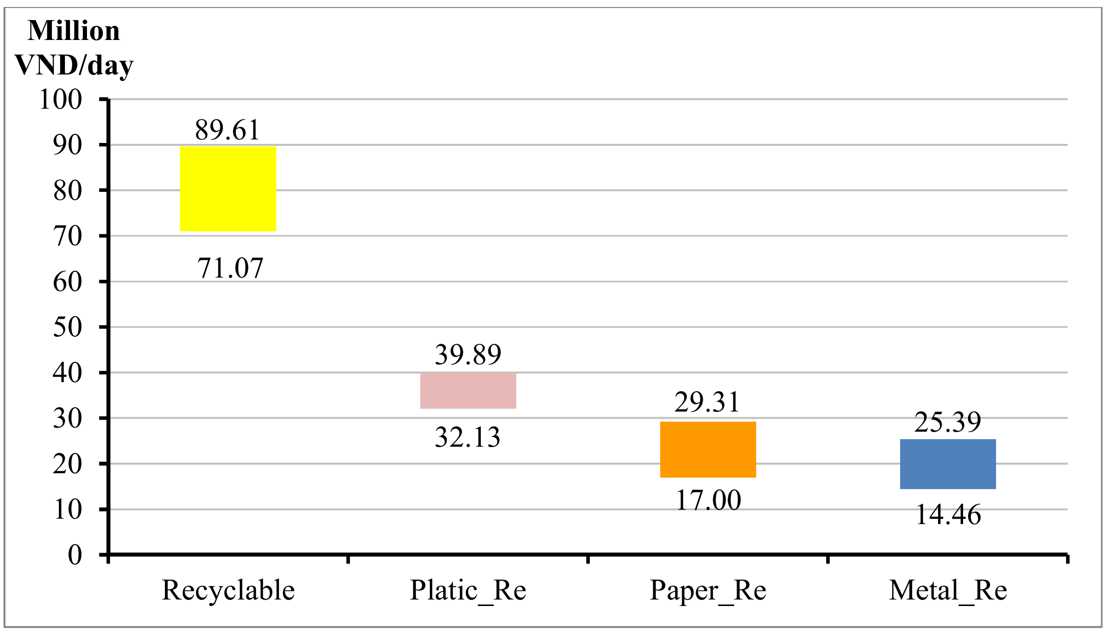

Figure 2.8 – Confidence interval estimation of revenue from recyclable

To estimate the impact of WGRs on the confidence interval estimation, a sensitivity analysis for all categories was conducted. The result in Figure 2.9 shows that kitchen waste has the major effects on total waste estimation because of the highest contribution in waste composition.

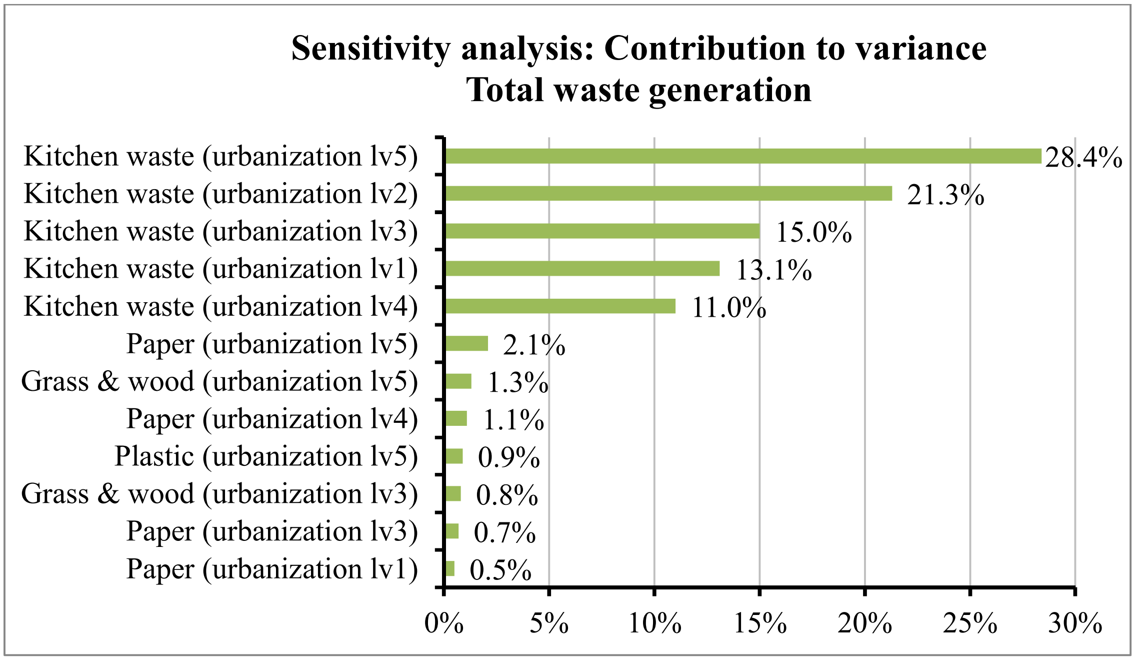

Figure 2.9 – Sensitivity analysis results of total waste generation

2.4. Conclusion

This study focused on HSW from 6 urban districts of Da Nang. The surveys were carried out from November 21th to December 5th, 2016, including four surveys; a questionnaire survey, a measurement survey, and a composition survey and a basis composition survey. The survey was conducted to measure waste discharge every day for 7 consecutive days from 150 households. The objectives were to identify HSW characteristic, recycling potential, and to estimate the total waste generation and its breakdown components.

The average of total HSW generation was 231.49 g/cap/day for an average of 4.6 residents per household of 150 target samples. Food waste contributed the largest part of the total HSW generation with around 157.95 g/cap/day (68.23%), following by plastic (10.95%), paper (9.4%), and others. For recycling potential, compostable waste accounted for the main proportion of the total with 168.38 g/cap/day (around 73% of total), followed by recyclable material (13.77%), and non-recoverable waste (13.5%). For the detailed compositions of recyclable HSW, plastic material distributed the greatest fraction of the total; in which, 49.38% of plastic bag (about half of the total recyclable HSW). The second largest component belonged to paper material, in which, newspaper/ magazine accounted for the main part with 8.29% of the total, followed by paper (carton paper) container & packaging (6.36%). For basis component, the moisture content was the highest with 45.16%, followed by combustible content (42.75%) and ash content (12.08%). The low heating value was 6,801 kJ/kg, which was suitable for incineration treatment process.

Factors affecting waste generation rate were urbanization level, household size, and income level. The higher the level of urbanization and income, the greater the amount of HSW generated per capita. The waste generation rate tended to decrease in the household with larger family size. Urbanization level and household size were two significant predictors for HSW generation rate.

Total HSW generation in six districts of Da Nang was estimated to be 186.9 – 233.5 tons/day, of which composting potential and recycling potential were estimated to be 131.1 – 177.0 and 25.2 – 32.8 tons/day, respectively. The total value of recyclables was estimated up to 79 million VND per day, equivalent to 716 labors to be employed.

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3. SCENARIO ANALYSIS ON GREENHOUSE GAS EMISSION FOR WASTE-TO-ENERGY ALTERNATIVES IN JAPAN

3.1. Introduction

Along with the dramatic increase in population, change of consumption style, economic development, and rapid urbanization, municipal solid waste (MSW) has become a large burden in Japan. Among the common methods used for treating MSW, waste incineration has received increased attention because of its properties of waste volume reductions and hygienic problem prevention (Psomopoulos et al., 2009). Since the introduction of the first waste incineration plant in Japan in 1924, the waste incineration technology has developed and expanded over the years.

In the past, the main benefits of waste incineration were to reduce the waste in mass and in volume to save the limited landfill site, as well as prevent sanitary problems (Gohlke and Martin, 2007). Nowadays, the technological improvement in the incineration field together with the increasing energy content in waste, affected by the change in the consumers' habits, has led to an additional attractiveness of energy recovery from waste incineration (Calabrò, 2010; Stehlók, 2012). With the goal of global warming prevention mission, greenhouse gas (GHG) mitigation has recently become one of the major objectives in the MSW management system. The national GHG inventory report of Japan for 2012 has stated that 20,874 thousand tons of CO2e were emitted from the waste sector (accounted for 1.7% of Japan's total GHG emissions), of which 14,356 thousand tons of CO2e was from waste incineration (represented 1.1% of the national total emissions) (National Greenhouse Gas Inventory Report of Japan, 2012).

As some studies confirmed, waste-to-energy (WtE) facilities reduced GHG emissions from the MSW treatment system by energy/material recovery processes (Murphy and McKeogh, 2004; Rand et al., 2000; Stehlók, 2012; Tabata, 2013). Japan Ministry of the Environment (JMOE) has intended to expand the introduction of the WtE facility and improve the energy recovery efficiency to establish the Sound Material-Cycle Society. JMOE has also promoted the introduction of the ash-melting process for material recovery and reductions of landfill amount.

However, the detailed breakdown of GHG emissions of the WtE facility and their influence factors, such as waste characteristics and specifications of the facility, has not been analyzed in detail. As Lombardi et al. mentioned, the basic data on the waste incineration plant performance was still limited in the scientific literature about energy recovery from waste. They suggested that publication with real plant data should be encouraged (Lombardi et al., 2015).

In the present study, the authors aimed to investigate the detailed composition of GHG emissions from the WtE facility and their relating factors using two Japanese databases on the operation of incinerators from JMOE and Japan Waste Research Foundation. The databases cover detailed data on the MSW amount and characteristics (annual treated waste amount, waste composition, calorific value, etc.), specs of the facility (scale, type of furnace, operation hours, type of ash melting, etc.), utility consumption (electricity, fuels and water), and annual energy/material recovery (annual power generation amount, annual heat recovery, annual slag amount, etc.). The authors analyzed the correlations among them and tried to develop predictive models for the detailed components of GHG emissions and reductions.

JMOE intended to group small municipalities for replacing small-scale incinerators to large-scale WtE facilities with higher energy recovery efficiency to promote GHG mitigation. All 47 prefectures have issued plans for block formation by small municipalities for MSW management. Based on the abovementioned data and models, the authors estimated the expected effect of the block formation for GHG emissions by a national level. The effects of major technological options were also discussed.

3.2. Methodology

3.2.1. System boundary and calculation condition

This study focuses on the GHG emissions and reductions of the MSW incineration process. The authors included the following components of GHG emissions and reductions:

1) direct CO2 emissions from waste burning: CO2 emissions from fossil plastic burning and synthetic textile burning
2) direct CO2 emissions from fossil fuels: CO2 emissions from burning fossil fuels

3) direct CH_4 and N_2O emissions from waste burning: methane gas (CH_4) and dinitrogen monoxide (N_2O) releasing from the combustion chamber
4) indirect CO_2 emissions by utility consumption: CO_2 emissions from the production of electricity, fuels, and water used at the facility
5) indirect CO_2 reductions by energy recovery: CO_2 reductions by saving energy by power generation and heat utilization at the facility
6) indirect CO_2 reductions by slag recycling: CO_2 reductions by recycling slag from ash melting

The GHG emissions and reductions were calculated by the amount of each GHG component multiplied by the corresponding GHG emissions factors (Table 3.1). The GHG emission factors were extracted from the Japan Environmental Management Association for Industry, "2006 IPCC Guidelines for National Greenhouse Gas Inventories," and "National Greenhouse Gas Inventory Report of Japan 2012" (Guendehou et al., 2006; National Greenhouse Gas Inventory Report of Japan, 2012). The function unit was defined as the management of 1 ton of combustible waste.

3.2.2. The dataset on the incineration facility

The authors aimed to investigate the detailed composition of the GHG emissions from the WtE facility and their relating factors using two Japanese databases on the operation of incinerators from JMOE and Japan Waste Research Foundation (JWRF).

Regarding the former database, JMOE has conducted a survey of all the incineration facilities for MSW every year. The survey items included the MSW amount and characteristics (annual treated waste amount, waste composition, calorific value, etc.), specs of the facility (scale, type of furnace, operation hours, type of ash melting, etc.), and annual energy/material recovery (power generation amount, heat recovery).

Regarding the latter database, JWRF has conducted a detailed survey for a part of the incineration facilities for MSW every year until 2010. The survey items covered the annual treated amount, utility consumption (electricity, fuels and water), detailed technological parameters (scale, type of furnace, operation hours, type of turbine, steam condition, type of ash melting, etc.), and annual energy/material recovery (power generation amount, heat recovery, slag amount, etc.).

The authors analyzed the data in 2009, which is the data from the last survey year of the JWRF database. The numbers of facilities from the JMOE and JWRF databases were 1,243 and 814, respectively.

3.2.3. Analytical process

The authors intended to clarify the influence factors for the GHG emissions and reductions.

Regarding the direct GHG emission components, the authors calculated the direct CO_2 emissions from waste burning (e.g., fossil CO_2 from plastic) based on the waste composition data for each facility in the JMOE and JWRF databases. The authors applied the emission factors for the direct CH_4 and N_2O emissions from waste burning (Table 3.1). The global warming potential from the IPCC AR4 was applied herein for methane and dinitrogen monoxide gases. The global warming potential for 100 years was applied to calculate the total GHG emissions by CO_2 equivalent. The authors did not consider the influence factors for the direct CO_2 emissions from waste burning and the direct CH_4 and N_2O emissions from waste burning. The direct CO_2 emissions from fossil fuels were calculated together with the indirect CO_2 emissions from fuels, as will be described later.

Regarding the indirect GHG emissions and reduction components, the authors estimated the indirect CO_2 emissions by utility consumption, indirect CO_2 reductions by energy recovery, and indirect CO_2 reductions by slag recycling by the amount of each GHG component multiplied by the corresponding GHG emission factors (Table 3.1). The authors also calculated the averages of the utility consumption rates and the energy/material recovery rates using the following major technological parameters: scale, type of furnace, operation hours, type of turbine type, steam condition, with/without ash melting, and with/without power generation. The analysis of variance (ANOVA) and rank correlation analysis by the Spearman method was applied to judge whether significant differences existed. The needed data was extracted from the JWRF database that covered utility consumptions, energy/material recovery, and detailed technological parameters.

The mathematical modeling for the utility consumption rates and the energy/material recovery rates was then implemented through a multi-regression analysis. The significant influence factors by ANOVA were used as candidates for explanatory variables. The outliers were detected and excluded by Cook's distance criterion (D > 4/n (n is the sample size)) (Cook and Weisberg, 1982).

