Thermochemical conversion characteristics of gas and tar generation from waste biomass and plastics

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Acronyms and Abbreviations

MSW	Municipal Solid Waste
WtE	Waste to Energy
GHG	Greenhouse Gas
MSDP	Myanmar Sustainable Development Plan
JCM	Join Crediting Mechanism
LHV	Lower Heating Value
YCDC	Yangon City Development Committee
DOC	Degradable Organic Carbon
AWMS	Animal Waste Management System
WWTP	Wastewater Treatment Plant
FBG	Fluidized Bed Gasifier
RPF	Refuse Paper and Plastic Fuel
C/H ratio	carbon to hydrogen ratio
C/O ratio	carbon to oxygen ratio
ER	Equivalence Ratio
GE	Gas Engine
ICE	Internal Combustion Engine
PDF	Packaging Derived Fuel
PET	Polyethylene Terephthalate
RDF	Refuse Derived Fuel
SRF	Solid Recovered Fuel
PAHs	Polycyclic Aromatic Hydrocarbons
PE	Polyethylene (PE)
PP	Polypropylene (PP)
MoEJ	Ministry of Environment Japan

Chapter 1 Introduction

1. Background

Sustainable management of waste materials, nowadays, is a greater concern owing to the role it plays in triggering climate change. Estimated world population growth is up to nearly 10 billion in 2050 (United Nations Department of Economic and Social Affairs, 2018); the global resource consumption will increase and thereby waste generation problems are expected to amplify. In the 2015 Paris Agreement, it was pledged to limit the rise of global average temperature to well below 2 °C and as close as possible to 1.5 °C above pre-industrial levels (United Nations, 2017). To maintain this global vision, it is crucial for reducing global temperature via the mitigation of GHG emissions and by countering the adverse impacts of climate change by effectively utilizing generated wastes resources. Frontier technologies and low carbon approach are the most encouraging ways to address the environmental problems for the sustainable future development of the world (United Nations Department of Economic and Social Affairs, 2018). To adapt to the globally changing climate, the spread of the scientific information, knowledge, action plans, and implementation tools in developing countries is obligatory (United Nations, 2017).

Being one of the most vulnerable paces to the impact of climate change (Eckstein et al., 2019), Myanmar has been facing threats due to various forms of climate change patterns such as the increase in the intensity and frequency of heavy rain, drought events, flooding, extreme temperatures, etc. Despite the insignificant contributions from Myanmar to the global GHG emissions, several prominent sectors that contribute towards GHG emissions are from agricultural, energy, waste, industrial, and livestock sectors, accounting to up to 86 million tons of CO_2 eq in 2005 (Necc, 2012). Currently, the agricultural-based economy has undergone industrialization owing to economic growth, rapid urbanization, and changing consumption behaviors.

Myanmar has immense potential to utilize generated waste and biomass resources (Institute for Environmental Strategies and UNEP, 2017; Pode et al., 2016). Taking advantage of the abundantly available biomass resources and generated wastes, Myanmar may potentially be transformed into a climate-resilient, low-carbon society that is sustainable, prosperous, and inclusive. To achieve sustainable harmonious development in economic, social, and environmental dimensions, a balance between resources consumption and environment preservation is urgently required by developing relevant policies and introducing appropriate technologies. Innovative research works have been encouraged in supporting mitigated and adaptive actions on the ground so as to increase renewable energy shares to become 9% of the country's energy mix in 2030, aligning Myanmar Energy Master Plan and Electrification Plan (ADB et al., 2015; WWF et al., 2016) with MSDP (MoPF, 2018). The MSDP was committed to a climate-sensitive development pathway bridging the partnership with the already developed countries for finance on clean energy innovative solutions investments, technical assistance, along with R&D as envisioned in the Kyoto Protocol and Paris Agreement.

To abate climate change through waste and biomass resource utilization, low carbon technologies such as renewable energy facilities and waste treatment plants are the promising alternatives. In developing countries, JCM through regional and international partnerships is an option for promoting climate-sensitive development. Myanmar already has partnerships with several Japanese cities for receiving the knowledge and technology know-how related to low-carbon development (Institute for Global Environmental Strategies, 2014; JFE Engineering and Kawasaki City, 2018; JICA and YCDC, 2013a; Kitakyushu Asia Center for Low Carbon Society, 2018; Ministry of the Environment Japan(MoEJ), 2017; Mitsubishi Research Institute, 2016; MoEJ, 2018). The experience from historical improvements in waste management practice, recycling technologies, and renewable energy efforts in developed countries, such as Japan, may be extended to developing countries, such as Myanmar, to mitigate the impacts of climate change.

2. Overall Research Framework

For effective waste resource utilization, the development of waste treatment facilities is crucial. Enhancing the power generation efficiency in the facilities will promote locally produced energy consumption as well as lower carbon emission owing to reduced GHG emissions. For energy recovery from generated wastes and biomasses, different recycling technologies based on material, thermal, and chemical processes may be utilized by coupling them with innovations in energy efficiency improvements and cost-effective approaches (Edenhofer et al., 2012) (Helm and Hepburn, 2009). To achieve the benefits of higher energy efficiency, the previous studies investigated WtE gasification technology to be utilized to generate GE power from solid wastes (Morris and Waldheim, 1998; Consonni and Viganò, 2012). WtE technologies have adopted appropriate roles in waste recycling in the waste management hierarchy (PWMI, 2019; Lombardi et al., 2012; Edo-Alcón et al., 2016; F Di Gregorio and Zaccariello, 2012;

Násner et al., 2017).

For biogenic waste and organic fractions of MSW, appropriate waste management options have been proposed (Bastian et al., 2013; Yano and Sakai, 2016; Møller et al., 2009; Khoo et al., 2010; Hla and Roberts, 2015). Moreover, FBG tests for waste wood pellets were conducted under varying gasification conditions in previous studies, (Hayakawa et al., 2016; Inoue et al., 2017b, 2017a; Takahashi et al., 2017). There are numerous studies on cost-effective assessments of electricity generated from waste and biomass (Luz et al., 2015; Pahla et al., 2017; Lombardi et al., 2012; Yassin et al., 2009; Consonni and Viganò, 2012). A wide range of waste categories were investigated, including various resources in FBG technology (Guo et al., 2015; Tanigaki et al., 2012) and WtE that utilize syngas in GEs from generated waste biomass and several types of feedstocks such as plastics, SRF, PDF, and RDF (Kim et al., 2013; Narvaez et al., 1996; Robinson et al., 2017, 2016; Násner et al., 2017; Arena and Di Gregorio, 2016; Dunnu et al., 2012; Pinto et al., 2014).

Unlike these waste derived fuels produced from MSW, RPF do not include the food waste that is usually contained in MSW. Once food waste is separated from MSW and recycled, RPF compositions will be the main source of MSW. In promoting the effective use of energy, the reduction of GHG emissions and the greater benefits of the generated feedstocks for the environment and society, the practical utilization of both RPF and wood pellets in an FBG at small and medium scales is still considerably limited. Therefore, it is important to further understand the gasification of RPF. In Japan, small- and medium-scale WtE facilities were developed for innovative R&D to enhance average power generation efficiency up to 21%, with the assistance of the MoEJ, because very few facilities with a capacity of less than 100 tons/day can produce electricity with an average efficiency of 12.6% (Ministry of the Environment Japan (MoEJ), 2017; MoEJ, 2017; NEDO, 2014a; KobelcoEco-Solutions, 2015). Therefore, higher energy density feedstock, RPF and wood pellet were investigated in FBG under different process conditions of ER, temperature, and feedstock characteristics to study the performance parameters of gas LHV, gas composition, tar content, etc. The feedstock, as pellets, prepared under high pressure and temperature exhibited better performance in terms of energy density and quality as well as in terms of lesser ash and moisture content (Artemio et al., 2018; Thornley and Adams, 2018).

As FBG was conducted for different characteristics of feedstock wood pellets and RPF, the observed composition of generated gas differed not only in terms of gas characteristics but for tar yield and composition as well. An interaction study between gas and tar generation behavior affected by feedstock under flash pyrolysis with momentary residence time (below 0.5 s) is important for the process design of FBG and gas treatment system by clarifying the behavior and mechanism of product gas formation. Flash pyrolysis process is essential to determine the devolatilization characteristics and to maximize the evolved volatile gases in high heating rate with shorter durations. Through flash co-pyrolysis of wood pellets, as representative of biomass, and polyethylene (PE) and polypropylene (PP), as representatives of plastics, both synergistic and non-synergistic effect differences in feedstock characteristics were observed. Wood pellet, PE, and PP were used as feedstock in flash pyrolysis experiments because the wood biomass and plastic fractions remaining in MSW after the removal of food waste are the main sources of RPF. RPF is mainly produced from plastics, paper, and other materials such as wood and fabric from industrial wastes and well-separated MSW from both municipalities and private sectors.

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3. Purpose of the Study

Generated waste and biomass are alternative resources for recovering energy and are considered as recycling options to minimize waste disposal. In this study, first and foremost, the estimation of generated waste biomass in a developing country, Yangon, Myanmar was conducted for potential fuel feedstock from various sectors; biogenic MSW, agriculture, livestock, and urban sanitation. Among the investigated waste types, food, paper, wood, rice straw , rice husk, pig sludge, chicken sludge, sewage sludge, and dry waste with high solid content such as paper and wood fractions was considered as potential feedstock in the FBG study including rice straw and rice husk in future gasification researches. The FBG study utilized wood pellet and RPF, pursuing the enhancement in electricity generation in small and medium scale waste treatment facilities by the possible utilization of GEs with sufficient level calorific values along with tar and gas compositions. It could provide the realization of waste treatment facilities to cope with varying fractions of different waste composition in both developing and developed countries. Flash pyrolysis research was conducted to understand the interaction behaviors and mechanisms, such as synergistic and non-synergistic effects during single and mixed pyrolysis for wood biomass and plastics, PE, and PP. It was assumed that FBG process could be attributed with a co-relationship with flash pyrolysis owing to the immediate combustion of pyrolysis gas in the reactions in FBGs. Flash pyrolysis is a very fast reaction below a resident time of 0.5 s; this is essential to understanding the devolatilization characteristics of the reaction gases that are produced in FBG processes.

This study addresses the following research aspects:

- Estimated waste biomass generation potential in rapidly urbanized Yangon and utilization status for the proper management of waste resources.
- Pathway for energy recovery technology from generated waste and biomass pursuing the utilization in GE power generation
- Key process performance parameters for the enhancement of power generation efficiency in FBG waste treatment facility by proposing the product gas.
- The interaction effect and phenomenon synergies for both pure and mixed cases of plastics and woody biomass in flash pyrolysis.

4. Structure of the Thesis

Figure 1 presents the structure of this thesis; it covers five main chapters, as described below:

- Chapter 1 outlines the background of this study and clarifies the research purposes.
- Chapter 2 presents the waste biomass resource in Yangon, Myanmar that could be used in initiatives that apply low-carbon technologies. The status of the generation of this waste, and its potential utilization, were discussed.
- Chapter 3 addresses the practical treatment of waste and biomass as high energy density fuels and how wood pellets and RPF are used to recover energy in FBGs using WtE technology.
- Chapter 4 explores fundamental flash pyrolysis experiments aiming to reproduce the behavior and conditions of practical FBG tests.
- Chapter 5 draws the conclusions of this study and outlines recommendations for the effective management of resources, potential utilization of energy recovery technologies, and future researches.

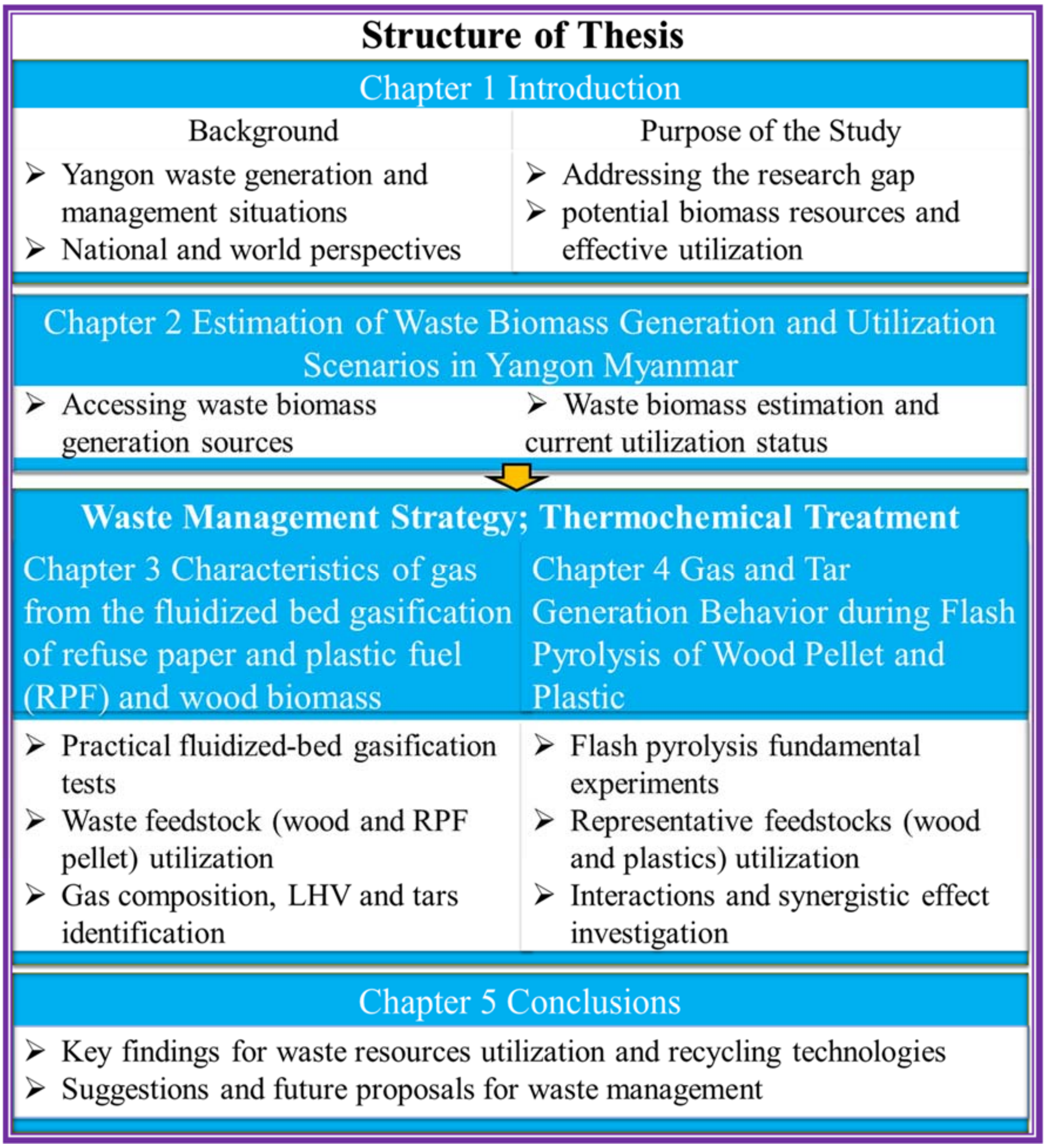

Figure 1. Structure of thesis for utilization of waste and biomass resources

Chapter 2 Estimation of Waste Biomass Generation and Utilization Scenarios in Yangon Myanmar

1. Introduction

The increase in solid waste generation is posing a serious challenge worldwide with respect to controlling emissions of GHGs. Solid waste generation is expected to owing to human consumption and behaviors (Karak et al., 2012). Among solid wastes, biomass-based carbon content is a sensitive parameter related to GHG emissions and the abatement thereof (Bastian et al., 2013) because the moisture in biomass-derived carbon may affect the methane concentration of gases from open landfills. Biomass-based carbon can usually be regarded as CO_2-neutral as it can be replenished. Biomass includes organic materials derived from various resources such as forests, agriculture, animal residues, vegetation, crops, the biogenic fraction of MSW (e.g., food, paper, wood debris), and biomaterials from industrial waste (MAFF, 2009; Iakovou et al., 2010; Müller et al., 2015). With regard to the improved environmental management of biodegradable wastes, both primary biomass and secondary biogenic wastes can be considered effective for biological and thermochemical waste to energy conversion, either separately or via co-treatment processes (Evangelisti et al., 2014; Hansen and International Solid Waste Association., 1996; Møller et al., 2009).

Rapid urbanization, large industrial complexes, human migration, and solid waste generation has been adversely affecting the environmental load of Yangon, Myanmar. Currently, MSW generated are mainly disposed of in open dumps (Hengesbaugh, 2016; Institute for Environmental Strategies and UNEP, 2017), leading to high risks of water contamination, soil deterioration, and GHG emissions (Nguyen Ngoc and Schnitzer, 2009). Therefore, a proper waste management system is urgently required to maintain urban sanitation, public health, and better environmental standards. Current proposals include the introduction of integrated solid waste management, based on understanding clear material cycles and 3R policies, in Yangon and other municipalities of Myanmar (MCDC, 2017; RRC.AP, 2015; JICA and YCDC, 2013a; JICA and YCDC, 2014).

In general, 77 % of MSW composition from major cities contained organic waste at to varying degrees in 2016: Mandalay had 64%, Yangon 68%, and Nay Pyi Taw 84 (Hengesbaugh, 2016; Institute for Environmental Strategies and UNEP, 2017; Fodor and Lin, 2019). Plastics and paper accounted for 20% and could be potential resources for high calorific RPF to be utilized to generate power in future WtE plant. GHG emissions from waste were reported to be approximately 3 million ton CO_2 eq. in 2000 and 3.5 million ton CO_2 eq in 2005 (UNEP, 2012). Daily waste generation in Yangon increased to 3000 tons in 2017 (Kawasaki_JFE, 2018); this is a significant change from 1690 tons in 2012, as reported in YCDC official documents[1] that noted the need for GHGs reduction through the proper utilization of biogenic MSW.

The total GHG emissions in Myanmar were reported to be approximately 265 million ton CO_2 eq in 2011 (UNEP, 2013); this which was triple the overall value reported in 2000. The agricultural sector contributed the most to GHG emissions, with 15 million ton CO_2 eq. in 2000; the livestock sector released 10 million ton CO_2 eq. in the same year (UNEP, 2012). There may be an increase in waste materials generated from both the municipal sector and sewage sludge owing to the extension of sewer pipelines and wastewater treatment facilities that are part of the 2040 Greater Yangon urban expansion and infrastructure development project (JICA and YCDC, 2014) (JICA and YCDC, 2013b). Moreover, areas on the periphery of Yangon, which are still rural (but under urbanization), rely mainly on agriculture; this generates residue such as rice husk and rice straw biomass. As Yangon is also one of the delta agroecological zones in Myanmar, different livestock raising patterns can be found in the area, with broiler chicken and pig husbandry the most common (NAPA, 2016). These activities generate waste manure that contains sludge biomass which has great potential to be applied, in due course, to the recovery of resources such as secondary feedstock and energy (Fischer and Schrattenholzer, 2001; Searle and Malins, 2015; Khoo et al., 2010; Yano and Sakai, 2016).

In Myanmar, the policies and strategies have already been enacted to guide the sustainable consumption and the efficient utilization of resources (MoNREC, 2017; Myanmar, 2019; MoPF, 2018); however, the implementation of baseline assessment of waste and biomass generation status and renewable energy potential is very limited. This study aims to estimate potential waste biomass generated as part of approaching sustainable management and efficient resource utilization. The waste biomass generated may be coupled with affordable, clean, and renewable energy processes for a climate-resilient society. Several attempts have been made, in previous studies, to research technologies to recover energy different wastes and biomass resources; the latter include industrial waste, MSW, and source separated organic MSW (Clavreul et al., 2012; Yoshida et al., 2012) and the latter include agricultural and forest residues processed via thermochemical and biochemical conversion processes (e.g., incineration,

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[1]YCDC 2012, Official documents, Pollution Control and Cleansing Department, Yangon City Development Committee

gasification, pyrolysis, anaerobic digestion) (Prasara-A and Grant, 2011; Shafie et al., 2014; Silalertruksa and Gheewala, 2013; Lim et al., 2012; Nakamura et al., 2008; Zhang et al., 2010); from livestock manure in AD processes (Bujoczek et al., 2000; Li et al., 2015; Wang et al., 2012; Cu et al., 2015; Haider et al., 2015a; Jabeen et al., 2015); and from sewage sludge co-gasification with woody biomass (K. W. Lee et al., 2014). Knowing the estimates for waste generated will be important for utilizing resources effectively in energy management systems. Estimates of waste biomasses generated are generally conducted, with a long-term perspective, for 2015–2030. Estimates of waste biomass generated will be preliminary initiatives, from the perspective of mitigating GHG emissions through future utilization potential of waste biomass, towards what will be regarded as a carbon-neutral approach.

2. Methodology

2.1.Study area

Yangon, which is seeing increasing population migration, is a commercial hub, and is the most industrialized area in Myanmar, is generating an increasing volume of waste. The system to manage the waste generated still requires improvement; wastes are mainly disposed in open dumps. Small scale incineration plants (60 ton/day) were first introduced in 2017 as energy recycling options to be integrated in the existing management system. As an early part of setting up integrated waste management system, a semi-aerobic sanitary landfill has been under construction since 2019, to be completed in 2021 (UN-Habitat, 2019). For future improvements in waste management systems, treatment schemes, and estimates of waste generated, this study especially focuses on biomass waste in Yangon.

Yangon has an area of 757 km^2 and is the most populated city in Myanmar, with 5.21 million residents that make up about 20% of the overall urban population (Myanmar census 2014). It has 33 townships and the YCDC is the main body responsible for waste management. Although the current sewer facilities are very limited for a city with the population of Yangon, there are plans for serious improvements. Crops (mainly paddy) are grown in agroecological zones in peri-urban areas, rural areas that are currently urbanizing, and the outskirts of Yangon; livestock breeding is also the way that many people earn their living.

2.2.Generated Waste Biomass

Raising the sustainable management of waste and biomass, the organic fractions of

MSW (food, wood, and paper), agricultural wastes (rice straw and rice husk), livestock wastes (pig manure and poultry chicken manure), and sewage sludge from WWTPs generated in Yangon city were considered to estimate their future potential generation and utilization status. Improper management of generated biomass waste leads to methane emissions that have important global warming potential. Organic matter such as separated MSW (food), garbage, and livestock wastes have been treated in combination with sewage sludge for co-digestion in AD and beneficially utilized as compost in farming and greening in Japan and some of the Europe (LeBlanc et al., 2008). Various studies have suggested the o-digestion of multi-biomass substrates from different sectors of MSW, agriculture, livestock, and sewage as a way to improve product quality and quantity (Wang et al., 2012; Jabeen et al., 2015; Tian et al., 2015), to optimize carbon/nitrogen ratios, a favorable pH, biodegradability, and retention time, among other parameters; however, this still needs to be studied in depth in terms of large-scale operations. The elemental composition of each waste biomass was summarized in Table 1. LHV is calculated using Eq. (1). Moisture content of sewage sludge from WWTP was considered after dewatering. (Li et al., 2015). The detailed explanation for each respective waste category is provided in Section 2.3.

Table 1 Characteristics of organic MSW and waste biomasses

Parameters	Unit	MSW			Agriculture		Livestock		WWTP	Ref.
		Food	Paper	Wood	RS	RH	PS	CS	SS	
LHV	MJ/ton	4,613	15,556	14,665	12,894	12,836	5,643	5,299	-568	c
Moisture	%wet	60 [a]	10 [a]	15 [a]	12[b]	11 [c]	53[c]	58 [c]	87[*c]	a, b, c
Combustible	%wet	32 [c]	84 [c]	80 [c]	70 [b]	68 [b]	36 [d]	35 [d]	8 [c, e]	c, b, d, e
Ash	%wet	8[f]	6 [f]	5 [f]	18 [b, c]	21 [b, c]	11 [c]	7 [c]	5 [c, e]	b, c, f
Carbon	%wet	15 [a]	40 [a]	43%[a]	33 [b]	34 [b]	19 [d]	14 [d]	4.19[c,e]	a, b, d
Nitrogen	%wet	1.2 [f]	0.2 [f]	0.7 [f]	0.3 [b, c]	0.8 [b, c]	2 [c, d]	3.8 [c, d]	0.16 [c, e]	b,c, d, f

RS rice straw, *RH* rice husk, *PS* pig sludge, *CS* chicken sludge; *SS* sewage sludg.

*For sewage sludge, sludge after dewatering was used

[a] *Table 2.4-IPCC,2006.;* [b] *Contreras L. M. et al., 2012.;* [c] *Calculation ;* [d] *Li K. et al.,(2015) 133–140;* [e]*Williams, P.T., 2005..;* [f]*Bastian et al. (2013);* **Sludge after dewatering was used*

$$\text{LHV} = \left(44.75 \times C_c \times 100 - 5.85 \times M_c * 100 + 21.2\right) * 4.19 \qquad \text{Eq. (1)}$$

LHV :lower heating value (MJ/ton)

C_c Combustible content (Coefficient)

Mc Moisture content (Coefficient)

2.3 Estimation Models

As material cycles and waste management must be considered and developed from long-term perspectives, estimation for waste biomass generation from the year 2015 to 2030 was considered in this study. The background conditions for the estimation of potential waste generation in Yangon were presented in the preceding sessions Figure 2, 3, 4, and 6; for which estimation methodologies were expressed. Key parameters used for the estimation of different waste categories are listed in Table 2.

