Analysis of MSW to Energy Conversion Process for Sustainable Community

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Abstract

Municipal solid waste witnessed an exponential increase globally due to plastic, paper and organic material high production without considering appropriate recycling strategies. Pyrolysis and gasification is considered the most promising chemical recycling techniques, which can help prevent incineration and landfilling. Both processes have low environmental impacts, high product value, ability of electricity generation illustrated in this work. The paper discusses the major process units in industrial chemical recycling plants, life cycle assessment (LCA) in terms of GHG emissions, process stages and system design and justifies gasification and pyrolysis over other thermal treatment methods. Pyrolysis and gasification produce hydrocarbon gaseous and liquid products which can be utilized for energy production or chemicals synthesis while only incineration produce thermal energy. Both processes also produce the highest electrical production per ton in comparison with incineration with higher carbon dioxide emissions than incineration but lower dioxins, NO_x, HCl, CO emissions.

Keywords: *Sustainable engineering, clean energy, global warming, pyrolysis, gasification, incineration*

1. Introduction

Municipal solid waste (MSW) management is an emerging sustainable technology in the modern industrial world. The vast economic development and expansion caused an exponential increase in MSW generation were countries like China emits 172 million tons annually (J.Havukainen, 2017). Study also reveals that Canada and the US generates enormous amount of waste per capita of 778.36 kg/capita and 744 kg/capita respectively. Canada also witnessed exponential rise in MSW since 1990 (Partners, 2013). Interpolated MSW generation in the three largest industrial countries which are USA, China and India expects MSW generation of 256 million tonne/ annum, 510 million tonne/ annum and 137 million tonne per annum respectively (R.R.Pai, 2014). The GHG emissions from MSW processes are CO (i.e. incomplete combustion), CO_2 (i.e. complete combustion), CH_4 (i.e. from landfilling), SO_2 and NO_x (i.e. in almost chemical recycling methods with varying emissions per ton) emissions.

Landfilling is responsible for methane release in great quantitities due to bioprocessing of organic materials in landfills. Countries such as Sweden included landfilling tax and eliminated landfilling since 2005. Therefore, the alternative chemical recycling methods such as pyrolysis and gasification eliminate landfilling methane emissions . In figure 1, the global waste hierarchy in waste policies is illustrated (G.Finnveden, 2005). Landfilling is not applicable in small countries such as Qatar due to unavailability of land space and dense populations (M.Al-Maaded, 2012). Thus,alternative chemical recycling methods are needed.Recycling is considered a much better waste management technique due to less Global Warming Potential (GWP) and Human Toxicity Potentials (HTP) indicators (M.Al-Maaded, 2012).

As seen in figure 1, the first priority in municipal solid waste management (MSWM) is reducing waste production through usage of more durable materials were applicable. This can be achieved by providing waste control on industrial activities and limiting plastic, paper, compostes usage or by implementig internal recycling activities in industrial areas. The second waste management method is mechanical recycling of solid waste, paper, plastics and composites to be reused in manufacturing. Mechanical recycling includes collection, sorting, shearing, milling, crushing of waste to be utilized in new products (Luijsterburg, 2015). The third waste management strategy is chemical recycling. incineration, gasification and pyrolysis are the main chemical recycling methods.

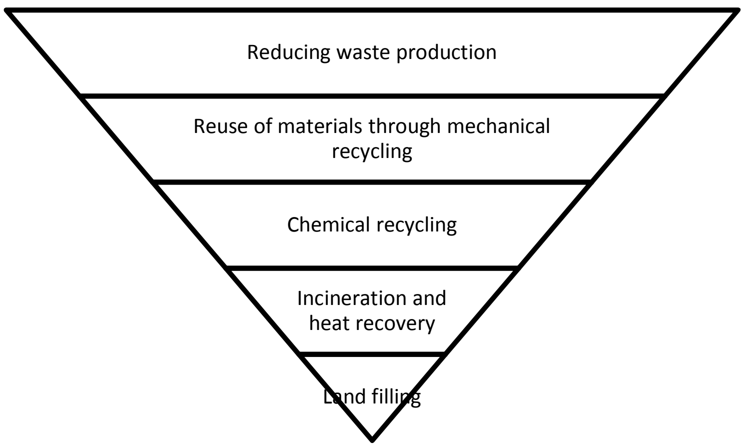

Fig. 1 - Global waste management hierarchy (G.Finnveden, 2005)