Table 3.1 – GHG emission factors applied in this study

Process	Component	Inventory	Direct emission factor	Indirect emission factor	Source
Operation	Fossil plastic burn	CO_2	Plastic burning: 2.69 tCO_2/t Synthetic textile: 2.29 tCO_2/t		JMOE
Operation	Fossil fuel burn	CO_2	Heavy oil: 0.0693 tCO_2/GJ Light oil: 0.0687 tCO_2/GJ Kerosene: 0.0679 tCO_2/GJ Coke: 0.108 tCO_2/GJ City gas: 0.0498 tCO_2/GJ LPG: 0.0595 tCO_2/GJ Gasoline: 0.0671 tCO_2/GJ	Heavy oil: 0.0096 tCO_2/GJ Light oil: 0.008 tCO_2/GJ Kerosene: 0.0073 $tCO_2/$ GJ Coke: 0.0206 $tCO_2/$ GJ City gas: 0.0105 $tCO_2/$ GJ LPG: 0.0149 $tCO_2/$ GJ Gasoline: 0.0142 $tCO_2/$ GJ	JEMAI
Operation	CH_4/N_2O from the combustion process	CH_4, N_2O	Continuous incinerator: 2.6 gCH_4/t Semi-continuous incinerator: 20.6 gCH_4/t Batch incinerator: 13.4 gCH_4/t Gasification: 7.0 gCH_4/t Continuous incinerator: 37.9 gN_2O/t Semi-continuous incinerator: 72.7 gN_2O/t Batch incinerator: 76.0 gN_2O/t Gasification: 11.2 gN_2O/t		JMOE
Operation	CH_4/N_2O from the combustion process	CH_4, N_2O	GWP (100-yr) of CH_4: 25 GWP (100-yr) of N_2O: 298		IPCC
Utility consumption	Power Water	CO_2		Power: 0.555 tCO_2/MWh Water: 0.99 $kgCO_2/m^3$	JMOE)
Energy/material recovery	Power generation Heat utilization	CO_2		Power: −0.555 tCO_2/MWh Steam: −0.06 tCO_2/GJ	JMOE
	Slag recycling			Slag: −0.0044 tCO_2/t	JEMAI

JMOE: (*Japan Ministry of the Environment: Reference material for calculating GHG emissions (In Japanese)*)
IPCC: (Al., 2007)
JEMAI: (JEMAI, 2014)

3.3. Results and discussion

3.3.1. Outline of incineration in Japan in 2009

The database of JMOE in 2009 showed that 1,243 operating facilities were among the 1,345 incinerators in Japan. Table 3.2 shows the number of waste incineration facilities in Japan in 2009 by capacity and applied technology.

Table 3.2 – Outline of the operating incinerators in Japan (2009)

	Operation hours			Furnace type							
Capacity (tons/day)	Continuous	Semi continuous	Batch	Stoker incinerator	Fluidized bed incinerator	Shaft Gasification	Other gasification	Other	With power generation	With ash melting	Total
≤ 100	121	200	363	472	99	15	15	83	12	51	684
100 ~ 150	140	32	-	117	31	15	8	1	35	23	172
150 ~ 200	102	3	-	70	20	7	8	-	29	15	105
200 ~ 300	131	-	-	104	13	3	11	-	81	36	131
300 ~ 450	73	-	-	48	14	6	5	-	58	21	73
450 ~ 600	57	-	-	52	2	2	1	-	57	24	57
600 ~ 800	6	-	-	5	-	1	-	-	6	3	6
800 ~ 1000	9	-	-	9	-	-	-	-	9	2	9
1000 ~ 1400	4	-	-	4	-	-	-	-	4	1	4
1400 ~ 1800	2	-	-	2	-	-	-	-	2	1	2
Total	645	235	363	883	179	49	48	84	296	177	1,243

The incinerators with a capacity smaller than 100 tons/day accounted for more than half of the total number of MSW incinerators in Japan (n = 684, 55%). Gohlke and Martin explained that the direct landfill was limited in Japan because of the lack of space. Thus, the municipal solid waste was incinerated in a high number of small plants (Gohlke and Martin, 2007). However, the treated waste amount by these small incinerators was 4,988 thousand tons, which is only 14% of the 35,523 thousand tons of total incinerated waste.

Regarding the operation hours, "Continuous (24-hour operation)" was 52% of the total facilities, followed by "Batch (8-hour operation)" and "Semi-continuous (16-hour operation)." For the furnace type, "Stoker incinerator" was widely applied (71%), which could be explained by some of the advantages of the stoker incinerator (e.g., no need for prior sorting or shredding; the technology is widely used and thoroughly tested for waste incineration; meets the demands for technical performance; can accommodate a large variation in the waste composition and calorific value; and allows for an overall thermal efficiency of up to 85%) (Rand et al., 2000). Castaldi and Themelis also affirmed that the technology of the stoker incinerator with a mobile grate combustor has reached a high level of development (Castaldi and Themelis, 2010).

The incinerators with power generation were only 296 plants and especially limited for smaller facilities. Tabata mentioned that approximately 80% of the MSW in Japan was incinerated, but only 24.5% of the MSW incineration plants applied energy recovery (Tabata, 2013). Tanigaki et al. explained that one of the main objectives of waste management in Japan was reducing the buried volume at the landfill. They also mentioned that the treatment of the MSW incinerator bottom ash, such as melting, had higher priority before landfilling because of the strict regulation of environmental management in Japan (Tanigaki et al., 2012). The ash melting process was applied to 177 plants (9%).

3.3.2. Outline of combustible waste in Japan in 2009

MSW is a heterogeneous mixture of several materials. Its compositions and characteristics are affected by cultural differences, climate, socio-economic conditions, and the recycling policy (Bandara et al., 2007; Calabrò, 2010; Rand et al., 2000; Stehlók, 2012; Thanh et al., 2010).

According to the JMOE database in 2009, the combustible waste generation rate in Japan was 899 g/cap/day. “Paper and textile” was dominant in the waste composition (49.1%, n = 1,095), followed by “plastic and leather” (20.2%, n = 1095), and “biogenic waste” (15.4%, n = 1,095). “Combustible,” “moisture,” and “ash” accounted for 42.3% (n = 1,095), 47.9% (n = 1,095), and 9.7% (n = 1,095), respectively. According to the JWRF database in 2009, the “plastic” content was 18.5% (n = 373), while the “synthetic textile” content was 13.1% (n = 171).

The lower heating value (LHV) of waste is the key parameter for the waste incineration operation. Komilis et al. mentioned that MSW can be incinerated without auxiliary fuels when its LHV exceeds 5–7 GJ/t (Komilis et al., 2014). Tanner suggested that the mass content of combustible waste must be higher than 25%, while moisture and ash must be lower than 50% and 60% for self-combustion, respectively (Tanner, 1965). Referring to these criteria, MSW in Japan was suitable for the incineration process. The LHV of the combustible waste was 8.5 ± 1.9 GJ/t (mean ± standard deviation), which contained the high calorific potential for the WtE facility.

3.3.3. Utility consumption and influence factors

Using the JWRF database, the authors calculated the averages of the utility consumption rates through the major technological parameters. Table 3.3 summarizes the results of the energy consumption rate by technological options.

The power consumption rate of the MSW incineration plants was significantly different ($F = 24.9$, $p < 0.001$) among the types of furnace. “Shaft gasification” had the highest consumption rate with 371 ± 125 KWh/t, followed by “other gasification” (343 ± 106 KWh/t), “incineration with ash melting by electricity” (298 ± 111 KWh/t), and “incineration without ash melting” (187 ± 137 kWh/t). The BREF/Best Available Technique (BAT) reported that the process energy demand of incineration plants was 60 to 700 kWh/t. The major power-consuming parts of the incinerator were the induced draught fan (30%), forced draught fan (20%), delivery and water pumps (20%), a condenser (10%), and other equipment (20%). BREF/BAT also stated that the power consumption rate had a negative correlation with facility scale (Gabor Doka, 2005). Using the Pearson correlation analysis, the authors found a negative correlation between the power consumption rate and the facility capacity ($r = -0.121$; $p = 0.013$; $n = 424$).

The incineration plants also consumed some auxiliary fuels (e.g., diesel, heavy oil, gasoline, city gas, or liquefied petroleum gas). The authors calculated and presented the fuel consumption rate by GJ per ton of waste (GJ/t) based on the consumed amount and the calorific value of each fuel type. The fuel consumption rate of the MSW incineration plants was significantly different among the types of the furnace ($F = 8.06$; $p < 0.001$). The gasification process consumed an additional amount of fuel to produce a syngas with the desired chemical composition and calorific value. Thus, the fuel consumption rates at the gasification facilities (2.25 ± 0.28 GJ/t for “shaft gasification” and 1.03 ± 0.20 GJ/t for “other gasification” plants) were much higher than those in the “incineration without ash melting” (0.07 ± 0.01 GJ/t). “Incineration with ash melting by fuel” consumed 0.59 ± 0.01 GJ/t of waste. The authors found a negative correlation between fuel consumption rate and scale ($r = -0.126$; $p = 0.003$; $n = 566$).

Table 3.3 – Energy consumption rate by technological options

Technological options	Fuel consumption rate (GJ/t)		Power consumption rate (KWh/t)	
	n	Mean ± SD	n	Mean ± SD
Shaft gasification	35	2.25 ± 0.28	25	371 ± 125
Other gasification	36	1.03 ± 0.20	27	343 ± 106
Incineration with ash melting (fuel/electricity)	25	0.59 ± 0.01	40	298 ± 111
Incineration without ash melting	412	0.07 ± 0.01	412	187 ± 137
ANOVA (F value)		8.06***		24.9***

***$p < 0.001$

Source: (*Japan Waste Research Foundation : Ledger on municipal solid waste incinerator in FY2009 (In Japanese)*, 2010)

The major water consumption in waste incineration plants was for flue-gas cleaning and steam production. The water consumption was reported to be 1 to 6 m^3/ton of waste and depended on the flue-gas cleaning system and re-circulating treated effluent of wastewater. The facilities without energy recovery consumed more water than the others (Gabor Doka, 2005). The authors used the data analysis and found a significant difference in the water consumption rate between the facilities with an energy recovery boiler (0.96 ± 0.36 m^3/t, n = 259) and those without (2.16 ± 1.2 m^3/t, n = 348) ($F = 200$; $p < 0.001$).

3.3.4. Energy/material recovery and influence factors

The possibilities of energy recovery depend on the local energy market conditions, including infrastructure for energy distribution (e.g., availability of a power grid, district heating network, and heat utilization facility nearby), price of various types of energy, and possible agreement with the consumer(s). According to the JMOE database, 296 incineration plants in Japan performed energy recovery, with a total electricity generation amount of 6,918,803 MWh. However, the power generation efficiency was still low with 10.9% of the national average.

Based on the analysis of the JWRF database, Table 3.4 shows the heat utilization rate from WtE incineration in Japan in 2009. The produced heat was used for the turbine generator for power generation, for onsite purposes (e.g., hot water, air condition, and road heating), and offsite purposes (i.e., heated pools and public facilities). The average percentage showed the allocated heat in the total heat for the target heat utilization. The results showed that the turbine generator at the facility with power generation consumed approximately 63.44% of the total input heat. Heat recovery was mainly used within the incineration plant (approximately 3.61% of the total input heat) because of the restrictions on the configuration and distance for supply. Moreover, a smaller amount was provided to the local facility (approximately 1.75% of the total input heat). The heat supply for district heating was not common.

Using the JWRF database, the authors calculated the averages of the power generation rate and the power generation efficiency by utilizing the major technological parameters. Table 3.5 summarized the results. The power generation (PG) rate was found to be significantly different among the types of the furnace through ANOVA ($F = 3.5$; $p = 0.03$). “Shaft gasification” was highest (347 ± 243 kWh/t), followed by “other gasification” (347 ± 243 kWh/t), “stoker incineration” (277 ± 129 kWh/t), and “fluidized bed incineration” (206 ± 90 kWh/t). The PG efficiency was also found to be significantly different among the types of the furnace through ANOVA ($F = 5.5$; $p = 0.007$). Excluding the fluidized bed incinerator, the PG rates of the gasification plants were higher than that of the stoker incinerators. However, the turbine generator was similar among the three types of furnace. The reason for the difference in the PG rate would be the larger fuel consumption in the gasification plants.

Table 3.4 – Heat consumption by heat utilization

Heat utilization	n[b]	Heat consumption rate (MJ/t)[a] 25% percentile	Mean	75% percentile	Average percentage of allocated heat in total heat (%)
Turbine generator	218	3,092	5,851	7,154	63.44
Onsite	542	141	332	877	3.61
Hot water	127	9	59	214	0.63
Air condition	47	6	31	128	0.34
Road heating	7	1	25	183	0.30
Others	59	17	77	426	0.84
Offsite	89	61	162	316	1.75
Heated pool	47	14	30	197	0.33
Public facility	5	23	90	460	0.81
Others	66	39	88	232	0.85

[a]Heat recovery from the incinerator boiler

[b]Number of the observed facility with available data

Source: JWRF

Table 3.5 – Power generation rate and efficiency by major technological parameters

Technological parameter	n	PG rate[a] (KWh/t)	PG efficiency (%)	Turbine generator efficiency (%)
Furnace type				
Stoker incinerator	174	277 ± 129	11.2 ± 4.9	17.7 ± 7.0
Fluidized bed incinerator	28	206 ± 90	8.6 ± 3.7	13.7 ± 5.3
Shaft gasification	27	347 ± 243	12.4 ± 4.1	17.3 ± 4.2
Other gasification	29	328 ± 157	11.4 ± 3.7	17.1 ± 6.6
ANOVA (F value)		3.5*	5.5**	2.9*
Turbine type				
Back pressure	51	140 ± 56	5.7 ± 1.9	9.7 ± 3.1
Condensing	120	271 ± 138	10.8 ± 3.5	16.7 ± 4.5
Extraction condensing	87	386 ± 119	11.2 ± 4.8	22.0 ± 6.0
ANOVA (F value)		107.0***	67.0***	90.6***
Steam condition				
Level 1 (≤2 MPa)	94	186 ± 85	7.8 ± 3.7	12.8 ± 5.2
Level 2 (>2 MPa, >200 °C)	100	283 ± 96	11.3 ± 3.5	17.3 ± 5.0
Level 3 (>3 MPa, >300 °C)	64	423 ± 175	15.7 ± 3.7	23.7 ± 17.1
ANOVA (F value)		90.7***	77.1***	78.1***
Rank correlation[b] (ρ)		0.538**	0.539**	0.517**

*p < 0.05; **p < 0.01; and ***p < 0.001 *Source:* JWRF

[a]PG: power generation and [b]rank correlation by the Spearman method

Table 3.5 also shows the averages of the PG rate and efficiency by turbine type. The PG rate of the "extraction condensing" turbine was highest (386 ± 119 KWh/t), followed by the "condensing" turbine (271 ± 138 KWh/t), and the "backpressure" turbine (140 ± 56 KWh/t). A significant difference by turbine type was also found through ANOVA (F = 107; p < 0.001). This result was caused by the different abilities of the turbine types. As regards the turbine design, the backpressure turbine was the simplest and had the lowest cost compared to the other turbine types with the same scale. However, the backpressure turbine was not common at medium- and large-scale WtE plants in Japan because of its requirement of a stable inlet steam condition. In contrast, the condensing turbine is widely used for power generation facilities that want to supply electricity to consumers as much as possible. A vacuum condition occurring through the condensing process increases the turbine efficiency, thereby generating a high amount of electricity. However, the condensing turbine consists of many turbine stages and requires a large condenser, causing more construction activities and a higher maintenance cost. The extraction condensing turbine is a condensing turbine with two or more outlets for independently adjusting the electric power and the processed steam flow. The extraction condensing turbine has features of both the condensing and backpressure turbines. It also has the capability of fulfilling the requirements of both electric power supply and process steam flow (Gabor Doka, 2005; *Japan Waste Research Foundation : Ledger on municipal solid waste incinerator in FY2009 (In Japanese)*, 2010; Rand et al., 2000; Tanuma, 2017). The extraction condensing turbine was applied for medium- and large-scale WtE plants in Japan. Kean et al. reported that the power generation efficiency of WtE incineration was affected by the turbine design (e.g., with/without condensing function). The same authors also stated that the condition of the supplied steam is one of the important factors in power generation. They noted that the greater the pressure and temperature drop through the turbine, the greater the amount of electricity that can be generated (Kean and Brickner, n.d.).