Table 2. Key parameters for estimation of waste biomass generation

Waste category	Parameters in calculation	Values	Units	Reference
Biogenic MSW	National GDP per capita (2015)	1123	$/capita	World bank (WB) 2018
(Food,	Yangon Population (2015)	4.85	Million	UN 2018
Paper,	MSW generation (2015)	0.421	kg/capita/day	Calculation, WB 2018
Wood)	MSW generation(default) (2030)	0.442	kg/capita/day	Calculation, WB 2018
	MSW generation (Min) (2030)	0.421	kg/capita/day	Calculation, WB 2018
	MSW generation (Max) (2030)	0.680	kg/capita/day	Calculation, WB 2018
	Composition of food in MSW	32.10	%	
	Composition of wood in MSW	14.80	%	YCDC 2012
	Composition of paper in MSW	12.00	%	
Agricultural	Paddy cultivation area	0.56	Million ha/yr	YAD 2015
residues	Average paddy yield (2015)	3.87	M ton/ha	FAO statistics
(Rice straw,	Average paddy yield (2030)	3.80	M ton/ha	Default assumption
Rice husk)	Average paddy yield (2030)	3.33	M ton/ha	Low case assumption
	Average paddy yield (2030)	5.15	M ton/ha	High case assumption
	Rice straw to grain ratio	75	%	UNEP 2012
	Rice husk to rice straw ratio	24	%	UNEP 2012
	Rice straw animal feeding ratio	40	%-	FAO 2016
	Rice husk energy utilization ratio	25	%	UNEP 2013
Livestock	Yangon Population (2015)	4.85	Million	UN 2018
Pig sludge	National GDP (2015)	58.845	Billion $	World bank (WB) 2018
	National GDP per capita (2015)	1123	$/capita	World bank (WB) 2018
	Pig population	0.77	Million	Calculation, FAO 2011
	Specific gravity of pig manure	0.95	-	Honda T. (1993)
	Dry matter in manure	32.5	% (Fresh)	IAEA, 2008
	Pig manure production	3.64	L/pig/day	Fleming R, et al., 1999:

Livestock (Poultry) chicken sludge)	National chicken population	318.5	Million	FAO statistics
	Yangon chicken inventory	14.3	%	Otte J, et al (2008)
Sewer sector (Sewage sludge)	Accessible population to sewer (2010)	0.30	Million	JICA/YCDC 2013 (Soe, 2013)
	Per capita suspended solid load in sewerage (average)	40	g/capita/day	Fernandes F et al.,(2007)
	Total Solid (TS) after dewatering	12.7%	%	Li K et al., 2015

2.3.1. Population and GDP forecasts

Various studies of waste generation considered socioeconomic factors such as urban population, living standards, income level as GDP status (Khajuria et al., 2010; Afroz et al., 2011; Chen Liu and Wu, 2011). They are proportional to MSW generation. In this study, UN world urbanization prospects and population statistics (see Figure 2(a)) were used to estimate MSW generation from 2015 to 2030. A population growth of 32% was estimated, from 4.8 million in 2015 to 6.4 million in 2030. The other parameters applied were GDP per capita reported in the National Accounts Main Aggregates Database of UN (Figure 2(b)) (United Nations, 2018) and MSW generation per capita which was calculated from the regression model in Eq. (2) provided in a World Bank report (Kaza et al., 2018); it applies the GDP per capita as an independent variable. According to estimation based on the statistical data, per capita GDP will increased to nearly double, 89%, as reflected by the change from 1123 US$/capita in 2015 to 2120 US$/capita in 2030.

$$W = \beta_0 - \beta_1 \times (\ln(x)) + \beta_2(\ln(x)\,\hat{}\,2) \qquad \text{Eq. (2)}$$

W : Per capita waste generation (kg/cap/day)

β_0 : 1647.41(coefficient)

β_1 : -419.73 (coefficient)

β_2 : 29.43 (coefficient)

x : GDP per capita

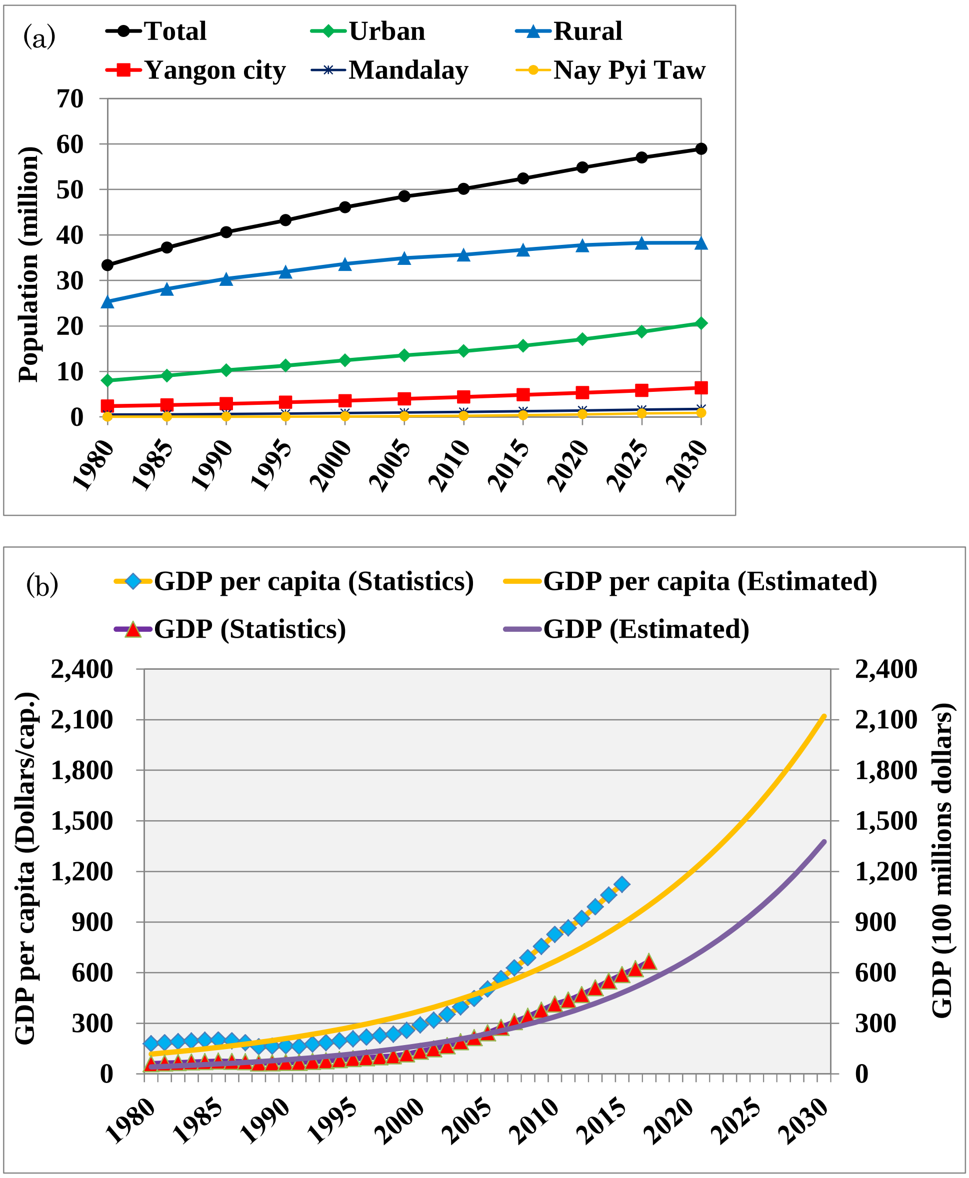

Figure 2. Myanmar (a) Major cities population, (b) GDP and GDP per capita

2.3.2. Organic fractions in MSW

aste composition data in Yangon as in Figure 3 was also included for organic MSW composition estimation that accounted for nearly 60%, as reported in the YCDC official documents. The composition was assumed to remain unchanged until 2030 (Table 2) owing to data limitation. Then amount of organic fraction in MSW generated was estimated by multiplying the human population, MSW generation per capita, and its composition.

In considering the uncertainty range of per capita MSW generation estimation for the year 2030, default value was calculated using the regression model developed by the

World Bank whereas low scenario was assumed to be the same as in 2015. Then, the high scenario was estimated from the reported average value of East Asia & Pacific region categorized by the World Bank (Table 2), where Myanmar was included as lower middle-income country.

$$P_{MSW} = H \times W \times \omega$$

Where,

P_{MSW} = MSW generation (million tons/ year)

H = Urban population (millions)

w = per capita waste generation (kg/cap/day)

2.3.3 Agricultural waste biomass

Yangon is one of the agroecological zones with agriculture in peri-urban and surroundings areas (NAPA, 2016). Most agricultural land in Myanmar is traditionally used for paddy cultivation that is widespread all over the country. Among them, 8% of paddy lands are distributed in Yangon (NAPA, 2016). According to the regional statistics as of 2014[2], land use for agriculture in Yangon is approximately 70%. Of all agricultural land areas (0.79 million hectares) in Yangon region, more than 70% is used for paddy cultivation and the rest is used for beans and oil pulses, culinary plants, long-term plantation etc. The land use and cropping pattern was shown in Figure 4 (a) and (b). Therefore, agricultural residues from paddy field, rice straw and rice husk are major generated waste.

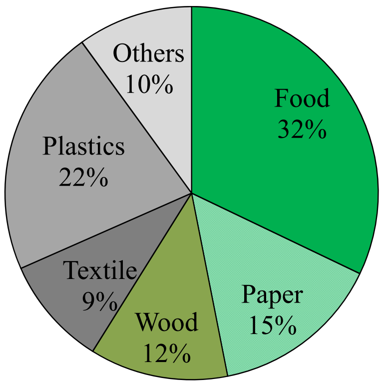

Figure 3. MSW composition in Yangon

To estimate generated agricultural biomass, paddy yield (ton per hectare) data (FAO statistics, 2019), paddy cultivated area (CSO, 2016), rice straw to grain (paddy) ratio, adopted to be 75% (Nygaard et al., 2012), rice husk to rice straw ratio, assumed to be

[2] Official report in Myanmar version from Yangon Administrative Department, 2015

24% (Nygaard et al., 2012) as presented in Table 2, were the parameters formulated. Rice straw generation was calculated as in Eq. (3) and rice husk generation was calculated in Eq. (4). The estimation for rice husk and rice straw was applied for unused amount remaining from their potential utilization status. Some of the generated rice straw are used for animal feeding (FAO, 2004) as well as rice husk is used for power generation and several energy utilization purposes (UNEP, 2013; Pode et al., 2016). For rice straw, animal feeding ratio was assumed as 40 % in 2015 as shown in Table 2 (FAO, 2004). Then the surplus amount became 60% for the overall generation as shown in Table 4. It was assumed the feeding status and surplus amount will remain unchanged in 2030 because the cattle-based plough system is still common in Myanmar despite the mechanization of agriculture. As rice husk utilization in 2015 was considered to be 25% as described in Table 2 (UNEP, 2013), the surplus amount of rice husk was 75%. Based on the future population growth scenarios in Yangon, as reported in UN world urbanization prospects and population statistics, the potential rice husk utilization increase in 2030 was estimated at 33% while the surplus was estimated to 67 % in 2030, as shown in Table 4. Regarding paddy yield status in 2015, it was assumed from FAO statistics to be 3.87 ton/ha. For paddy cultivation area in both timelines of 2015 and 2030, assumption was made to be constant in the calculation process. It was because from the FAO data, harvested area remained the same in decades in Yangon and the whole Myanmar as in the statistics (FAO statistics, 2019; CSO, 2016; MOAI, 2014). In addition, the fact is that the paddy lands are protected for non-agricultural purpose by Farmland Law (Melorose et al., 2015; UN-Habitat translation, 2012) in Myanmar and can be rarely altered for other purposes.

$$P_{y_{RS}} = R_y \times A \times \alpha_{RS} \qquad \text{Eq. (3)}$$

$$P_{y_{RH}} = R_y \times A \times \alpha_{RH} \qquad \text{Eq. (4)}$$

Where,

$P_{y_{RS}}$ = Rice straw generation (million tons/ year)

R_y = Rice yield (ton/ha)

A = Harvested area (ha)

α_{RS} = Rice straw to grain ratio

$P_{y_{RH}}$ = Rice husk generation (million tons/ year)

α_{RH} = Rice husk to rice straw ratio

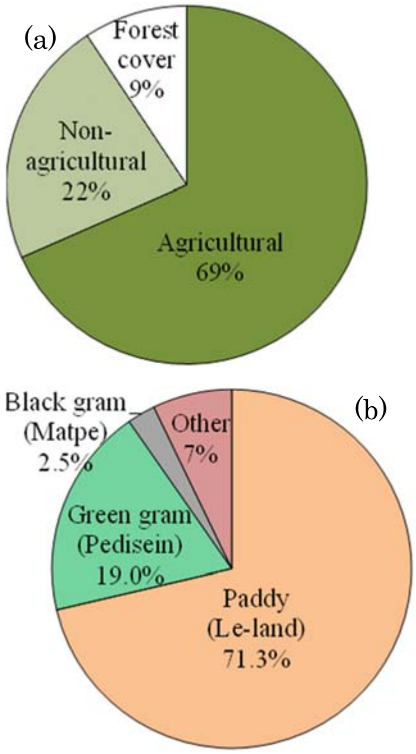

Figure 4. Yangon (a) land use exlcuding residential area; (b) crop distribution pattern

After 2015, paddy yield (FAO statistics) appeared to be decreasing at 3.80 ton/ha till 2017. However, it could be expected to increase again up to 3.87 ton/ha, which was assumed to be the default value in 2030, due to crop yield planning in Climate Smart Agriculture Strategy 2016 (MoNREC, 2017). Then the low scenario for the year 2030 paddy yield was also assumed to be as low as in the past, i.e., 3.33 ton/ha which was set as minimum range. Because there could be constraints to paddy yield, which is sensitive to climate conditions and incorrect practice of pesticides and chemical fertilizers. From time to time, the untimely rain and crop disease spread-out might also cause reduction in paddy yield in Myanmar.

Among ASEAN countries paddy yield (see Figure 5), the status of Myanmar is moderate (FAOSTAT, 2019). Paddy yield in ASEAN countries ranged from 2.15 to 5.76 ton/ha as of 2015. Reforming currently on agricultural inputs such as irrigation extension, fertilizers utilization, farm mechanization, land preparation and quality seeds, the high scenario for the maximum range estimation in 2030 was assumed to rise as high as that in Indonesia, i.e. to increase up to 5.15 ton/ha (Figure 5).

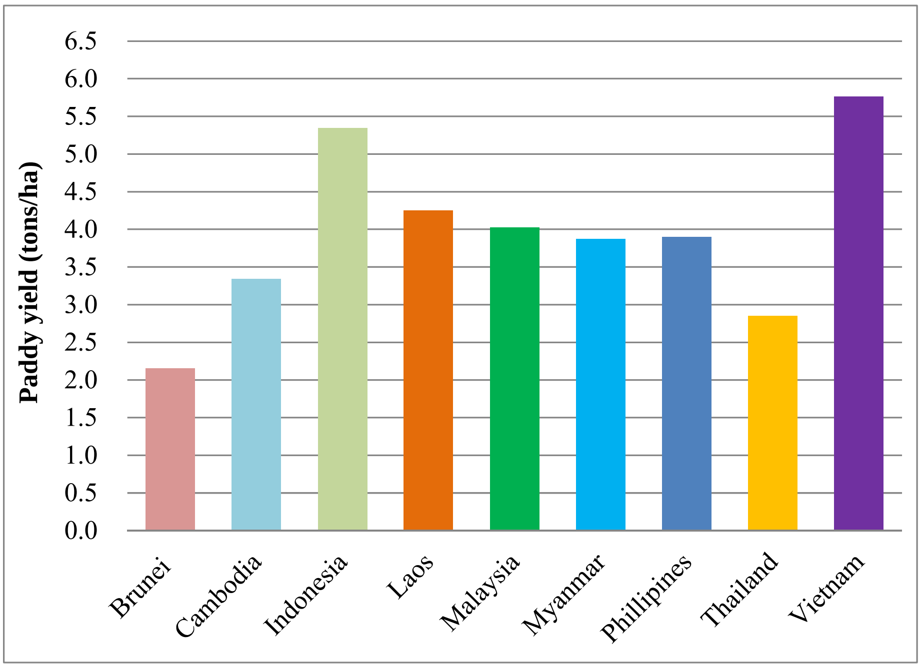

Figure 5 Paddy yield profile in ASEAN countries in 2015 (FAO statistics)

2.3.4 Livestock waste biomass

About 70% of Myanmar population is in rural area where 8 million farmers widely practice households and smallholder livestock-cropping that is reserved as additional and emergency income reserves (NAPA, 2016). On the other hand, there are nearly 5,000 commercial farms for pig and chicken at different scales nearby the peri-urban and surroundings area of big cities such as e.g., Yangon and Mandalay; the majority are raised by nearby farmers. In Yangon, pigs and chickens have the highest consumption rate, thereby reflecting the highest livestock population[3] (see Figure. 6). Therefore, livestock consumption pattern raises concern on waste generation from the two most significant categories, i.e., chicken manure and pig manure.

[3] Official report in Myanmar version from Yangon Administrative Department, 2015

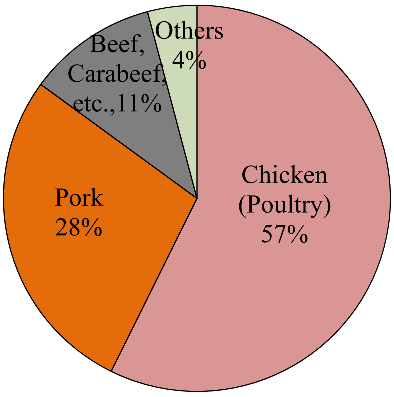

Figure 6. Livestock consumption (weight basis) status in Yangon

The current and future quantities of generated pig sludge can be estimated by multiplying the calculated pig population with the daily pig sludge generation as in Eq. (5). Assuming consumption growth to be proportional to human population growth, pig population data of Yangon in 2009 (Tobergte and Curtis, 2013) was used for estimation in 2015. For daily pig sludge generation rate, the specific gravity of manure (0.95) (Honda T., 1993), dry matter content of manure (32.5%) (IAEA, 2008), and average pig manure generation rate (3.64 L/pig-day) (Fleming et al., 1999) were multiplied and found to be 0.41 ton sludge/pig-year (Table 4). Pig sludge generation was on the increase in 2030, given by rising status of the percentage of the pig population that is consumed. The pig population growth scenario was estimated by assuming that meat consumption growth is proportional to 1) human population, 2) GDP per capita, and 3) GDP. Thus, pig population projection was assumed to vary as minimum, default, and maximum ranges in 2030. Pig population estimation results were shown in activity factor of Table 4 at "Results and Discussion".

$$P_{PS} = P_{pg} \times A_{PS} \quad \text{Eq. (5)}$$

Where,

P_{PS} = Pig sludge generation (million tons/ year)

P_{pg} = Pig population

A_{PS} = Annual pig sludge generation (ton/pig/year)

Generated amount of chicken manure was also estimated from the multiplication of chicken population and average manure generation rate adapted from layer and broiler chicken. The average manure generation was calculated to be 0.01 ton sludge/chicken-year basing on the generation status reported in Barker et al., (Barker et al., 2001). In estimation, the generation rate was assumed from already grownup chicken on a one-time basis. For chicken population status, the basis was taken from

Yangon chicken inventory data distributed by the national chicken population of Myanmar (Table 2) that was 14% of the total in 2005 (Burgos et al., 2008). Then, chicken population inventory estimation for 2015 was considered with the same assumption as that for pig population; consumption growth was assumed proportional to human population growth that equaled to be 17% in 2015. The change in population growth by rising chicken consumption was considered to affect the future chicken sludge generation in 2030. Therefore, the chicken population inventory in 2030 was assumed proportional to growth of human population, and GDP per capita. Taking the above mentioned three assumptions as minimum, default and maximum projections in 2030, Yangon chicken population inventory was adapted to be 22%, 34 % and 41%, respectively. The model of the national chicken population statistical data was adapted together with Yangon inventory data in estimating the chicken sludge generation as in Eq. 6.

$$P_{CS} = P_N \times P_{Inventory} \times A_{CS} \qquad \text{Eq.6}$$

P_{CS} : Chicken sludge generation (tons/yr) in the year T

P_N : National chicken population

$P_{Inventory}$: Yangon chicken inventory by National population

A_{CS} : Annual chicken sludge generation rate

2.3.5 Sewage Sludge (Sewer waste biomass)

Sewage sludge is the byproduct of the processing WWTP in sewer systems. It contains insoluble residues produced after the number of subsequent sludge stabilization procedures (Arthurson, 2008; Yang et al., 2015). Sludge is produced in all of the primary, secondary, and tertiary stages of treatment (Doorn et al., 2006). Myanmar has been lacking a sufficient sewer system and facing problems of sewage sludge collection. As the current biggest commercial city in Myanmar, the existing sewerage system in Yangon is accessible to only approximately 7% (0.3 million) of the city population as of 2010 (IGES-UNEP, 2017; Soe, 2013). The remaining of the urban area can access onsite and septic systems from which sewage were transported by collecting vehicles to be discharged to the waterways directly and/or to WWTPs. In this study, the focus was the potential sewage sludge discharged from the centralized WWTP system currently used by the primary treatment system. To extend the sewer lines, Greater Yangon Master Plan was drawn to the service coverage population of 4.2 million in 2040 which can be calculated to be 60% of the population that can access the sewerage system in the future (JICA and YCDC, 2013b). To improve management of waste problems related to sewer and WWTP system, the estimation of the potential sewage sludge generation was conducted in this study.

In developing sanitation system improvement such as WWTP infrastructure and sewage sludge management, adaption of good practice and technology from developed countries could be very useful (Lwin et al., 2015). Sewage sludge generation is in related to the factor of WWTP access rate (% population connected to WWTP) (Lwin et al., 2015) was assumed as generation factor in this estimation model. WWTP access rate was also considered to be a positive correlation as a function of GDP per capita (Lwin et al., 2015; Yang et al., 2015). Meanwhile, the level of sewerage treatment and type of treatment system could influence per capita sludge generation (Mininni et al., 2015). It could also be varied by the difference in processes of WWTP (Yang et al., 2015).

Owing to successive measures for economic competitiveness, investment, and industrial improvement in Myanmar, GDP growth has been steadily increased (Gelb et al., 2017; Khin Mar Thet, 2018; Myanmar Investment Commission, 2018). Accordingly, to estimate WWTP access rate in Yangon, the tendency of the statistical WWTP access rate trend line data in three OECD countries, Mexico, Turkey and Belgium (OECD, 2018) were adapted to be future 2030 scenarios of minimum, default, and maximum. The assumption was made basing on the planned WWTP access rate in official reports of future Yangon Water Supply and Sewerage Sector Master Plan which expected WWTP access rate to be approximately 60% (JICA and YCDC, 2013b). The default assumption in 2030 was considered as in Turkey sewer coverage profile. Then low and high scenarios were assumed from the statistical WWTP access rate data of Mexico and Belgium to be minimum and maximum in 2030. The observed results were discussed in Section 3.3 in details. Based on the recent most available WWTP access rate in Yangon at 7% (0.3 million) (IGES-UNEP, 2017) (Soe, 2013), the adaption of WWTP access rate from OECD cases was estimated using Eq. (7), Eq. (8), and Eq. (9) for 2015 and 2030.

$$P_{WWTP(min)_T} = 2.15 \times t + 21.06 \qquad \text{E.q. (7)}$$

$$P_{WWTP(default)_T} = 2.86 \times t + 21.53 \qquad \text{E.q. (8)}$$

$$P_{WWTP(max)_T} = 3.51 \times t + 36.97 \qquad \text{E.q. (9)}$$

Where,

P_{WWTP_T} = % population connected to WWTP in the year T

t = Passed year from 2009 (t=1,2,…; t= T-2010)

For the sewage sludge generation, it was estimated by multiplying the estimated WWTP access rate in Yangon and per capita sewage sludge produced per day. Per capita sewage sludge generation, in fact, could be expected high in developed countries owing to better applied WWTP technology, improved economy, etc.,(Yang et al., 2015). In the previous study, the moisture content of sewage sludge was 87%, calculated from dry matter content of 13%, after dewatered AD process (Li et al., 2015). The moisture content of untreated sludge after clarifiers is typically to be 98%, which is reported to be 95% after primary pre-treatment and gravity thickening(Yang et al., 2015; Evans, 2016). Dewatered sludge is usually reduced to 20–30% dry matter (80–65% moisture) owing to conditioned chemical dosing to easily separate water and cake by floc formation. Moisture content of dewatered sludge is different depending on the type of sludge and the method of dewatering (Evans, 2016). As reported in (Fernandes et al., 2007), per capita sludge load was assumed to be 11 g/ cap-day considering moisture content after AD process to be 87% (Li et al., 2015) which implies that the conversion is 0.03 ton sludge/cap-year.

2.4 GHG emission potential from waste biomass

Although waste biomasses can be generally considered to be CO_2-neutral (Iakovou et al., 2010), mismanaged practices such as open disposals can cause GHG emissions. In waste sector, disposing in landfills and incineration are sources of GHG methane emissions, which is, specifically, regarded as the largest CH_4 emission from final disposal sites (IPCC, 2006). Owing to incomplete combustion, CH_4 emissions from incineration and open burning of waste can produce other gases, such as CO_2 and nitrous oxide (N_2O), of which CO_2 is dominant. The estimation of CH_4 emission from improper management will be important in due course.

Considering the environmental impacts of global warming, CH_4 emission has been targeted from the generated solid waste in order to estimate CO_2 from biogenic waste as it is considered to be CO_2-neutral. Considering the 100-year time horizon Global Warming Potential for methane (GWP_{CH4}) to be 25 ton CO_2 eq/ton CH_4 (IPCC, 2014). The emissions from operational activities and waste degradation from the treatment of waste biomass generated in Yangon City in 2015 and 2030 were considered in this estimation. CH_4 emission is calculated based on methane generation potential of the waste of decomposable degradable organic carbon as described in IPCC guidelines 2006 (IPCC, 2006) as shown in Eq. 10. In the case of animal waste management system and sewer system, N_2O emission was considered. In order to estimate N_2O emission from wastewater after disposal of effluents of sewer system into waterways, lakes, or seas, IPCC guidelines for wastewater treatment and discharge were followed to calculate it (Doorn et al., 2006) as in Eq. 11. For animal waste manure emission, an IPCC guideline for animal manure waste management system (Jun et al., 2000) was referred using Eq. 12. The parameters used for the estimation of GHG emissions calculation process (IPCC, 1997; Toyota, 2004; Doorn et al., 2006; Disposal et al., 2006; IPCC, 2007; Jun et al., 2000; Yano et al., 2014) are described in Table 3.

For CH_4 emission from disposed solid waste fraction,

$$EM_{CH4} = (1 - OX) \times DOC_f \times MCF \times \sum (W_i \times DOC_i) \times F \times {}^{16}/_{12} \quad \text{Eq. 10}$$

EM_{CH4} : Amount of CH_4 emission [t-CH_4/yr]

OX : Oxidation factor [–]

DOC_f : Fraction of degradable organic carbon decomposed [–]

MCF : CH_4 correction factor for aerobic decomposition [–]

W_i : Amount of biogenic waste type *i* [tons]

DOC_i : Fraction of degradable organic carbon in waste type *i* [–]

F : Fraction of CH_4 in generated landfill gas [–]

For N_2O emission from wastewater discharge of sewer system,

$$EM_{N2O} = \{(P \times Protein \times F_{NPR} \times F_{NON-CON} \times F_{IND-COM}) - N_{Sludge}\} \times EF_{Effluentf} \times {}^{44}/_{28} \quad \text{Eq. 11}$$

EM_{N2O} : Amount of N_2O emission [t- N_2O/yr]

$EF_{Effluent}$:Emission factor for N_2O emissions from discharged to wastewater, [kg N_2O-N/kg N]

P : Human population [Millions]

Protein : Annual per capita protein consumption, [kg/person/yr]

F_{NPR} : Fraction of nitrogen in protein, default [0.16, kg N/kg protein]

$F_{NON-CON}$: Factor for non-consumed protein added to the wastewater [-]

$F_{IND-COM}$: Factor for industrial and commercial co-discharged protein into the sewer system [–]

For N_2O emission from animal waste management system (AWMS),

$$EM_{N2O} = \{(N_T \times Nex_T \times AWMS_T)\} \times EF_{AWMS} \times {}^{44}/_{28} \quad \text{Eq. 12}$$

EM_{N2O} : Amount of N_2O emission [t- N_2O/yr]

Nex_T : N excretion of animals of type T in the country [kg N/animal/yr]

N_T : Animal population [Millions]

$AWMS_T$: Fraction of nitrogen in protein, default [0.16, kg N/kg protein]

EF_{AWMS} : N_2O emission factor for an AWMS [kg N_2O-N/kg of *Nex* in AWMS]

Table 3. Parameters used for estimated GHG emissions

Emission sources	Parameters	Value	Unit	Reference
Operational activities	Electricity Consumption	6.38	kWh/ton	Yano et al,. (2014)
	Diesel Consumption	0.763	L/ton	
	LHV of diesel	35.5	MJ/L	Toyota (2004)
	Emission factor (EF) of diesel	0.080	kg CO_2/MJ	
	EF of electricity	0.232	kg CO_2/kWh	Calculation
	GWP_{CH4}	25	ton CO_2 eq/ton CH_4	IPCC,2007
	GWP_{N2O}	298	ton CO_2 eq/ton N_2O	
Open dumping	MCF	0.6	-	
	OX	0	-	
	F	0.5	-	
	DOC_f	0.5	-	
Livestock manure	EF of N_2O	0.005	kg N_2O-N/kg N	Jun, P et al,. 2000
	Nitrogen excretion (pig)	16.00	kg N/animal/yr	
	Nitrogen excretion (chicken)	0.6	kg N/animal/yr	
	AWMS pig	93	% N/ system	
	AWMS chicken	99	% N/ system	IPCC, 1997
	Pig population (2015)	0.77	Million	Table 4
	Pig population (2030)	0.97	Million	Table 4
	Chicken population (2015)	36.7	Million	Table 4
	Chicken population (2030)	379.9	Million	Table 4
Sewer wastewater	Population	4.85	Million	UN statistics
	Population	6.39	Million	UN statistics
	Protein consumption (2015)	95	g/cap/day	FAO statistics
	Protein consumption (2030)	140	g/cap/day	FAO statistics, calculation
	EF of N_2O	0.005	kg N_2O-N/kg N	
	F_{NPR}	0.16	kg N/kg protein	Doorn et al., 2006
	$F_{NON\text{-}CON}$	1.4	-	
	$F_{IND\text{-}COM}$	1.25	-	
	Nitrogen removed with sludge	0	kg N/yr	

3. Results and Discussion

3.1 Estimation process for generated waste biomass

The summary of the waste generation estimation process is presented in Table 4. Here, the generation intensities of each waste category were first estimated using assumptions, statistics, and reported models. Unit generation and dependent activity factors relevant to each waste generation category were thereafter estimated. The estimated waste biomass generation was finally calculated by multiplying the unit generation rates and activity factors. A detailed explanation of the estimation models and the waste generation categories was discussed in section 2.3.