The development of sustainable and clean enviornmental technologies has many advantages including reduced GHG emissions, energy production, waste elimination, syngas generation, synthesized hydrocarbon fuels and avoidance of landfilling and incineration (V.Giorgio Dovı, 2009). Landfilling is still considered the most common waste management pratice and accounts for nearly 50% of MSW treatment in the US (M.Abbas Bozorgirad, 2013).

This paper illustrates the advantages of pyrolysis and gasification in terms of energy production and the ability of both processes to eliminate incineration and landfilling in provinces which reflects in less environmental impacts in terms of dioxins, NOx and CO emissions.

Incineration is a thermal treatment method that has less environmental impact than landfilling and its main advantages are waste reduction by up to 90% and thermal energy recovery from waste (E.Rendek, 2006). The main products of incineration are solid residues, bottom ash, fly ash and gaseous products including 12% CO_2 (E.Rendek, 2006). Incineration chemical plants are equipped with heat recovery equipment that utilizes the thermal energy steam generation (M.Abbas Bozorgirad, 2013). 1 ton of MSW releases 1.1 tonne of CO_2, 393 g of SO_2, 1790 CO, and 852 g of NO_x and can generate up to 0.98 MWh of electricity in optimum conditions (Sundqvist, 1999).

List of Abbreviations

GWP	Global warming potential
LHV	Lower heating value MJ/nm^3
HTP	Human toxicity potential
MSW	municipal solid waste
MSWM	municipal solid waste management
RDF	Refused derived fuel (i.e. treated MSW feedstock)
Nomenclature	
K	Kelvin

1.1. Pyrolysis and gasification industrial stages

Although, MSW generation is as large as 2.02 billion per tonnes annually, still more than 50% is landfilled. The shortage of fossil fuel and environmental problems have caused a huge interest of cleaner resources of energy (E.Kwon, 2010). Pyrolysis is defined as the thermal decomposition in absence of oxygen for elongated residence time to release hydrocarbon gases, liquids, waxes and tar. On the other hand, gasification is the volatilization of solid waste in limited oxygen supply to syngas which is a gaseous fuel mixture of hydrogen and carbon monoxide. Gasification is not a combustion process and the syngas produced can be directly used as a fuel, or synthesized to chemicals such as methanol. Pyrolysis and gasification have common industrial stages including the following (Earth, 2009):

- MSW feedstock preparation: A prepared MSW feedstock is known as RDF. RDF is a fuel ready for chemical recycling were metals, non-combustibles are removed from the initial feedstock.
- Waste thermal treatment: The waste is heated to elevated temperatures in a reaction chamber (i.e. pyrolysis 500-900℃, gasification 900-1500℃)
- Gas scrubbing: Removal of particulates, Sulphur compounds, NO_x to meet environmental standards.
- Electricity Generation: This is achieved by syngas and steam turbines. The hydrocarbon products are combusted to produce high pressure steam followed by a steam turbine than produces electricity. This stage has two efficiencies which are thermal and electrical efficiency in the steam boiler and turbine respectively.

1.2. Incineration and landfilling industrial stages

Incineration and landfilling is still main practices of waste management in many countries around the globe. Incineration is preferred in countries with limited landscape or difficult accessibility of free land areas such as Switzerland, Japan, France, Germany, Sweden and Denmark were still MSW incineration accounts for more than half of solid waste produced (O.Hjelmar, 1995). Landfilling has longer environmental impacts in comparison with incineration due to continuous methane release due to anaerobic digestion of organic materials. Below is the typical composition of products from incineration MSW (O.Hjelmar, 1995):

Table 1 – MSW incinerator final products mass composition (O.Hjelmar, 1995)

An example of a column heading	Percentage per ton of MSW (%)
Settled Ash	25 – 42
Flying ash	1 – 3
Dry acid gas	2 – 5
Semi dry acid gas	1.5 – 4

Incineration and landfilling has common industrial stages. However, for the treatment of MSW incineration is carried in an incinerator reactor, while for landfilling, a landscape is used and methane and carbon dioxide emissions are expected (B.Assamoi, 2012).