Figure 3.1 presents the distribution of the steam condition by turbine type using the JWRF database. The authors applied a cluster analysis for the data on steam pressure and temperature, then categorized the steam condition into three levels as follows:

– Level 1: the steam pressure is equal to or less than 2 MPa.
– Level 2: the steam pressure is from 2 MPa to 3 MPa, and the temperature is higher than 200 °C
– Level 3: the steam pressure is higher than 3 MPa, and the temperature is higher than 300 °C

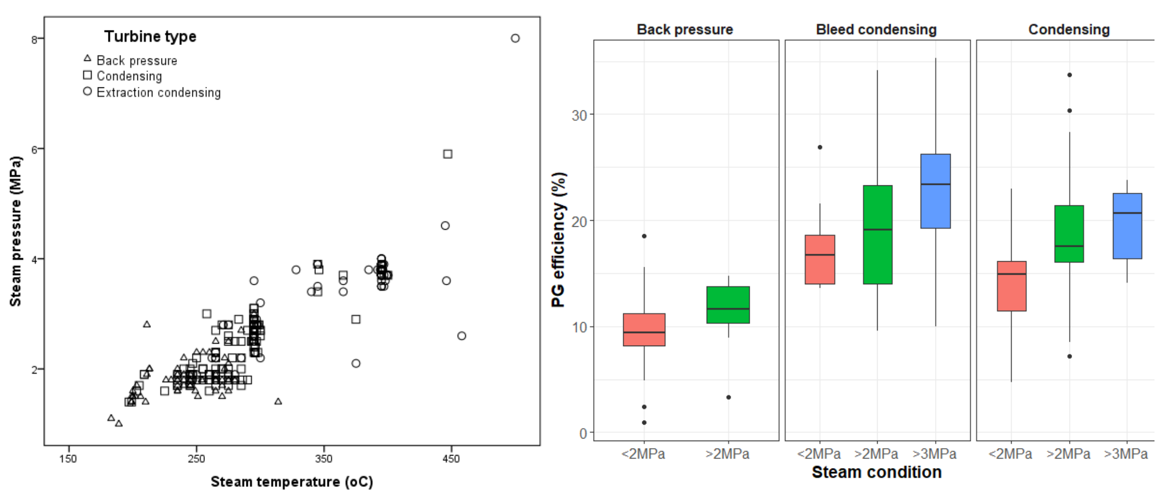

Figure 3.1 – PG efficiency by steam condition and turbine type

As regards the steam condition, the PG rate at “Level 3” (423 ± 175 KWh/t) was approximately two times higher than that at “Level 1” (186 ± 85 KWh/t) and approximately 1.5 times higher than “Level 2” (283 ± 96 KWh/t). These differences were found significant by ANOVA ($F = 90.7$; $p < 0.001$). According to the rank correlation analysis results by the Spearman method, the steam level, and the PG rate had a positive correlation ($\rho = 0.538$; $p < 0.01$). The results were also similar to the PG efficiency by the steam condition.

The power generation efficiency is defined as the ratio between the useful electricity output from the generating unit in a specific time unit and the energy value of the primary energy source supplied to the unit within the same time. Different energy conversion processes have different thermodynamic limitations; hence, the power generation efficiency should not be compared with the energy sources that use different kinds of fuels (Rand et al., 2000; Stehlók, 2012; Tanuma, 2017). In the abovementioned energy consumption section, the “gasification” process consumed more fuels than the “incineration” process; thus, the PG efficiency at the “gasification” plants was significantly higher than that at the “incineration” plants. However, as regards the turbine generator (TG) efficiency, no difference was found between the “stoker incinerator” and the “gasification” plants.

Therefore, for further analyses, the authors would like to focus more on the technological parameters affecting the power generation by TG efficiency. The TG efficiency was significantly affected by the turbine type and the steam condition ($p < 0.001$). Table 3.6 shows the turbine generator efficiency by turbine type and steam condition categories. The TG efficiency at “Level 2” (11.0 ± 3.5%) for the “backpressure” turbine was higher than that at “Level 1” (9.7 ± 3.4%). However, the authors could not find the significant difference ($F = 0.87$; $p = 0.07$). The TG efficiency for the “condensing” turbine was the highest at steam condition “Level 3” (19.6 ± 4.0%), followed by “Level 2” (18.5 ± 4.8%) and “Level 1” (14.4 ± 4.2%). A significant difference was found ($F = 8.1$; $p = 0.001$). The rank correlation analyses by the Spearman method showed a positive correlation between the TG efficiency and the steam condition level (rank correlation = 0.37; $p < 0.001$). A positive rank correlation between the TG efficiency and the steam condition level ($\rho = 0.433$; $p < 0.001$) was observed for the “extraction condensing” turbine. At the same steam condition, the TG efficiency was the highest at the "extraction condensing" turbine, followed by the "condensing" and "backpressure" turbines. A significant difference was observed among the turbine types.

Table 3-6. Turbine generator efficiency (%) by steam condition and turbine type

	Steam condition						
	Level 1		Level 2		Level 3		
Turbine type	n	Mean ± SD	n	Mean ± SD	n	Mean ± SD	ANOVA (F value)
Back pressure turbine	38	9.7 ± 3.4	13	11.0 ± 3.5	-	-	0.87
Condensing turbine	46	14.4 ± 4.2	61	18.5 ± 4.8	13	19.6 ± 4.0	8.1**
Extraction condensing turbine	8	17.6 ± 4.6	28	19.2 ± 6.8	51	23.3 ± 6.6	8.3**
ANOVA (F value)	20.3***		12.1***		4.9*		

*p < 0.05; **p < 0.01; and ***p < 0.001
Source: JWRF (*Japan Waste Research Foundation : Ledger on municipal solid waste incinerator in FY2009 (In Japanese)*, 2010)

Regarding the ash melting function, the slag recycling rate by gasification (78 kg slag/ton of waste) was 53% higher than that of ash melting by electricity/fuel (51 kg slag/ton of waste). A significant difference was detected by ANOVA ($F = 8.3$; $p = 0.044$).

3.3.5. Mathematical modeling for utility consumption and energy recovery

In reference to the results of the abovementioned analyses, the authors implemented mathematical modeling for the utility consumption and energy/material recovery rates using a multi-regression analysis. The significant influence factors by ANOVA were used as candidates for explanatory variables. Table 3.7 shows the definition of the objective and explanatory variables. Tables 3.8 and 3.9 present the multilinear regression models on the utility consumption and energy/material recovery rates.

As regards the fuel consumption rate of "gasification," the dummy variables for "shaft gasification" and "power generation function" were selected as the explanatory variables. For the fuel consumption rate of "incineration," the dummy variables for "ash melting by fuel" and "power generation function" were selected. Meanwhile, the dummy variables for "gasification furnace," "ash melting by electricity function," and "facility capacity" were selected as the positive predictors for the power consumption rate. "Capacity of the facility" was selected as a negative predictor.

Regarding the TG efficiency, the authors separately developed two models for the "condensing" and "extraction condensing" turbines (Table 3.8). The dummy variables for the steam condition in both models (i.e., "Steam level 2" and "Steam level 3") and the capacities of the facility by steam condition (i.e., "Capacity of the facility with steam level 2" and "Capacity of the facility with steam level 3") were selected as predictors. The coefficients for the capacities of the facility were slightly larger at the models on the "extraction condensing turbine."

Table 3.7. Definition of variables

	Variable	Factor	Range of variable
Response variable	Y_1	Fuel consumption rate (GJ/t)	
	Y_2	Power consumption rate (MWh/t)	
	Y_3	Water consumption rate (m^3/t)	
	Y_4	Turbine generator efficiency of the condensing turbine (%)	
	Y_5	Turbine generator efficiency of the extraction condensing turbine (%)	
Predictor variable	C	Constant	
	Cap	Capacity of facility (t/d)	0.1–1,000
	Gas	Gasification furnace	"Yes" = 1; "No" = 0
	Gas_{Shaft}	Shaft gasification furnace	"Yes" = 1; "No" = 0
	Gas_{Other}	Other gasification furnace	"Yes" = 1; "No" = 0
	AM_{fuel}	Ash melting by fuel	"Yes" = 1; "No" = 0
	$AM_{electricity}$	Ash melting by electricity	"Yes" = 1; "No" = 0
	PG	Power generation function	"Yes" = 1; "No" = 0
	St_2	Steam level 2 (>2 MPa, >200 °C)	"Yes" = 1; "No" = 0
	St_3	Steam level 3 (>3 MPa, >300 °C)	"Yes" = 1; "No" = 0

Table 3.8 – Results of the multilinear regression analyses for utility consumption

Variable	Explanatory factor	Fuel consumption rate (gasification) (GJ/t)	Fuel consumption rate (incineration) (GJ/t)	Power consumption rate (kwh/t)	Water consumption rate (m^3/t)
		β (Standard Error)			
C	Constant	1.214 (0.06)***	0.071 (0.01)***	216 (12)***	2.13 (0.05)***
Cap	The capacity of the facility (t/d)			−0.14 (0.04)**	
Gas	Gasification furnace			155 (24)***	
Gas_{Shaft}	Shaft gasification furnace	0.222 (0.06)**			
AM_{fuel}	Ash melting by fuel		0.549 (0.002)***		
$AM_{electricity}$	Ash melting by electricity			236 (31) ***	
PG	Power generation function	1.261 (0.05)***	0.03 (0.001)**		−1.21 (0.08)***
n	Number of case	71	495	467	607
R^2	Coefficient of determination	0.885***	0.89***	0.371***	0.347***

*: $p<0.05$, **$p < 0.01$ and ***$p < 0.001$

Table 3.9 – Results of the multilinear regression analyses for energy consumption and recovery

Variable	Explanatory factor	Turbine generation efficiency of the condensing turbine (%)	Turbine generation efficiency of the extraction condensing turbine (%)
		β (standard error)	
C	Constant	14.7 (0.54)**	18.0 (0.8)***
St_2	Steam level 2 (>2 MPa, >200 °C)	1.5 (0.7)**	0.6 (0.02)**
St_3	Steam level 3 (>3 MPa, >300 °C)	2.9 (1.1)**	2.4 (0.9)**
Cap_{St2}	Capacity of facility with steam level 2	0.023 (0.002)***	0.028 (0.003)***
Cap_{St3}	Capacity of facility with steam level 3	0.031 (0.003)***	0.032 (0.002)***
n	Number of case	104	72
R^2	Coefficient of determination	0.551***	0.512***

*$p < 0.05$; **$p < 0.01$; and ***$p < 0.001$

3.3.6. Scenario analysis for the GHG emissions and reductions

Based on the abovementioned analytical results on energy/material consumption and recovery, the authors intended to estimate the total GHG emissions by a national level and investigate the effects of some political and technological alternatives using a scenario analysis.

(1) Scenario definition

a) Scenario 1: business as usual (BAU) scenario

The authors estimated the current status of the GHG emissions and reductions from all the 1,243 operating facilities in 2009 as Scenario 1 ($S_{1\text{-}BAU}$): business as usual scenario.

b) Scenario 2: Block formation scenario

As a political alternative, the authors estimated the expected GHG emissions and reductions by block formation by small municipalities as Scenario 2: Block formation scenario. In 1997, the Japanese government sent one official notice requesting municipalities to establish plans for promoting the block formation. The government intended to group small municipalities for replacing small-scale incinerators by large-scale WtE facilities with a higher energy recovery efficiency. All 47 prefectures in Japan issued plans for the block formation by small municipalities for MSW management (*Ministry of Health and Welfare, Japan: Notice for block formation for municipal solid waste management. (1997) (In Japanese)*, n.d.). Small-scale incinerators with a smaller than 100 t/day capacity were expected to be closed and replaced by a new larger-scale facility with 300 t/d capacity or more (*Japan Waste Research Foundation : Ledger on municipal solid waste incinerator in FY2009 (In Japanese)*, 2010).

The authors used the following conditions to design the blocks for estimation based on the plans for the block formation from the 47 prefectures: 1) close facilities without power generation, 2) facilities with 300 t/day or more with power generation keeping the operation, and 3) integrate facilities in the designated block with a smaller than 300 t/day capacity. In some specific blocks (e.g., isolated islands), the scales of the waste incinerators were smaller than 100 t/d. Table 3.11 shows the number of incineration plants in reference to the plans for the block formation (*Master plans of block formation for municipal solid* *waste management (issued by 47 prefectures in 1998-2017) (In Japanese).*, n.d.). A total of 1,007 plants among the 1,243 incineration plants operated in 2009 were assumed to be closed; 236 plants kept operating, and 286 facilities would be newly built.

The following four representative technological options for the 286 newly built facilities are defined by the predictive models in Tables 8 and 9: 1) stoker with minimum net GHG emissions ($S_{2s\text{-}min}$), 2) stoker with maximum net GHG emissions ($S_{2s\text{-}max}$), 3) gasification with minimum net GHG emissions ($S_{2g\text{-}min}$), and 4) gasification with maximum net GHG emissions ($S_{2g\text{-}max}$).

c) Scenario 3: Block formation scenario with BAT

The authors estimated the expected GHG emissions and reductions using BAT. According to the IPCC document on the BAT, the energy recovery efficiencies for combined heat and power plants are 22.5% for power generation and 37.4% for heat recovery (Gabor Doka, 2005) defined as Scenario 3-CHP ($S_{3\text{-}CHP}$): Block formation scenario with BAT for combined heat and power. As the maximum heat recovery condition, the energy recovery efficiency was defined as 74.3% for heat use only (Gabor Doka, 2005), which was defined as Scenario 3-H ($S_{3\text{-}H}$): Block formation scenario with BAT for heat use only. Table 3.12 summarizes the definition and the technological condition of each scenario.