In determining the estimation parameters and procedures, it was found different assumptions and modeling process depending on the waste biomass generation sources. For the activity factors determination as in Table 4, demographic data was used for estimating MSW generation. Similarly, the data was also used for estimating livestock consumption, and sewer accessibility status. In the case of the agricultural sector, land use status for paddy cultivation was considered as an activity factor. The estimation process of unit generation for agricultural was approached by paddy yield status on a per hectare basis. The hypothesis parameters for unit generation of MSW, livestock, and sewer sectors were defined by per capita waste/sludge generation. But, in calculating the per capita generation of organic MSW, additional information such as waste composition data was necessary to determine the unit generation of each organic MSW fraction. Additionally, in agricultural waste generation, the unit generation of rice straw and rice husk yield was determined using paddy yield and the respective yield to grain ratio. The calculation process model presented in Section 2.3 discussed the calculation procedures, parameters used, and assumptions made in detail. The estimated waste biomass generation observed for both timelines, 2015 and 2030, can be seen in Table 5.

Table 4 Summary of generated waste estimation process

Waste category		Generation factor	Unit	Unit Generation 2015	2030 Default	2030 Min	2030 Max	Activity factor 2015	2030 Default	2030 Min	2030 Max	Estimated Generation (ton/yr)
MSW		Yangon population	Million					4.85 [d]	6.39 [d]	6.39 [d]	6.39 [d]	Estimated generation = Unit generation × Activity factor (The detailed background for each waste generation can be seen in Session 3.1)
	Food	Generation/capita	kg/cap/day	0.135 [a]	0.142 [a]	0.135 [a]	0.218 [a]	-	-	-	-	
	Paper	Generation/capita	kg/cap/day	0.062 [b]	0.065 [b]	0.062 [b]	0.101 [b]	-	-	-	-	
	Wood	Generation/capita	kg/cap/day	0.050 [c]	0.053 [c]	0.050 [c]	0.082 [c]	-	-	-	-	
Agricul-ture		Harvesting area	Mil ha/yr	-	-	-	-	0.56 [e]	0.56 [e]	0.56 [e]	0.56 [e]	
	RS	RS surplus	%	-	-	-	-	60 [f]	60 [f]	60 [f]	60 [f]	
	RH	RH surplus	%	-	-	-	-	75 [g]	67 [α]	67 [α]	67 [α]	
	RS	RS yield	tons/ha	2.90 [h]	2.90 [h]	2.50 [h]	3.87 [h]	-	-	-	-	
	RH	RH yield	tons/ha	0.70 [i]	0.68 [i]	0.60 [i]	0.93 [i]	-	-	-	-	
Livestock	PS	Pig population	Million	-	-	-	-	0.77 [j]	0.97 [j]	1.95 [j]	2.54 [j]	
		Generation/capita	ton/pig/yr	0.41 [k]	0.41 [k]	0.41 [k]	0.41 [k]	-	-	-	-	
	CS	Chicken population	Million	-	-	-	-	36.7 [l]	79.9 [l]	78.9 [l]	126.5 [l]	
		Generation/capita	ton/chicken/yr	0.01 [m]	0.01 [m]	0.01 [m]	0.01 [m]	-	-	-	-	
WTTP		Yangon population	Million	-	-	-	-	4.85 [d]	6.39 [d]	6.39 [d]	6.39 [d]	
		WWTP access rate	%	-	-	-	-	10.8 [n]	57.1 [n]	43.0 [n]	70.2 [n]	
		Access population	Million	-	-	-	-	0.7 [o]	3.6 [o]	2.7 [o]	4.4 [o]	
	SS	Generation/capita	ton/cap-yr	0.03 [p]	0.03 [p]	0.03 [p]	0.03 [p]	-	-	-	-	

Captions of Table 4

RS rice straw, RH rice husk, PS pig sludge, CS chicken sludge; SS sewage sludge

[a]*Multiplication of estimated MSW generation/capita in 2015 and 2030 with composition of food in MSW as described in Table 2*

[b]*Multiplication of estimated MSW generation/capita in 2015 and 2030 with composition of paper in MSW as described in Table 2*

[c]*Multiplication of estimated MSW generation/capita in 2015 and 2030 with composition of wood in MSW as described in Table 2*

[d] *United Nations: World Urbanization Prospects 2018*

[e] *Myanmar Statistical Year Book (2016) statistics used for 2015 and the same assumptions were made for 2030*

[f] *Calculation results from (100% - rice straw animal feeding ratio in Table 2)*

[g] *Calculation results from (100% - rice husk energy utilization ratio in Table 2)*

[α]*Calculation results as described in Section 2.3.3*

[h] *Multiplication of average paddy yield in 2015 and 2030 with rice straw to grain ratio from Table 2*

[i] *Multiplication of average paddy yield in 2015 and 2030 with rice husk to rice straw ratio from Table 2*

[j] *Calculated estimation of projected pig population for 2015 and 2030 scenarios from statistics and pig population growth assumptions as discussed in Section 2.3.4*

[k] *Calculated unit generation of pig sludge from Fleming R., et al.(1999), (Honda T., 1993)and (IAEA, 2008) which was described in Section 2.3.4*

[l] *Estimated chicken population for 2015 and 2030 by multiplying national chicken population statistics (FAOSTAT 2019) and Yangon chicken inventory statistics (Burgos 2008) and estimation assumed from human population and GDP per capita as discussed in Section 2.3.4*

[m] *(Barker et al,. 2001)*

[n] *Statistical WWTP access rate data from (OECD, 2018) were adapted to estimate for the future 2030 scenarios of minimum, default and maximum. Linear trend line model was developed for estimation.*

[o] *Calculated by multiplying WWTP access rate and Yangon population accessed from UN urban population statistics*

[p] *Calculated per capita sewage sludge generation from (Evans, 2016) and (Fernandes et al., 2007)*

Table 5 Estimated results of waste biomass generation

Waste category		2015	2030			Unit
			Default	Min	Max	
MSW	Food	0.26	0.33	0.31	0.51	Million ton/yr
	Paper	0.12	0.15	0.15	0.23	
	Wood	0.10	0.12	0.12	0.19	
Agriculture	RS	0.98	0.98	0.84	1.30	
	RH	0.39	0.35	0.30	0.46	

Livestock	PS	0.32	0.80	0.40	1.04
	CS	0.35	0.76	0.75	1.20
WWTP	SS	0.07	0.36	0.27	0.44
Total generated wastes		2.59	3.85	3.14	5.39

3.2 Waste biomass generation in 2015

3.2.1 Estimated results

The estimated waste biomass generation (wet basis) in 2015 for each waste category is shown in Figure 7 The generated waste biomasses are indicated by wet basis weight. The generation factors for each activity differed based on the waste biomass category. The total biomass generation amounted to be 2.59 million tons (Table 5) wherein agricultural residues shared nearly half of the overall biomass generation. Rice straw was estimated to generate the most waste followed by rice husk with 0.98 and 0.39 million tons, respectively. It is important to note that Myanmar is one of the top 20 rice producing countries in the world (FAOSTAT, 2019) as it is the staple food of Myanmar. It is the most cultivated crop in all of the different agricultural zones around the country (Pode, 2016).

Regarding the generated agricultural residues, open burning is a common method used in Myanmar for removal of such waste and for land clearance of surplus after utilization. Data on the proportion of agricultural residues subjected to opening burning is very limited. A previous study estimated that in Myanmar around 15% of agricultural residues are subjected to open burning (Kim Oanh et al., 2018). Incomplete waste combustion could emit CH_4 gas.

The livestock sector displayed a high generation of pig and chicken sludge. It was right behind the agricultural sector at about 0.63 million tons of waste generated. It was equivalent to a quarter of overall generated waste biomass. This could be reflected in the livestock consumption behavior in Yangon. The inventory of pig and poultry relative to the domestic population was high. This sheds light on a reason for such estimation for pig and chicken manure generation. The total daily consumption of 92 g per capita was moderate among other ASEAN countries which ranged from 27 to 137 g per capita (NAPA, 2016).

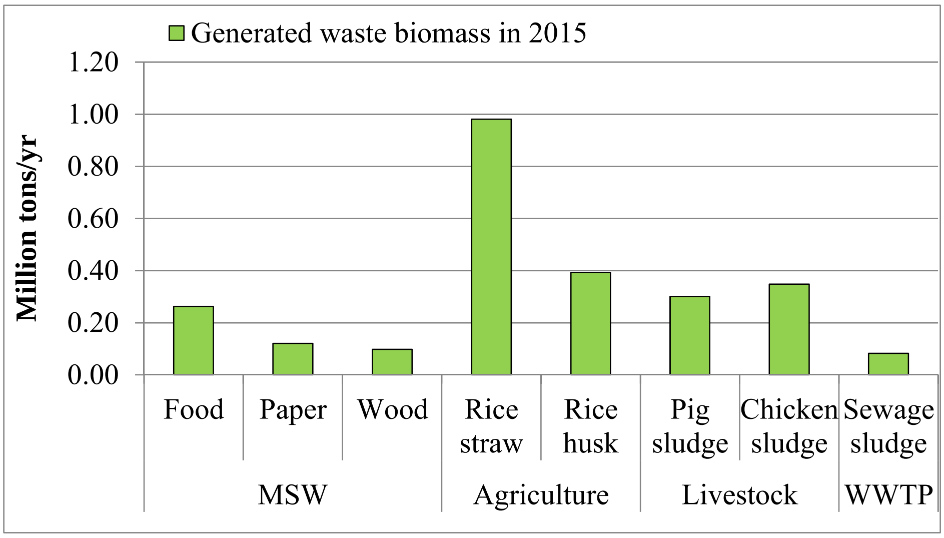

Figure 7 Estimated waste biomass generation in 2015 for Yangon (Wet basis)

The comparative waste biomass generation from agricultural sector for rice straw and rice husk and from livestock sector for pig sludge and chicken sludge are presented in Figure 8. The generation was estimated by utilizing data on agricultural (paddy) and livestock population in 2015 for Myanmar and ASEAN countries from FAO statistics and other studies (FAOSTAT, 2019; Kamuang and Siriratpiriya, 2017). As provided in Figure 8, Myanmar paddy production is moderate. Although the per hectare paddy yield status of Malaysia is quite high, its overall paddy production is the lowest which was reflected by the paddy sown area which is less than that of the other ASEAN countries. In contrast, paddy production in Thailand was quite significant in spite of its decreased paddy yield. This may be due to its status as one of the top ten rice exporting countries. In fact, paddy production could be influenced by different factors such as crop varieties causing the variation in crop paddy yield, the weather, water availability, soil fertility, farming practices, etc. (Koopmans and Koppejan, 1997).

For the estimated generation of rice straw and rice husk from paddies, it could be observed that there were variations in residues to grain ratios among ASEAN countries. The rice straw to grain ratios ranged between 40–75% while the rice husk to grain ratio could be found between 18–27% (Lasko et al., 2017; Silalertruksa and Gheewala, 2013; Koopmans and Koppejan, 1997; Prasara-A et al., 2012; Agamuthu, 2015). In addition, other variation factors such as harvesting practices and moisture content of the crop could be influential on the generated amount of rice straw and rice husk.

In the case of pig sludge and chicken sludge from livestock, the manure generation and its dry matter content differ throughout Asian countries as mentioned in livestock reports and studies. Such could be due to differing farming practices and manure management systems that will affect sludge generation (Abdeshahian et al., 2016; Fleming et al., 1999). Vietnam was found to have the highest pig sludge generation whereas Thailand had the highest chicken sludge generation. Malaysia and Myanmar generated the least waste for pig sludge and chicken sludge (See Figure 8). The generation of pig sludge and chicken sludge varied from 0.38-0.73 ton sludge/pig-year and 0.03-0.05 ton sludge/chicken-year, respectively (Abdeshahian et al., 2016; Fleming et al., 1999; Williams, 2013; Kuyama, 2016; Agamuthu, 2015). Growing GDP drives production and consumption in Myanmar. Given this, the generated waste could be expected to increase as in other higher income ASEAN countries.

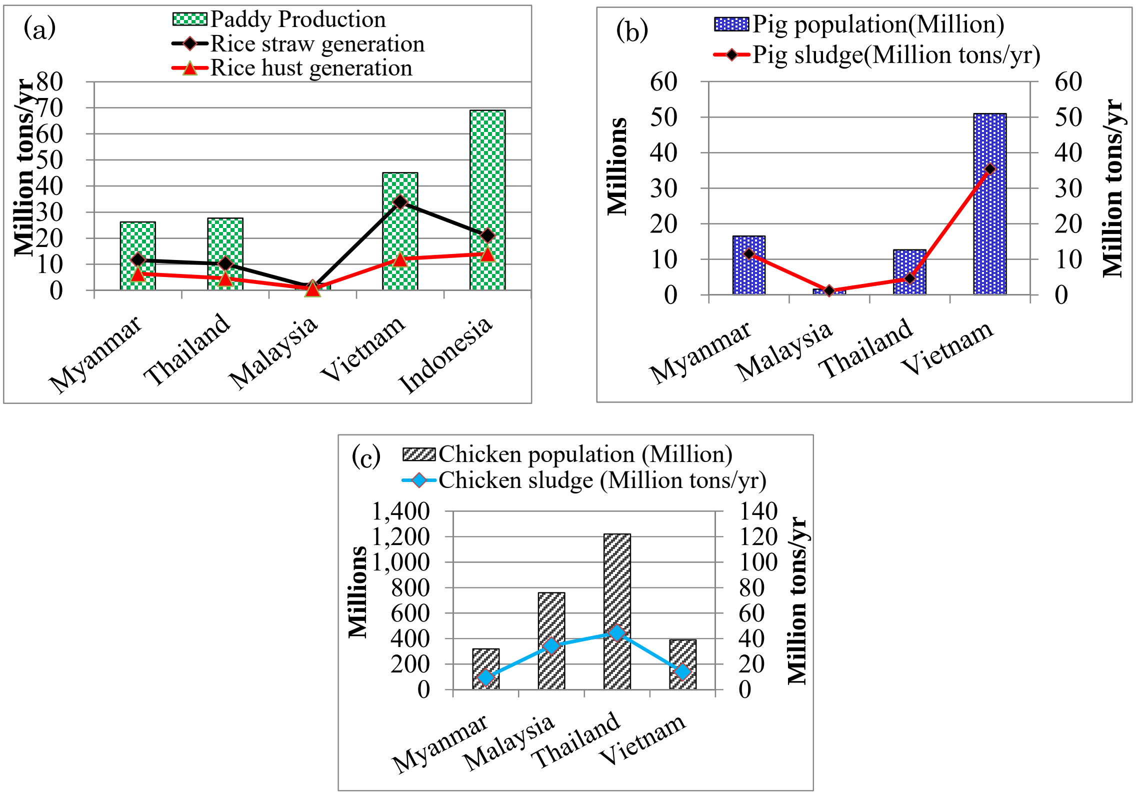

Figure 8 Comparison of ASEAN countries waste generation from (a) agricultural (paddy) sector; (b) livestock (pig) sector; and (c) livestock (chicken) sector

The generation of organic MSW was 0.48 million tons with the overall MSW generation being 0.80 million tons in 2015. Due to public health, environmental impacts and urban sanitation problems, the generation of MSW is the most pressing issue for Yangon. As in other developing countries, Yangon also has a significant composition of organic wastes (Hengesbaugh, 2016; IGES-UNEP, 2017) which emit GHGs from improper disposal. Under incomplete combustion during incineration and open burning, methane can also be generated (Pipatti et al., 2006) although not in significant amounts. This could happen if there are low oxygen levels inside the waste bunker of incinerators and subsequent anaerobic processes occur (Pipatti et al., 2006). The scale and technology of incineration could be one of the important factors affecting the emission of such GHGs.

Sewage sludge was found to be the least generated of all the waste biomasses amounting to be around 0.09 million tons in 2015. This may be reflected in the present WWTP access rate at 11% which demonstrates that at present, Yangon still has limited coverage and a poor sewer system. Sludge dewatering could also affect sewage sludge production. The process is important for the subsequent process for sludge generation. Sewage sludge may contain disease causing organism such as pathogens and potential toxic elements (Mininni et al., 2015; Arthurson, 2008) and methods on its appropriate handling and treatment should be introduced. In addition, open sewers could produce CH_4 when the sludge is processed in anaerobic conditions due to heat. WWTP sludge production and disposal practices are expected to improve with a more open and developed economy in Yangon.

3.2.2 Current status of utilization for generated waste biomass

Agricultural residues are abundantly available. These residues are utilized for several purposes such as the use of rice straw for animal feed; this accounts for nearly 40% of the total rice straw generated (FAO, 2004). This suggests that 60% of the rice straw generated remains to be utilized and managed. Rice husk is utilized in energy production such as in steam boilers, household cooking stoves, brick-furnace works, and rice husk power plants and gasifiers. Currently, Myanmar utilizes rice husk biomass for power generation by operating around 1000 small scale facilities, each generating 15–150 kW (Pode et al., 2016). Utilization for power plants accounts for approximately 10% of the total rice husk volume in Myanmar (Pode et al., 2016). Recently, the demand for rice husk for energy utilization has been reported to be 25% of the total rice husk generation (UNEP, 2013). This leaves the other 75% as a surplus. The utilization of rice husks for power generation is projected to increase due to Myanmar's low-carbon initiatives and a rise in demand for renewable biomass energy. (MRI-Fujita.Corporation, 2015; WWF et al., 2016).

Waste generated from pig farming is, typically, in the form of slurry. This poses a challenge for proper management. Most livestock farms are small commercial farms in the peri-urban area of Yangon. There is limited data on the utilization of livestock waste in Myanmar but it has been reported that manure from commercial farms of layer/broiler chickens and pigs is used as fertilizer for crops and vegetable plots (NAPA, 2016). The alternative practice of raising livestock is the growing of pigs and chickens in farms near fishponds. Then manure generated from livestock are utilized as feeds for fish production (NAPA, 2016). The utilization of manure in this manner must be assessed for potential problems such as water pollution and eutrophication.

MSW generation has been increasing from 1700 ton/day to 3000 ton/day between the years 2011 and 2017 (Kawasaki_JFE, 2018). Currently, the main disposal method is open dumping but new waste to energy recovery plants have begun operations and account for 60-tons of MSW/day. Semi aerobic landfills are also under construction and are to be utilized for future waste disposal in an integrated waste management system.

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3.3 Estimated waste biomass in 2030 and its uncertainty

Estimated results for each category of waste biomass generation in 2030 are shown in Figure 9. In total, the future generation was estimated to be 3.85 million tons/yr for the default set-up in 2030. The minimum to maximum uncertainty range was found to be 3.17–5.45 million tons/year and indicated a wide range of difference. The uncertainty range for pig sludge and chicken sludge generation varied the most. This is primarily due to the fact that their estimation was based on future potential GDP status. To estimate the uncertainty projection, future livestock inventory was related with variables of city population, GDP, GDP per capita. The practice of farming might also be an influential factor. The current status of livestock farming in Myanmar involves mostly household breeding and small scale commercial farms (NAPA, 2016). This has been changing due to the increase in private large-scale commercial farming to provide food for the enhancement of the national protein intake. This could be a potential driving factor in waste generation pattern from the livestock sector.

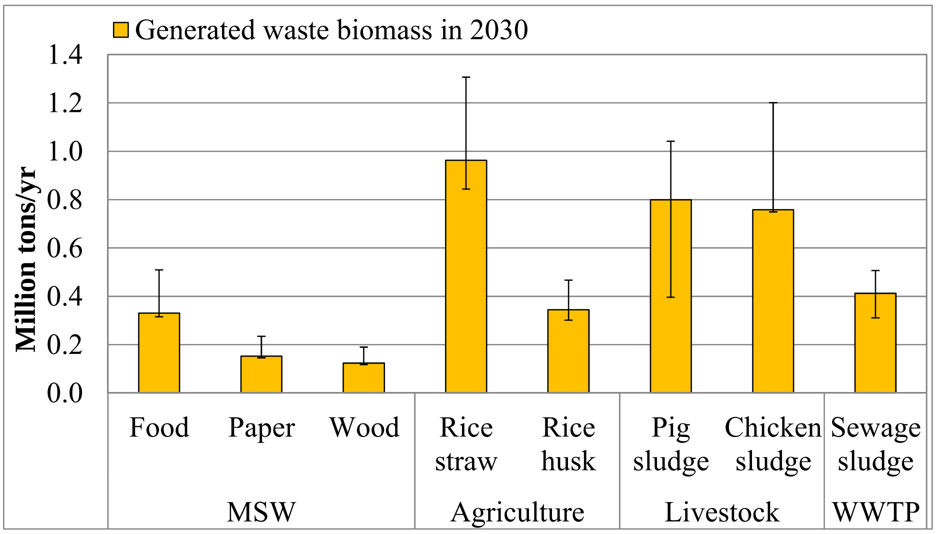


Figure 9. Estimated future waste biomass generation (Wet basis)

In estimating the future organic MSW generation, the quantitative level was calculated based on a regression model developed by the World Bank (Kaza et al., 2018). The default generation of future organic MSW was around 0.61 million tons/year. The default estimation between 2015 and 2030 differs (only 0.12 million tons/yr). Although unit generation was assumed to be the same, the activity factor such as urban population varied. More variation is observed as income level increases because the uncertainty is based on per capita GDP growth which is one of the generation factors. Adapting the per capita GDP growth established in the World Bank model as an independent parameter, per capita MSW generation variation is found to be one of the prominent factors in organic MSW generation uncertainty. In addition to activity levels such as urban population and GDP, the unit generation of MSW is also an important parameter for sensitivity of each parameter and estimation. The uncertainty range was quite significant in the variation of future MSW generation between the default and maximum which was driven by GDP per capita variation as the key factor. Aside from quantitative generation, the qualitative performance of waste biomass in FBG, such as cold gas efficiency (CGE) was found to be roughly over 50%.

For sewage sludge generation in Yangon, drastic rising generation was at 0.41 million tons/year in 2030 as the default. The generation was significantly higher than that of 2015 and was has critically affected by the WWTP access rate through sanitation infrastructure development and the extension of sewer pipelines. The increase in WWTP access rate was estimated to be 57% in 2030 default rate which was increased from 11% in 2015. For the highest scenario in 2030, the maximum WWTP access rate reached up to 70% whereas the minimum rate was estimated to be 43%. Accordingly, the estimated population connected to WWTP could be around 3.6 to 4.4 million of future Yangon population of 6.4 million in 2030. The drastic sewage sludge generation was significantly reflected in the increased coverage of WWTP access rate. A previous study by Lwin et al. estimated the sudden increase of WWTP access rate to be 2% in 2010 to 66% in 2050 in Myanmar (Lwin et al., 2015).

In addition to sewage coverage ratio (WWTP access rate), the sludge generation amount can also vary with per capita sludge production affected by applied technology of sludge processing, pre-treatment steps, type of sewer system, method of dewatering and level of treatment, etc,. (Yang et al., 2015; Mininni et al., 2015; Evans, 2016). In the case of storm water drainage discharge combination sewerage system, sewage sludge production could be decreased with the removal of volatile organic nutrients (Mininni et al., 2015). According to the previous reports (Li et al., 2015; Skoglund et al., 2016; Evans, 2016), the moisture content of dewatered sludge varies from 65-87%, alternatively there is 13-35% of dry matter content due to different dewatering techniques. Yang, G., et al., reported that the industrial structure might affect per capita sludge production even in the similar GDP per capita status (Yang et al., 2015) A great variation can be observed around the world with the minimum being in China, Brazil and with the maximum in Japan and Netherlands (Yang et al., 2015; Mininni et al., 2015; LeBlanc et al., 2008) as presented in Figure 10.

Therefore, sewage sludge production is very much case specific based on management practices and differences in applied technology scenarios. In the Myanmar, Yangon case, development of sewer and wastewater infrastructure, management practices and technology installed might be important factors in future sewage sludge generation. The potential sewage generation amount will be provided for policy making, practice and enforcement to extend the distance of sewer coverage in urban planning.

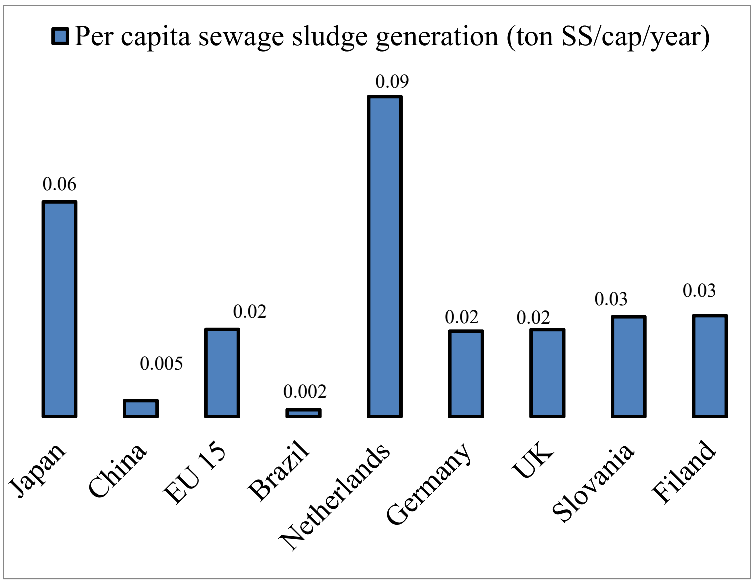


Figure 10. Variation of per capita sewage sludge generation in the world

The agricultural sector displays a somewhat different generation pattern in 2030 for estimated default value. This is depicted through the comparison in Figure 11. Agricultural waste generation was estimated to be 1.37 million tons/yr in 2030 with a decreasing trend for default generation at around 1.33 million tons/yr. This is because of the paddy yield which had a decreasing trend after 2015 but the default paddy yield assumption in 2030 was assumed to be similar in to that in 2015. In addition, paddy straw utilization potential was considered unchanged for animal feeding in Myanmar as in FAO statistics (FAO, 2004). Another factor is rice husk energy utilization potential in future that had an increasing trend for power generation in gasifier and other various types of local consumption for energy purpose (Pode et al., 2016). These all affect the default value of future agricultural waste generation.

The paddy yield in Myanmar is expected to be higher like that of ASEAN's top yield countries (FAOSTAT, 2019) owing to the paddy yield measures that have been undertaken by improving the inputs in agricultural sector through high quality, high yielding varieties, farm mechanization, irrigation improvement, combined harvesting and others (Myat Thida Win and Aye Mya Thinzar, 2016; Raitzer et al., 2015). Meanwhile, paddy production and livestock consumption in Myanmar was expected to rise alongside the regional trend as in Thailand and Vietnam due to Myanmar' consistent increasing trend for paddy production and livestock consumption as provided in FAO statistics (FAOSTAT, 2019). This would reflect ASEAN's common target of renewable energy contribution, accounting for 23% of primary energy by 2025 in implementing the policies with potential generation of biomass resources (IRENA, 2016). Agricultural waste generation dynamics has been explored in ASEAN countries..