The industrial pretreatment stages for both incineration and landfilling are listed below (B.Assamoi, 2012):

1. Collection of raw municipal solid waste
2. Reusable and recyclable materials collection such as metals, plastics, paper wood, organic matter
3. Material separation and preparation of treated MSW feedstock.
4. For incineration:
    a. High temperature thermal treatment
    b. Ash removal and separation
    c. Energy recovery and electricity
    d. Ash disposal
5. For landfilling:
    a. Leachate treatment and gas extraction such as methane
    b. Energy recovery from hydrocarbon gas release
6. Emission control facility

1.3. Recommended feedstock for different chemical recycling MSW feedstock

The MSW feedstock collected from municipalities contains organic, non-organic and other solid waste. Inorganic and combustible materials are recommended for incineration, while organic and decomposable materials are recommended for pyrolysis and gasification. Other solid wastes such as tar, ash, slug is sent for landfilling due to inability of processing (A.U.Zaman, 2010).

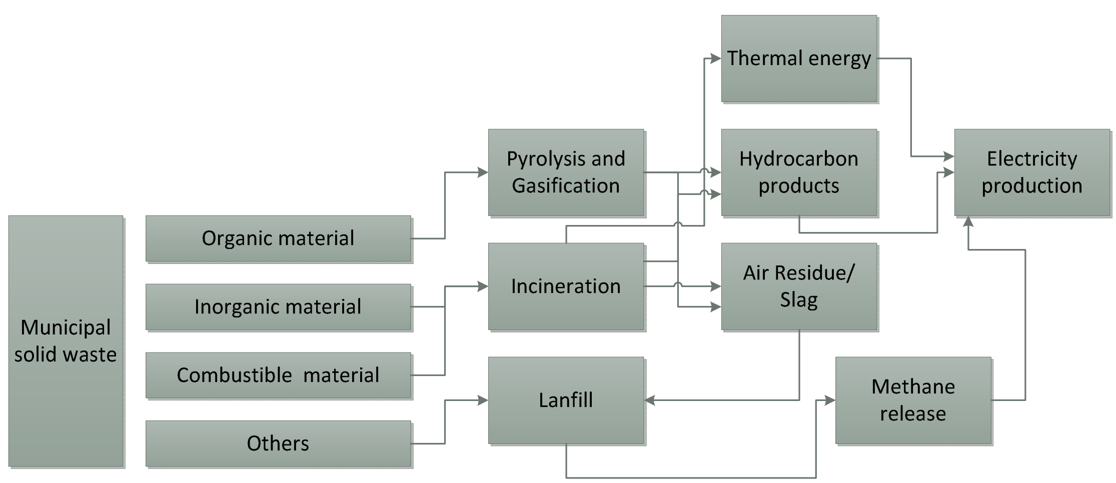

Fig.2 - MSW feestock separation and processing routes (A.U.Zaman, 2010)

As seen above, organic material is suitable for pyrolysis or gasification due to ability of fast conversion and thermal cracking. For gasification, syngas is released which is used for combustion to produce steam for electricity generation. For pyrolysis, the organic matter is thermally cracked in absence of oxygen to hydrocarbon products which can be utilized in different designs for electricity generation (i.e. gasoline or diesel production). Incineration feedstock is inorganic material excluding incombustibles that is incinerated at elevated temperature in a complete combustion process releasing thermal energy that is utilized in electricity production. Landfilling as a last option is used for slag, non-combustibles and other materials which can't be utilized in alternative processes releasing methane. In a typical landfilling site the following systems are installed (A.U.Zaman, 2010):

- MSW cover system
- Gas collection system
- Environmental monitoring system
- Gas to electricity generation system
- Ground water protection system

2. WTE Process systems

The MSW thermal treatment process systems has limiting factors such as reactor conversion, thermal efficiency, thermodynamics of process systems, boiler conditions, turbine efficiency for electricity generation (H, 2003).