(2) The methodology of the GHG estimation

For GHG estimation, the authors applied the original data on the components of the GHG emissions and reductions from the JMOE and JWRF databases as much as possible. Table 3.13 summarizes the outline of the applied data for the scenario analysis.

Regarding the waste composition of each facility, the authors applied the percentages of plastic and synthetic textile from the JWRF database for the facilities with waste composition data. For the facilities without waste composition data, the corresponding prefectural average values calculated based on the JWRF database were used.

Regarding the utility consumption of each facility, the authors applied the original data on the utility consumption from the JWRF database that covered 814 facilities. For the remaining facilities without data on utility consumption, the authors calculated their amount by assigning the type of facility to the models in Table 3.8.

Table 3.11 – Number of WtE plants by the integrated waste management system

Capacity range	Operating in FY 2009	Status of operation after block formation: Stop operation	Upgraded	Newly built	Total
≤ 100	684	644	40	47	87
100 ~ 150	172	132	40	51	91
150 ~ 200	105	82	23	39	62
200 ~ 300	131	92	39	46	85
300 ~ 450	73	39	34	73	107
450 ~ 600	57	15	42	29	71
600 ~ 800	6	0	6	3	9
800 ~ 1000	9	0	9	0	9
1000 ~ 1400	4	1	3	0	3
1400 ~ 1800	2	0	2	0	2
Total	1,243	1,007	236	286	522

Table 3.12 – Definition and technological condition of the scenarios

Code	Scenario definition	Technological condition: Furnace	Turbine	Steam level	Ash melting
$S_{1\text{-BAU}}$	Business as usual	Current status			
$S_{2S\text{-Min}}$	Block formation with stoker furnace with minimum net GHG emissions	Stoker	Extraction condensing	Level 3	No
$S_{2S\text{-Max}}$	Block formation with stoker furnace with maximum net GHG emissions	Stoker	Back pressure	Level 1	Electricity
$S_{2G\text{-Min}}$	Block formation with gasification furnace with minimum net GHG emissions	Other gasification	Extraction condensing	Level 3	Gasification
$S_{2G\text{-Max}}$	Block formation with gasification furnace with maximum net GHG emissions	Shaft gasification	Condensing	Level 1	Gasification
$S_{3\text{-CHP}}$	Block formation with BAT with combined heat and power	Stoker	BAT	BAT	No
$S_{3\text{-H}}$	Block formation with BAT with heat use only	Stoker	BAT	BAT	No

Regarding the power generation of each facility, for Scenario 1, the authors applied the original data from JMOE database that covered the power generation amount for all facilities with power generation. For Scenario 2, the authors calculated their amounts by assigning the type of facility to the models in Table 3.8 for the four representative technological options mentioned earlier. Meanwhile, the calculation for Scenario 3 was based on the condition mentioned in the "scenario" definition.

Regarding the heat utilization and slag generation, the authors applied the original data from the JWRF database that covered some of the facilities. For the facilities without data, the authors applied the national average rates calculated based on the JWRF database. The calculation for Scenario 3 was based on the condition mentioned in the "scenario" definition.

Table 3.13 – Outline of the applied data for the scenario analysis

Component	Scenario	Target facility	Applied data	Reference
Direct CO_2 emissions from waste burning	All	Facilities with original data	Data on percentages of plastic and synthetic textile	JWRF
		Facilities without original data	Corresponding prefectural average of percentages of plastic and synthetic textile calculated based on the JWRF database	JWRF
Direct CO_2 emissions from fossil fuels	All	Same as indirect CO_2 emissions by utility consumption		
Direct CH_4 and N_2O emissions from waste burning	All	All facilities	Emission factors for CH_4 and N_2O by type of furnace in Table 1	JMOE
Indirect CO_2 emissions by utility consumption	All	Facilities with original data	Data on utility consumption rate (electricity, fuel, water)	JWRF
		Facilities without original data	Calculated rate by assigning the type of facility to the models in Table 8	
Indirect CO_2 reductions by power generation	Practice 1	All facilities with power generation	Data on the power generation rate	JMOE
	Practice 2	236 facilities, which keep operation (300 t/day or larger in 2009)	Data on the power generation rate	JMOE
		286 newly built	Calculated power	

		facilities	generation rate by assigning the designated technological parameters to the models in Table 8	
	Practice 3	236 facilities, which keep operation (300 t/day or larger in 2009)	Data on the power generation rate	JMOE
		286 newly built facilities	Energy recovery efficiency for power generation: 22.5% for $S_{3\text{-}CHP}$	IPCC
Indirect CO_2 reductions by heat utilization	Practices 1 and 2	Facilities with original data	Data on the heat utilization rate	JWRF
		Facilities without original data	National average rate calculated based on the JWRF database	JWRF
	Practice 3	236 facilities, which keep operation (300 t/day or larger in 2009) with original data	Data on the heat utilization rate	JWRF
		236 facilities, which keep operation (300 t/day or larger in 2009) without original data	National average rate calculated based on the JWRF database	JWRF
		286 newly built facilities	Energy recovery efficiency for heat utilization: 37.4% for $S_{3\text{-}CHP}$, 74.3% for $S_{3\text{-}H}$	IPCC
Indirect CO_2 reductions by slag recycling	All		National average rate calculated based on the JWRF database	JWRF

3.3.7. GHG emissions and reductions by scenario

Table 3.14 presents the results of the scenario analyses. The net GHG emission rate for Scenario 1 ($S_{1\text{-}BAU}$) was estimated to be 653 kg-CO2e/t, of which the total GHG emission rate was 758 kg-CO_2e/t, and the total GHG reduction rate was −105 kg-CO2e/t. The major GHG emission components were plastic burning (392 kgCO_2e/t), synthetic textile burning (225 kgCO_2e/t), and power consumption (108 kgCO_2e/t). The contributions of fuel consumption (21 kgCO_2e/t), CH_4 and N_2O (12 kgCO_2e/t), and water consumption (0.19 kgCO_2e/t) were less than 5%. These results were consistent with those of the past studies stating that the amount of CO_2 emissions from the waste treatment processes mainly depended on the waste compositions (Rand et al., 2000; Thanh and Matsui, 2013; Zaman, 2009). Power generation was dominant for the GHG reduction components (−103 $kgCO_2e/t$), and the contributions of "heat utilization" (−2.1 $kgCO_2e/t$) and "slag recycling" (−0.04 $kgCO_2e/t$) were relatively smaller.

In Scenario 2 (block formation with four technological alternatives), the results showed that Scenario $S_{2\text{-SMin}}$ had the lowest net GHG emission practice (454 $kgCO_2e/t$), followed by $S_{2\text{-GMin}}$ (542 $kgCO_2e/t$), $S_{2\text{-SMax}}$ (685 $kgCO_2e/t$), and $S_{2\text{-GMax}}$ (718 $kgCO_2e/t$). The stoker furnace showed a smaller net GHG emission rate than the gasification furnace.

For the stoker incineration furnace, the difference between $S_{2\text{-SMin}}$ (454 $kgCO_2e/t$) and $S_{2\text{-SMax}}$ (685 $kgCO_2e/t$) was 231 $kgCO_2e/t$. The turbine efficiency of $S_{2\text{-SMin}}$ (extraction condensing turbine with steam level 3) was higher than that of $S_{2\text{-SMax}}$ (backpressure turbine with steam level 1). Consequently, the GHG reduction of power generation for $S_{2\text{-SMin}}$ (239 $kgCO_2e/t$) was much larger than that of $S_{2\text{-SMax}}$ (93 $kgCO_2e/t$). The power consumption of $S_{2\text{-SMin}}$ (without ash melting) was smaller than that of $S_{2\text{-SMax}}$ (with ash melting by electricity). Consequently, the GHG emissions of the power consumption for $S_{2\text{-SMin}}$ (82 $kgCO_2e/t$) were smaller than that of $S_{2\text{-SMax}}$ (168 $kgCO_2e/t$). The GHG reductions of the slag recycling of $S_{2\text{-SMin}}$ and $S_{2\text{-SMax}}$ were 0.04 and 0.24, respectively. The GHG reduction by slag recycling was relatively smaller compared with the larger power consumption for ash melting. The difference of the net GHG emissions between $S_{2\text{-SMin}}$ and $S_{2\text{-SMax}}$ (231 $kgCO_2e/t$) came from the differences in the turbine condition (146 $kgCO_2e/t$), ash melting (85 $kgCO_2e/t$), and slag recycling (0.2 $kgCO_2e/t$).

For the gasification furnace, the difference between $S_{2\text{-GMin}}$ (542 $kgCO_2e/t$) and $S_{2\text{-GMax}}$ (718 $kgCO_2e/t$) was 176 $kgCO_2e/t$. The turbine efficiency of $S_{2\text{-GMin}}$ (extraction condensing turbine with steam level 3) was higher than that of $S_{2\text{-GMax}}$ (condensing turbine with steam level 1). Consequently, the GHG reduction of power generation for $S_{2\text{-GMin}}$ (274 $kgCO_2e/t$) was much larger than that of $S_{2\text{-GMax}}$ (106 $kgCO_2e/t$). Moreover, the fuel consumption of $S_{2\text{-GMin}}$ (other gasification furnaces) was smaller than that of $S_{2\text{-GMax}}$ (Shaft Gasification furnace).

Consequently, the GHG emissions of fuel consumption for $S_{2\text{-GMin}}$ (98 $kgCO_2e/t$) were smaller than that of $S_{2\text{-GMax}}$ (107 $kgCO_2e/t$). Both gasification furnaces consumed a larger amount of fuel when compared with stoker furnaces, which resulted in a net GHG emission rate of the gasification furnace to be larger than that of the stoker furnace. The difference of the net GHG emission rate between $S_{2\text{-GMin}}$ and $S_{2\text{-GMax}}$ (176 kgCO2e/t) came from the differences in the turbine condition (168 kgCO2e/t) and the furnace type (8 kgCO2e/t).

Regarding Scenario 3 ($S_{3\text{-CHP}}$ and $S_{3\text{-H}}$) (block formation with the BAT), the net GHG emission rate would be 242 $kgCO_2e/t$ for combined heat and power ($S_{3\text{-CHP}}$), best in all the estimated scenarios. The total GHG reduction rate of $S_{3\text{-CHP}}$ was 483 kgCO2e/t, of which the GHG reduction rate of power generation (288 kgCO2e/t) was 20% larger than that of $S_{2\text{-SMin}}$ (239 kgCO2e/t), while that of heat utilization (189 kgCO2e/t) was seven times larger than that of $S_{2\text{-SMin}}$ (27 kgCO2e/t). The net GHG emission rate for Scenario $S_{3\text{-H}}$ would be 346 $kgCO_2e/t$.

The result in Table 3-11 shows that the current net GHG emission rate from 1,243 operating waste incineration plants in Japan was estimated to be 653 $kgCO_2e/t$ in Scenario 1 ($S_{1\text{-BAU}}$). This rate could be cut off to 454 $kgCO_2e/t$ by the block formation, as shown in Scenario $S_{2\text{-SMin}}$. This reduction would be achieved by (1) replacing the smaller facilities and the facilities without power generation by large-scale WtE facilities and (2) applying technological alternatives with a higher power generation efficiency (stoker furnace and extraction condensing turbine with steam level. Ash melting had larger GHG emissions by the increase in energy consumption, and the GHG reduction by slag recycling was limited. Furthermore, the net GHG emissions would be reduced to 242 $kgCO_2e/t$ if all the newly built facilities fulfill the energy recovery efficiency by BAT with combined heat and power (Scenario $S_{3\text{-CHP}}$). The results in Scenario $S_{3\text{-CHP}}$ also showed that GHG reductions by heat utilization played an important role in the total GHG reductions (189 in 483 $kgCO_2e$ reductions per ton of waste). Based on the comparison of the GHG reduction components between the current status ($S_{1\text{-BAU}}$) and the status by BAT ($S_{3\text{-CHP}}$), BAT can reduce 185 $kgCO_2e/t$ by improving the power generation efficiency and the comparable rate, 187 $kgCO_2e/t$, by expanding heat utilization. At present, heat utilization is very limited in Japan, but it should be more focused on and promoted for GHG mitigation decisions.

The carbon emission reduction rates in the seven scenarios were in the range of 105 to 483 kgCO2e/t, which were similar to the range of 100 to 350 kgCO2e/t reported by the World Energy Resources in 2016 (World Energy Council, 2013).

Table 3.14 – Scenario estimation results of the GHG emission and reduction rates ($kgCO_{2e}/t$)

Components	Scenario						
	$S_{1\text{-}BAU}$	$S_{2S\text{-}Min}$	$S_{2S\text{-}Max}$	$S_{2G\text{-}Min}$	$S_{2G\text{-}Max}$	$S_{3\text{-}CHP}$	$S_{3\text{-}H}$
GHG emissions	758	719	805	847	856	719	719
Plastic burn	392	392	392	392	392	392	392
Synthetic textile burn	225	225	225	225	225	225	225
Power consumption	108	82	168	125	125	82	82
CH_4, N_2O	12	11	11	7	7	11	11
Fuel consumption	21	9	9	98	107	9	9
Water consumption	0.19	0.13	0.13	0.13	0.13	0.13	0.13
GHG reductions	−105	−266	−112	−306	−138	−483	−373
Power generation	−103	−239	−93	−274	−106	−288	−71
Heat utilization	−2.1	−27	−27	−31	−31	−189	−302
Slag recycling	−0.04	−0.04	−0.24	−0.5	−0.5	−0.05	−0.05
Net GHG	653	454	685	542	718	242	346

3.4. Conclusion

(1) This study focused on the GHG emissions and reductions of MSW incineration. The detailed composition of GHG emissions from the waste incineration facility and their influence factors were investigated using two databases on the annual operation report from 1,243 facilities in Japan in 2009.

(2) The detailed energy/material consumption and recovery rates were analyzed by major technological factors. Gasification consumed more fuel and electricity than incineration. Incineration with ash melting also caused more consumption of fuel or electricity than incineration without it. The power generation rate/efficiency was significantly affected by the type of turbine and the steam condition.

(3) The multilinear regression models were developed on the fuel consumption rate, power consumption rate, water consumption rate, and turbine generator efficiency.

(4) Based on the abovementioned data and models, the current net GHG emission rate from 1,243 operating waste incineration plants in Japan in 2009 was estimated to be 653 kgCO_2e/t. The GHG emission and reduction rate from waste incineration in 2009 were estimated to be 758 kgCO_2e/t and 105 kgCO_2e/t, respectively. Plastic burning accounted for the majority part with 392 kg kgCO_2e/t, followed by synthetic textile burning (225 kg kgCO_2e/t) and power consumption (108 kg kgCO_2e/t). For the GHG reduction rate, power generation contributed the highest proportion of −103 kg kgCO_2e/t. The results showed that "plastic burn" and "synthetic textile burn" were the major contributors to GHG emissions, and "power generation" played an important role in reducing GHG.