In fact, the challenge for agricultural yield enhancement in Myanmar is to solve complex issues. This does not only cover agricultural inputs such as mechanization, quality seeds, irrigation sufficiency, but for also agricultural practices and the social context and perspectives of the farmers which must be closely assessed and corrected. Geographical and climatological conditions also make the country more vulnerable to natural disasters, such as the extreme flooding in 2015 which affected agricultural yield. The utilization change was also one of the factors reducing agricultural waste generation. Due to the growing demand for purposes of energy feedstock utilization of rice husks (Pode et al., 2016; UNEP, 2013), the generation pattern was also changed in the estimation process. In 2015, 25% of the rice husk generated was utilized for several purposes including as energy feedstock but in 2030, its utilization ratio will be increased to 33% according to estimation. As a matter of fact, its future generation stock was decreased. Agricultural inputs and cultivation practices might be the future potential factors affecting agricultural yield and waste biomass generation from paddies. Regarding agricultural land use in Myanmar, it was not found to affected crop yield because it is unlikely to change due to the prevention of Farmland Law in which agricultural land alteration procedures for any other purposes is quite complex and difficult..

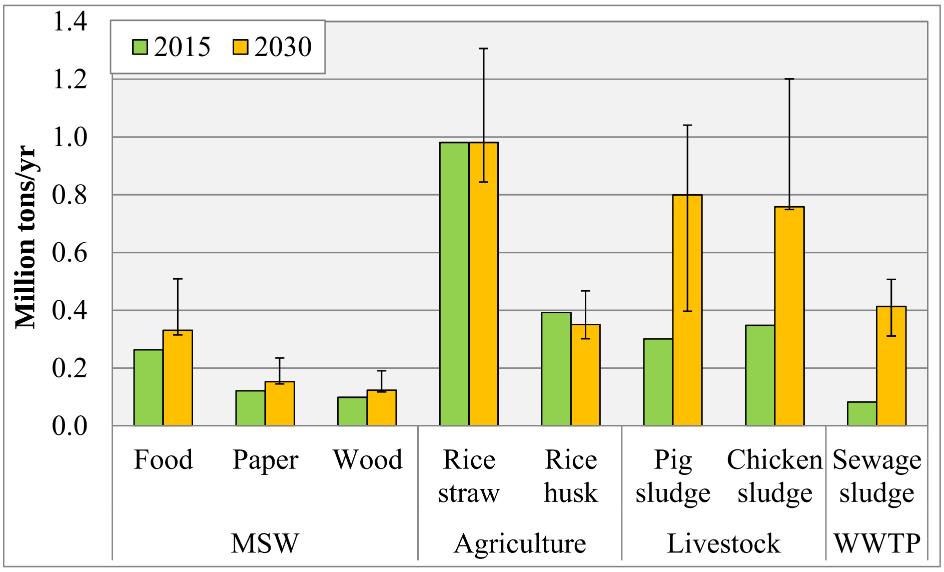


Figure 11. Comparison of waste biomass generation in 2015 and 2030

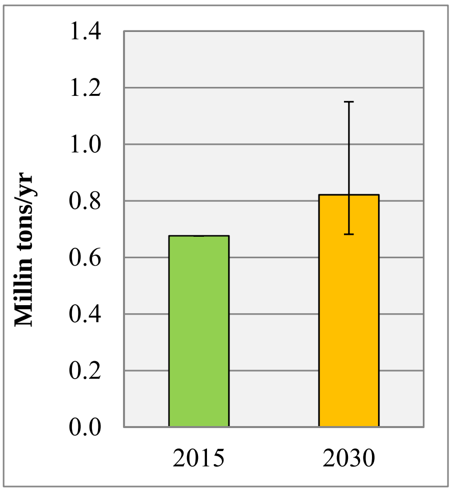
MSW also showed wider range of variation because of the large uncertainty of the generated amount of MSW per capita. Sewage sludge was found to have the highest increasing rate at 401% followed by livestock waste at 168%. Therefore, developing the treatment and/or utilization system of those generated waste biomass would significantly reduce the environmental burden in the future. MSW management systems integrated with other biomass resources should especially be prepared considering its rapidly increasing generation.

3.4 Waste biomass generation potential and carbon basis

In this study, carbon content each waste biomass category was estimated and is presented in Figure 12(a). The available carbon resource increased from 0.68 million tons-C/year in 2015 to 0.89 million tons-C/year for default generation with a 24% increment. The maximum range depicts a 71% increase from the 2015 generation. As in Figure 12(b), the generated carbon in waste estimation was conducted in wet basis. The analysis of the results of carbon content is found in (Table 2).

The carbon in agricultural waste accounted for more than half of overall generated carbon in all categories even if its future generation profile has negative effect. The Degradable Organic Carbon (DOC) fraction content would be beneficial for consideration of low-carbon models involving waste to energy technologies. It would in turn, prevent the apparent field burning and open emissions from wasted agricultural biomass. As Myanmar is one of the countries with the highest incidences of open burning of biomass (Vadrevu and Justice, 2020), a low-carbon society model in the agricultural sector will be beneficial to both the environment and local energy demand. With the utilization of biomass carbon in generated rice husk and rice straw, the formation of low carbon communities in Yangon can be realized. Rice husk utilization in small scale power generation with gasifiers has been common in Myanmar. Over 1000 gasifiers operating around Myanmar with different capacities have been reported (Pode et al., 2016). There is potential for carbon credits and offsets from international carbon markets (Sovacool, 2013). The low-carbon model progress in Ayeyarwaddy Region (MRI-Fujita.Corporation, 2015), an be adapted as alternative agricultural waste biomass carbon utilization in Yangon. An integrated waste management system with other available biomass resources can be initiated to curb against the potential emission problems.

(a)



(b)

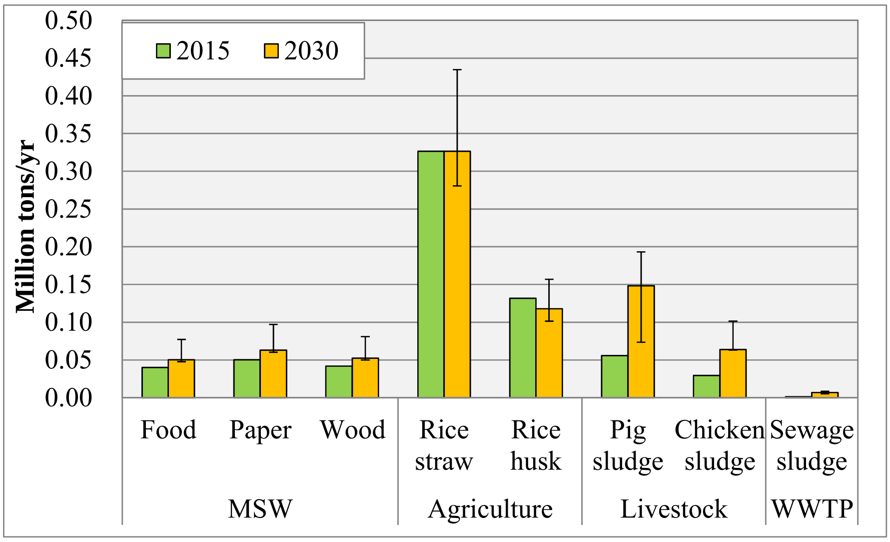


Figure 12. Estimated waste biomass carbon generation in (a) All waste category; (b) Each waste category.

From the carbon perspective, the MSW organic fraction was significantly higher than the livestock and sewerage sludge. Meanwhile, the agricultural waste was observed to have the highest future composition of generated carbon. The biomass carbon generation of MSW from 2015 to 2030 was increased by 26%. Although the biomass fraction can be regarded as a potential alternative input for bioenergy/biofuel on CO_2-neutral basis (Iakovou et al., 2010), CH_4 emissions bring about negative consequences for climate change and could degrade the environment if the generated biomass is treated improperly such as in the cases of disposal in open dump sites and open burning in the fields (Edenhofer et al., 2012; Peter et al., 2019). MSW in the study area of Yangon has a larger proportion of organics and has been primarily disposed of in several open dump sites without any measures for environmental protection (Kawasaki_JFE, 2018; IGES-UNEP, 2017). In addition, the lack of onsite operations such as site lining, compaction, and covering may lead to moisture retention and inadequate oxidation, leading to the release of methane and other greenhouse gasses, landfill emissions like dioxins, and leachate contamination to surrounding farmland and water bodies. The methane produced in open dump sites is a major environment problem. The outbreak of frequent landfill fires (Aung, 2018; AHA Center ASEAN, 2018) was found to be due to high heat and radiation intensity in Yangon, and lead to the production of foul-smelling smoke and sparked health concerns among the public. Carbon content can have an effect on this due to its influential factor of DOC during several treatments. The carbon content can have an effect on the outbreak of landfill fires due to being an influential factor of DOC during degradation.

Livestock carbon and sewage carbon generation significantly increased from 2015 to 2030, up to 150% and 400% respectively. Carbon sludge could be used in treatment plants to divert carbon emissions, nutrients and pollutant discharge to rivers and water mediums. Currently, the need for open discharge is urgent in Yangon due to the lack of proper management of livestock and sewage carbon sludge generated. The limited facilities for the handling, treatment and disposal of the waste lead to a loss of valuable nutrients such as phosphorous. Moreover, the use of livestock waste on land as fertilizer has been substituted by chemical fertilizers in producing crop, leading to waste and causing atmospheric pollution and water contamination.

It would be better to consider setting up small and medium scale power generation plants from various waste resources rather than large scale power plants for treatment and energy recovery. In composting, organic fertilizer could provide the avoided emission when chemical fertilizers are substituted (Boldrin, Alessio; Andersen, Jacob Kragh; Møller, Jacob; Christensen, Thomas Højlund; Favoino, 2009). When AD is applied, biogas could replace utilization of fossil fuel and digestate will compensate the chemical fertilizers (Møller et al., 2009).

In previous studies, co-digestion could be carried out for several wet waste biomasses from MSW, livestock, agriculture, and sewer sectors for a better utilization (Ramachandran et al., 2016; LeBlanc et al., 2008; Cu et al., 2015; Win et al., 2016; Yoshida et al., 2012; Callaghan et al., 2002; Haider et al., 2015a; Jabeen et al., 2015; Tian et al., 2015; Wang et al., 2012; Weerayutsil et al., 2016; Yong et al., 2015; Haider et al., 2015b). On the other hand, dry waste biomass such as paper, wood, rice straw, and rice husk have a high solid (dry matter) content (Table 2). This waste biomass fraction has a high combustible potential. As an alternative to recycling, feedstock pellet production can be used as a consistent energy source. The technology development for energy efficiency improvement of mixed feedstock pellet and wood pellet in FBG was targeted to improve the small and medium scale waste treatment facilities, currently facing limited viability of recovering energy. The potential scenarios for the generated waste biomass from the sewer system, agricultural, and livestock sectors are still dilemmas to be considered for the improvement of sanitation and a comprehensive waste management system. Due to the present status of poor logistics, enlarged bulk density, and handling difficulties, the assessment of integrated management among the generated waste categories is further needed.

3.5 Estimated GHG emission from generated waste biomass

Methane is the second most important anthropogenic emission, reported to have increased by 45% since 1850 (Thompson et al., 1992). The estimated methane emission potential from improper management of waste biomass in open disposal sites is presented in Figure. 13. Based on the current disposal practice of waste biomass, the estimated overall GHG emissions from methane was observed to be 3.68 and 4.73 million tons CO_2 eq/year in 2015 and 2030, respectively. The overall emissions from each generated waste biomass category were calculated from estimated methane emissions per ton of waste biomass. Of all the types of waste biomass, methane emissions from the wood fraction of MSW were observed to be the highest at 2.15 ton CO_2 eq/ton waste. It was observed that methane was primarily emitted by degradable organic carbon content (DOC) in waste biomass.

GHG emission from agricultural wastes is the highest for both 2015 and 2030. Emissions from the agricultural sector were found to have a decreasing trend with projected future emissions lower than current emissions. This is because of improved utilization potential for generated agricultural residues. In terms of future potential increase in emissions, there were increasing rates for all waste types except for agricultural waste biomass; 26% for organic MSW waste, 131% for livestock waste and 122% for sewer waste is projected for 2030.

Nutrient nitrogen is dispersible in the animal waste management system (AWMS) and sewer system. The N_2O is released into rivers, watercourses and other associated environments. Nitrification then occurs under aerobic conditions and then progresses to denitrification (Doorn et al., 2006). The nutrient recovery for future waste management could achieved by the promotion of compost facilities, recovering energy and digestates utilization options. The co-digestion potential for organic waste biomass from MSW, livestock, agriculture and sewer bio solids was researched in numerous studies (Wang et al., 2012; Jabeen et al., 2015; LeBlanc et al., 2008; Tian et al., 2015) to meet the requirements on optimized parameters such as C/N ratio, pH and so on. A strategic approach to integrated waste management in the developing nations should consider alternative emission mitigation.

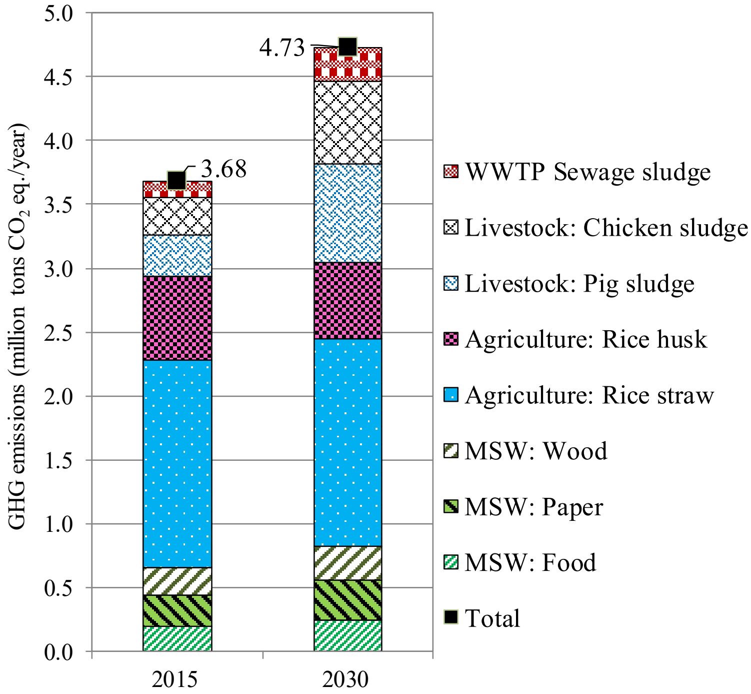


Figure 13. GHG emissions from disposal of generated waste biomass

4 Conclusions

Burgeoning as the most developed hub in Myanmar, Yangon's biomass generation potential was studied in order to better understand the city's potential resource availability, future utilization, and consumption in its pursuit of sustained development.

In total, waste biomass generation in Yangon city was estimated to increase over 50%; from 2.59 million tons/year in 2015 to 3.85 million tons/year in 2030. The management of such generated biomass remains a challenge. Agricultural waste accounted for most of the generated waste with 1.37 million tons/yr at present, in 2015 whereas livestock was projected to generate the most waste with 1.56 million tons/yr in 2030. Although sewage sludge from the sewer sector contributes the least waste generation in both timelines, it had the highest increasing rate of waste generation. There was a 400% projected increase (0.07 to 0.36 million tons/yr) due to drastic infrastructure development leading to higher WWTP access rate with the planning for more accessible sewerage to the population.

From the perspective of the future generation, waste biomass generated from the livestock and sewer sectors will be the most important due to their increased generation shares from 25.1% (0.66 million ton/yr) and 3.2% (0.07 million tons/yr) in 2015 to 40% (1.56 million tons/yr) and 11% (0.36 million tons/yr) in 2030, respectively.

Biogenic MSW also displayed a 26% growth from 2015 (0.48 million tons/yr) to 2030 (0.61 million tons/yr). This must be given great consideration because of its environmental impact and the threat it poses to public health and sanitation. The default generation for future organic MSW in 2030 accounted for 0.61 million tons /yr seems to only have a slight difference, with only a 0.12 million tons/yr increase, from 2015. Unlike other sectors, the generation factors are complex and dynamic for MSW sector in the case that each waste composition has the potential for different kinds of recycling such as material, chemical and energy recovery options.

In considering waste biomass carbon, its utilization as a renewable source of energy can be an option. But another concern is the improper treatment of biomass carbon in open disposal sites which can cause methane emissions contributing to climate change. And also the nitrous oxide emission potential by nutrient nitrogen which exists in livestock manure and wastewater discharged channel. According to estimated GHG emissions, the overall generation is substantial, amounting to 3.68 million tons CO_2 eq. in 2015 and 4.73 million tons CO_2 eq. in 2030. The diversion of unsanitary disposal practices to proper treatment with while also generating energy shall be viable alternatives to counteract methane emission.

Estimating the potential of generated waste biomass, the sustained availability for the effective utilization could be achievable. The diverse characteristics of waste biomass favored a wide range of resources in waste management options and treatment. As Myanmar is agricultural country, biomass such as rice husk should be the main feedstock for gasification for electricity production. On the other hand, there is a possibility that waste plastics would also be one of the available feedstocks for energy recovery combined with the most abundant fractions of MSW in Myanmar; wood, soiled paper, to produce the noble feedstock RPF for electricity generation. When food waste is separately collected from MSW and recovered as feedstock for methane fermentation in AD, other compositions such as wood, paper, pieces of textile will be the main composition of RPF feedstock. The fraction of generated waste paper, wood, rice husk and rice husk have higher combustible and carbon content and may be utilized for chemical and energy recycling in gasification process technologies. Accordingly, developing small and medium scale treatment facilities is also important as one of the management solutions for generated waste biomass. In this way, mitigating GHG emission from generated waste biomass can be gradually installed by integrated waste management system in Yangon. As waste resources are widely distributed inner and outer of the urban Yangon in this study area, collection system should be well improved through better logistic management.

Chapter 3 Characteristics of gas from the fluidized bed gasification of refuse paper and plastic fuel (RPF) and wood biomass

1. Introduction

1.1 Background

The generated waste biomasses can be abundantly available in Yangon as in Chapter 2. Due to agricultural based economy in Myanmar, rice husk generation was quite significant that has also been substantially utilized for electricity generation in small scale gasifier power plants. While the organic waste composition indicated the most available in methane fermentation such as food waste and paper waste, the remaining fractions should be subjected to thermal treatment as the energy recovery. They can also be the main feedstock for producing RPF in combination with soiled plastics contained in MSW for power generation. The potential of waste biomass including organic MSW for future renewable energy and waste to energy system were reported to utilize resources effectively (Alberta Carbon Offset System, 2018; Department of Energy and Climate Change, 2013; Iakovou et al., 2010; World Energy Council, 2016; Tabasová et al., 2012; Müller et al., 2015). In utilizing as power generation, the efficiency in waste treatment facilities is of great importance for both energy productions from combustible waste streams that cannot be available for material recycling, and for regional disaster-waste debris piles. Accordingly, Ministry of the Environment, Japan (MoEJ) launched Waste Treatment Facility Development Plan to enhance power generation efficiency up to 21% in average for waste treatment facilities developed between 2013 and 2017 (KobelcoEco-Solutions, 2015). Since the enactment of sound material-cycle society, in 2000, for promoting 3R practice and proper disposal of recyclable resources (Ministry of Environment Japan (MoEJ), 2000), generation of MSW in Japan has been decreasing from its peak of 55 million tons in 2000 to 44 and 43 million tons, in 2016 and 2017, respectively (Ministry of Environment, 2018; Ministry of the Environment Japan(MoEJ), 2019; Ministry of the Environment Japan (MoEJ), 2018). Of all generation, 80% was processed in MSW treatment facilities, including incineration and gasification plants, facilitating the consumption of locally produced energy and promotes lower carbon emissions in waste-to-energy conversion (Ministry of the Environment Japan(MoEJ), 2019; Ministry of the Environment Japan (MoEJ), 2018). In total of 1,100 MSW treatment facilities operated in Japan, around 400 have electricity production equipment; as of 2017 their average efficiency is 13%. Because power production is uneconomic at smaller scales, very few small scale facilities (i.e., 20 out of 500 facilities with a processing capacity below 100 tons/day) produce power (KobelcoEco-Solutions, 2015; Ministry of the Environment Japan(MoEJ), 2019; NEDO, 2014b). Therefore, it is important to improve the energy efficiency of small and medium scale waste-to-energy facilities.

Gasification could be one of the treatment processes available for improving energy recovery from generated waste and biomass. It is a reaction of fuel, partially combusting with a controlled amount of air or steam in limited oxygen-containing medium to convert solid fuel, such as biomass and/or waste, into intermediate gases useful for various applications (Basu, 2010; Gómez-Barea and Leckner, 2010). The syngas produced through gasification can be widely used for both fuel and chemical raw materials. Recently, commercial-scale waste gasification has been described as an alternatives expanding the common waste incineration practices (Morris and Waldheim, 1998; Psomopoulos et al., 2009; Yassin et al., 2009). Despite the mature and proven steam turbines application in incineration facilities, increasing use of Gas Engines (GE) and turbines has been developed to generate power in order to achieve the potential benefits of higher efficiency at small and medium commercial scales (Consonni and Viganò, 2012; Morris and Waldheim, 1998). Approaching the small and medium scale gasification facilities development, Cardoso et al., (2018) compared two different sizes of pilot-scale FBG to investigate the effects of scaling up and resolving technical issues, including controlling combustible gas and air ratios, stabilizing gaseous quantities and properties, and removing tar and corrosion.

1.2 Waste feedstock development in gasification

For several types of feedstock, syngas utilization in GE has received increasing attention. Wood biomass is a common feedstock for gasification (Maglinao et al., 2015; Weerachanchai et al., 2009). Narváez et al. (1996) investigated the operational variables affecting the quality, composition, and purity of gas produced in an FBG system, including the use of secondary air and the temperatures of the gasifier bed and freeboard. Kim et al,. investigated improvements in syngas quality from woody biomass gasification and its applicability to GE at a pilot plant scale Kim et al. (2013).

Nasner et al,. conducted research for a pilot plant air-blown downdraft gasifier using an Otto-cycle Internal Combustion Engine (ICE) to study a technical and economic assessment of RDF from MSW Násner et al. (2017). This research reported that a LHV of raw product gas in the 5.6-5.8 MJ/Nm^3 range with equivalence ratios (ER) of 0.25-0.3 and temperatures of 650 -700 °C was optimal for application in ICE, with efficiencies of 57-60%. Solid fuel that has been processed to improve its quality and LHV was defined as SRF by a European standard (CEN 15359:2011, Solid recovered fuels-Specifications and classes). In numerous studies, Arena (Arena et al., 2015; Arena and Di Gregorio, 2016, 2014) investigated the gasification of SRF produced from sorting platforms for MSW under thermal and chemical steady state conditions in a small-scale air-blown pilot plant FBG. A mild combustion method was introduced that allowed direct burning in the thermal gasifier due to the high content of tar and dust. Economic assessments suggest that SRF gasification could be a sustainable approach, with the potential to save landfills up to 85% in costs if incentive tariffs for energy recovery would be introduced.

In other studies, blending SRF with biomass have suggested for use in thermal gasifiers because high tar and dust content has been shown to lower the efficiency of fuel performance and decrease heating values (Dunnu et al., 2012; Pinto et al., 2014). It was also presented the use of PDF from food industry processing scraps in FBG systems using a power gasification mode coupled with an ICE Di Gregorio and Zaccariello (2012). Robinson et al., (Robinson et al., 2017, 2016) conducted FBG tests using wood pellets, Polyethylene Terephthalate (PET) pellets, and RDF to investigate the feasibility of gasification for mixed waste and plastics, recording important data on coke and agglomeration temperatures and thermal output. Brachi et al. (2014) also investigated the co-gasification of regional biomass residues and polymeric and tire waste in a pre-pilot FBG. Several studies have investigated different types of waste and biomass in FBG systems in order to explore the effectiveness of various measures on operation and performance parameters, as well as to better define challenges, including tar content, agglomeration, and sintering effects, for the in-bed catalyst performance of small and medium scale industrial power production systems (Campoy et al., 2014, 2010; Gómez-Barea et al., 2013a, 2013b).

Unlike RDF, which is produced from MSW, RPF do not include the food waste that is usually contained in MSW. In 2015, there were approximately 120 facilities for RPF and RDF in Japan (MoEJ, 2017), which accounted for approximately 73% and 27% of the overall production of 1.3 million tons of waste, respectively (National Institute for Environmental Studies, 2018). Once food waste is collected separately from MSW and recycled, RPF compositions will be the main source of MSW. Therefore, shedding light on the gasification of RPF is important. However, it should be noted that, despite many other studies, the practical utilization of RPF and biomass wood pellets in small municipalities has received very limited research attention. Such research could improve the energy efficiency and economics of this approach by promoting low carbonization. Experimental gasification tests for wood pellets under different conditions (e.g., gasifying agents, ER, and temperature) have been conducted in our previous studies (Hayakawa et al., 2016; Inoue et al., 2017a, 2017b; Takahashi et al., 2017), in addition to life cycle assessments of waste biomass, including wood waste (Win et al., 2016). However, comparative experimental gasification tests for RPF have been never conducted.

This study aims to investigate the performance and product characteristics of RPF and wood pellets using an FBG at small and medium scales. In terms of the effective use of energy and the reduction of GHG emissions, it is important to efficiently use RPF and wood pellets for the production of power and heat. One option is gasification for GE generation, although it is necessary to determine various optimal conditions for gasification such as calorific values, tar and dust compositions. In particular, the relationships between ER and temperature, calorific values, and tar are critically important. Thus, the gasification experiment was conducted at a maximum scale of 1.0 ton per day. However, dust behavior was not observed in detail as it significantly changes depending on plant size. In comparison to previous studies, relatively large amounts of feedstock input was used in order to better simulate conditions for small and medium scale FBGs. The relationships between ER and temperature, LHV, gas composition, and tar concentrations were obtained. Subsequently, the LHV and tar were analyzed in order to understand the operating conditions required for power generation in GEs. Our results are intended to promote the effective use of these feedstocks for the greater benefit of the environment and society.

2. Methodology

2.1 Fluidized bed gasifier

The test data for the gasification experiments were acquired in an air-blown FBG with an inner diameter of 200 mm and a height of approximately 3 m (Figure 14). A refractory was installed on the inside wall of the gasifier to minimize the heat radiation. Eleven kilograms of silica sand (average particle diameter: 800 μm) were used as the bed material. The feedstock was fed into the gasifier by a screw feeder. Primary air was supplied to the sand bed at the bottom of the gasifier through a distributor. To increase the gasifier temperature through partial combustion, secondary air was also supplied to the free board at a height of 1.7 m above the primary air distributor. The ER of the fluidizing air was set to 0.3 for all of the experiments to promote bubbling fluidization and to avoid an agglomeration of the bed material. A superficial velocity of approximately 1.0 m/s in the sand bed was maintained during the experiment, which was sufficient for bubbling fluidization. The ER of the secondary air was adjusted to match the total designated ER. The volume of injected primary and secondary air was separately measured through a variable area flowmeter.