2.1. Incineration process systems

Incineration is the combustion of heterogeneous materials in excess oxygen including inorganic materials, minerals, moisture and other MSW products. Below are the main process system steps in a large scale incineration plant (Commission, 2006):

1. **Drying and degassing stage:** This stage ensures no moisture content is allowed inside the gasifier to ensure optimum heat transfer sine water content lowers the heat efficiency.
2. **Incinerator stage:** A complete combustion process of the MSW is oxidized releasing flue gas generally in range of 1073.15 k - 1773.15 k. The objective of the incinerator furnace is volume reduction of solid waste, complete combustion and minimizing and removal of ash content after the process. A typical incinerator has more than one heat zone and a primary and secondary air supply to ensure complete combustion (A.Buekens, 2012).
3. **Flue gas scrubbing stage:** This stage removes slug, heavy metal contaminants,
4. **Boiler stage:** The combustible gases are burned to generate steam in a boiler. The objective of the boiler is to maximize energy recovery.

The flue gas consists of mainly of water vapor, nitrogen, carbon dioxide and oxygen in various quantities depending on mass composition of MSW. In order to ensure complete combustion, excess oxygen supply is ensured based on stoichiometric calculations. The quality of incinerator complete combustion is determined by mass percentage of carbon monoxide since complete combustion exists only negligible carbon monoxide (i.e. $<$ 5 CO ppm) (J. Aurell, 2009).

MSW in incinerator has a residence time of few seconds to a maximum of 60 minutes. The combustion process is influenced by the following:

- Incinerator grate design and the heat transfer surface area inside the incinerator furnace.
- High temperature zones were incineration occurs to ensure complete combustion.
- Homogenous flue gas and complete mixing for complete combustion (L.Branchini, 2015).

Incineration regulations ensure a minimum flue gas exposure temperature of 853 k with minimum residence time of 2s after secondary air zone. The flue gas from incineration is used to produce high pressure steam in a three stage boiler as seen in figure 3. The high temperature flue gas passes through the economizer that heats the inlet water stream to a temperature slightly below boiling point. The economizer outlet stream then passes through the evaporator till it reaches saturated steam temperature. The saturated steam is then heated to maximum superheated temperature (673.15 k – 773.15 k). Incinerator boilers can vary in design between horizontal, vertical or a combination of both (J.V.Caneghema, 2012).

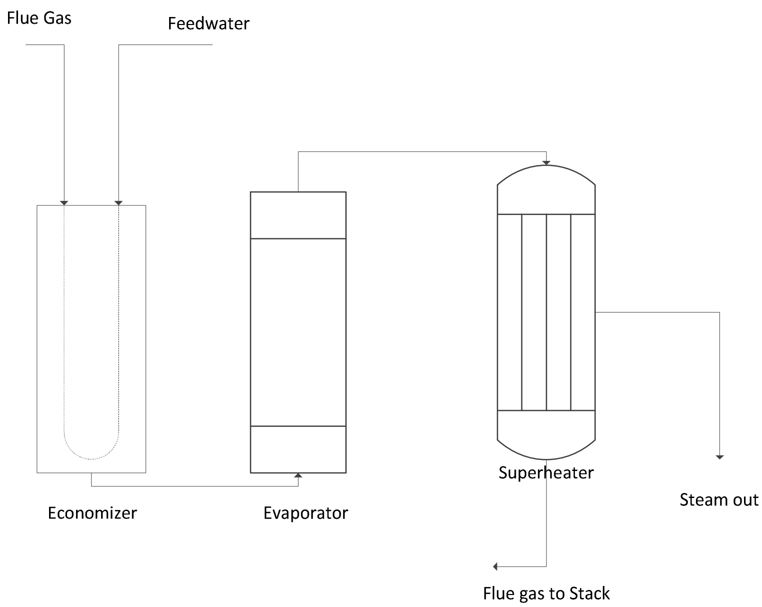

Fig. 3 - Steam production from incineration flue gas

2.2. Pyrolysis and gasification process systems

MSW pyrolysis and gasification systems has an advantage over incineration of less harmful emissions such as dioxins and NO_x emissions. The thermal efficiency for both processes is calculated using the following equation (J.Dong, 2016):

Gasifier energy efficiency (%) = $\frac{Esyngas+Etar}{LHVmsw}\ x\ 100\%$ (1)

Pyrolysis energy efficiency (%) = $\frac{E\ liquid\ fuel + Etar}{LHVmsw}\ x\ 100\%$ (2)

Pyrolysis requires a heating at a controllable rate to achieve maximum process conversion and an advised rate of 10℃/ min is recommended. These reactions occur at longer residence time in comparison with gasification and incineration. Below are the different classifications of pyrolysis.