(5) Japan Ministry of the Environment intended to group small municipalities for replacing small-scale incinerators to large-scale waste-to-energy (WtE) facilities with a higher energy recovery efficiency. The net GHG emissions could be reduced to 454 kgCO_2e/t by applying the block formation and technological alternatives with a higher energy recovery efficiency (the stoker furnace with power generation by the extraction condensing turbine, and the steam condition is higher than 3 MPa and 300 °C). Ash melting caused larger GHG emissions by the increase in energy consumption. The GHG reduction from slag recycling was limited.

(6) The net GHG emission rate could be reduced to 242 kgCO_2e/t by applying BAT for combined heat and power plants. When compared with the current status, BAT can reduce 185 kgCO_2e/t by improving the power generation efficiency and 187 kgCO_2e/t by expanding heat utilization.

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4. HOUSEHOLD SOLID WASTE TREATMENT ALTERNATIVES TOWARD GREENHOUSE GAS EMISSION MITIGATION

4.1. Introduction

According to recent estimates the waste sector contribute about one-fifth of global anthropogenic methane emissions and methane contribution to climate change is about one- third to a half of that of carbon dioxide (IPCC, 2007). Waste sector emissions have grown steadily globally and are expected to increase in the forthcoming decades especially in developing countries such as Vietnam because of the increase in population and GDP (Pariatamby and Tanaka, 2014). In Vietnam, most of municipal solid waste (MSW) is disposed of at open dumping and landfill sites, and the methane gas from waste is the unignorably source of GHG emission (Thanh and Matsui, 2013).

There are many methods available for assessing the performance of MSW management system, especially on waste treatment practices; among them, "life cycle" approach is a proper comparative evaluation of various waste management practices (Barton et al. 1996; Del Borghi et al. 2009). Life cycle assessment (LCA) is a technique to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. It is a holistic approach that is increasingly utilized for solid waste management especially in the decision support (Konstadinos, 2011).

LCA has been utilized in the field of solid waste management (SWM) to assess environmental impacts of different scenarios for SWM systems, especially for the developed countries with advanced methods and more reliable database (Del Borghi et al. 2009; Finnveden et al. 2009). When exploring the correlation between MSW treatment and greenhouse gas (GHG) emission, the quantity and physical composition of the waste matter must be taken into account. Due to differences in local environments and lifestyles, the quantity and composition of waste often vary.

Until now, as other developing countries, Vietnam has been lacking the database and calculation methods for assessing environmental impacts of alternative waste treatment methods (Thanh and Matsui, 2013). The assessment of applicable solid waste treatment alternatives is very important and indispensable for understanding the status of the emissions appropriately and designing mitigation actions.

The purpose of this section was to clarify the pros and cons of HSW treatment alternatives toward GHG mitigation in Da Nang, a representative major city in Vietnam. A scenario analysis based on LCA was conducted with reliable data on waste generation and composition for all available treatment methods that could apply for the current situation of Vietnam. The examined waste treatment alternatives including: (i) landfill with/without LFG recovery, (ii) material recycling, (iii) biological treatment such as composting, anaerobic digestion to energy, animal feeding, (iv) waste-to-energy incineration.

4.2. Methodology

4.2.1. System boundary and calculation condition

The system boundary for GHG estimation included all processes related to waste treatment, ancillary materials, energy use and environmental emissions as defined in Figure 4.1 (a) to (g). Material and energy inputs and outputs of each treatment method, emission factors, and system boundary and calculation conditions were presented in Table 4.1. The recycled products are considered to be substitutes for chemical fertilizers, animal feeding product, recycling material, heat utilization, and power generation. Accordingly, the GHG reductions through material recycling were subtracted from total GHG emission of each scenario. CO_2, CH_4, and N_2O emission were calculated as Carbon dioxide equivalency (CO_2e). Carbon dioxide equivalency is a quantity that describes, for a given mixture and amount of greenhouse gas, the amount of CO_2 that would have the same global warming potential (GWP), when measured over a specified timescale (generally, 100 years). Carbon dioxide equivalency thus reflects the time-integrated radiative forcing of a quantity of emissions or rate of greenhouse gas emission—a flow into the atmosphere—rather than the instantaneous value of the radiative forcing of the stock (concentration) of greenhouse gases in the atmosphere described by CO_2e. The Global Warming Potential (GWP) of CH_4 and N_2O are 25 and 298, respectively, over a 100 year time scale, according to the IPCC Four Assessment Report (2007). The functional unit is defined as the management of one ton of HSW.

4.2.2. Scenario definition

The flow charts and system boundaries of seven HSW management alternatives are presented in Figure 4-1.a) to g). Scenario 1 represents the current HSW treatment; meanwhile scenarios 2-7 represent the major HSW treatment options. The author excluded GHG emission from HSW collection and transportation activities.

Scenario 1 (S1): Sanitary landfill without energy/material recovery (Figure 4-2.a)

Khanh Son sanitary landfill is the primary waste disposal in Da Nang, which has been in operation since 2007 and scheduled to be closed in 2020 (Da Nang People's Committee, 2016). The landfill is operated under un-managed anaerobic condition (methane correction factor (MCF) = 0.4, and oxidation factor (OX) = 0.1) without landfill gas collection system. The degradation coefficient for each waste component is based on the default value in Viet Nam suggested by IPCC (2007). The assumed leachate generation is 500 L/t of typical HSW with 1,900 g BOD_5/L, and the corresponding emission factor for anaerobic treatment process is 0.6 kg CH_4/kg BOD_5. Landfill operation also requires fuel (diesel) input that is assumed to be 0.7 L/t of waste, and the emission factor of diesel is 2.867 $kgCO_2e$/L. Power consumption rate of operation facilities is 2 kWh/t of waste (McDougall et al., 2001).

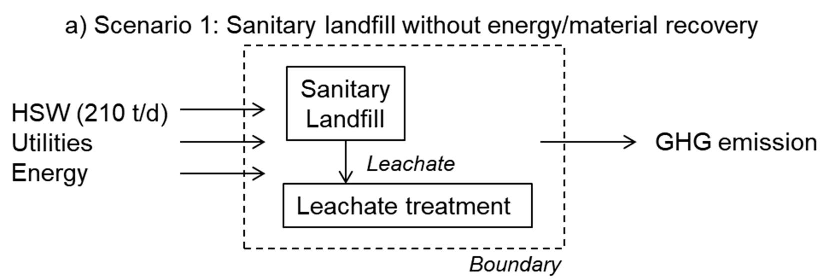

Figure 4.1. a) Simplified flow charts and boundary for scenario S1

Scenario 2 (S2): Sanitary landfill with energy recovery (Figure 4-2.b)

In this scenario, the landfill is operated under managed anaerobic condition (MCF = 0.5, OX = 0.1). In addition, a landfill gas recovery (LFG) power generation facility is equipped to collect and convert 70% LFG to electricity. The LFG recovery rate is 250 Nm^3 per ton of biodegradable waste and the power generation rate is 1.5 kWh/Nm^3 LFG (McDougall et al., 2001). The emission factor 0.585 $kgCO_2e$ per kWh was applied as referred from Tuyen and

Michaelowa, (2004). The fuel consumption, leachate generation and treatment process were assumed to be same as Scenario 1.

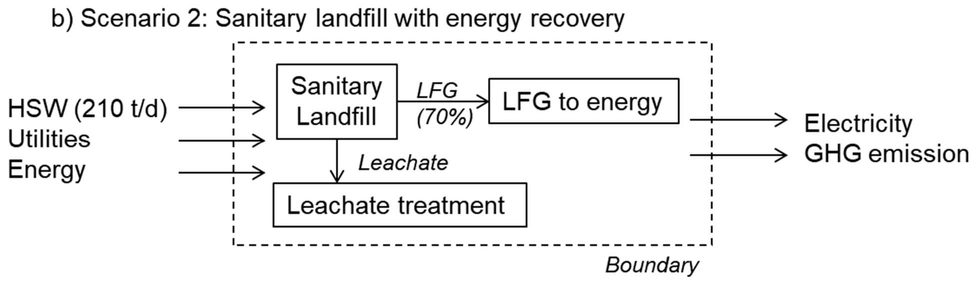

Figure 4.1. b) Simplified flow charts and boundary for scenario S2

Scenario 3 (S3): Sanitary landfill with material recovery (Figure 2.c)

Waste management authorities have suggested that HSW need to be sorted prior to disposal for urban areas within Viet Nam (Vietnam Government, 2015). In this scenario, the common assumption is that waste disposal was sorted by three categories: (1) edible food waste for animal feeding, (2) recycling potential wastes (plastic, paper, metal) for material recycling, (3) remaining residues for landfilling. Ogino et al., (2007) reported that the average amount of GHG emission from producing one ton of liquid feeds from food residue is 268 kgCO_2e. For material recycling, Menikpura et al., (2013) reported that 0.9 ton of virgin plastic is produced from 1 ton of recyclable plastic waste; with recycling efficiency is 90%. For paper and metal, the recycling efficiency is 89.3% and 90%, respectively. The same author also estimated the GHG emission from recycling process of plastic, paper, and metal is 2.14, 1.25, and 1.1 tCO_2e per ton of input material. Meanwhile, the GHG emission from virgin plastic, paper and metal production is 1.89, 0.967, and 2.94 tCO_2e/t, respectively. The remaining residues are treated by the sanitary landfill without energy recovery as scenario S1.

To account for the different biological treatment alternatives for organic waste, the composting scenario (S4) and the anaerobic digestion to energy scenario (S5) are conducted. The assumption is that waste disposal involved sorting at home by three categories: compostable waste (food waste, garden waste) for biological treatment, recyclables (plastic, paper, metal) for recycling, and remaining components for landfilling.

c) Scenario 3: Sanitary landfill with material recycling

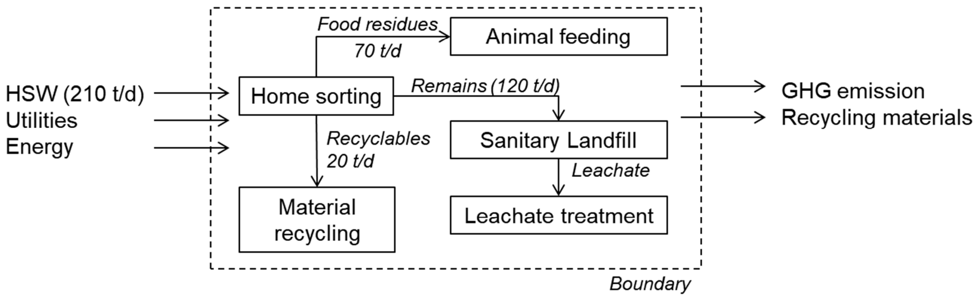

Figure 4.1. c) Simplified flow charts and boundary for scenario S3

Scenario 4 (S4) Composting

In Vietnam, 30 composting facilities out of 43 facilities were constructed after year 2010, with the common capacity is less than 100 ton/day (JICA, 2017). The GHG emission from anaerobic decomposition at composting facility and GHG emission related to utility consumption is 189.4 $kgCO_2e/t$ and 136 $kgCO_2e/t$, respectively. Meanwhile, the average composting product and residue rate is 170 kg/t and 150kg/t. Organic waste compost is appropriated for applying agriculture as safety fertilizer. For GHG avoidance, compost can be used to replace commercial fertilizer, of which the GHG emission rate is 9.5 tCO_2e/t (Ishikawa, 2011; Takata et al., 2012).

d) Scenario 4: Composting

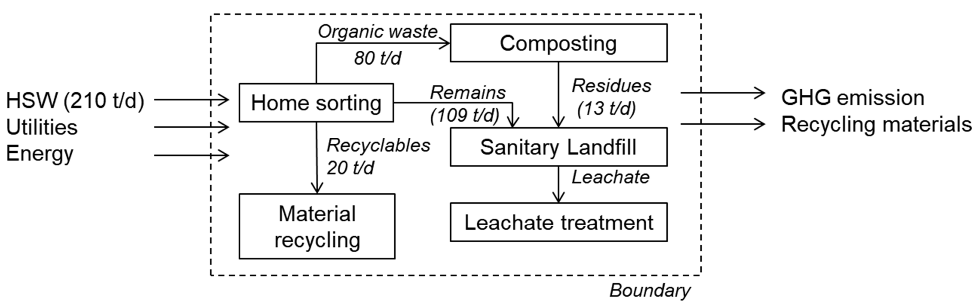

Figure 4.1. d) Simplified flow charts and boundary for scenario S4

Scenario 5 (S5) Anaerobic digestions to energy

Biogas generation during anaerobic digestion operation consumes electricity (112 kWh/t) and diesel (4.62 L/t). The total GHG emission from utility consumption and leachate treatment is 91.69 $kgCO^2e/t$ and 5.69 kgCO2e/t, respectively. The average power generation and the average residue is 150 kWh and 160 kg per 1000 kg of input organic waste (Ishikawa, 2011).

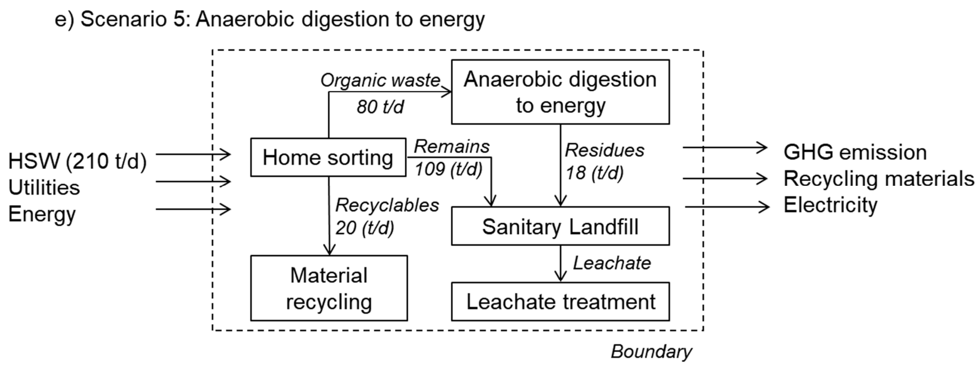

Figure 4.1. e) Simplified flow charts and boundary for scenario S5

Scenario 6 (S6) Waste to energy incineration (Figure 2.f)

By the year 2016, 161 solid waste incineration facilities have been constructed and been in operation in Vietnam, in which 73 facilities were constructed after year 2015 However, there are only 22 incinerators with capacity more than 100 ton/day, and most of the remaining facilities are small with the capacity less than 50 ton per day (JICA, 2017). In this scenario, the combustible waste is treated by incineration facility with energy recovery and capacity is assumed to be higher than 100 ton/day. A continuous stoker incinerator without ash melting function was applied for analyzing in this scenario. The operation parameters are acquired from 814 operating MSW incinerators in Japan (LE and MATSUI, 2018). Fuel consumption (Diesel) and water consumption rates are 0.074 GJ/t and 0.92m^3/t, respectively. The power consumption rate (kWh/t) is defined as $PW_{Con} = 216 - 0.14 \times Capacity$. The power generation efficiency (% of the total energy from input material) from extraction condensing turbine with high temperature (>300^{o}C) and high pressure (>3MPa) steam condition was defined as $PG_{EF} = 20.4 + 0.032 \times Capacity$. The emission factor of burning fossil carbon in plastic and synthetic textile is 2,726 and 2,287 kgCO2e/t of dry waste, respectively. The average residue (bottom ash and flying ash) from combustion process is approximately 5% of input waste (GIO et al., 2012; LE and MATSUI, 2018; McDougall et al., 2001). The material recycling process does not change relative to scenario S3. The residues from incinerators, after being solidified and stabilized by cement, together with all remaining waste (excluding combustible waste and recyclables abovementioned) are treated by sanitary landfill without energy/material recovery (S1).