The ER is the ratio of the actual flow rate of supplied air to the theoretical flow rate of air required for complete combustion of feedstock as shown in Eq. (13), and is an important operational variable in air-blown gasification, as it is an influential parameter for the heat evolved in exothermic reactions and can also strongly affect gas composition, including the tar, char, and the energy content of the product gas (Narváez et al., 1996; Radmanesh et al., 2006).

$$\mathrm{ER} = \frac{\text{Actual flow rate of supplied air } [\mathrm{Nm^3/h}]}{\text{Theoretical flow rate of air } [\mathrm{Nm^3/kg_{-fuel}}] \times \text{Fuel throughput } [\mathrm{kg/h}]} \quad \text{Eq. (13)}$$

The freeboard temperature was increased by changing the ER of the secondary air to examine the temperature dependence of the produced gas. As reported by Narvaez (1996) and Robinson (2016), it is assumed that the tar decreases due to thermal decomposition and steam reforming; Robinson et al. (2016) indicated that introducing secondary air above the bed might assist in tar reduction by providing oxygen to convert volatiles and significantly raising the gas temperature. Similarly, earlier studies reported that thermal cracking and steam reforming by increasing of the temperature through secondary air contributed to tar reduction (Narváez et al., 1996; Campoy et al., 2010.; Gómez-Barea et al., 2013a).

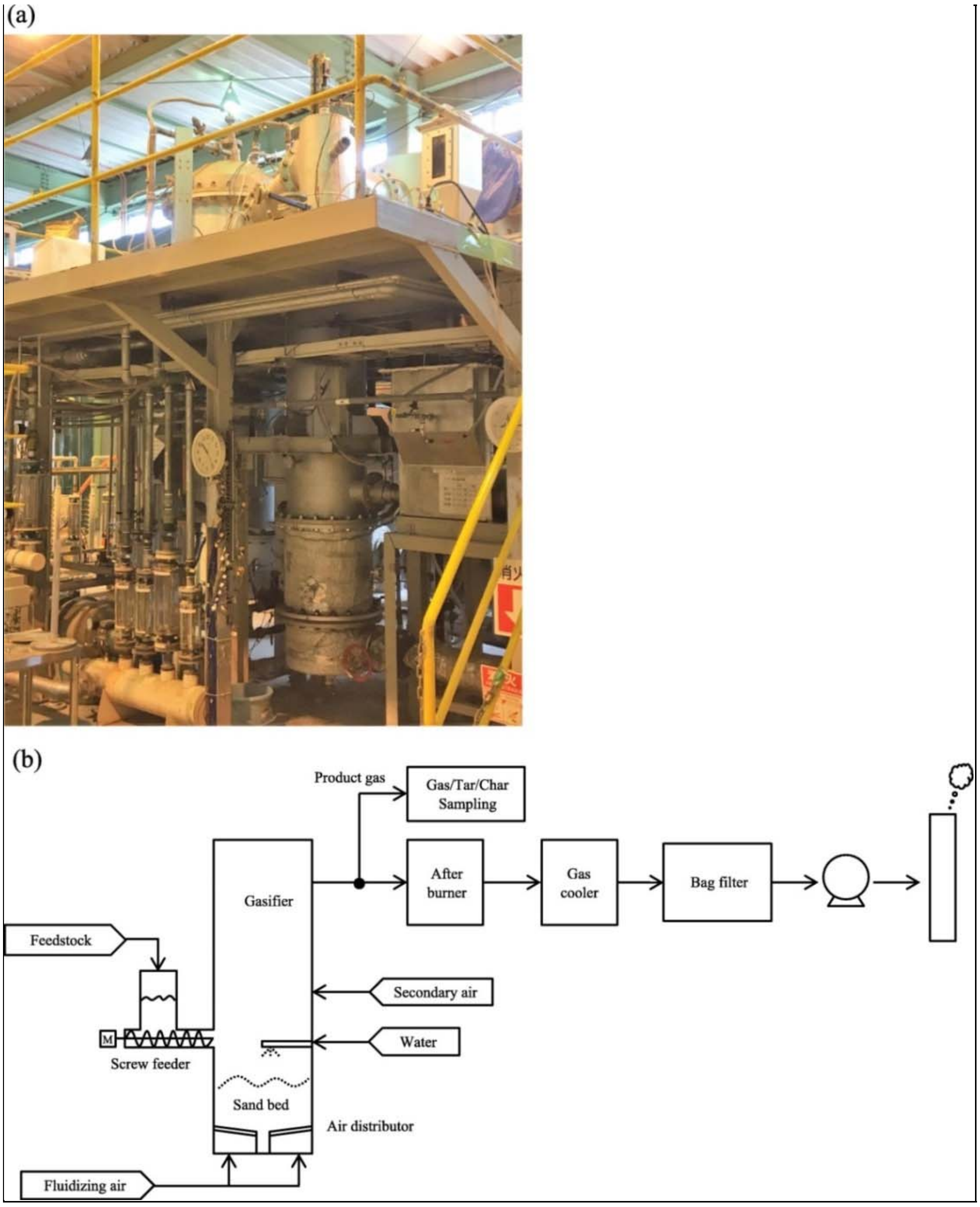


Figure 14. The bubbling fluidized-bed gasifier (FBG) used in this study: (a) photo showing the pilot plant; and (b) the process flowchart.

2.2 Feedstock

Wood pellets were used to represent wood and paper fractions in MSW, and RPF was used to represent mechanically sorted MSW, which excluded biodegradable materials, such as food waste. The wood pellets were produced from a blend of white spruce, red pine, various cedar species, and other woods without bark, and the blended materials were solidified to a diameter of 6 mm and a length of 5–25 mm. The RPF commercially introduced in Japan was used in this study. The RPF was mainly produced from commercial and industrial waste that consisted primarily of waste plastics, waste paper, and waste woods, as per the specifications of Japanese Industrial Standards (JIS Z7311:2010, refuse derived paper and plastics densified fuel). According to an interview with the supplier, the RPF was blended at a 40:60 weight ratio of biomass to plastics, and the blended materials were solidified to a diameter of 10 mm and a length of 5–25 mm. A full analysis of the feedstock properties is shown in Table 6.

Table 6. Properties of wood pellets and RPF used as feedstock.

Feedstock	**Wood pellet**	**RPF**
Picture		
Moisture [wt%$_{\text{-wet}}$]	8.1	1.8
Ash [wt%$_{\text{-dry}}$]	0.4	10.8
Volatile [wt%$_{\text{-dry}}$]	85.3	81.4
Fixed carbon [wt%$_{\text{-dry}}$]	14.3	7.8
Carbon [wt%$_{\text{-dry}}$]	51.4	48.5
Hydrogen [wt%$_{\text{-dry}}$]	5.1	6.9
Nitrogen [wt%$_{\text{-dry}}$]	0.5	0.3
Oxygen [wt%$_{\text{-dry}}$]	42.2	33.4
LHV* [MJ/kg]	18.7	19.5
C/H* ratio [-]	10.1	7.1
C/O* ratio [-]	1.2	1.5
Fuel ratio* [-]	0.2	0.1

* LHV: Lower Heating Value, C/H: carbon to hydrogen ratio, C/O: carbon to oxygen ratio, Fuel Ratio: the ratio of fixed carbon to volatile matter.

2.3 Gasification test conditions

The maximum feeding rate of the screw feeder was 40 kg/h, equivalent to a 1.0 ton/day capacity. Before the input of the feedstock, the sand bed was preheated to approximately 350 °C (the self-ignition point of feedstock) using electric heated air, which was stopped during the gasification. In a previous study, Vounatsos et al. (2016) (Vounatsos et al., 2016) conducted RDF sampling and process modeling and showed that the fuel composition determined the optimal operating conditions. As such, the LHV of the feedstock (RPF and wood pellets) was adjusted to be approximately 15–17 MJ/kg, which is equal to the LHV of the remaining MSW after food waste separation (Yano and Sakai, 2016), using steam to approximate the actual operating conditions.

In order to obtain the gasification characteristics and behavior of the gas composition for the desired temperature ranges, both wood pellets and RPF were fed into the gasifier under the realistic range of ER (Table 7). This study used a relatively large FBG with the maximum capacity of 1.0 ton/day in order to demonstrate the actual operation in the commercial FBG facility. Therefore, as the gasification furnace cannot be controlled only with ER, for temperature control, two factors were considered: the ER was set as the first factor and water injection as the second factor. No other factors were changed. Temperature was monitored at the sand bed, freeboard, and gasifier outlet. The product gas was treated with an afterburner, cooled, and passed through a bag filter before the flue gas was released into the atmosphere.

Table 7. Designed experimental conditions for the gasification tests.

	Run1	Run 2	Run 3	Run 4	Run 5	Run 6
Feedstock	Wood pellet (+Water)			RPF (+Water)		
Throughput [kg/h]		23			20	
Water injection [kg/h]	4.5		3.0		3.5	
ER* (Fluidizing Air) [-]		0.3			0.3	
ER (Secondary Air) [-]	0.2	0.1	0.0	0.2	0.1	0.0
ER (Total)	0.5	0.4	0.3	0.5	0.4	0.3

* ER: equivalence ratio.

2.4 Product analysis

A part of the product gas from each test condition was absorbed from the gasifier outlet and collected with a sampling bag (JIS K0095:1999, methods for the sampling of flue gas) for composition analysis. Of the collected gases, H_2/O_2/N_2/CO/CO_2 were quantitatively analyzed with a GC-17A Ver.3 gas chromatograph (Shimadzu), CH_4/C_2H_2/C_2H_4/C_2H_6/C_3H_6/C_3H_8 were quantitatively analyzed with a GC-8A gas chromatograph (Shimadzu), and the moisture content of the product gas was measured with a moisture absorption tube (JIS Z8808:2013, methods of measuring dust concentration in flue gas). The LHV of the product gas was calculated from the concentration and LHV of combustible gases using Eq. 14.

$$LHV_{pg} = \sum_i (C_i \times LHV_i) \quad (14)$$

Where LHV_{pg} is the LHV of the product gas [MJ/Nm^3], C_i is the concentration of combustible gas i (H_2, CO, CH_4, C_2H_2, C_2H_4, C_2H_6, C_3H_6, and C_3H_8) [%-dry], and LHV_i is the LHV of combustible gas i [MJ/Nm^3].

Cold gas efficiency was also calculated using Eq. 15 to evaluate syngas production efficiency.

$$Cold\ gas\ efficiency = \frac{\sum_i (HHV_i \times V_i)}{F\_HHV_i \times T} \quad (15)$$

Where

HHV_i is the higher heating value of the product gas [MJ/Nm^3],

V_i is the volume of product gas [Nm^3/h],

F_HHV_i is the higher heating value of feedstock, and

T is feed stock throughput [kg/h].

Tar was collected through six impingers (with 50 ml of isopropanol per impinger) after product gas collection, and particle filters were used in order to catch char and dust from the gasifier outlet. Of the six impingers, four were placed in a water bath (20 °C), while the remaining two were cooled in a salt and ice bath (-20 °C). The tar was condensed in the sampling tube between the particle filter and the impinger, and adhered to the particles caught by the filter. They were washed with solvent and collected at 350 °C so as not to condense tar in the sampling tube and particle filter. Isopropanol from the filter extraction procedure was bulked with the isopropanol solution collected from the impingers and condenser. The amount of tar was determined by means of solvent distillation and evaporation. An analysis of tar and char was conducted according to a European standard (Guideline for Sampling and Analysis of Tar and Particles in Biomass Producer Gases Ver. 3.3).

3 Results and Discussion

3.1 Operational performance

Operational stability is important for obtaining accurate data in gasification studies, especially with respect to mixed waste with different characteristics in RPF, as previously observed in the gasification of PET, RDF, and PDF (Di Gregorio and Zaccariello, 2012; Robinson et al., 2016, 2017). As shown in Figure 15, the temperature profile for RPF was stable during the gasification.

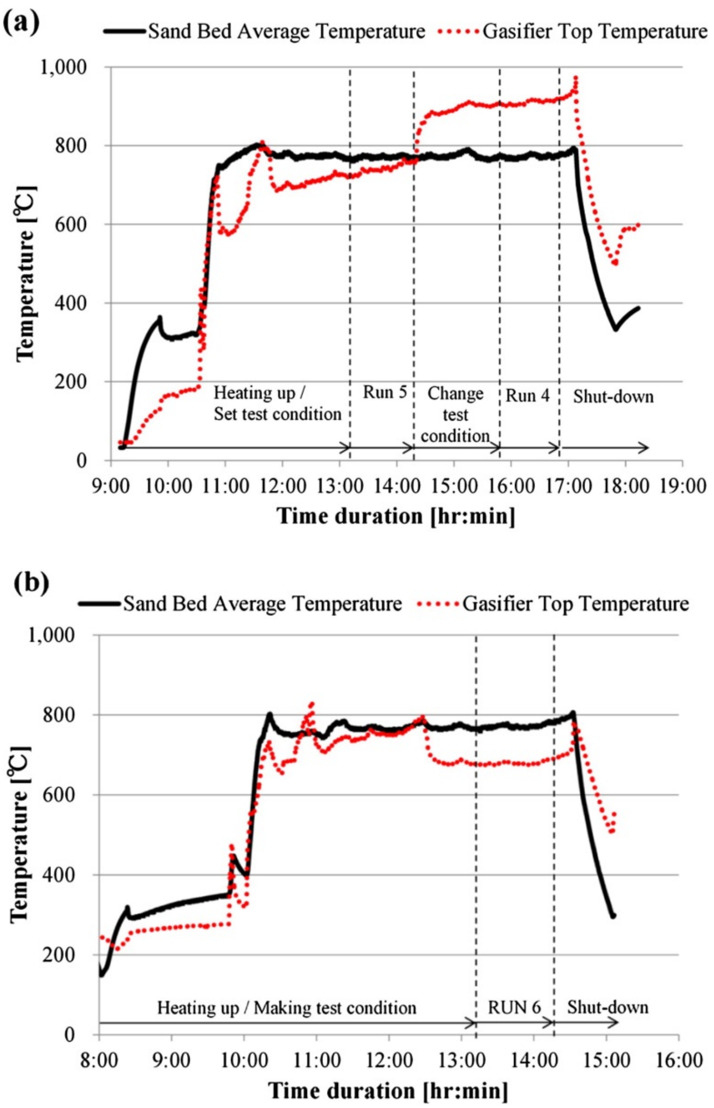


Figure 15. Temperature profiles of the RPF gasification process: (a) Run (4, 5) and (b) Run (6).

3.2 Gas composition

The observed experimental results with the operational parameters were shown in Table 8. Regarding cold gas efficiency, 46.4－48.5% was observed for wood pellets, and 64.7－69.9% for RPF. This is because the fuel ratio of wood pellets (0.2) was higher than that of RPF (0.1), which meant that the RPF contained more volatile matter. As shown in Figure 16, the gasifier top temperature increased with increasing ER, although small differences in the temperature profiles were observed at higher ER. One explanation for this could be that the wood pellets contain more fixed carbon than RPF, and a part of the fixed carbon would be combusted at the free board. Figure 16 shows the concentration profiles of CO and H_2 in relation to the gasification temperature. As the ER increased,

CO concentrations showed a decreasing trend for wood pellets and an increasing trend for RPF. Because the fuel ratio of wood pellets is higher than that of RPF, in regard to the wood pellets, it is assumed that the oxidization of fixed carbon ($C+1/2O_2 \rightarrow CO$) and/or a water-gas reaction ($C+H_2O \rightarrow CO+H_2$) were activated at higher ER, and in the case of RPF, an oxidization of CO ($CO+1/2O_2 \rightarrow CO_2$) was promoted at higher ER.
In comparison to the use of RPF, H_2 concentrations were higher when using wood pellets, and the concentration tendencies of H_2 were more varied than for CO. It is likely that more hydrogen from the feedstock was consumed while forming C_mH_n when using RPF than wood pellets during thermal tar cracking. Therefore, the generation of product gas compositions for CO and H_2 concentrations differed depending on the feedstock.

Table 8. Key experimental results of gasification tests.

Feedstock		Wood pellet (+Water)			RPF (+Water)		
Operation tests		Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Operational parameters	Throughput [kg/h]		23			20	
	Water injection [kg/h]	4.5		3.0		3.5	
	ER	0.48	0.39	0.32	0.54	0.44	0.33
Performance parameters	Gasifier top temperature[°C]	939	790	690	900	728	677
	H_2 [vol%$_{-dry}$]	7.3	6.4	7.4	4.8	3.8	4.3
	CO [vol%$_{-dry}$]	10.8	12.4	12.8	11.6	8.6	7.6
	CH_4 [vol%$_{-dry}$]	2.3	3.3	3.4	2.9	3.0	3.1
	CO_2 [vol%$_{-dry}$]	15.8	15.7	15.5	13.1	14.5	16.3
	C_mH_n [vol%$_{-dry}$]	0.8	1.4	1.7	1.8	4.0	5.1
	Tar [g/Nm$^3_{-dry}$]	2.5	3.8	12.1	3.4	4.5	14
	LHV (MJ/Nm$^3_{-dry}$]	3.4	4.3	4.7	4.1	5.1	5.9
	Char [g/Nm$^3_{-daf}$]	6.7	6.1	19.6	3.6	5.4	3.9
	Cold gas efficiency [%]	46.4	48.4	48.5	68.3	69.9	64.7

In comparison with the other studies shown in Figure 16, the product gas compositions were compared in relation to gasification temperatures instead of ER because the range of ER for the other studies is limited at lower ranges. The overall tendency of the trend line for wood pellets was similar to the other studies; however this study observed CO concentration levels that varied from those of Campoy et al. (2014) and H_2

concentration levels that varied from those of Kim et al. (2013); it is suggested that these discrepancies relate to different gasifying conditions. In this study, the total air was fed separately into the sand bed and freeboard as primary and secondary air, whereas in Campoy et al. (2014), it was directly fed into the sand bed after preheating. Therefore, the bed temperature should be expected to increase in the latter study, and active carbon sites in hot char might favor the formation of CO in char gasification with CO_2 (Boudouard reactions) under the high temperature forward endothermic regime (Basu, 2010; Littlewood, 1977). Additionally, the increased oxidation of CO into CO_2 at higher ER in this study could result in decreased CO concentrations.

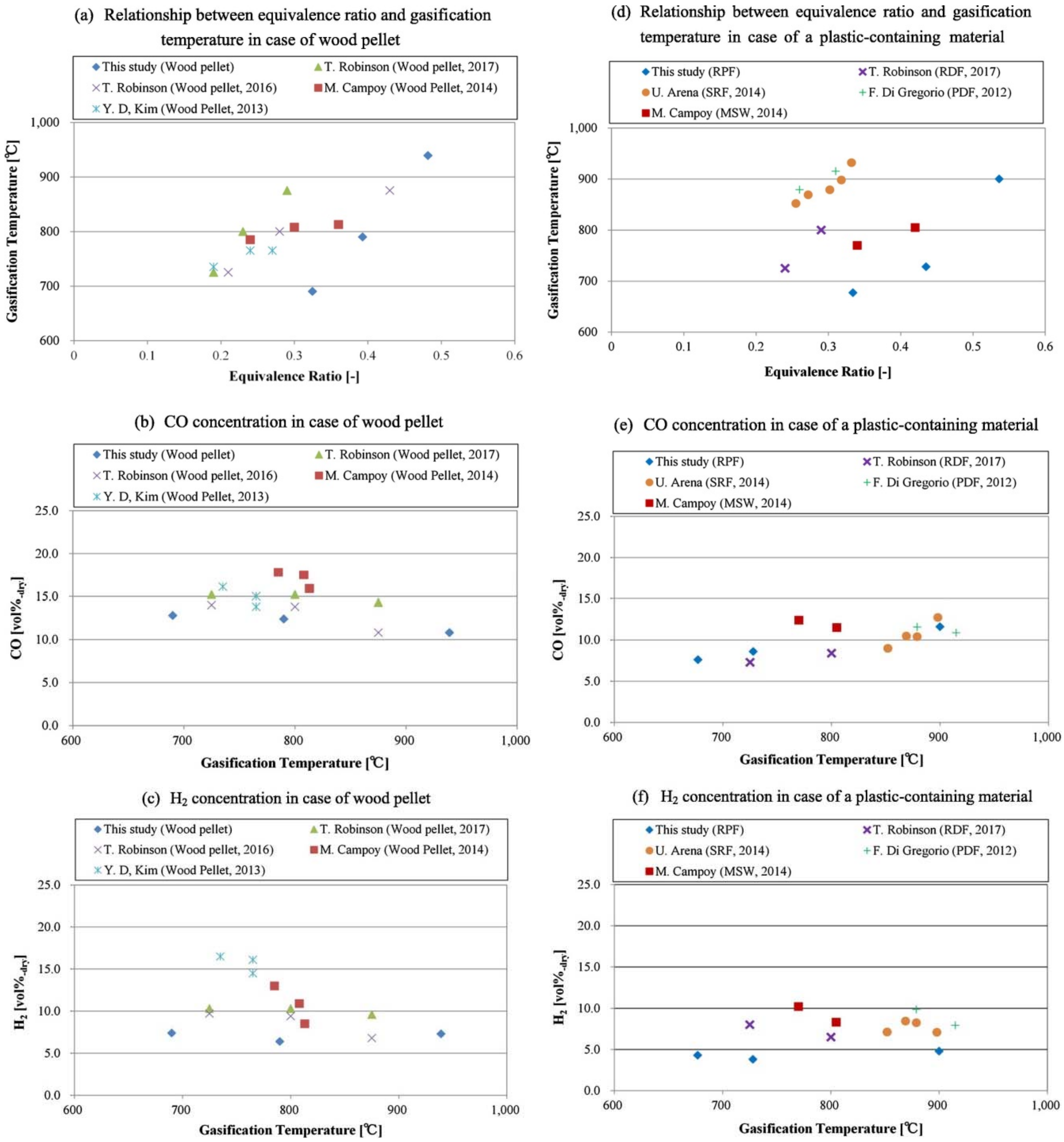


Figure 16. Relationship between equivalence ratio and gasification temperature, and tendency of CO and H2 concentration of different feedstocks: wood pellet, Refuse Paper and Plastic Fuel (RPF), Refuse-Derived Fuel (RDF), Solid Recovered Fuel (SRF), Plastics-Derived Fuel (PDF), and MSW.

The differences in H_2 concentration levels between this study and Kim et al. (2013) may also relate to the gasifier geometry, in which the reactor diameter, height, and feedstock feeding system were all different. The latter study introduced feedstock at the top of the gasifier, whereas in this study, the feedstock was fed on the sand bed. In addition, the larger reactor dimension of the latter study might enhance the dispersed contact with the feedstock-air mixture and good mass and heat transport for the reactive species to favor the important water-gas shift reaction (i.e., $CO + H_2O \rightarrow H_2 + CO_2$), which tends to form higher hydrogen concentrations (Basu, 2010; Littlewood, 1977). In addition, the top fuel feeding system could produce a longer residence time owing to interactions between the species of solid carbon and devolatilized gases regardless of superficial velocity (independent of gasifier dimensions) (Klinghoffer and Castaldi, 2013).

There were slight differences in H_2 concentration when comparing RPF cases. These might be due to more stoichiometric air in this study as compared to others, which could affect the hydrogen combustion with air, favoring low H_2 levels. H_2 concentrations in the previous studies tended to be slightly higher at a given temperature, likely due to the water-gas shift reaction that affects the final equilibrium gas-phase reaction (Littlewood, 1977; Shaw, 1977). Overall, the previous wood pellets and mixed plastics waste studies were mostly in agreement with the results of wood pellet and RPF gasification studies in terms of gas concentration tendencies and temperature dependencies for CO and H_2.

Other product gas compositions (with regard to hydrocarbon concentrations) are provided in Appendix A. The tendency of CH_4 was the same regardless of the feedstock; methane yield is likely stable during devolatilization at primary conversion stages in the gasifier (Gómez-Barea and Leckner, 2013c). Additionally, the most obvious gasification reactions, such as steam-methane reforming (i.e., $CH_4 + H_2O \rightarrow CO + 3H_2$ and $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$), might not be so active in our atmospheric FBG. Morita (1978) described the behavior of methane-active reactions, but only at high atmospheric pressures.

In the case of C_mH_n, the concentration tendencies were different between wood pellets and RPF, especially around 700 °C. It is assumed that polymer cracking was activated at this temperature owing to the thermal decomposition characteristics of RPF derived from plastics. A similar tendency in plastic decomposition was reported by Sharuddin et al. (2016). Therefore, the tendencies of gas concentrations for CH_4 and C_mH_n are comparable among this study and previous studies. However, in all gas compositions, the product gas compositions for CO, H_2, and C_mH_n concentrations followed different tendencies depending upon the feedstock type, whereas the same tendencies were confirmed for CH_4 regardless of the feedstock.

3.3 Performance of the process parameters for syngas engine utilization

As a major focus in this study was the performance and product characteristics of syngas produced by FBG, GE operation and pretreatments before GE usage were not conducted. However, observations for two important process performance parameters LHV and tar concentration are presented in Figure 17, which are relevant for the development of syngas engine utilization in small and medium scale facilities around the world. It should be noted that there were other significant factors for stable GE operation, such as dust and flow rate, which were not discussed in this study.

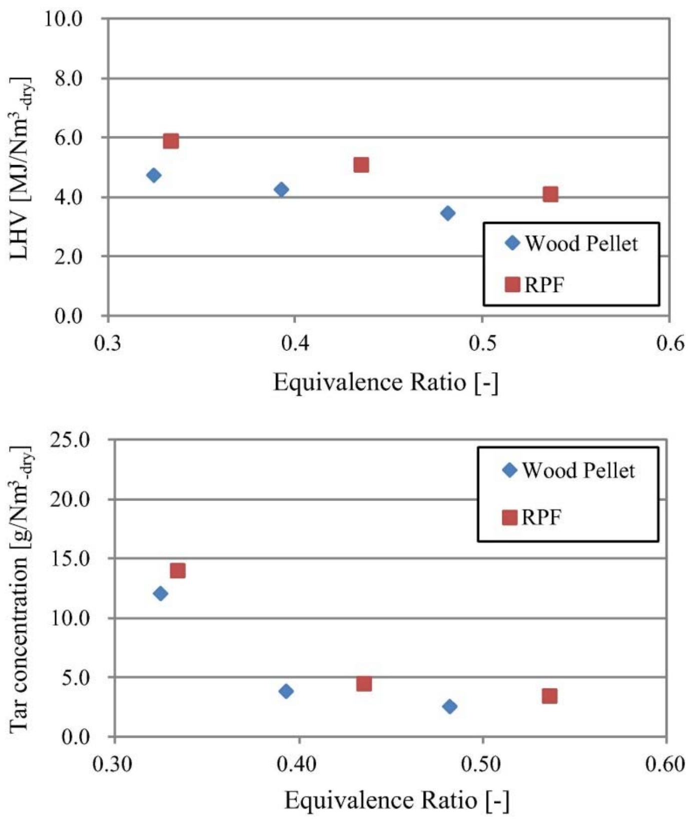


Figure 17. Process performance in this study for: (a) product gas LHV; and (b) tar concentration. For temperature control, water injection was controlled in addition to ER.

3.3.1 Lower heating value (LHV)

LHV is very important parameter for GE, and the ranges are related to consistent gas composition. In this study, wood pellets resulted in an LHV of 3.4–4.7 MJ/Nm^3$_{\text{-dry}}$, while RPF resulted in an LHV of 4.1–5.9 MJ/Nm^3$_{\text{-dry}}$ (Figure 17a). The concentration of C_mH_n contributed to an increase in LHV. As shown in Figure 18, when the ER was increased, C_mH_n decreased. Subsequently, a decline in LHV was observed for both types of fuel, but the performance of tar cracking was improved. Carbon monoxide and methane provided the greatest contributions to the heating values of the gases produced from both types of pellets. For wood pellets, the contribution was via C_2H_4, while for RPF, both C_2H_4 and C_3H_6 contributed; each was comparable to the others' product gas. The distributed data for C_mH_n concentrations in the FBG for both feedstocks is provided in Appendix B. The contributions made by hydrogen were the lowest, and were smaller than those made by the hydrocarbons.

It was possible to enhance the predictability of LHV in this study because the feedstock characteristics were adjusted using water injection to exclude the effects of the LHV of feedstock during the operational tests for our design. At all ER ranges, the product gas from RPF had greater heating values than the product gas from wood pellets. Through the above-mentioned applicable LHV performance, the ER range could be optimized at around 0.3–0.4.