Table 2 – Pyrolysis classifications and operating conditions (M.Ky.Bahng, 2009)

	Slow pyrolysis	Fast pyrolysis	Flash pyrolysis
Pyrolysis temperature (K)	573 - 973	873 - 1273	>1073
Heating rate (K/ min)	0.1- 1	10 -200	>1000
Residence time (min)	5-9	<1	<0.01

Pyrolysis chemical reactions occur in absence of oxygen. Thus oxidation is avoided and the thermal cracking process can follow the equation below (T.Noma, 2012):

$$C_nH_{2m} \longrightarrow aH_2 + bCO_2 + cCO + hydrocarbon + char + dH_2O \quad (3)$$

In case of optimal pyrolysis conditions, carbon monoxide show exist in negligible amounts. An industrial scale pyrolysis plant should have the following process units:

- MSW pretreatment: prevents non-combustibles from entering the pyrolysis reactor
- Pyrolysis reactor: processing of MSW at elevated temperatures in nitrogen gas medium (i.e. absence of oxygen is achieved by inert gases such as N_2 gas)
- Condenser unit: A heat recovery unit from reactor gaseous products
- Liquid fuel burner : This unit is used to combust collected fuel for steam generation purposes
- Steam turbine: This unit utilizes generated steam to produce electricity

Gasification is defined as conversion of heterogeneous solid waste mixture to syngas at elevated temperatures in range of 1000 k – 1500 k with very short residence time (i.e. 1-10 seconds) in a limited oxygen supply reaction process. The syngas includes main products which are CO and H_2 with minimal amounts of CO_2, CH_4 and H_2O (V.Belgiorno, 2002). Industrial gasifiers vary in design from fixed bed, fluidized bed, and entrained flow designs (J.E.Preciado, 2012).

A typical industrial gasification process includes the following processing units:

1. MSW preprocessing: This stage involves removal of rejected materials such as metals, glass, non-combustibles and other materials which cannot be reprocessed inside a gasifier.
2. Gasification Chamber: A high temperature chamber with limited oxygen supply based on stoichiometric calculations.
3. Slag removal stage: This stage is operated in batch process and slag need to be removed to ensure optimized heat transfer to MSW (C.Young, 2010).
4. Syngas cleanup: This includes removal of sulphur dioxides, NOx and other elements to meet environmental standards.
5. Steam and power generation: This cycle involves steam generation in a boiler which is converted to electricity through a steam turbine.

MSW syngas has a LHV between 6.7 - 9.8 MJ/Nm^3 with expected boiler efficiency n_{boiler} 81 %, steam turbine efficiency $n_{steam\ turbine}$ 23% and gas turbine efficiency of $n_{gas\ turbine}$ 40 % (Naami, 2015).

3. Energy analysis of WTE process systems

The energy analysis of WTE process system involves the feedstock conversion to useful products known as thermal efficiency, while the conversion of useful products to electricity is defined as electric efficiency. Below are the expected thermal and electrical efficiencies for WTE process systems (Astrup & T.Davide, 2015):

Table 3 – Thermal and electrical efficiency in MSW thermal treatment processes (Astrup & T.Davide, 2015)

Thermal process	**Thermal efficiency**	**Electrical efficiency**
	Average (%)	Average (%)
Incineration	44	19
Gasification	30	34
Pyrolysis	70.3	15.25
Gasification - pyrolysis	40	35

As seen above, the average thermal efficiencies are higher than electrical efficiencies in all MSW thermal treatment processes. Highest thermal efficiency is for pyrolysis, followed by a combined system of pyrolysis and gasification while incineration shows acceptable thermal efficiency. For electrical efficiency, incineration showed lowest while gasification systems showed highest electrical efficiency due to existence of both gas and steam turbines in the process system.