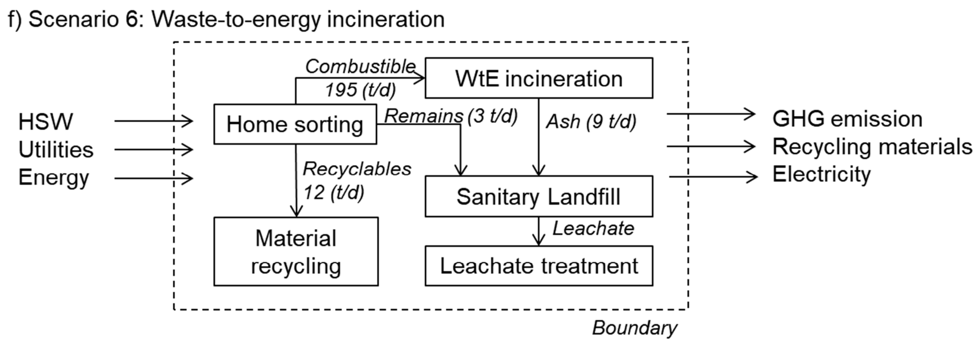

Figure 4.1. f) Simplified flow charts and boundary for scenario S6

Scenario 7 (S7) Integrated HSW management (Figure 2.g)

In this scenario, HSW is assumed to be sorted into four categories: (1) Organic waste for anaerobic digestion to energy as scenario S5, (2) recyclables for material recycling as scenario S3, (3) combustible waste for WtE incineration as scenario S6, and (4) the remaining (excluding organic waste, combustible waste, recyclables abovementioned) as well as residues from anaerobic digestion and combustion process are treated by landfilling as scenario S1. The schematic system flow and detailed procedure for each scenario is introduced in Section 3.5 after these results are elaborated.

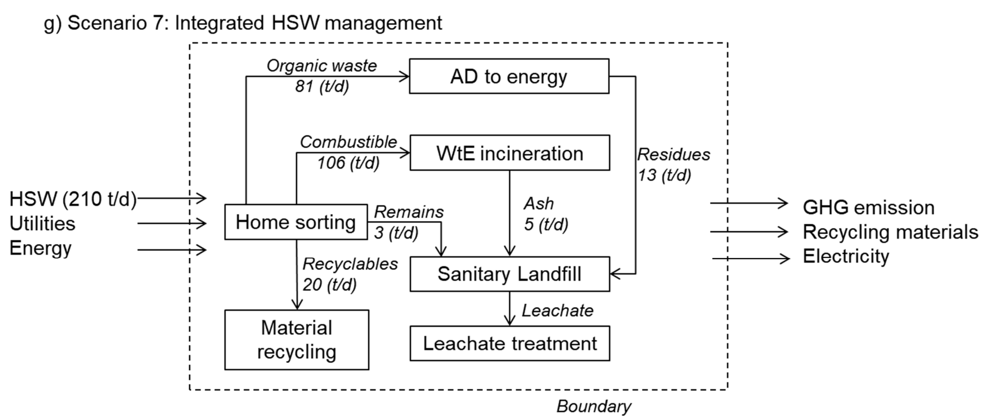

Figure 4.1. g) Simplified flow charts and boundary for scenario S7

Table 4-1. Calculation condition and emission factors

Scenario	Component	Inventory	Calculation condition	Emission factor
S1	Biological decomposition[1]	CH_4, CO_2	Un-managed anaerobic, shallow (<5m waste)	MCF=0.4, OX=0.1 DOC $_{Kitchen\ waste}$ = 0.67 DOC $_{Garden\ waste}$ = 0.04 DOC $_{Paper}$ = 0.06 DOC $_{Wood\ and\ straw}$ = 0.01 DOC $_{Textile}$ = 0.02 DOC $_{Disposable\ nappies}$ = 0.04
	Transportation[2]	CO_2e	Diesel consumption rate = 0.7 L/t of waste	2.84 kgCO_2e/L of Diesel
	Leachate treatment[2]	CH_4	Leachate rate = 150 L/t of waste BOD5 = 1,900 mg/L of leachate	0.6 kg CH_4/kg BOD_5
S2	Biological decomposition[1]	CH_4, CO_2	Semi-anaerobic	MCF=0.5, OX=0.1 DOC $_{Kitchen\ waste}$ = 0.67 DOC $_{Garden\ waste}$ = 0.04 DOC $_{Paper}$ = 0.06 DOC $_{Wood\ and\ straw}$ = 0.01 DOC $_{Textile}$ = 0.02 DOC $_{Disposable\ nappies}$ = 0.04
	Transportation[2]	CO_2e	Diesel consumption rate = 0.7 L/t of waste	2.84 kgCO_2e/L of Diesel
	Leachate treatment[2]	CH_4	Leachate rate = 150 L/t of waste BOD5 = 1,900 mg/L of leachate	0.6 kg CH_4/kg BOD_5
	LFG recovery[2], [3]	CO_2e	LFG collection rate=70% LFG leakage rate = 30% PGE = 30%	250 Nm3 LFG/t of biodegradable waste 1.5 kWh/Nm3 LFG 0.585 tCO_2e/MWh
S3	Animal feeding[4], [5]	CO_2e	Energy consumption 204 kWh/ton Commercial animal feed production 670 kg dry animal feed production from 1 ton of kitchen waste	0.585 tCO_2e/MWh 426.5 kgCO2e/ton of dry feed
	Plastic recycling[6]	CO_2e	900 kg virgin plastic production per ton of plastic waste	2,140 kgCO2/t of plastic waste recycling 1,580 kgCO2/t of virgin plastic production
	Paper recycling[6]	CO_2e	893 kg virgin paper production per ton of paper waste	1250 kgCO2/t of paper waste recycling 961 kgCO2/t of virgin paper production
	Metal recycling[6]	CO_2e	900 kg virgin metal production per ton of metal waste	1050 kgCO2/t of metal waste recycling 2690 kgCO2/t of virgin metal production
	Biological decomposition[2]	CH_4, CO_2	Semi-anaerobic	MCF=0.5, OX=0.1 DOC $_{Kitchen\ waste}$ = 0.67

				$DOC_{Garden\ waste} = 0.04$ $DOC_{Paper} = 0.06$ $DOC_{Wood\ and\ straw} = 0.01$ $DOC_{Textile} = 0.02$ $DOC_{Disposable\ nappies} = 0.04$
	Transportation[2]	CO_2e	Diesel consumption rate = 0.7 L/t of waste	2.84 $kgCO_2e$/L of Diesel
	Leachate treatment[2]	CH_4	Leachate rate = 150 L/t of waste BOD5 = 1,900 mg/L of leachate	0.6 kg CH_4/kg BOD_5
S4	Composting[7]	CO_2e	Compost = 17% initial compostable waste Residue = 15% initial compostable waste Electricity=132 kWh/t Diesel=24 L/t Water=0.113 m^3/t Activated carbon=3.24 kg/t Sulfuric acid=0.81 kg/t	Net carbon flux = 0.055 tCO_2e/t 4 $kgCH_4$/ton 0.3 kgN_2O/ton 3.56 $kgCO_2$/kg fertilizer 0.001 kg CH_4/kg fertilizer 0.02 kg N_2O/kg fertilizer
	Plastic recycling[6]	CO_2e	900 kg virgin plastic production per ton of plastic waste	2,140 kgCO2/t of plastic waste recycling 1,580 kgCO2/t of virgin plastic production
	Paper recycling[6]	CO_2e	893 kg virgin paper production per ton of paper waste	1250 kgCO2/t of paper waste recycling 961 kgCO2/t of virgin paper production
	Metal recycling[6]	CO_2e	900 kg virgin metal production per ton of metal waste	1050 kgCO2/t of metal waste recycling 2690 kgCO2/t of virgin metal production
	Biological decomposition[1]	CH_4, CO_2	Semi-anaerobic	MCF=0.5, OX=0.1 $DOC_{Kitchen\ waste} = 0.67$ $DOC_{Garden\ waste} = 0.04$ $DOC_{Paper} = 0.06$ $DOC_{Wood\ and\ straw} = 0.01$ $DOC_{Textile} = 0.02$ $DOC_{Disposable\ nappies} = 0.04$
	Transportation[2]	CO_2e	Diesel consumption rate = 0.7 L/t of waste	2.84 $kgCO_2e$/L of Diesel
	Leachate treatment[2]	CH_4	Leachate rate = 150 L/t of waste BOD5 = 1,900 mg/L of leachate	0.6 kg CH_4/kg BOD_5
S5	Anaerobic digestion to energy[7]	CO_2e	Electricity=112 kWh/t Diesel=4.62 L/t Water=2.61 m3/t Sodium hydroxide=5.31 kg/t Polymer coagulant=0.55 kg/t Sodium hypochlorite=3.06 kg/t	0.585 tCO_2e/MWh 2.84 $kgCO_2e$/L of Diesel

			Anti foaming agent=0.1 kg/t Citrid acid = 0.17 kg/t Desulfurizing agent = 0.99 kg/t Water = 1.55 m3/t Residue = 16% input waste PG = 149.99 kWh/t	
	Plastic recycling[6]	CO_2e	900 kg virgin plastic production per ton of plastic waste	2,140 kgCO2/t of plastic waste recycling 1,580 kgCO2/t of virgin plastic production
	Paper recycling[6]	CO_2e	893 kg virgin paper production per ton of paper waste	1250 kgCO2/t of paper waste recycling 961 kgCO2/t of virgin paper production
	Metal recycling[6]	CO_2e	900 kg virgin metal production per ton of metal waste	1050 kgCO2/t of metal waste recycling 2690 kgCO2/t of virgin metal production
	Biological decomposition[1]	CH_4, CO_2	Semi-anaerobic	MCF=0.5, OX=0.1 $DOC_{\text{Kitchen waste}} = 0.67$ $DOC_{\text{Garden waste}} = 0.04$ $DOC_{\text{Paper}} = 0.06$ $DOC_{\text{Wood and straw}} = 0.01$ $DOC_{\text{Textile}} = 0.02$ $DOC_{\text{Disposable nappies}} = 0.04$
	Transportation[2]	CO_2e	Diesel consumption rate = 0.7 L/t of waste	2.84 $kgCO_2e$/L of Diesel
	Leachate treatment[2]	CH_4	Leachate rate = 150 L/t of waste BOD5 = 1,900 mg/L of leachate	0.6 kg CH_4/kg BOD_5
S6	Waste to energy incineration[8]	CO_2e	Fossil plastic burning Fossil synthetic textile burning Combustion (Continuous stoker furnace) Utility consumption Power generation	2,726 kg CO2e/t of dry plastic 2,287 kg CO2e/t of dry synthetic textile 2.6 gCH_4/t, 37.9 gN_2O/t 314 kWh/t 0.585 tCO2e/MWh
	Plastic recycling[6]	CO_2e	900 kg virgin plastic production per ton of plastic waste	2,140 kgCO2/t of plastic waste recycling 1,580 kgCO2/t of virgin plastic production
	Paper recycling[6]	CO_2e	893 kg virgin paper production per ton of paper waste	1250 kgCO2/t of paper waste recycling 961 kgCO2/t of virgin paper production
	Metal recycling[6]	CO_2e	900 kg virgin metal production per ton of metal waste	1050 kgCO2/t of metal waste recycling 2690 kgCO2/t of virgin metal production
	Transportation[2]	CO_2e	Diesel consumption rate = 0.7 L/t of waste	2.84 $kgCO_2e$/L of Diesel
S7	Anaerobic digestion to energy	CO_2e	Electricity=112 kWh/t Diesel=4.62 L/t Water=2.61 m3/t	0.585 tCO_2e/MWh 2.84 $kgCO_2e$/L of Diesel

		Sodium hydroxide=5.31 kg/t Polymer coagulant=0.55 kg/t Sodium hypochlorite=3.06 kg/t Anti foaming agent=0.1 kg/t Citrid acid = 0.17 kg/t Desulfurizing agent = 0.99 kg/t Water = 1.55 m3/t Residue = 16% input waste PG = 149.99 kWh/t	
Waste to energy incineration	CO_2e	Fossil plastic burning	2,726 kg CO2e/t of dry plastic
		Fossil synthetic textile burning	2,287 kg CO2e/t of dry synthetic textile
		Combustion (Continuous stoker furnace)	2.6 gCH_4/t, 37.9 gN_2O/t
		Utility consumption	314 kWh/t
		Power generation	0.585 tCO2e/MWh
Plastic recycling	CO_2e	900 kg virgin plastic production per ton of plastic waste	2,140 kgCO2/t of plastic waste recycling 1,580 kgCO2/t of virgin plastic production
Paper recycling	CO_2e	893 kg virgin paper production per ton of paper waste	1250 kgCO2/t of paper waste recycling 961 kgCO2/t of virgin paper production
Metal recycling	CO_2e	900 kg virgin metal production per ton of metal waste	1050 kgCO2/t of metal waste recycling 2690 kgCO2/t of virgin metal production
Transportation[2]	CO_2e	Diesel consumption rate = 0.7 L/t of waste	2.84 $kgCO_2$e/L of Diesel

Source: [1] (IPCC, 2007), [2] (McDougall et al., 2001), [3] (Tuyen and Michaelowa, 2004), [4] (Takata et al., 2012), [5] (Ogino et al., 2007), [6] (Menikpura et al., 2013), [7] (Ishikawa, 2011),[8] (LE and MATSUI, 2018)

4.3. Results and discussions

4.3.1. Waste quantity and composition

Section 2 introduced the HSW estimation and breakdown components. In this section, the author calculated the waste quantity and ten physical components as well as the energy content for each scenario. The waste separation rate was assumed to be 70% as mentioned in master plan on waste management in Da Nang (Da Nang People's Committee, 2016). The waste quantity and composition for each scenario are shown in Table 4.3 and Table 4.4.