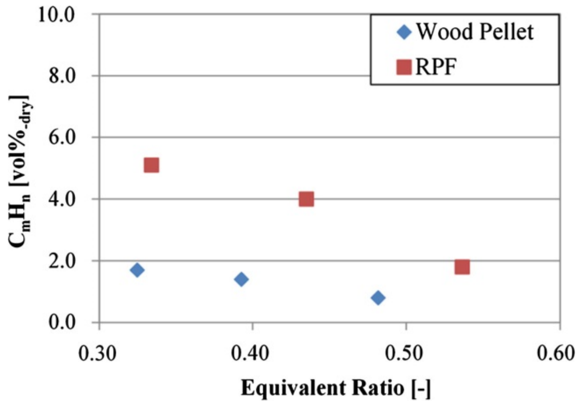


Figure 18. Relationship between equivalence ratio and tendency of hydrocarbons (C_mH_n): wood pellet, Refuse Paper and Plastic Fuel (RPF).

In the case of coal or biomass air-blown gasification, previous studies reported the LHV of product gas to be around 4.0 MJ/Nm^3, or slightly higher, due to N_2 dilution (Arena, 2012; Basu, 2010; Dunnu et al., 2012; Gómez-Barea et al., 2013a). If lower-LHV gas could be used, air-blown gasification could be applied to the power generation process without any nitrogen removal, saving plant operation costs. For this reason, combustion control systems for gas turbines with lower LHV gas have been under development (Hasegawa, 2006). Gas turbines for power generation were originally developed for relatively large scale plants, but GE generation would be suitable for small scale plants. Specifically, Hasegawa (2006) developed a GE for woody biomass gasification with air-blown capabilities that has already been effectively implemented. Furthermore, with regard to the development of sewage sludge gasification and power generation processes, Haneda et al. (2011) demonstrated relatively high power-generation efficiency, with 3.1–3.8 MJ/Nm^3 of product gas. There are no common regulations for gas LHV with regard to engines or turbines for product gas, but 4.0 MJ/Nm^3 of LHV could be considered as one standard.

3.3.2 Tar concentration levels

It is important to operate the system in a way that maintains proper LHV while ensuring that the level of tar in the product gas is as low as possible. In this study, tar concentrations tended to decrease with increasing ER (Figure 17b). This decreasing trend may have been produced by thermal cracking in the freeboard. Tar concentration levels ranged from 2.5–12 g/Nm^3$_{\text{-dry}}$ for wood pellets and 3.4–14 g/Nm^3$_{\text{-dry}}$ for RPF. The tar yield is also important because of the difficulty involved in predicting the exact composition of the gas from a gasifier (Puig-Arnavat et al., 2010). During power generation, tar condensation can hinder and/or clog the operation of GE and turbines. If this can be estimated through the observed characteristics, it would be very useful in designing gas treatments and gasifier systems. Previous research has reported various tar concentration levels in FBG systems ranging from 1–73 g/Nm^3 in air-blown FBG (Narváez et al., 1996; Kiel et al., 2004; Han and Kim, 2008; Gómez-Barea et al., 2009, 2013b; Arena et al., 2010; Basu, 2010; Campoy et al., 2010, 2014; Di Gregorio and Zaccariello, 2012; Ruiz et al., 2013; Arena and Di Gregorio, 2014; Stark et al., 2015), as shown in Table 9.

The comparison of tar content among this study and previous studies was described in Figure 19. Although there was a similar trend of decreasing yields with rising temperatures, the concentration levels in previous studies were higher than in this study for both wood pellets and RPF. This occurred even at similar gasification temperatures; however, the ER regime in this study was higher than that of the previous research (Figure 19), which could impact tar concentrations and account for observed differences. Tar concentrations in this study ranged from 2.5–14 g/Nm^3$_{\text{-dry}}$, which was lower than that of other studies. For wood pellets at 940 °C, the reported tar concentration at the gasifier outlet (2.5 g/Nm^3$_{-dry}$) dropped below the utilizable range of LHV (minimum 4.0 MJ/Nm^3). Therefore, the optimum ER for FBG operation should be carefully set in order to avoid burning fuel gas, which contributes to heating values while negatively affecting tar concentrations.

Table 9. Tar concentration performance of FBG in previous studies.

Biomass		**Waste**	
Gasification Studies	Tar reported [g/Nm^3$_{-dry}$]	Gasification Studies	Tar reported [g/Nm^3$_{-dry}$]
Narvaez et al. (1996)	2-10	Arena and Di Gregorio (2014)	5-73
Campoy et al. (2010)	30-44	Campoy et al. (2014)	22-24
Stark et al. (2015)	2-50	Di Gregorio and Zaccariello (2012)	5 -23
Robinson et al. (2017)	14-32	Robinson et al. (2017)	40-50
Robinson et al. (2016)	10-35	Arena et al. (2010)	15-54
Gómez-Barea et al. (2013b)	10-40	Gómez-Barea et al. (2009)	17-21
Han and Kim (2008)	1-23		-
Ruiz et al. (2013)	4-62		-
Kiel et al. (2004)	13-18		-
Basu (2009)	10 (average)		-

When the LHV levels were held within the required limits in this study, the tars concentrations at the gasifier outlet (at the optimum ER) ranged from 4–14 g/Nm3-dry, which were lower levels compared to other studies (Table 9). With regard to the observed tar levels when used with GE, the desired concentration should be reduced by, not only the primary in-process treatment, but also by post-gasification removal via secondary treatment technology (Basu, 2010). The performance of tar concentration conversion was also reported in Gómez-Barea et al. (2013a) through consideration of operational parameters, as well as different gasifier configurations. As reported in Gómez-Barea and Leckner (2010), FBG operations cannot avoid tar problems completely without extensive secondary treatment when used in GE power generation. Thus, the tar dew point can also be appropriately cited in identifying tar concentrations for GE applications.

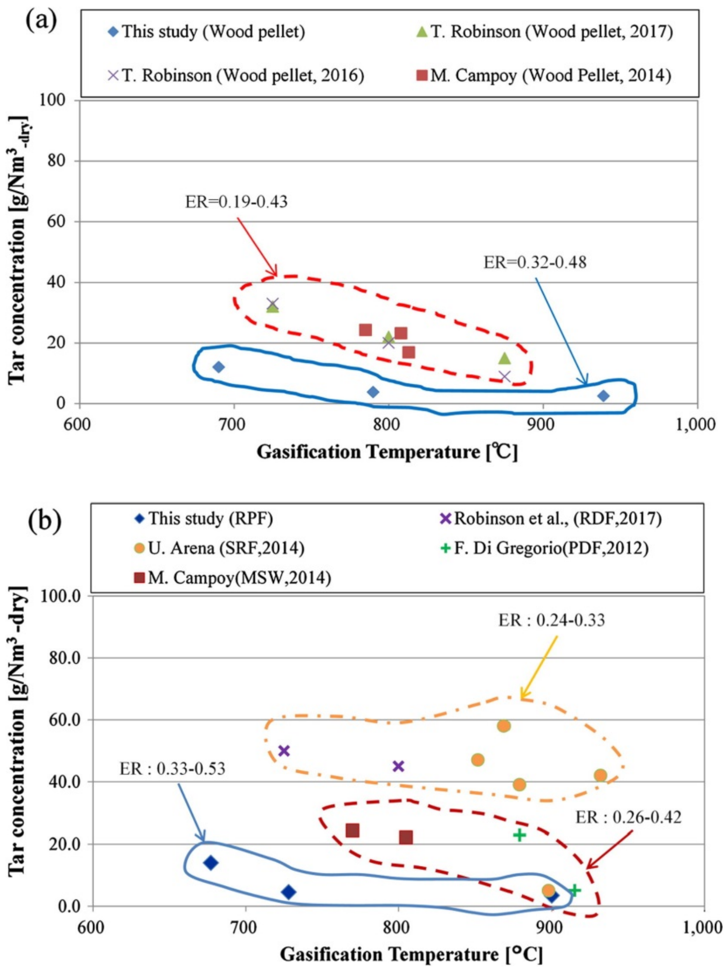


Figure 19. Comparison between this study and previous studies of tar concentration from different feedstocks: (a) wood pellet; (b) Refuse Paper and Plastic Fuel (RPF), Refuse-Derived Fuel (RDF), Solid Recovered Fuel (SRF), Plastics-Derived Fuel (PDF), and Municipal Solid Waste (MSW).

Considering that the product gas will be cooled at ambient temperatures, the target tar dew point was set to 40 °C or less, and verification tests were conducted to confirm secure operation in GE. This is similar to and agreeable with the reported range of tar dew points in other studies, such as Gómez-Barea et al. (2013a), which recommended that the dew point be lower than 30 °C.

As described above, tar should not be condensed under stable operations during GE generation. A previous study of sewage sludge gasification and power generation showed that tar concentrations ranged from 20–690 mg/Nm^3 at the GE inlet (Haneda et al., 2011). Another study reported tar concentrations of <10–4,000 mg/Nm^3 at the GE inlet. Stassen (1995) suggested 100 mg/Nm^3 as the GE requirement for tar concentrations. Overall, in order to achieve stable and problem-free operation, lower tar concentrations are preferable for GE. However, a single ideal tar level for stable operation cannot be defined, because the tar dew point is different depending on the tar composition, even if the gasification tar concentration is the same.

The Energy Center of Netherlands presented tar classifications and a tar dew point calculator showing that the tar dew point varies by composition (ECN, 2009). Thus, depending on the type of gasifier and its operating conditions, tar composition should vary such that both composition and concentrations should be considered.

It was confirmed that tar concentrations were significantly reduced when ER were >0.4 and gasification temperatures were >750 °C (Figure 17 and Figure 19). Lower ER values were needed to maintain 4.0 MJ/Nm^3 of LHV; an ER of approximately 0.4 was the optimal condition for the biomass and RPF used in this study. However, a tar concentration of approximately 5.0 g/Nm$^3{}_{\text{-dry}}$ at the gasifier outlet remained, such that further tar reduction by in-process thermal/catalytic cracking or downstream post treatment would be necessary, as discussed in the studies mentioned above, see (Figure 17 and Figure 19).

4 Conclusions

In these fluidized bed gasification tests, the investigation for the performance and product gas characteristics of RPF and wood pellets in a small and medium scale air-blown FBG system was conducted for use in GE. The gasification characteristics were obtained under varying ER (0.3–0.5) and range of temperatures from 700 to 940 °C, with a pilot scale air-blown FBG to survey the optimum gasification conditions for GE. Product gas characteristics were analyzed and the importance of some of the most important parameters such as the LHV and tar concentration levels was discussed. The following observations can be realized from the study:

- When ER increased, the concentration of CO from wood pellets increased while that from RPF decreased. It is assumed that this resulted from a water-gas reaction of the fixed carbon in wood pellets and the promotion of oxidization of CO in RPF. Polymer cracking of the plastic fraction in RPF resulted in a higher concentration of C_mH_n. The concentration of H_2 from RPF was lower than that from wood pellets because more hydrogen in RPF might be consumed during hydrocarbon formation.
- For both types of feedstock, when ER increased, the tar concentration decreased. Tar concentrations in this study ranged from 2.5–14.0 g/Nm$^3{}_{\text{-dry}}$. As the production behavior of tar had a significant effect owing to ER and temperature, it would be

preferable to take into account gasification temperatures in addition to feedstock characteristics in designing gas processing facilities.

- Considering LHV and tar concentration, an ER of approximately 0.4 was the optimal condition for GE power generation. It was indicated that air-blown FBG could be applied to the GE power generation process without any nitrogen removal, thereby saving plant operation costs.

Due to the higher tar concentrations for each condition as compared to the GE requirements, further tar reduction by in-process thermal/catalytic cracking or downstream post treatment will still be necessary to operate GE for higher efficiency energy recovery.

Chapter 4 Gas and Tar Generation Behavior during Flash Pyrolysis of Wood Pellet and Plastics

1. Introduction

1.1 Background

In our previous fluidized bed gasification experiment as in Chapter 3, the composition of generated gas differed not only with change in equivalence ratio and temperature, but also with changes in feedstock characteristics. Gas yield and composition are important factors as they significantly affect the amount of electricity produced through GE. On the other hand, the amount of tar generated from RPF and wood pellet were similar. However, it was thought that their tar compositions differed as the chemical characteristics of the RPF and wood pellet used were different. In addition to the amount of tar generated, tar composition is also a significant factor for GE operation; for instance, heavy tar results in a higher dew point, which causes serious problems. It is necessary to properly select the solvent of the gas scrubber depending on the composition of tar. As there is an interaction between gas and tar generation behavior, which will also be affected by feedstock, clarifying such behavior is important for process design.

Regarding feedstock, RPF mainly contains plastics at about 60-70% based on the survey of supplier for the feedstock we conducted. The remaining are other fractions such as paper, wood debris, textiles, etc,. As in reported plastics composition in MSW, it was estimated to be 11% in 2013. Among the plastics types, the composition of polyethylene (PE) and polypropylene (PP) were contributed the most to 34 % and 30 %, respectively (Japan Plastics Recycling Association, 2018). In both municipal and industrial waste streams of Japan, it was estimated that in 2017, 86% of the 9.03 million tons of plastics was recycled, of which the highest percentage (58%) was attributable to thermal (energy) recycling, followed by material (mechanical) recycling at 23%, and chemical recycling at 4% (PWMI, 2019). As an example of thermo-chemical recycling technologies for plastics waste stream, Lee et al., (J. E. Lee et al., 2014) conducted circulating fluidized bed gasification to study complex hydrodynamic characteristics by numerical modeling and simulation using computational fluid dynamics (CFD). There is a need to design efficient reactors to improve effective resource utilization with fluidized bed technology. Currently in Japan, only a few small- and medium-scale (i.e., capacity below 100 t/d) MSW treatment plants can produce electricity because such plants have low electricity generation efficiency (Ministry of the Environment Japan(MoEJ), 2019; MoEJ, 2007; NEDO, 2014b). The use of fluidized bed gasifiers (FBGs) and gas engine (GEs) could potentially enhance this efficiency. The lower heating value of product gas, the concentrations of tar and char, and impurities are important factors for the stable operation of GE and for the design of gas treatment processes. These factors depend on operational conditions and feedstock characteristics. However, as MSW consists of varying fractions of different components such as paper, food, plastics, wood, and rubber; therefore, it is difficult to estimate the composition of the product gas and by-products, such as tar, char, and impurities, generated. To realize the interactions and clarification of such behavior, flash pyrolysis could be available due to its higher heating rate and devolatilization characteristics similarly incurred in the early gasification conditions of FBG where combustions happen immediately. It is considered that pyrolysis and combustion has occurred in the sand bed in FBG.

1.2 Flash Pyrolysis

Pyrolysis tests conducted in previous studies are summarized in Appendix C. The typical pyrolysis temperature range for thermal processes is between 350°C and 900°C (Al-Salem et al., 2017). The pyrolysis mechanisms of biomass and plastics has also been studied (Al-Salem et al., 2017; Anuar Sharuddin et al., 2016; Collard and Blin, 2014; Murata; and Makino, 1975; Takeshi et al., 1976; Wang et al., 2017; Zhang et al., 2016). Based on the rate of heat transfer to the materials, pyrolysis technologies are generally categorized into slow pyrolysis, fast pyrolysis, and flash (very fast) pyrolysis (Scheirs and Kaminsky, 2006). Slow pyrolysis involves a low heating rate (approximately 10°C/s) within a temperature range of 400°C–500°C and long residence time (5–30 min). The heating rate and residence time of fast pyrolysis are approximately 100°C/s at 400°C-650°C and 0.5-2 s, respectively, while those for flash pyrolysis are above 500°C/s at 700°C–1000°C and below 0.5 s, respectively (The Pennsylvania State University, n.d.). Slow pyrolysis typically forms solid products with low oil production, while fast pyrolysis and flash pyrolysis generate large amounts of gases and oil. Several studies have explored different pyrolysis modes for pure and mixed biomass and plastics, including slow pyrolysis of pure wood biomass (Zhou et al., 2015) and mixed wood biomass with plastics (Alvarez et al., 2014; Fujita et al., 2015; Grieco and Baldi, 2012; Kumagai et al., 2016), fast pyrolysis (Sophonrat et al., 2017), and flash pyrolysis for pure wood biomass(Hwang et al., 2014), pure plastics(Matsunaga et al., 2017; Nedjalkov et al., 2016) and mixed wood biomass with plastics (Bhattacharya et al., 2009; Ephraim et al., 2018). Furthermore, several studies have conducted the co-pyrolysis of wood biomass and plastics for a wider temperature range (450°C-750°C) and investigated the yield and composition of the target products (gas, tar, and char) to understand the interaction between these two feedstock types (Alvarez et al., 2014; Bhattacharya et al., 2009; Ephraim et al., 2018; Fujita et al., 2015; Grieco and Baldi, 2012; Kumagai et al., 2016; Sophonrat et al., 2017). However, product type and proportion and the mechanism of product formation for different modes of single and co-pyrolysis require further clarification. Furthermore, knowledge of the yield and composition of gas and tar, and their behaviors and interactions during flash co-pyrolysis remains limited.

Gasification is a partial oxidation process that is usually applied for syngas while pyrolysis is oxidant free process. Flash pyrolysis with momentary residence time (below 0.5 s) generates gas, tar and char. Flash pyrolysis process is essential to know the devolatilization characteristics and to maximize the evolved volatile gases in high heating rate with shorter duration. The process was previously studied in several works (Önal et al., 2014; Scott et al., 1985; Shuangning et al., 2006) in different reaction furnaces to be probably reproduced the reaction conditions closer to those encountered as one of the processes in practical fluidized bed gasification. Fluidized bed gasification could be attributed a co-relationship between 1) flash pyrolysis and 2) pyrolysis gas partial combustion as it is generally known that the gasification reaction in FBG is completed immediately. In order to collect and organize data on the differences among feedstocks by fluidized bed gasification, this study first examined differences in flash pyrolysis behavior. Through flash co-pyrolysis of wood pellet, as representative of biomass, and polyethylene (PE) and polypropylene (PP), as representative of plastics, both synergistic and non-synergistic effects among difference of feedstock characteristics were observed.

2. Materials and methods

2.1 Feedstock

Wood pellet, PE, and PP were used as feedstock because the wood biomass and plastic fractions remaining in MSW after removal of food waste are the main sources for RPF. RPF is produced from plastics, paper, and other materials such as wood and fabric from industrial wastes and well-separated MSW from both municipalities and the private sector (Kodera, 2012; Ministry of Environment Japan (MoEJ), 2012). In addition, PE and PP account for 33.8% and 30.1% (total: 63.9%) of the waste plastic stream in Japan, respectively (Japan Plastics Recycling Association, 2018). Although PE and PP have the same chemical composition, their structures are different.

The wood pellet was produced from a blend of white spruce, red pine, various cedar species and other woods without bark. Wood pellet was pulverized and screened to obtain particle sizes between 0.6 to 2.0 mm. Commercial grade resins of PE and PP with 3 mm were used. The characteristics of the wood pellet, PE, and PP are listed in Table 10. The mixing ratios between wood pellet, PE, and PP were varied in different tests as listed in Table 11.

Table 10. Characteristics of feedstock used for flash pyrolysis

Feedstock	Wood pellet	Polyethylene	Polypropylene
Moisture [wt.%-wet]	8.1	0.0	0.0
Ash [wt.%-dry]	0.4	0.0	0.0
Volatile [wt.%-dry]	85.3	100	100
Fixed carbon [wt.%-dry]	14.3	0.0	0.0
C [wt.%-dry]	51.4	85.7	85.7
H [wt.%-dry]	5.1	14.3	14.3
N [wt.%-dry]	0.5	0.0	0.0
O [wt.%-dry]	42.2	0.0	0.0

Each characteristic is not theoretical but analyzed value.

Table 11 Mixing ratios between wood pellet, polyethylene (PE), and polypropylene (PP) for different tests

Feedstock	Unit	RUN1	RUN2	RUN3	RUN4	RUN5	RUN6
Wood pellet	[g]	1.5	0.0	0.0	0.75	0.75	0.75
		(100%)	(0%)	(0%)	(50%)	(50%)	(50%)
Polyethylene	[g]	0.0	1.5	0.0	0.75	0.0	0.375
		(0%)	(100%)	(0%)	(50%)	(0%)	(25%)
Polypropylene	[g]	0.0	0.0	1.5	0.0	0.75	0.375
		(0%)	(0%)	(100%)	(0%)	(50%)	(25%)

2.2 Experimental procedure

2.2.1 *Test conditions*

Flash pyrolysis experiments have been conducted using an electric heater at the gasification temperature under an inert atmosphere. A schematic diagram of the flash pyrolysis process and the associated experimental apparatus is shown in Figure 20. The heating temperature of the electric furnace was fixed at 900°C to achieve complete volatilization of the sample based on JIS M 8812:2004. After this set temperature was attained, 1.5 g of the sample to be studied was placed in a quartz sample boat, which was inserted into the center of the furnace, and heated for 120 min. N_2 was used as the carrier gas at a flow rate of 50 ml/min, regulated using a mass flow controller (Model 3660, Kojima Instruments Inc., Kyoto, Japan). Each experimental test was done one time.

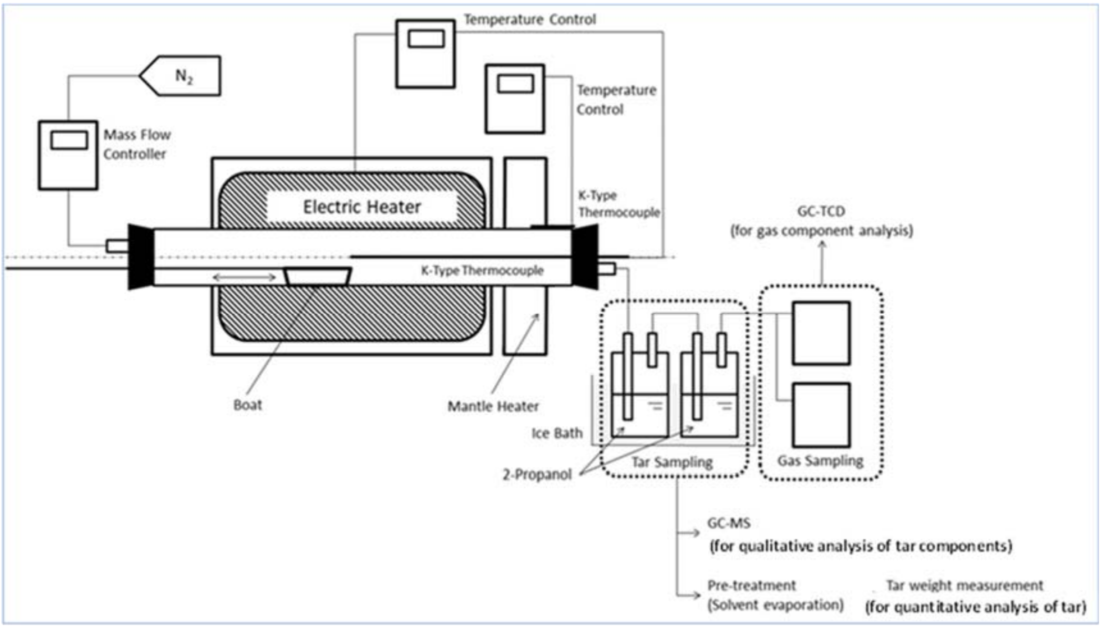


Figure 20. Schematic diagram of flash pyrolysis process

2.2.2 *Gas sampling and analysis*

Gas samples were collected using 1 L sampling bags every 15 min for 120 min (1, 15, 30, 45, 60, 75, 90, 105, and 120 min). These samples were collected after initiation of heating so that all the gas generated in the furnace could be captured. The gas samples were analyzed for H_2, O_2, N_2, CH_4, CO, CO_2, and hydrocarbons (C_mH_n: C_2H_4, C_2H_6,C_3H_6,C_3H_8, i-C_4H_{10}, n-C_4H_{10}) using a gas chromatograph-thermal conductivity detector (GC-TCD, 490 Micro GC; Agilent Technologies Japan, Ltd.) with Molsieve 5A (Ar carrier) and PoraPLOT Q (He carrier) columns. Furthermore, the gas volume in each gas bag was measured with a Pyrex syringe. Product yields were calculated using Eq. 16:

$$P_y[wt\%] = P_w[g]/F_{th}[g] \times 100 \qquad \text{Eq.16}$$

where P_y is the product yield, P_w is the product weight, and F_{th} is the fuel throughput.

2.2.3 *Tar sampling and analysis*

The sampling of tars was carried out in line with the pyrolysis experiment. A tar extraction module was fixed to the gas discharge side, of the pyrolysis system, before the gas sampling bags. The temperature at this point was maintained at 300°C with a mantle heater to prevent tar condensation along the path of product gas. The product gas was allowed to pass through two impingers filled with 2-propanol in the tar extraction module to extract the tar present in the gas stream. Both impingers filled with the tar extraction solvent (2-propanol) were submerged in an ice cooling bath. The tars adhered to the reactor tube inside the furnace were washed with acetone and collected in the impingers. The tar extraction solvent was suction-filtered using a membrane filter (0.45 μm) to remove dust. The filtrate was concentrated in a rotary evaporator at 55°C and 20 kPa (abs) to enable determination of tar yield. Tar components in the solvent were identified using a gas chromatograph-mass spectrometer (GC-MS; GC: 7820A / MS: 5977B, column: L 30 m × I. D. 0.25 mm, df: 0.25 μm, DB-5; Agilent Technologies Japan, Ltd.). Measurement of tar weight in both qualitative and quantitative analysis was carried out based on the guidelines provided in the sampling and analysis of tar and particles in biomass producer gases version 3.3 (Neeft et al., 2005).

3. Results and discussion

3.1 Mass balance

Table 12 showed gas yield and composition and tar yield of each test. Approximately 60-84% of the input (1.5 g) was measured as gas, tar, and residue fractions. It was thought that there were 1) undetected tar which failed to be captured in two impingers and therefore partitioned into gas bags, and/or 2) volatilized tar fractions with lower boiling point such as benzene and toluene during concentrating the filtrate in a rotary evaporator at 55°C and 20 kPa. During the experiments, the mass loss was expected to be the volatility of some tars compounds which might condense in impingers bottles and gas channel as well as gas collection bags under the standard collection procedures in recovering product gas.

3.2 Gas yield and composition

Gas yield and composition and tar yield were different for pure and mixed feedstocks as listed in Table 12. In the flash pyrolysis experiments with pure feedstock (RUN1-3), CO was produced from wood pellet, while C_mH_n was produced from plastics. Flash pyrolysis of PE (RUN2) tended to generate higher levels of C_2H_4, while that of PP

(RUN3) released higher amounts of CH_4 and C_3H_6. The total gas yields were higher for mixed feedstock (69.6%–73.5% in RUN4-6) than for pure feedstock (41.7%–51.0% in RUN1-3).