The energy production per ton of MSW for gasification is the highest electrical production from MSW followed by pyrolysis and incineration (C.Young, 2010). Below is the expected electrical production per ton of MSW from different thermal processes:

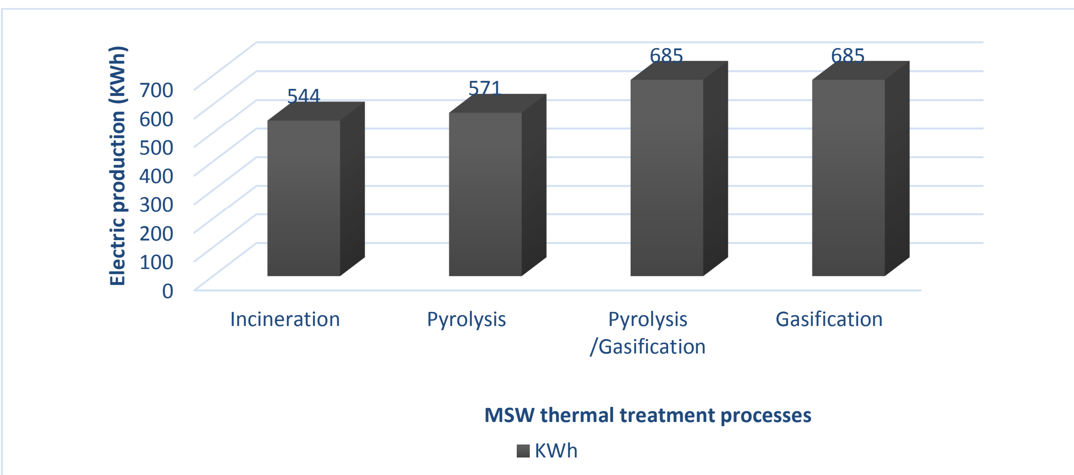

Fig.4- Thermal treatment processes energy generation per ton of MSW (C.Young, 2010)

4. LCA of WTE process systems

The life cycle assessment is used to evaluate the environmental performance of thermal waste to energy plants and limit its capacity as well as effluent gases composition emitted to the atmosphere. Amount of syngas produced from 1 ton of MSW vary between 0.8 – 1.1 nm^3/kg. Below are the expected gaseous emissions for MSW incineration, pyrolysis and gasification thermal systems:

Table 4 –Environmental emissions from incineration and co-pyrolysis-gasification process (A.Azapagic, 2007)

WTE process	Gaseous effluent	Mass percentage
Incineration	CO2 (Y.Tang, 2013)	7.31 wt%
	NO_x	0.134 wt%
	SO_2	0.0335 wt%
	HCl	0.00672 wt%
	CO	0.0336 wt%
	Dioxins and furans	0.0672 wt%
Pyrolysis & Gasification	CO2	58 wt%
	NO_x	0.0147 wt%
	SO_2	0.000062 wt%
	HCl	0.000407 wt%
	CO	0.0091 wt%
	Dioxins and furans	3.12×10^{-12} wt%

5. Conclusion

In conclusion, with the exponential increase of MSW, pyrolysis and gasification justifies over incineration and landfilling treatments. Pyrolysis and gasification produces hydrocarbon liquids and gases respectively which can be utilized for combustion and electricity generation, unlike incineration were only thermal energy is produced with high toxicity and GHG emissions. The electricity generation of both chosen thermal process are higher than incineration with higher CO_2 emissions and lower SO_2, dioxins, HCl and carbon monoxide emissions. Both gasification and incineration chemical plants requires syngas cleanup and treatments. However, incineration plants require additional pollution control to meet environmental emissions. The average thermal efficiencies of all processes are in range of 30 70% were pyrolysis has the highest thermal efficiency. Maximum electrical efficiency is achieved by gasification-pyrolysis process and minimum electrical efficiency of only 19% is achieved by incineration due to only thermal energy heat recovery source for electricity production.

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