Table 4.3 – Basis fraction and energy content by physical component

Component	Proportion (%)	Combustible (%)	Moisture (%)	Ash (%)	LHV (kJ/kg)
Plastic	14.56	67.58	17.09	15.33	24,159
Paper	10.86	47.44	47.10	5.46	7,753
Kitchen waste	64.10	38.08	52.83	9.09	2,677
Rubber	0.56	52.60	15.20	32.20	18,499
Grass & wood	4.51	40.20	55.57	4.23	8,695
Textile	1.53	57.22	37.66	5.12	11,552
Metal	0.83	-	7.12	92.88	-
Glass	1.41	-	1.90	98.10	-
Ceramic	0.22	-	1.98	98.02	-
Miscellaneous	1.42	25.90	30.85	43.24	3,815
Total	100.00	42.75	45.16	12.08	6,801

Regarding waste separation, 20.14 tons of recyclables could be separated and recycled if waste separation rate achieved 70%. Meanwhile, 80.31 tons of organic waste could be separated for composting or anaerobic digestion to energy treatment. The LHV of incinerated waste, therefore, could be increased from 6.8 MJ/kg to 10.4 MJ/kg, compare with scenario S1.

4.3.2. GHG emission and reduction

In evaluating GHG emissions from organic waste and mixed HSW buried in the landfill, the main emission items were considered including CH_4 and CO_2 produced during carbon storage (EPA, 2002). CH_4 can be chemically oxidized or converted by bacteria to CO_2. This part was assumed to be 10% of the total CH_4 output. The landfill gas (LFG) recovery rate in particular has a big influence on the net GHG emissions due to the greater global warming potential (GWP) value of CH_4. The effect of these variations in net emissions will affect the choice of

HSW management strategy. So, for this study, the average LFG recovery rate was set at 70% (EPA, 2002). As the ash from complete incineration contained no organic carbon when it arrives at the landfill, the burial of ash would generate no LFG. No incineration will completely remove the carbon but it can be assumed that the landfill of incinerator ash will result in no LFG emissions (McDougall et al., 2001).

The organic waste composting is benefit not only for reducing the GHG emissions from HSW and the waste burden gone to landfill site, but also for producing the composted soil amendment that is useful for agriculture. The GHG emissions that may be produced by composting included: (1) CH_4 generated by anaerobic decomposition; (2) carbon storage caused by long-term carbon compounds; and (3) N_2O produced by materials' initial nitrogen content. The biogenic CO_2 emissions caused by the composting process and the use of fertilizer on soil were discounted in accordance with the GHG inventory guidelines developed by the IPCC. On the other hand, the application of compost into agriculture increases the soil's carbon level, and the carbon content in compost is continuously reduced by an increase in crop yields or other soil activities. Moreover, the stable carbon compounds created by composting process included an increase in humus substances and aggregates allowing carbon to be stored long periods of time in the soil. The soil carbon restoration and increased humus formation factor values were used to derive the carbon storage factor for soil and when tallied resulted in its net GHG emissions, called "net carbon flux". This aspect was also taken into consideration in this study. This emission factor had a value of −0.055 tons CO_2e/ton.

For anaerobic digestion to energy treatment, the fermenter in the form of a wet thermophilic digestion system was applied. In addition, Biogas-derived electricity was used in the scenario S6 and S7. The GHG emissions mainly come from utility consumption, waste water treatment. Meanwhile, the GHG was reduced by power generation with the rate approximately 150 kWh/ton of organic waste.

The GHG emission produced during incineration were discussed in Section 3. In this section, the author assumed the capacity of waste to energy incinerator in scenario S6, and S7 were 200 tons/day, and 100 tons/day, respectively. In addition, the technical conditions used in this study were: continuous stoker incinerator with bleed condensing turbine providing 3MPa, 300°C steam. The power generation rate was estimated to be 291kWh/t and 314 kWh/t for scenario S6, and S7, respectively.

Table

		Waste component			
		Paper	Plastic	Kitchen waste	Metal
Treatment alternatives	Landfill without LFG recovery				-
	Landfill with LFG recovery				-
	Material recovery			-	
	Animal feeding	-	-		-
	Composting	-	-		-
	Anaerobic digestion	-	-		
	Incineration				

Unit: $kgCO_2e/t$

The total GHG emission and reduction by waste treatment alternatives for HSW in Da Nang in 2016 are shown in Table 4.5 and Figure 4.4.

Table 4.4 – Waste quantity and composition for scenario analysis

		Waste treated amount (tons/day) and energy content (kJ/kg)												
Scenario	Treatment alternative	Total	Plastic	Paper	Kitchen waste	Rubber & Leather	Grass & wood	Textile	Metal	Glass	Ceramic	Miscellaneous	Residue	LHV (kJ/kg)
S1	Open dumping landfill	209.69	23.11	19.89	143.65	0.64	11.32	3.32	1.96	2.41	0.49	2.89		
S2	Landfill with LFG recovery	209.69	23.11	19.89	143.65	0.64	11.32	3.32	1.96	2.41	0.49	2.89		
S3	Separately collected for recycling	20.14	12.21	5.75		0.42			1.75					
	Separated for animal feeding	69.82			69.82									
	Open dumping landfill	119.73	10.90	14.15	73.83	0.21	11.32	3.32	0.21	2.41	0.49	2.89		
S4	Separately collected for recycling	20.14	12.21	5.75		0.42			1.75					
	Separately collected for composting	80.31			73.57		7.74							
	Open dumping landfill	109.24	10.90	14.15	70.08	0.21	3.58	3.32	0.21	2.41	0.49	2.89	16.13	
S5	Separately collected for recycling	20.14	12.21	5.75		0.42			1.75					
	Separately collected for anaerobic digestion to energy	80.31			73.57		7.74							
	Open dumping landfill	109.38	10.90	14.15	70.08	0.21	3.58	3.32	0.21	2.41	0.49	2.89	18.61	
S6	Separately collected for recycling	11.58	3.66	5.75		0.42			1.75					
	Incineration with PG	194.59	19.45	14.14	143.65	0.22	11.32	3.32	0.21			2.89		6,801
	Open dumping landfill	11.98								2.41	0.49		9.08	
S7	Separately collected for recycling	20.14	12.21	5.75		0.42			1.75					
	Separately collected for anaerobic digestion to energy	80.31			73.57		7.74							
	Incineration with PG	104.65	10.9	14.14	70.08	0.22	3.58	3.32	0.21			2.89	18.61	10,447
	Open dumping landfill	7.49								2.41	0.49		4.59	

Table 4.5 – Total GHG emission by waste treatment alternatives (unit: tCO_2e)

Scenario	Emission	Reduction	Net GHG
S1: BAU	259,578	-	259,578
S2: LFG recovery + PG	91,998	2,964	89,034
S3: Recycling + Animal feeding	59,917	2,651	57,266
S4: Recycling + Composting	99,200	13,928	85,272
S5: Recycling + Anaerobic digestion to energy	62,676	16,069	46,607
S6: Incineration	40073	20,009	20,064
S7: Recycling + Anaerobic digestion to energy + incineration	31,488	26,029	5,459

The results show that the net GHG emission of scenario S1 – business as usual discharge 259,578 tCO_2e, and this amount could be reduced more than half, to 89,034 tCO_2e by applying sanitary landfill with LFG recovery for power generation. The net GHG in scenario S7 was the best alternative for GHG mitigation.

4.3.3. Scenario analysis on GHG emission mitigation

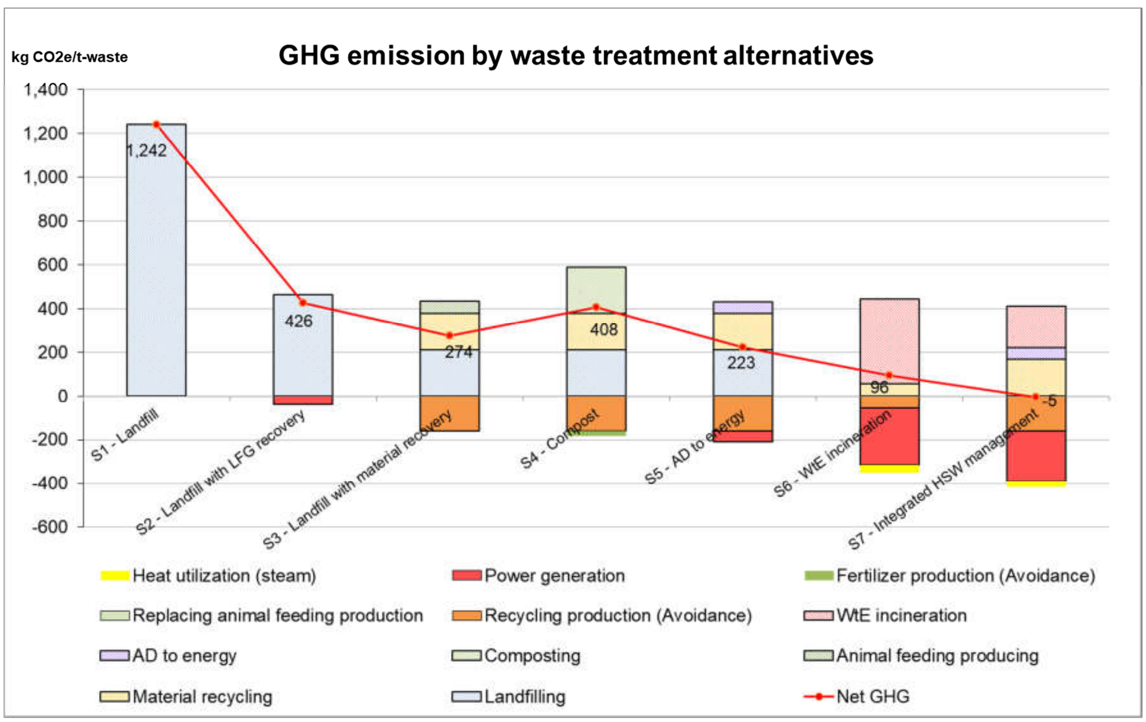

Figure 4.2 – GHG emission of waste treatment alternatives

Figure 5 expressed the GHG emission and reduction rate (kgCO2e/t) by each waste treatment alternatives. Compare with scenario S1 – BAU, the results show that GHG reduction was the lowest for scenario S7, followed by S6, S5, S3, S4 and S2. There were significant different in GHG emissions among these waste treatment alternatives. For landfilling, the CH_4 emission from degradation of biodegradable waste was the main source of GHG emission, which made the net GHG emission in scenario 1 were 1,242 $kgCO_2e/t$. In scenario S2, with semi-aerobic condition and LFG collection faciltity, the net GHG emission were estimated to be 426 $kgCO_2e/t$ (decreased 66% compared with BAU scenario). The net GHG emission can be cut off 78% (to 274 $kgCO_2e/t$) by waste separation and material recycling. A significant amount of GHG emission caused by organic landfilling could be avoided by separating kitchen waste for animal feeding.

For composting, scenario S4 could achieve 834 kgCO2e/t reductions (67% compared with BAU scenario) by avoiding raw HSW landfilling and considerable carbon sink is formed from compost product utilized on land. Compared with composting, with the energy recovery in the anaerobic digestion to energy, the net GHG emissions could be further reduced in scenario S5, which is estimated to be 223 $kgCO_2e/t$.

Scenario S6 has the lowest net GHG emission compared with initial waste treatment alternatives abovementioned. The power generation and heat utilization play an important role in GHG emission reduction; and the net GHG emission is estimated to be 96 $kgCO_2e/t$. In this scenario, the author assumed the plastic separation rate for recycling is 30% to ensure the LHV of HSW is higher than 6000 kJ/kg, which is presented section 3.4 and in Figure 4.

To evaluate the effect of waste separation and combustion efficiency, the author analyzed the GHG emission from WtE incineration with different waste composition by assuming different waste separation rate. The result in Figure 4.3 shows that the higher the plastic separation rate, the lower the net GHG emission. It is explainable because the GHG emission from incineration is mainly from the fossil carbon (plastic) burning. On the other hand, the higher the kitchen waste separation rate, the higher the net GHG emission. It can be explained that the amount of GHG emission from fossil fuel is constant while the amount of input waste decrease by kitchen waste separation. It is noted that if the kitchen waste separation rate is higher than 70%, the capacity of incineration could be less than 100t/d, which is not preferable for high power generation efficiency turbine (LE and MATSUI, 2018).

The scenario S7 expressed that the integrated HSW management with material recycling (70% plastic recycling), anaerobic digestion to energy (70% kitchen waste) and WtE incineration is the best alternative for GHG mitigation with net GHG emission is estimated to be -5 kgCO2e/t.

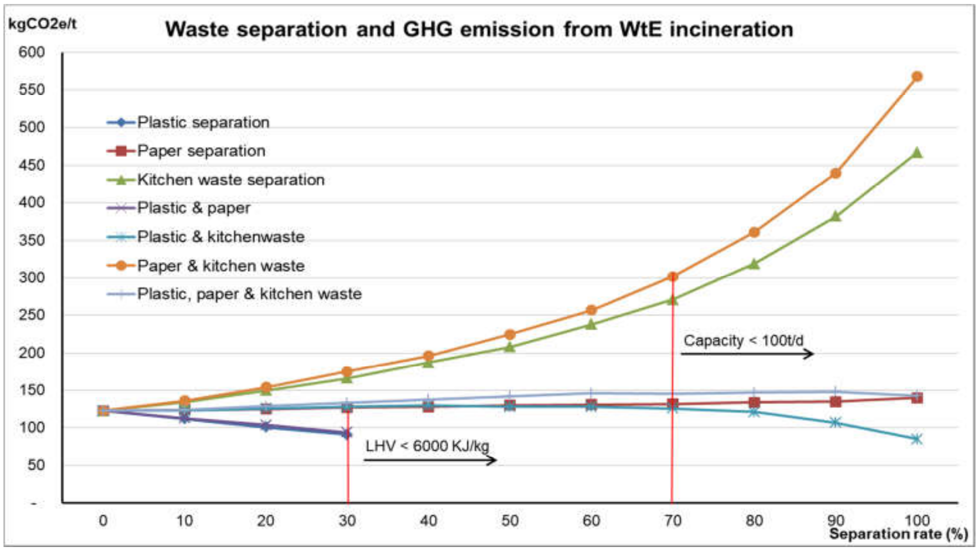

Figure 4.3 – GHG emission from WtE incineration with different waste separation rate

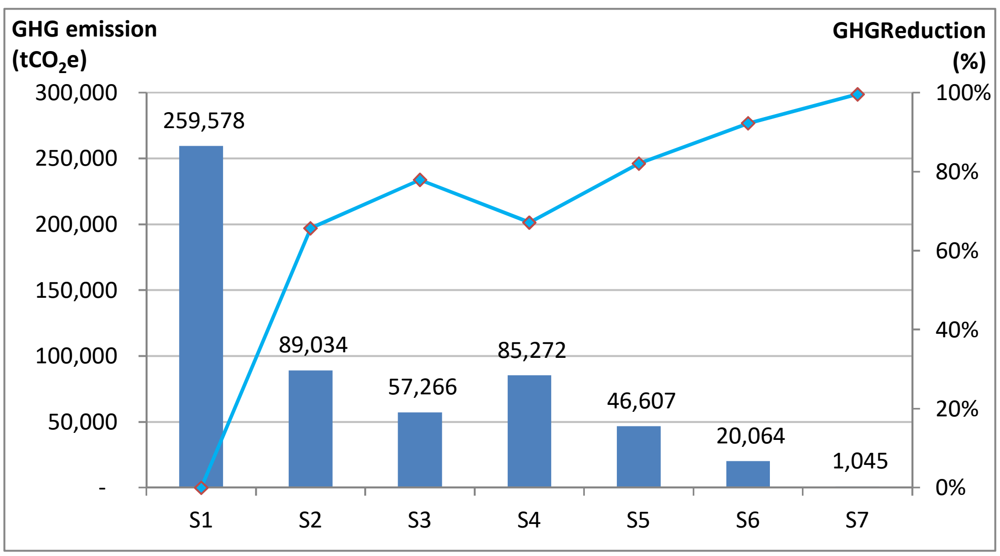

Figure 4.4 - GHG emission reduction of waste treatment alternatives

The author also conducted 95% confidence interval estimation of GHG emission rates by Monte Carlo simulation with resampling method. The results (Figure 4.5) show that the scenario S5, S6, S7 were the most suitable waste treatment alternatives to reduce the GHG emission, compare with scenario S1-BAU. The results of 95% confidence interval estimation of GHG emission rate by waste treatment alternatives show that scenario S1-BAU has a wide range, from

990 kgCO2e/t to 2,160 kgCO_2e/t. In contrast, the range of scenario S7 was much better, from 1 kgCO2e/t to 140 kgCO2e/t. To improve the reliability, further study should focus on organic waste composition and the degradable organic components, regarding the results of contribution to variance analysis.