Table 12. Gas composition, total gas, and tar yields for each test

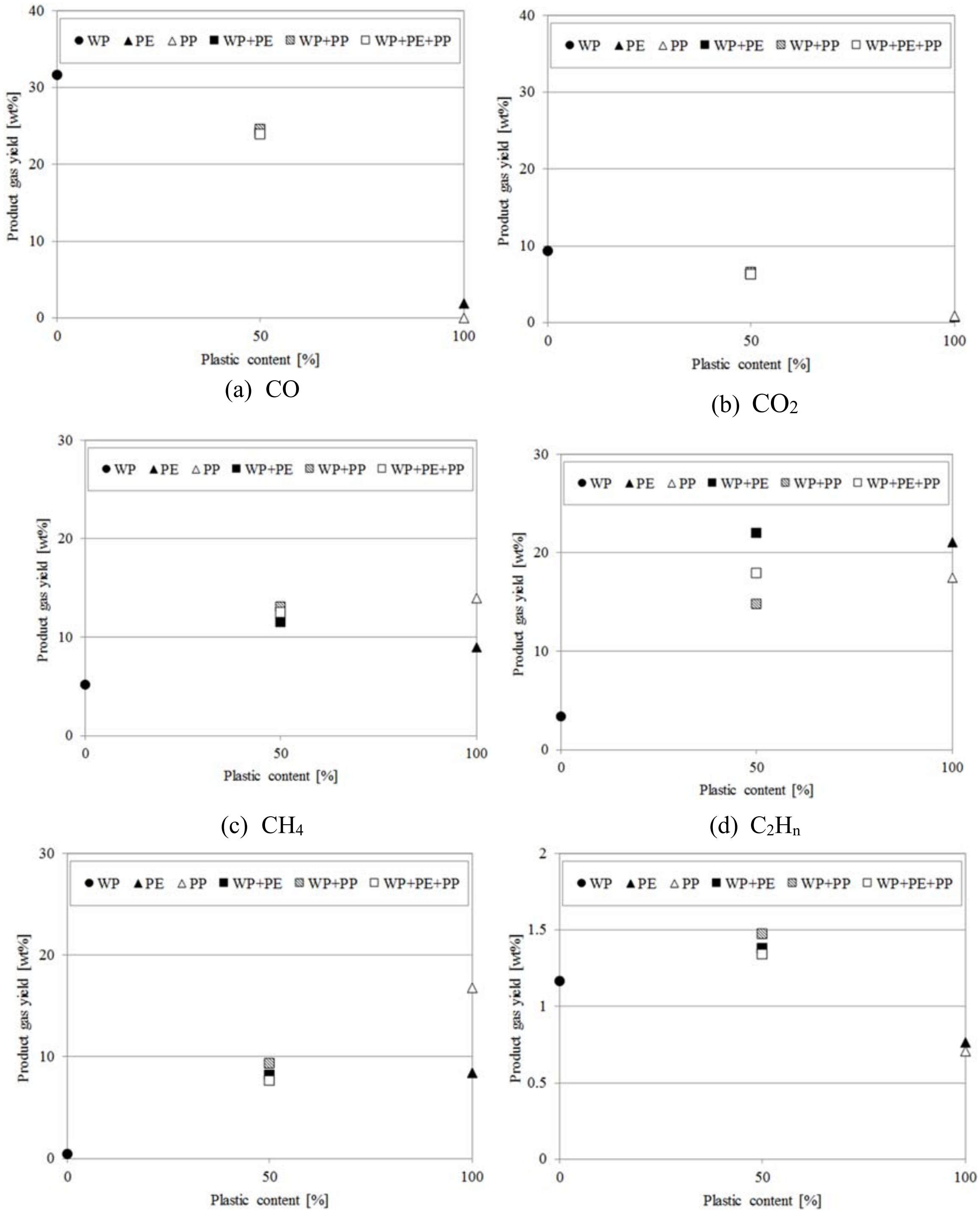
		Unit	RUN1	RUN2	RUN3	RUN4	RUN5	RUN6
Feedstock	WP	wt.%	100	0	0	50	50	50
	PE	wt.%	0	100	0	50	0	25
	PP	wt.%	0	0	100	0	50	25
Product gas	CO	wt.%	31.6	1.8	0.0	24.1	24.6	23.9
	H_2	wt.%	1.2	0.8	0.7	1.4	1.5	1.3
	CH_4	wt.%	5.2	9.0	13.9	11.5	13.1	12.5
	C_2H_4	wt.%	3.0	18.6	13.7	19.4	12.3	15.5
	C_2H_6	wt.%	0.3	2.5	3.7	2.6	2.5	2.4
	C_3H_6	wt.%	0.3	7.9	16.1	7.9	9.0	7.3
	C_3H_8	wt.%	0.1	0.5	0.7	0.4	0.4	0.3
	CO_2	wt.%	9.4	0.7	0.8	6.3	6.6	6.3
	Total	wt.%	51.0	41.7	49.6	73.5	69.9	69.6
Residue		wt.%	5.5	0.0	0.0	4.5	4.6	4.5
Tar		wt.%	4.3	13.0	8.7	5.5	6.5	5.7

WP-wood pellet; PE-polyethylene; PP-polypropylene

Note 1: unit "wt. %" is input feedstock (1.5 g) basis.

Note 2: N_2 injected as carrier gas and leaked O_2 in sampling gas was excluded.

The relationship between plastic content and gas yield is illustrated in Figure 21. As shown in Figure 21 (a) and (b), CO and CO_2 yields increased with a decrease in plastic (PE and PP) content. This is derived from the cracking of oxygen containing function groups such as carboxyl and carbonyl (Qu et al., 2011). The effect of water-gas reactions ($C+H_2O \rightarrow CO+H_2$, $C+2H_2O \rightarrow CO_2+2H_2$) caused by the oxygenates and moisture present in the wood pellet also contributed to it (Alvarez et al., 2014; Hwang et al., 2014). CO and CO_2 yields decreased from 31.6 wt.% and 9.4 wt.%, respectively, at 0% plastic content (pure wood pellet) to 24.1–24.6 wt.% and 6.3–6.6 wt.%, respectively, at 50% plastic content. As plastics do not contain oxygen, CO and CO_2 yields at 100% plastic content were almost zero.



(a) CO

(b) CO_2

(c) CH_4

(d) C_2H_n

(e) C_3H_n

(f) H_2

Figure 21. Gaseous yields of (a) CO, (b) CO_2, (c) CH_4, (d) C_2H_n, (e) C_3H_n, and (f) H_2

CH_4 is generated by the cracking of methyl and methoxy and methylene groups (Ma et al., 2015). As shown in Figure 21 (c)-(e), the yields of CH_4 and C_3H_n from PP were higher than those from PE; however, the C_2H_n yield from PE was higher than that from PP. This difference in C_mH_n yield may be attributable to the different structures of

PP, which is a polymer of propylene, and PE, which is an ethylene polymer. The study findings confirm that feedstock structure affects syngas composition, even if the feedstocks have the same chemical composition. Furthermore, the methyl group present in PP may be converted into CH_4 and C_3H_n through cracking. For fluidized bed gasification process design, not only do chemical composition and heating value of feedstocks need to be accounted for, but also the chemical structure needs to be considered.

The yield of H_2 from wood pellet was higher than that from plastics (Figure 21 (f)). This is likely because of the water-gas reaction caused by the fixed carbon and moisture present in wood pellet. However, the H_2 yield was the highest (1.3–1.5 wt.%) at a plastic content of 50%. This may be because the moisture/steam and oxygen in wood pellet promotes H_2 release from the aromatic hydrocarbons present in plastics. Hydrogen donor radicals promoted the H_2 yield in the co-pyrolysis experiments owing to the higher H/C ratio of plastics (Alvarez et al., 2014).

There are some previous studies to support the results observed in this study. Hwang et al., Nedjalkow et al., and Matsunaga et al. (Hwang et al., 2014; Matsunaga et al., 2017; Nedjalkov et al., 2016) conducted flash pyrolysis of pure wood biomass and plastics at relatively high temperatures (700°C–900°C). Hwang et al. (Hwang et al., 2014) used wood chip, Refuse derived fuel, and RPF (70% paper and 30% plastic) as feedstock and observed that H_2 and CH_4 yields increased with increase in temperature. They suggest that the increase in the H_2 yield was due to dry reforming reactions ($CH_4 + CO_2 \rightarrow 2CO + 2H_2$) and that the increase in the CH_4 yield was because the decomposition of hydrocarbons released more CH_4 than was consumed during the dry reforming reactions. At 900°C, the CH_4 yield from RPF, which contains plastic and wood, was higher than that from wood chip. While the CO and CO_2 yields from woody biomass chip were higher than those from RPF due to oxidation and water-gas reactions; as discussed, the C_mH_n yield of wood chip was lower than that of RPF. This suggests that the oxygen and/or moisture present in the wood fraction reacts with chain hydrocarbons in the tar to form light hydrocarbon gases, as described in Section 3.3.

Kumagai et al. (Kumagai et al., 2016) conducted co-pyrolysis of beech wood and PE when heating from room temperature to 650°C at a rate of 10°C/min (slow pyrolysis) and reported an increased gas yield with increasing beech wood content. However, Fujita et al. (Fujita et al., 2015) using the same feedstocks in flash pyrolysis and obtained different results. They observed that gas yield via co-pyrolysis was higher than that via pyrolysis of either beech wood or PE at a constant temperature (650°C, flash pyrolysis). Fujita et al. (Fujita et al., 2015) suggested that this difference may be attributable to the stabilization of radicals in beech wood due to hydrogen abstraction from PE pyrolysates in the vapor phase under rising temperature conditions (Fujita et al., 2015). In contrast, at a constant temperature (Fujita et al., 2015), melted PE prevented the aggregation of levoglucosan from beech wood and increased levoglucosan yield, which in turn increased gas yield. In our study, co-pyrolysis at 900°C improved the gas yield; similar results might be obtained even at medium temperatures (above 600°C), but might not be obtained at lower temperatures (450°C–525°C), at which fixed carbon in the feedstock cannot be decomposed by steam from the moisture in wood pellet (Bhattacharya et al., 2009; Hwang et al., 2014).

Overall, flash pyrolysis in this study confirmed that gas yield increases by mixing wood pellet and plastic materials because of oxygenates and moisture contents in wood pellet. Previous studies have shown a similar trend.

3.3 Tar yield and composition

The higher plastic content displayed higher tar yield as shown in Figure 22; tar yields at plastic contents of 0%, 50%, and 100% were 4.3 wt.%, 5.5–6.5 wt.%, and 8.7–13.0 wt.%, respectively. Plastics are polymers (PE is a polymer of ethylene and PP is a polymer of propylene), which are hydrolyzed to hydrocarbons, including tar; therefore, plastics tend to have higher tar yields than do wood pellet. Some previous studies reported similar tar yield trends. Increases in tar yield with increasing plastic fraction was observed during co-pyrolysis of PE-wood and PE-paper mixtures at heating rates of 0.1°C/s and 1°C/s (Grieco and Baldi, 2012).

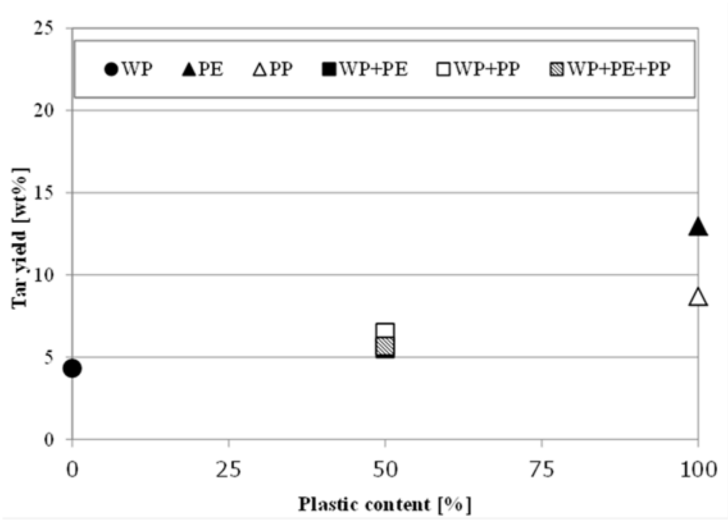


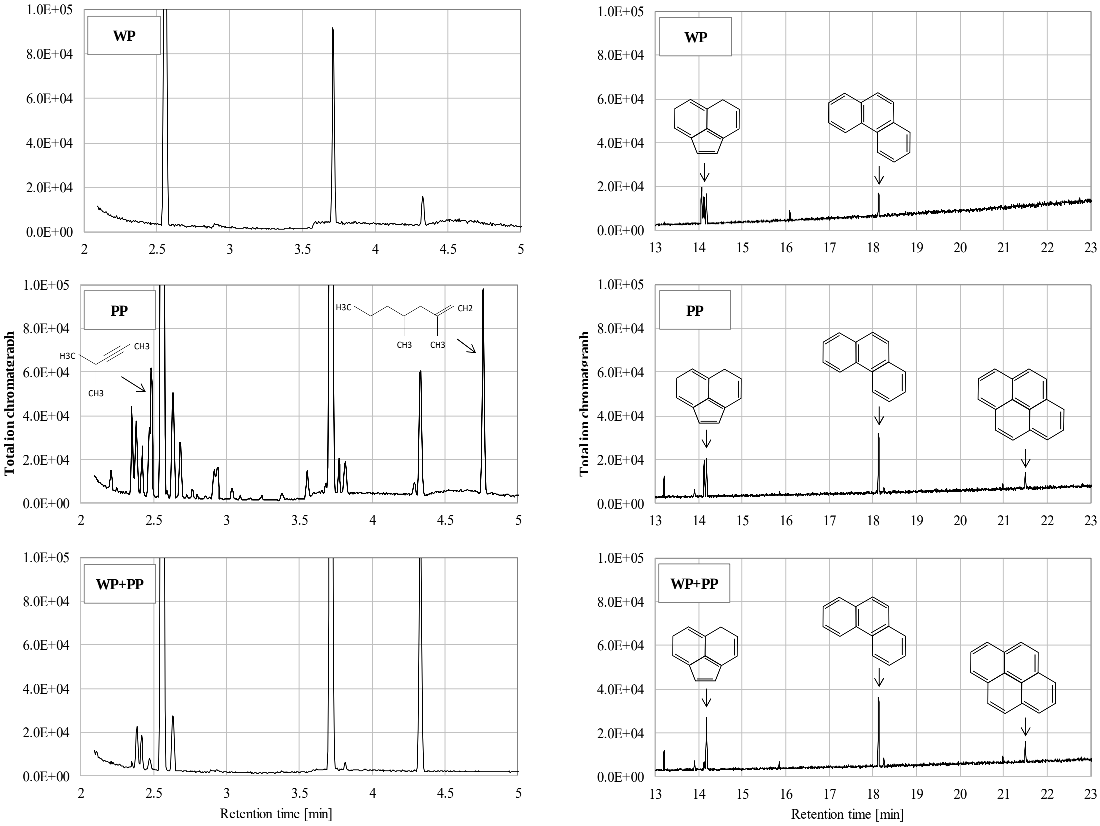
Figure 22. Relationship between tar generation and plastic content

Tar composition determined via GC-MS analysis is shown in Appendix D. The peak areas of the total iron chromatograph (TIC) are proportional to the respective concentrations; higher peak area values mean a higher concentration of that component in the tar. Tar composition was different for the different feedstocks. However, benzene, toluene, naphthalene, styrene, acenaphthylene, and phenanthrene were always common tar components. Figure 23 shows the TIC of the tar from wood and PP during certain cases of retention time. The results from pure and mixed PE as in Appendix E show similar tendencies.

When pure PP was used as feedstock, several chain hydrocarbons, which are likely generated via thermal decomposition of plastic, were detected, as shown in Figure 23 (a). Unlike PE, PP has a branched structure and contains CH_3, and therefore branched-chain hydrocarbons were detected in tar generated from PP (see also Appendix E). According to Murata and Makino (Murata; and Makino, 1975), the by-products of PP thermal decomposition retain this branched structure, in which CH_3 groups, derived from the monomers of PP (C_3H_6), are regularly arranged. Similarly, branched tars with regularly arranged CH_3 groups were observed in this study. As shown in Figure 23(b), the pure PP and mixed PP with wood pellet released higher levels of heavy aromatics such as acenaphthylene, acenaphthylene, and pyrene as compared with pure wood pellet.

Polycyclic Aromatic Hydrocarbons (PAHs) are one of the major components of tar. As shown in Appendix D, the same PAHs (naphthalene, methylnaphthalene, acenaphthylene, and phenanthrene) reported by Zhou et al. (Zhou et al., 2015) were detected in the tar produced from PE in this study. Similarly, wood pellet in this study yielded similar PAHs as that reported by Zhou et al. (Zhou et al., 2015) for cellulose.

This study confirmed that the tar yield decreases by mixing wood pellet with plastic fractions. Tar compositions revealed that most chain hydrocarbons are not observed when wood pellet and plastic mixtures are used as the feedstock, which implies that PAHs concentrations are relatively increased.



(a) Chain hydrocarbons (b) PAHs

Figure 23 Results of TIC of the tar from wood and PE via GC-MS analysis

3.4 Mixture effects and behavior

This study considered the effects and interactive behaviors of mixing wood pellet and plastic fractions. Synergistic and non-synergistic effects among the different compositions (feedstocks) were observed.

Firstly, the two synergistic effects by co-pyrolysis were 1) increasing the gas yield, and 2) decreasing the tar yield. The gas yields were higher for mixed feedstock (RUN4-6) than for pure feedstock (RUN1-3) (Table 12 and Figure 21). By mixing wood pellet and plastic fractions, the cracking of oxygen containing function groups such as carboxyl and carbonyl (Qu et al., 2011) and water-gas reactions ($C+H_2O \rightarrow CO+H_2$, $C+2H_2O \rightarrow CO_2+2H_2$) (Alvarez et al., 2014; Hwang et al., 2014), which resulted in increasing CO and CO_2 yields.

Furthermore, decreased tar was converted into gases. GC-MS analysis in this study (Figure 23a) showed that thermal decomposition of plastics alone produces abundant tar as chain hydrocarbons, while in co-pyrolysis, there is less tar of chain hydrocarbons. This could be because O_2 and/or steam released from the wood pellet reacted with chain hydrocarbons in tar to form light hydrocarbon gases such as C_2H_n and C_3H_n (Figure 21). Therefore, it contributed to increasing the gas yield and reducing the tar yield. As illustrated in Figure 22, tar yield was not proportional to plastic content; tar yield with mixed wood pellet and PE (RUN4) was slightly lower than at the proportional level with either pure wood pellet or pure PE. However, as shown in Figure 21, gaseous CO and C_mH_n yields with mixed wood pellet and plastics were higher than those with either pure wood pellet or plastics. Hwang et al. (Hwang et al., 2014) suggested that this behavior was due to oxygen and/or moisture in the wood fraction reacting with chain hydrocarbons in the tar to form light hydrocarbon gases. It was said that potassium in biomass facilitate the cracking reaction (Higman and Burgt, 2008). Jin et al. (Jin et al., 2017) also reported that the alkali and alkaline earth metals in biomass ash act as catalysts for secondary co-pyrolysis reactions, such as cracking and dehydrogenation to increase gases. According to Zhang et al. (Zhang et al., 2016), as the thermal stability of biomass is lower than that of plastics during the co-pyrolysis process, free radicals from the degradation of biomass (with lignin being the major source) could promote the decomposition of plastic-derived macromolecules.

On the other hand, in terms of non-synergistic effects, this study revealed that PAHs are not reduced even if wood pellet is mixed, which means that the PP or PE fraction was halved (Figure 23 and Appendix E). It was reported that co-pyrolysis of cellulose and LDPE generate aromatics through Diels-Alder reactions followed by dehydration reaction (Zhang et al., 2016). Diels–Alder reactions is cycloaddition in cyclic transition state during harsh reaction conditions, and formed by the concerted process for thermodynamically favoring compact cyclic nature such as, BTX (benzene, toluene, xylene) and PAHs (Zhou et al., 2015). It was also assumed that cracking of PP led to the removal of hydrogen radicals, after which carbon atoms would bond to form aromatic structures (Zhang et al., 2016). It has been suggested that dimerization of propargyl radicals (C_3H_3) derived from CH_2 and C_2H_2 leads to the formation of benzene rings (STEIN et al., 1990; Tonokura, 2014). In mixed wood pellet and PP (RUN5), as chain hydrocarbons in tar were converted to not only gases but also PAHs, tar yield seemed to the proportional trend (Figure 23). Thus, the decrease in chain hydrocarbons of tars seemingly means that PAHs concentration is relatively increased. Moreover, it should be noted that increasing concentrations of PAHs derived from plastics increases the dew point of the tar, which significantly impacts GE operation and therefore these PAHs should be removed or reformed.

The synergetic effects observed in this study supported the results in our previous gasification test in FBG. Results in Chapter 3 showed that RPF tends to produce higher hydrocarbon gases than pure wood pellet. Previous gasification tests also show similar tar yields among different feedstocks, which might be because the tar derived from plastic fractions in RPF was decomposed to hydrocarbons and PAHs owing to the existence of steam and oxygen.

4 Conclusions

Clarifying the relationship between gas and tar generation behaviors and feedstock is useful for process design of fluidized bed gasification and to predict gas and tar yields and compositions, as feedstock compositions vary widely based on regional characteristics. In order to collect and organize data on the differences of gas and tar generation behavior among feedstocks, flash pyrolysis tests for pure and mixed wood pellet, PE, and PP at 900°C were conducted. As the synergetic effects of co-pyrolysis, tar yields were decreased because it was converted into light hydrocarbon gases. On the other hand, tar composition analysis via GC-MS revealed that co-pyrolysis did not reduce PAHs because chain hydrocarbons were converted into not only gasses but also PAHs.

Chapter 5 Conclusion

The scope of this study covers the estimation of the available resources and the development of the waste treatment technology through pre-commercial scale facilities and fundamental research by experiments. The estimation of waste biomass resources was carried out from potential generation sectors which can support the formulation of effective waste management techniques from urban and peri-urban waste streams (i.e. biomass resources from MSW, agricultural, livestock, and sanitation). For the development of technology using such resources, the enhancement of energy efficiency was investigated to improve power generation efficiency of waste treatment facilities, especially small and medium scale plants which encounters low efficiency.

Biomass wood pellets and RPF, which is prepared mainly from paper and plastics with other waste fractions such as rubber, textile, and burnable debris, were utilized for practical tests in fluidized bed gasifier (FBG). RPF was considered as feedstock because the composition of RPF is similar to the remaining MSW composition if food waste is recycled for methane fermentation and composting in the future in Myanmar. From the viewpoint of a system approach, this study is meaningful as it considers waste-to-energy systems from MSW. Another unique point of this study is that a relatively larger FBG plant compared to previous studies, with a maximum capacity of 1.0 ton/day, was used to demonstrate the actual operation of commercial small and medium scale FBGs. It was believe that, determining tar conditions and calorific values of recovered gases for GE, made the points of energy recovery and GHG reduction aspects clear. Considering that pyrolysis and combustion have occurred in the sand bed in FBG, laboratory experimental tests using an electrical furnace with pyrolysis conditions were conducted to investigate the gas composition and tar generation behavior in sand beds for pure plastics, pure biomass, and a mixture of plastics and biomass.

This study provides the information useful for the development of technology for waste treatment facilities using the estimated waste and biomass resources potential for generation. It could be useful not only in developed world but also in developing countries such as Myanmar because the problem of generated wastes and environment issues has posed a similar burden in both developed and developing world.

1. Conclusions of the Thesis

Our research acknowledges the problem of generated waste and biomass from the perspective of potential resource availability by studying the waste based on estimation and its utilization status. The development of the FBG technology was conducted with wood pellets and RPF, to produce fuel with a high energy density, for pursuing higher energy efficiencies for GEs. The key performance parameters in FBG process such as LHV and tar concentration level of product gas were investigated because of its importance for the stable operation of GE. In addition, flash pyrolysis, was studied to make sure that feedstock structure does in fact affect syngas composition, even if the feedstocks have the same chemical composition. From the observed pyrolysis of pure biomass and pure plastics, PE and PP, as well as by combination, the interaction mechanism was found having both a synergistic and non-synergistic effect. For the FBG process design, not only do chemical composition and heating value of feedstocks need to be accounted for, but the chemical structure must also to be considered.

The key findings of this study are as follows.

- During the study timeline, the estimated waste biomass generation in Yangon will increase by over 50%; from 2.59 million tons/yr in 2015 to 3.85 million tons/yr in 2030. From the perspective of future generations, waste biomass generated from the livestock and sewer sector will be the most important due to their increased generation shares
- As the overall GHG emissions are substantial, at 3.68 million tons CO_2 eq. in 2015 and 4.73 million tons CO_2 eq. in 2030, mitigation options must be investigated. Organic MSW was observed to increase by 26% in 2030. Fractions in MSW such as paper and wood are similar to rice straw and rice husk as they have a high carbon content and their heating values are high enough for production of chemical syngas and energy in incineration and gasification process technologies.
- FBG practical tests for biomass wood pellet and RPF revealed the LHV to be around 4.0 MJ/Nm^3 and tar concentration to be approximately 5.0 g/Nm^3$_{\text{-dry}}$ for determining the applicability to GE. An ER of approximately 0.4 was the optimal condition for gas yield and composition, which is potentially useful to enhance power generation efficiency in GE.
- The yield of the generated gas and its composition differed not only with changes in ER and temperature but also with changes in feedstock characteristics. They consequently affect the amount of electricity produced through GE.

- Considering the importance of tar yield and composition from FBG operation, flash pyrolysis at a gasification temperature of 900 °C was conducted with wood biomass, PE, and PP, which simulated the feedstock of wood pellets and RPF, under single and co-pyrolysis conditions.
- It was realized that co-pyrolysis made tar yield decrease due to the synergistic effect but PAHs were not reduced indicating a non-synergistic effect. This is because chain hydrocarbons were also converted into PAHs apart from lighter C_mH_n gases.

2. Implications and Recommendations

- The utilization of biomass can be a potential alternative renewable energy source to reduce impacts on the environment and to switch from fossil fuels consumption. The exploitation of biomass should be therefore be explored.
- The promotion of biomass resource management is urgently in need of a systematic assessment on their contribution to sustainable development plans. In the case of rice husk and rice straw, they should be considered as a stable feedstock for gasification processes. Pre-treatment of feedstock such as densification should be explored because rice straw and rice husk are so light that it would be difficult for them to reach the sand bed otherwise.
- For gasification of agricultural waste, the preferred temperature should be researched and tested to prevent clinker trouble in furnaces since the ash melting temperature of rice is low. For the fate of by-products from gasification (char, tar, etc.), countermeasure techniques for their treatment should be considered along with post-process wastewater treatment.
- Through analysis of product gas characteristics from FBG, the practical operational challenges for GE should be determined. In this way, the mitigation of GHG from energy recovery system can thus be realized.
- The observation of synergistic and non-synergistic effects during flash pyrolysis thermal conversion could be useful not only for understanding the reaction conditions in practical FBG but also for providing a process for accepting different feedstocks for independent process operation.
- To reduce the drawbacks of negative impacts from their utilization status, different scenarios of management and treatment options for this generated waste should be investigated to make a comparison of GHG mitigation potentials.

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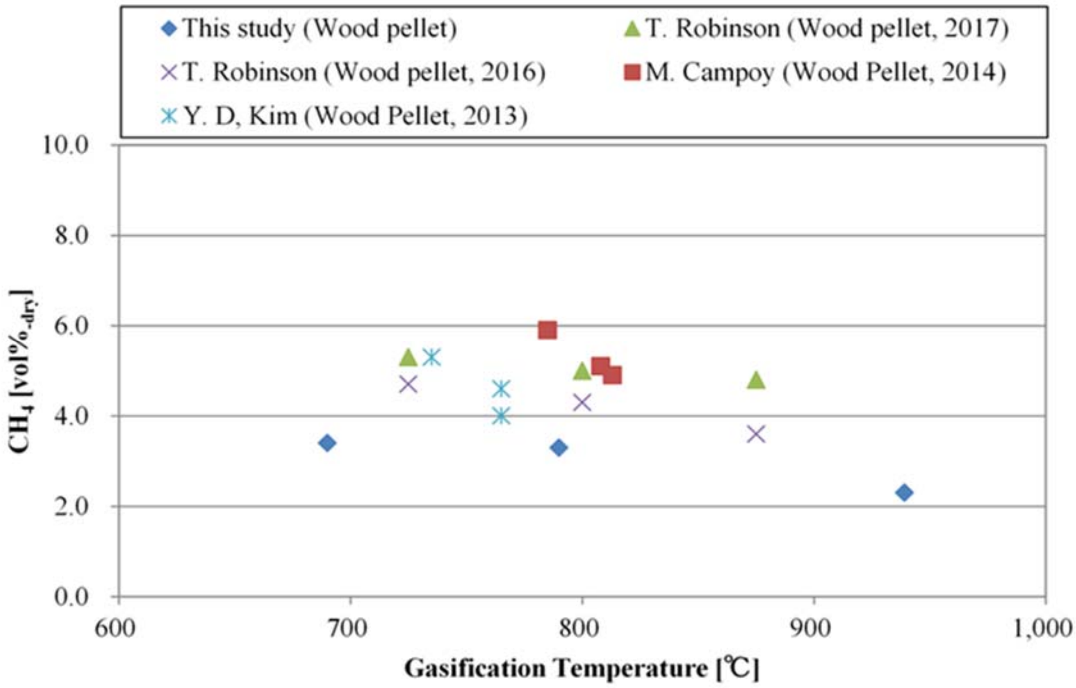
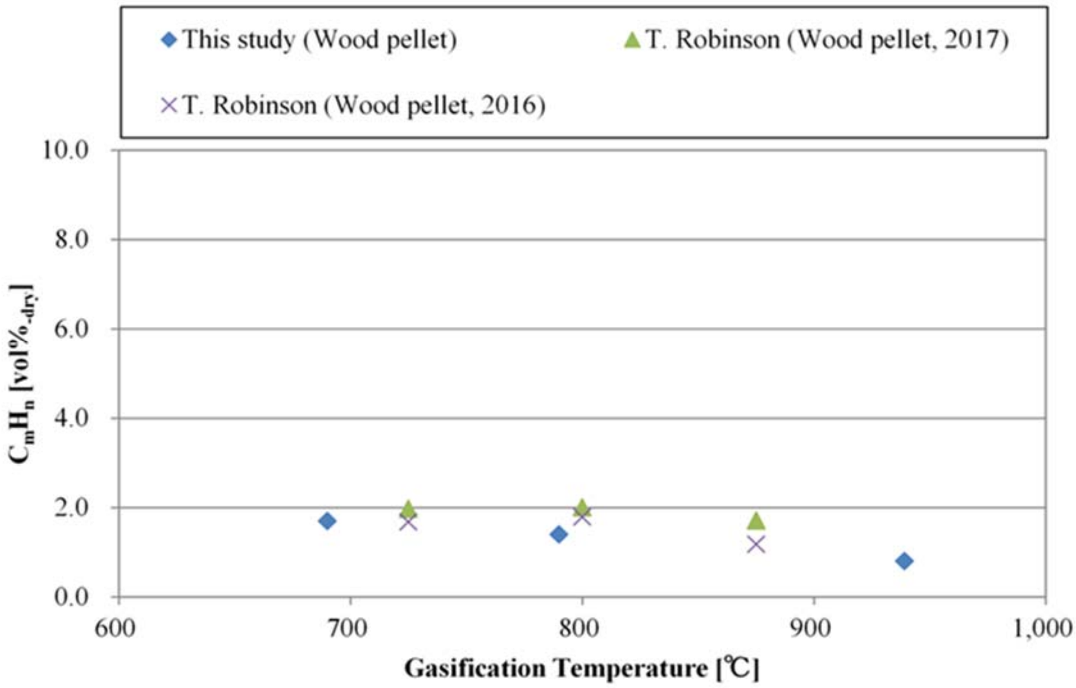
Appendix

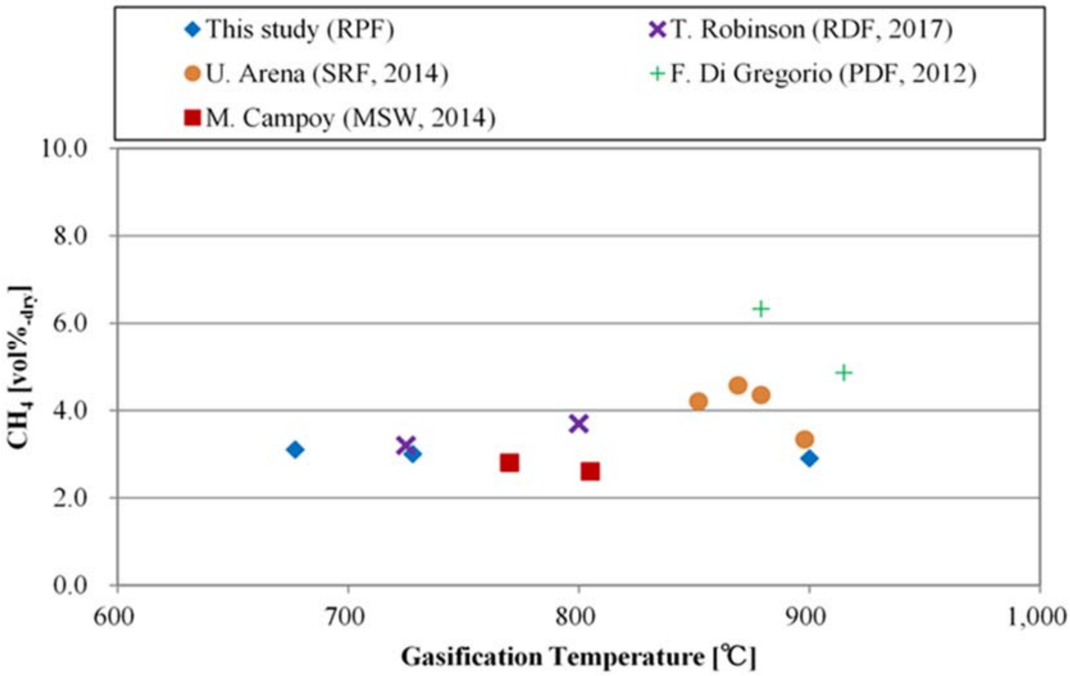
Appendix A. Product gas composition of hydrocarbon species for different feedstocks: wood pellet, Refuse Paper and Plastic Fuel (RPF), Refuse-Derived Fuel (RDF), Solid Recovered Fuel (SRF), Plastics-Derived Fuel (PDF), and Municipal Solid Waste (MSW)



(a) CH_4 concentration in case of wood pellet

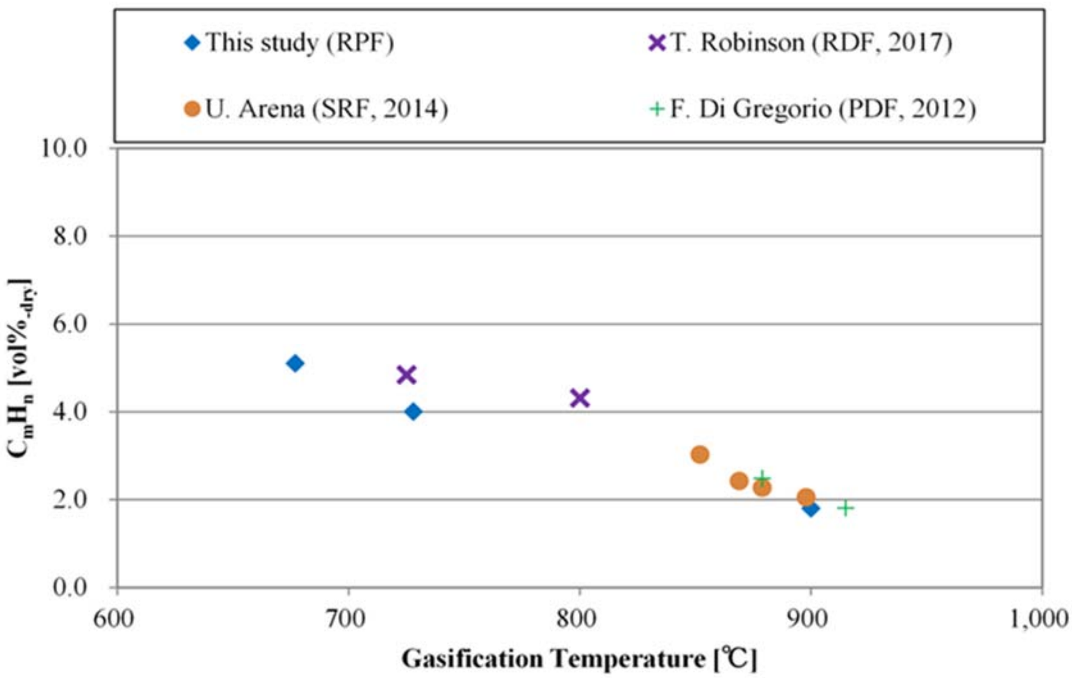


(b) C_mH_n concentration in case of wood pellet



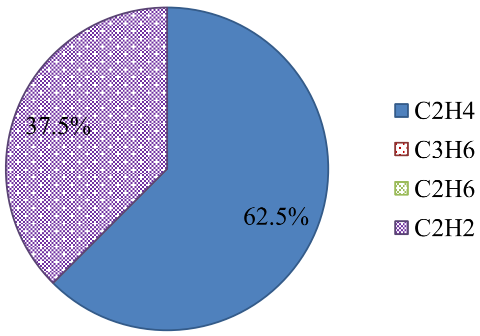
(c) CH_4 concentration in case of a plastic-containing material

(d)

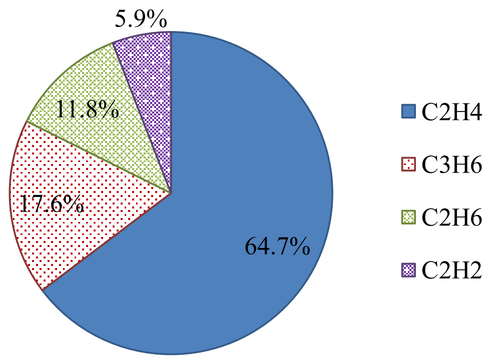


(e) C_mH_n concentration in case of a plastic-containing material

Appendix B. Breakdown of hydrocarbon (C_2H_6, C_2H_4, C_3H_6 and C_2H_2): (a) Run1(ER=0.48, wood pellet); (b) Run3 (ER=0.32, wood pellet); (c) Run4 (ER=0.54, RPF); (d) Run6 (ER=0.33, RPF)



(a)



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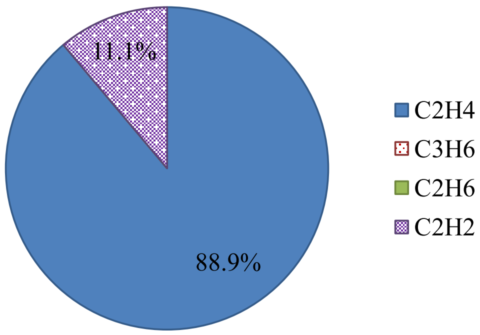
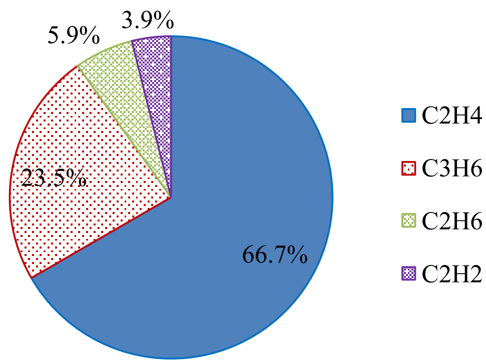


(c)



(d)

Appendix C. Pyrolysis tests from previous studies

Note : Studies focused on wood and/or plastic materials are included, those that used a catalyst are excluded.

Pyrolysis type	Reference	Feedstock		Pyrolysis temperature	Carrier gas	Analyzed contents	Primary findings
		Pure feedstocks	Mixed feedstocks				
Flash	This study	Wood pellet, polyethylene (PE), and polypropylene (PP)	Wood:PE = 50:50, Wood:PP = 50:50, Wood:PE:PP = 50:25:25	900°C	N_2	Gas composition and yield; Tar composition and yield	・ CO and CO_2 yields increase with decreasing plastic content. ・ The yield of H_2 from wood pellet was higher than that from plastics and was highest at a plastic content of 50%. ・ The yields of CH_4 and C_3H_n from PP were higher than those from PE; the yield of C_2H_n from PE was higher than that from PP.
Flash	Bhattacharya et al. (2009)	Pine chip	Pine/PS, Pine/High-density polyethylene (HDPE), Pine/PP Mixing ratio of plastic was 50%	450°C (10°C/ms, 400°C/s)	Not reported	Gas composition; Liquid and char yield; Qualitative analysis of liquid products; Oil characteristics	・ Presence of plastics decreased CO, CO_2, and CH_4 yields.
Flash	Hwang et al. (2014)	Woody biomass chip, refused derived fuel (RDF), and refused paper and plastics fuel (RPF)	—	500—900 °C	N_2 and steam	Gas composition; Qualitative analysis of liquid products; Carbon distribution in liquid products; Specific surface area of solid residue	・ H_2 and CH_4 concentration increased with increasing temperature. ・ At 900°C, CH_4 yield from RPF was higher than that from wood chip. ・ CO and CO_2 yields from woody biomass chip were higher than those from RPF.
Flash	Fujita et al. (2015)	Beech wood and PE	Beech wood/PE Mixing ratios of PE	650°C	He	Gas composition;	・ Gas yield from co-pyrolysis was higher than those from pyrolysis of pure beech

Pyrolysis type	Reference	Feedstock		Pyrolysis temperature	Carrier gas	Analyzed contents	Primary findings
		Pure feedstocks	Mixed feedstocks				
			were 0%, 40%, 60%, and 100%			Tar, oil and char yields	wood or pure PE. ・ Melted PE prevented aggregation of levoglucosan from beech wood and increased levoglucosan yield, which in turn increased gas yield.
Flash	Nedjalkov et al. (2016)	Acrylonitrile-butadiene-styrene (ABS), polycarbonate (PC), and PE	—	600°C–1000°C	N_2 and steam	Tar and char yields; Qualitative analysis of tar via time-of-flight spectrometry (TOF-MS)	・ Increase in temperature decreased tar yield but increased the average molecular weights of tar hydrocarbons, which implies the difference in tar composition and was dependent on pyrolysis temperature.
Flash	Matsunaga et al. (2017)	ABS, PC, and PE	—	700°C–900°C	N_2 and steam	Gas composition; Tar and char yield	・ H_2 and CH_4 yields from ABS increased with increasing temperature owing to desorption of CH_3 groups and dehydrogenation by multi-cyclization.
Flash	Ephraim et al. (2018)	Poplar wood, PS, and polyvinyl styrene (PVS)	Poplar wood/PVS, and poplar wood/PS Mixing ratios of plastic were 0%, 5%, 10%, 30%, 50%, and 100%	750°C (20°C/min)	N_2	Gas composition; Tar and char yields	・ Synergistic interactions with PS led to increased yields of H_2, CH_4, CO, and CO_2.
Fast	Sophonrat et al. (2017)	Cellulose and PE mixed with PET, PP, and PS	PS was mixed with other feedstocks (cellulose and PE mixed with PET and PP) at 12 different mixing ratios	450°C, 500°C, and 600°C (200 K/s)	He	Total ion chromatogram (TIC) area	・ Yield of single ring aromatics increased with the addition of PP.
Slow	Grieco and Baldi (2012)	Sawdustwood, paper, LDPE	LDPE/wood sawdust, LDPE/paper Mixture ratios of LDPE were 0, 25,	1°C/s, 0.1°C/s	Not known	Gas composition; Tar and char yields	・ Tar yield decreased with increasing mixing ratio of biomass materials.

Pyrolysis type	Reference	Feedstock		Pyrolysis temperature	Carrier gas	Analyzed contents	Primary findings
		Pure feedstocks	Mixed feedstocks				
			50, 75, and 100%				
Slow	Alvarez et al. (2014)	Wood sawdust	Wood sawdust, PP, high-density polyethylene (HDPE), PS, mixture of RP Mixing ratios of PP were 0%, 5%, 10%, and 20%, while that of other plastic types was 20%.	Pyrolysis: 600°C (40°C/min) Gasification: 800°C	Pyrolysis: N_2 Gasification: Steam	Gas composition; Liquid and char yields *Process consists of two reactors (pyrolysis and gasification reactors). Sampling is done after gasification	・ Co-pyrolysis of wood sawdust with plastics (ratio of up to 20%) increased the yields of gas, especially H_2. ・ The highest H_2 yield was achieved with the addition of PP.
Slow	Kumagai et al. (2016)	Beech wood and PE	Beech wood/PE Mixing ratios of PE were 0%, 40%, 60%, and 100%	650°C (10°C/min)	He	Gas composition; Tar, oil, and char yields	・ Gas yield increased with increasing beech wood content. ・ PE promoted the formation of levoglucosan and methoxyphenols, with unsaturated alkyl side chains, from beech wood.
Slow	Zhou et al. (2015)	Xylan, cellulose, lignin, pectin, starch, PE, PS, PVC, and PET	—	800°C (350°C/min)	N_2	Gas composition; Tar and char yields; PAH yield	・ More PAHs were released from plastic materials than from biomass.

Appendix D. Tar composition determined via gas chromatograph-mass spectroscopy (GC-MS) analysis

Note: Peak area in GC-MS chromatogram is proportional to the respective concentration

(a) Aromatics

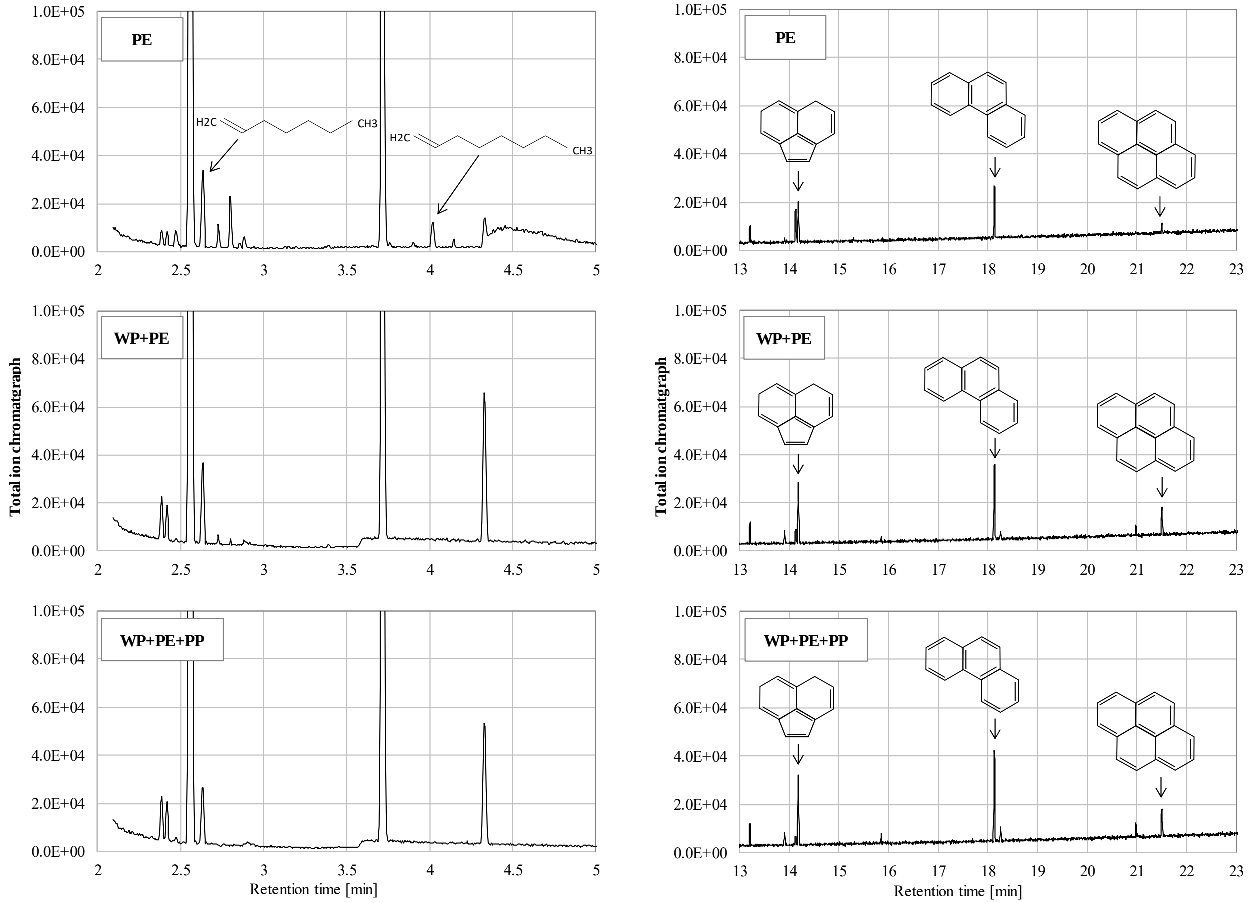
Composition	Formula	Benzene ring	RUN1 WP	RUN2 PE	RUN3 PP	RUN4 WP+PE	RUN5 WP+PP	RUN6 WP+PE+PP
Phenol	C_6H_5OH	1	22,860	-	-	10,871	9,579	11,063
Benzene	C_6H_6	1	374,951	1,629,002	2,136,851	2,105,241	2,065,605	2,162,646
Toluene	C_7H_8	1	126,788	434,469	1,211,114	607,383	1,004,613	785,045
p-Xylene	C_8H_{10}	1	-	-	-	-	68,944	36,126
o-Xylene	C_8H_{10}	1	-	-	84,799	-	-	-
Ethylbenzene	C_8H_{10}	1	-	-	-	-	-	26,338
Styrene	C_8H_8	1	15,694	128,699	159,083	179,669	172,013	190,732
Benzene, 1-Propynyl	C_9H_8	1	42,340	6,347	72,989	80,466	-	19,399
3-Methylphenylacetylene	C_9H_8	1	-	46,465	-	-	20,633	75,510
Indene	C_9H_8	2	-	-	-	-	64,555	-
2-Methylindene	$C_{10}H_{10}$	2	-	-	-	1,990	-	2,205
1,4-Dihydronaphthalene	$C_{10}H_{10}$	2	-	-	6,878	-	3,234	-
Naphthalene	$C_{10}H_8$	2	127,717	322,651	343,040	362,530	348,536	405,120
1,2,4-Benzenetricarboxylic acid, 1,2-dimethyl ester	$C_{11}H_{10}O_6$	1	-	-	-	-	6,790	5,624
Naphthalene, 2-methyl-	$C_{11}H_{10}$	2	-	6,590	37,235	19,876	34,924	29,647
1H-Indene, 1-ethylidene	$C_{11}H_{10}$	2	-	8,363	-	-	-	17,187
Biphenyl	$C_{12}H_{10}$	2	-	8,263	13,783	11,108	13,513	14,195

Composition	Formula	Benzene ring	RUN1 WP	RUN2 PE	RUN3 PP	RUN4 WP+PE	RUN5 WP+PP	RUN6 WP+PE+PP
Biphenylene	$C_{12}H_8$	2	-	23,404	-	35,351	33,382	39,201
Acenaphthylene	$C_{12}H_8$	3	17,514	4,039	42,274	10,967	11,165	11,864
1H-Phenalene	$C_{13}H_{10}$	3	-	-	-	2,625	4,368	3,691
Phenanthrene	$C_{14}H_{10}$	3	11,599	37,272	47,316	46,833	59,138	66,848
9H-Fluorene, 9-methylene-	$C_{14}H_{10}$	3	2,896	-	-	17,731	3,807	5,737
Benzonitrile, m-phenethyl-	$C_{15}H_{13}N$	2	-	-	92,991	69,380	45,891	-
Fluoranthene	$C_{16}H_{10}$	3	-	-	-	3,911	3,297	-
Pyrene	$C_{16}H_{10}$	4	-	3,833	8,721	14,919	10,202	14,193
Benzene, 1-1'-(1-ethenyl-1,3-propanediyl)bis	$C_{17}H_{18}$	2	-	2,543	2,340	4,417	20,766	10,090

(b) Chain hydrocarbons

Composition	Formula	Branched	RUN1 WP	RUN2 PE	RUN3 PP	RUN4 WP+PE	RUN5 WP+PP	RUN6 WP+PE+PP
1,3,5-Hexatriene	C_6H_8	✓	-	46,465	25,754	18,843	22,142	19,465
4-Methyl-2-pentyne	C_6H_{10}	✓	-	-	36,240	-	-	-
3,5-Hexadien-2-ol	$C_6H_{10}O$	✓	-	-	20,973	-	-	-
1,5-Hexadiene, 2-methyl-	C_7H_{12}	✓	-	-	24,886	-	-	-
1-Pentene, 2,4-dimethyl-	C_7H_{14}	✓	-	-	2,683	-	-	-
1-Hexane, 2-methyl-	C_7H_{16}	✓	-	-	2,215	-	-	-
1,4-Hexadiene, 2,5-dimethyl-	C_8H_{14}	✓	-	-	14,413	-	-	-
2-Hexene, 3,5-dimethyl-	C_8H_{16}	✓	-	-	13,382	-	-	-
2,4-Dimethyl-1-heptene	C_9H_{18}	✓	-	-	121,764	-	-	-
3-Heptene, 2,6-dimethyl-	C_9H_{18}	✓	-	-	4,623	-	-	-
1-Decene, 2,4-dimethyl-	$C_{12}H_{24}$	✓	-	-	3,158	-	-	-
Dimethylamine	C_2H_7N	-	-	-	-	-	5,750	-
2,4-Hexadiene	C_6H_{10}	-	-	-	38,597	-	-	-
1-Heptene	C_7H_{14}	-	-	28,383	-	2,279	-	-
Heptane	C_7H_{16}	-	-	3,403	-	5,054	-	-
6-Hepten-2-ol, 4-methylene-	$C_8H_{14}O$	-	-	919	-	-	-	-
1-Octene	C_8H_{16}	-	-	11,405	-	-	-	-
Octane	C_8H_{18}	-	-	2,680	-	-	-	-
1,7-Octadiene	C_8H_{14}	-	-	1,720	-	-	-	-
1-Undecene	$C_{11}H_{22}$	-	-	6,405	-	-	-	-

Appendix E. Total iron chromatographs (TICs) of tar from polyethylene (PE) containing feedstock via gas chromatograph-mass spectroscopy (GC-MS) analysis.



(a) Chain hydrocarbons

(b) PAHs

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List of publications

For Chapter 2 Estimation of waste biomass generation and utilization scenarios in Yangon Myanmar.

Myo Min Win; Junya Yano; Misuzu Asari; Shin-ichi Sakai.Scenario Analysis of Waste Biomass Utilization in Yangon, Myanmar. Proceedings of the 3rd 3R International Conference on Material Cycles and Waste Management (3RINCs), March 2016 Vietnam.

Myo Min Win; Junya Yano; Misuzu Asari; Shin-ichi Sakai.Scenario Analysis of Waste Biomass Utilization in Yangon, Myanmar. Proceedings of the 4th 3R International Conference on Material Cycles and Waste Management (3RINCs), March 2017 India.

For Chapter 3 Characteristics of gas from the fluidized bed gasification of refuse paper and plastic fuel (RPF) and wood biomass.

Myo Min Win; Misuzu Asari; Ryo Hayakawa; Hiroyuki Hosoda; Junya Yano; Shin-ichi Sakai. Characteristics of gas from the fluidized bed gasification of refuse paper and plastic fuel (RPF) and wood biomass. *Waste Management*. 2019, 87, 173–182. https://doi.org/10.1016/j.wasman.2019.02.002.

For Chapter 4 Gas and Tar Generation Behavior during Flash Pyrolysis of Wood Pellet and Plastics

Myo Min Win; Misuzu Asari; Ryo Hayakawa; Hiroyuki Hosoda; Junya Yano; Shin-ichi Sakai. Gas and Tar Generation Behavior during Flash Pyrolysis of Wood Pellet and Plastics. *Journal of Material Cycle and Waste Management*. 2019, November 25. https://doi.org/10.1007/s10163-019-00949-8.