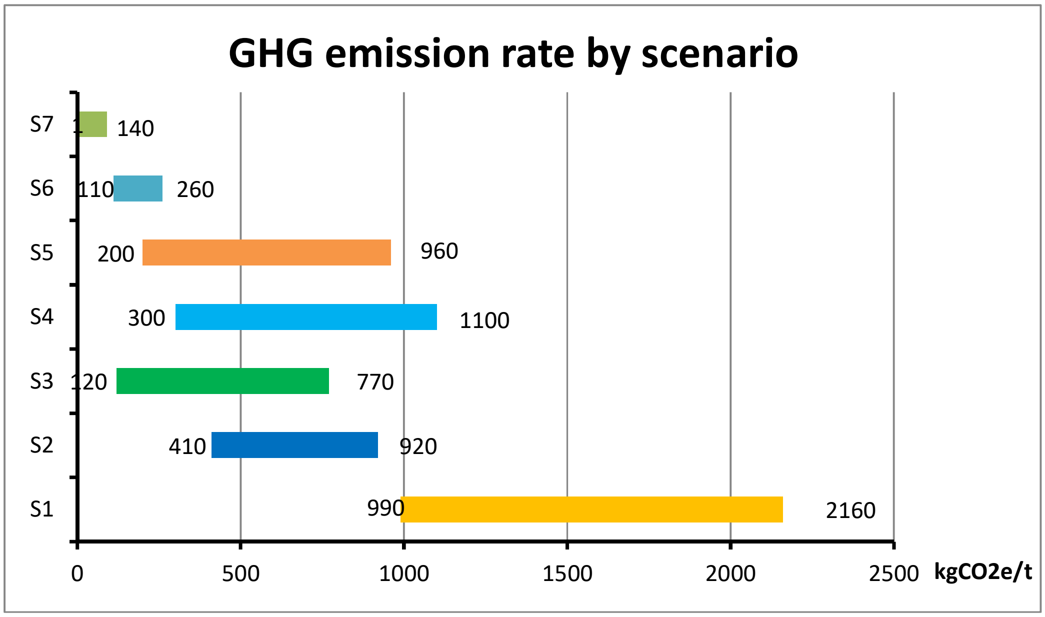

Figure 4.5 – 95%CI of GHG emission rate of waste treatment alternatives

4.4. Conclusions

The GHG emission from HSW in Da Nang in 2016 was estimated to be 259,587 tCO_2e. The GHG emission rate was calculated as 1,242 kgCO_2e per ton of waste.

The organic waste accounted for major component of total HSW. This share has a high potential for biological treatment as composting or anaerobic digestion to energy.

A scenario analysis was carried out to evaluate the waste treatment alternatives, such as waste recycling, kitchen waste separation for animal feeding, composting, anaerobic digestion to energy, and waste to energy incineration. An assessment based on GHG emission/reduction was conducted and compared among waste treatment alternatives.

The integrated waste management with 70% of recyclable was separated, 70% of organic waste was separated for anaerobic digestion to energy, and the remains was incinerated at waste to energy incineration with capacity 100 tons/day, was the best alternative for GHG mitigation. The GHG emission will be cut off 98% compare with current status in scenario S1-BAU. Therefore, the feasibility study on GHG reduction by using low carbon waste treatment technology under JCM is considered as the future task.

The results of 95% confidence interval estimation of GHG emission rate by waste treatment alternatives show that scenario S0-BAU has a wide range, from 990 $kgCO_2e/t$ to 2,160 $kgCO_2e/t$. In contrast, the range of scenario S7 was much better, from 1 $kgCO_2e/t$ to 140 $kgCO_2e/t$. To improve the reliability, further study should focus on organic waste composition and the degradable organic components, regarding the results of contribution to variance analysis.

The evaluations and discussions in this section expected to be useful for decision makers, authorities, and planners for choosing, improving, or planning the waste treatment methods to achieve the sustainable development regarding solid waste management with three areas: environmental sustainability, economical sustainability and social acceptance.

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5. CONCLUSIONS AND RECOMMENDATIONS

The aim of this dissertation was to study the household solid waste generation and composition to identify opportunities for recycling waste in Danang, the capital city of the middle region in Vietnam. HSW analyzed and discussed in detailed compositions. In addition, the GHG emission and reduction from waste incineration in Japan was investigated to identify the good condition for waste to energy method. Finally, the evaluations of the alternative waste treatment methods toward GHG emission reduction were surveyed and evaluated.

5.1. Conclusions

The research background and overview of the research area were introduced in section 1. The rapid population growth and expanding urbanization in Vietnam have caused the increase of the waste generation and the variety of waste composition. HSW has become a serious problem for treatment and management of MSW. The demand for reliable data on waste had grown in recent years in Vietnamese cities for basic research, planning, and management. It is a need to create a waste arising database to provide credible information for waste managers and planners into local and region term. Thus, a number of proposed objectives, which planned to study in this dissertation presented.

Through review of existing literatures in terms of HSW generation and composition studies, the proposed research outline and applied methodology for data collection and analysis were described. Regarding the sampling points, were selected considering their respective urbanization levels and the geographical distribution. It was assumed that the population density was the representative indicator of the urbanization level. For target sample selection, households were chosen according to the share of household size in Danang. Regarding HSW generation survey, 150 households was selected and surveyed in 2016. HSW was collected from each household and classified into 10 physical categories and 66 subcategories; which based on the relative shares, such as recyclable and compostable wastes, their usage function and purpose, discharge source, and hazardous wastes. Besides, many surveys as questionnaire survey with the face-to-face interview and daily diary survey during the period of waste generation survey were conducted. Another simple questionnaire survey of recyclable-junk buyers and recycling-junk shops was also conducted.

The major focus of this dissertation was to assess the HSW generation and characteristic and treatment alternatives toward GHG mitigation. The detailed compositions discussed with various aspects, such as compostable/recyclable/ hazardous wastes, usage function and purpose, discharge source, etc. The influence of the main factors for HSW generation was analyzed; then, the major relevant factors were explored to develop mathematical predicting models. Besides, a comparison to another Vietnamese city by the similar methodology approach was mentioned. The main achievements were shown as follows:

1) The average of total HSW generation was 231.49 g/cap/day for an average of 4.6 residents per household of 150 target samples. Food waste contributed the largest part of the total HSW generation with around 157.95 g/cap/day (68.23%), following by plastic (10.95%), paper (9.4%), and others. For recycling potential, compostable waste accounted for the main proportion of the total with 168.38 g/cap/day (around 73% of total), followed by recyclable material (13.77%), and non-recoverable waste (13.5%). For the detailed compositions of recyclable HSW, plastic material distributed the greatest fraction of the total; in which, 49.38% of plastic bag (about half of the total recyclable HSW). The second largest component belonged to paper material, in which, newspaper/ magazine accounted for the main part with 8.29% of the total, followed by paper (carton paper) container & packaging (6.36%). For basis component, the moisture content was the highest with 45.16%, followed by combustible content (42.75%) and ash content (12.08%). The low heating value was 6,801 kJ/kg, which was suitable for incineration treatment process.
2) Factors affecting waste generation rate were urbanization level, household size, and income level. The higher the level of urbanization and income, the greater the amount of HSW generated per capita. The waste generation rate tended to decrease in the household with larger family size. Urbanization level and household size were two significant predictors for HSW generation rate.
3) Total HSW generation in six districts of Da Nang was estimated to be 186.9 – 233.5 tons/day, of which recycling potential and

composting potential were estimated to be 131.1 – 177.0 and 25.2 – 32.8 tons/day, respectively. The total value of recyclables was estimated up to 25.23 to 32.75 million VND per day, equivalent to 716 labors to be employed.

The GHG emission and reduction from waste incineration in Japan was discussed in this dissertation. The authors aimed to investigate the detailed composition of GHG emissions from the WtE facility and their relating factors using two Japanese databases on the operation of incinerators from JMOE and Japan Waste Research Foundation. The databases cover detailed data on the MSW amount and characteristics (annual treated waste amount, waste composition, calorific value, etc.), specs of the facility (scale, type of furnace, operation hours, type of ash melting, etc.), utility consumption (electricity, fuels and water), and annual energy/material recovery (annual power generation amount, annual heat recovery, annual slag amount, etc.). The authors analyzed the correlations among them and tried to develop predictive models for the detailed components of GHG emissions and reductions. The main findings were shown as follows:

1) For waste incineration technology, the detailed energy/material consumption and recovery rates were analyzed by major technological factors. Gasification consumed more fuel and electricity than incineration. Incineration with ash melting also caused more consumption of fuel or electricity than incineration without it. The power generation rate/efficiency was significantly affected by the type of turbine and the steam condition.
2) Based on the abovementioned data and models, the current net GHG emission rate from 1,243 operating waste incineration plants in Japan in 2009 was estimated to be 653 kgCO_2e/t. The GHG emission and reduction rate from waste incineration in 2009 was estimated to be 758 kgCO_2e/t and 105 kgCO_2e/t, respectively. Plastic burning accounted for the majority part with 392 kg kgCO_2e/t, followed by synthetic textile burning (225 kg kgCO_2e/t) and power consumption (108 kg kgCO_2e/t). For the GHG reduction rate, power generation contributed the highest proportion of −103 kg kgCO_2e/t. The results showed that “plastic burn” and “synthetic textile burn” were the

major contributors to GHG emissions, and “power generation” played an important role in reducing GHG.

3) Japan Ministry of the Environment intended to group small municipalities for replacing small-scale incinerators to large-scale waste-to-energy (WtE) facilities with a higher energy recovery efficiency. The net GHG emissions could be reduced to 454 $kgCO_2e/t$ by applying the block formation and technological alternatives with a higher energy recovery efficiency (the stoker furnace with power generation by the extraction condensing turbine, and the steam condition is higher than 3 MPa and 300 °C). Ash melting caused larger GHG emissions by the increase in energy consumption. The GHG reduction by slag recycling was limited.
4) The net GHG emission rate could be reduced to 242 $kgCO_2e/t$ by applying BAT for combined heat and power plants. When compared with the current status, BAT can reduce 185 $kgCO_2e/t$ by improving the power generation efficiency and 187 $kgCO_2e/t$ by expanding heat utilization.

Finally, the contribution of HSW treatment alternatives to mitigate GHG emission has been investigated under various possible analysis scenarios. The examined waste treatment alternatives include: (i) landfill with LFG recovery, (ii) recycling, (iii) kitchen waste separation for animal feeding, (iv) composting, (v) bio-gasification, and (vi) incineration. The author also conducted the an assessments based on GHG emission/reduction. The interesting calculations were presented as follows:

1) The GHG emission from HSW in Danang in 2016 was estimated to be 85,193 tCO2e. The GHG emission rate was calculated as 1,113 $kgCO_2e$ per ton of waste.
2) The integrated waste management with 70% of recyclable was separated, 70% of organic waste was separated for bio-gasification, and the remains was incinerated at waste to energy incineration with capacity 100 tons/day, was the best alternative for GHG mitigation.

The evaluations and discussions in this dissertation expected to be useful for decision makers, authorities, and planners for choosing, improving, or planning the HSW treatment and management methods to achieve the sustainable development regarding solid waste management with three areas: environmental sustainability, economical sustainability and social acceptance.

5.2. Recommendations

This dissertation dealt with survey and evaluation of the HSW generation, characteristic, and management with the focus on Vietnamese cities. Some shortcomings with regard to data and method identified, and future research of these was recommended. Moreover, based on the current results, the future researches will be suggested and improved. Some recommendations were given out for future researches, listed as follows:

1) Regarding the sampling points, these should be selected considering their respective urbanization levels and the geographical distribution. The population density seems the representative indicator of the urbanization level, a category of urbanization classification.
2) For target sample selection, this study recommends that target households should be chosen according to the demography characteristics of the study area such as the share of household size, household income, household expenditure, etc. And other factors such as household expenditure, individual education level, numbers of children and elder people stay-at-home time and number of meals at home relating to HSW generation by detailed composition should be examined and discussed.
3) Regarding monitoring survey on HSW quantification and characterization, it was suggested that HSW survey should be conducted at least one consecutive week and different seasons in a year
4) For classification categories of HSW, it was recommended that HSW should be classified into 10 physical categories and many subcategories; which based on the relative shares of recyclable and compostable wastes, their usage function and purpose, discharge source, and hazardous wastes. Besides, the classification

subcategories of HSW should be also based on the classification of recycling market.

5) For waste incineration technology, other processes, such as the air pollution control system and its efficiency, should be investigated to improve the model.
6) The applied life cycle assessment method was deficient in several ways and could be developed to be more suited for environmental assessment of waste management system. Moreover, the emission factors and normalization references used for calculating in the assessment were in general cases, which might be little suitable for developing countries, especially Vietnam. It was recommended that other life cycle assessment methods should be applied and assessed to compare and interpret. This may be make life cycle assessment a more reliable tool for decision-support.

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