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ORIGINAL PAPER

Life cycle assessment of pyrolysis–gasification as an emerging municipal solid waste treatment technology

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Abstract Waste-to-energy technologies are considered as one of the key waste treatment technologies due to their energy and heat recovery efficiencies from the waste. A number of research studies were accomplished to understand the potential environmental burdens from emerging waste treatment technologies such as pyrolysis–gasification (PG). The aim of this study was to examine the PG of municipal solid waste (MSW) treatment process through a life cycle assessment (LCA) method. The study also includes a comparative LCA model of PG and incineration to identify the potential environmental burdens from the existing (incineration) and emerging (PG) waste treatment technologies. This study focused on ten environmental impact categories under two different scenarios, namely: (a) LCA model of PG and (b) comparative LCA model of PG and incineration. The scenario (a) showed that PG had significant environmental burdens in the aquatic eco-toxicity and the global warming potential impact categories. The comparative scenario (b) of PG and incineration of MSW showed that PG had comparatively lower potential environmental burdens in acidification, eutrophication, and aquatic eco-toxicity. Both LCA models showed that the environmental burdens were mainly caused by the volume of the thermal gas (emissions) produced from these two technologies and the final residue to disposal. Therefore, the results indicate that the efficiency and environmental burdens of the emerging technologies are dependent on the emissions and the production of final residue to the landfill.

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Keywords Waste management · Waste treatment technology · Waste-to-energy technology · Environmental burdens · Comparative study

Introduction

Waste management systems (WMS) are significantly influenced by socio-economic, political, and environmental factors, including population growth, consumption pattern, and technological development of waste systems (Buttol et al. 2007). A number of studies (Contreras et al. 2006; El-Haggar 2007; Agamuthu et al. 2009; UN-HABITAT 2010) are analyzed to understand different development drivers in the WMS and such drivers are as gross domestic product (GDP), volume of waste, waste regulations, and increasing awareness on the global climate change.

The current WMS in most of the developed countries are based on the concept of integrated WMS. Waste-to-energy technologies are considered as one of the key technologies of the WMS due to resource recovery (energy and heat) facilities. Therefore, emerging waste-to-energy technologies such as pyrolysis, gasification, and plasma-arc are in focus for their higher degree of energy and heat recovery efficiency compared to the incineration of municipal solid waste (MSW).

The appropriate selection of the technology used for MSW treatment is dependent on many factors such as technological efficiency, economic benefit, and social and environmental acceptability. Therefore, decision-making process of the WMS is very complex and hard to determine the best strategy for long-term environmental sustainability. Different assessment tools and methods are developed to address the potential strength, weakness, socio-economic, and environmental benefit from certain waste treatment technologies. As a part of assessment methods, different models (Morrissey and Browne 2004) particularly computerized waste management decision support tools (DST) including multi-criteria optimization (MCO) or multiple criteria analysis (MCA) tools and cost-benefit analysis were started at the end of 1960s (Björklund 2000).

This study focused on the potential environmental impacts and benefits of pyrolysis–gasification (PG) as an emerging MSW treatment technology through a life cycle assessment (LCA) model. In addition, this study also compared PG technology with incineration of MSW in the context of the potential environmental burdens and energy recovery facilities from both waste treatment technologies.

Life cycle assessment also known as 'cradle-to-grave' analysis (Curran 1996) is one of the important tools for decision-making of the WMS (Finnveden and Moberg 2005). The society for environmental toxicology and chemistry (SETAC) defined the concept of LCA in the 1990 (Azapagic 1999). According to ISO 14040 guideline, LCA is "compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle" (ISO and IOFS 1997).

Different LCA methods are developed and applied in different countries such as DST (USA), Integrated Waste Management (IWM, UK), the IFEU project (Germany), ORganic WAste REsearch (ORWARE, Sweden), and Environmental Assessment of Solid Waste Systems and Technologies (EASEWASTE, Denmark) (Christensen et al. 2006). A number of studies are also conducted to examine the scope, limitations, and potentiality of LCA models as a DST and such studies are Barton and Patel (1996), Björklund (2000), Morselli et al. (2005), Bilitewski and Winkler (2007), Björklund and Finnveden (2007), Ekvall et al. (2007), Cherubini et al. (2008 a, b), Liamsanguan and Gheewala (2008), Manfredi and Christensen (2009), Rigamonti et al. (2010) and Fruergaard and Astrup (2011).

Materials and methods

Study area

Sweden, with a land area of about 450,295 sq km, is the third largest country in the European Union by area, with a total population of approximately 9.4 million (Statistics Sweden 2010). Sweden follows the EU waste strategies based on four levels of waste hierarchy such as reduction of waste production, material and energy recovery, and landfill (European Union 2006). In the early 1960s, landfill of waste started widely in Sweden (Miliute and Plepys 2009), and in the late 1970s, incineration of MSW was applied extensively in Sweden due to their energy and heat recovery facilities. About 48.4 % of the household waste was treated through incineration with energy recovery in Sweden in 2009, and a total of 13.9 TWh of energy was produced of which 12.3 TWh was used for heating and 1.6 TWh for electricity. That corresponds to electricity for 275,000 normal sized homes and heating for 820,000 homes (Avfall Sverige 2010). The aim of this study is to analyze PG of MSW through LCA model and to compare potential environmental burdens and energy recovery benefits with the existing waste treatment technology such as incineration.

LCA model for emerging waste treatment technology

The LCA model of PG of MSW was developed by SimaPro computer software. The Centre for Environmental Studies (CML 2) baseline (2000) method was applied to analyze environmental burdens from the waste treatment technology by ten different impact categories such as abiotic depletion, acidification, eutrophication, global warming potential (GWP 100), ozone layer depletion (ODP), human toxicity, fresh water aquatic eco-toxicity, marine aquatic eco-toxicity, terrestrial eco-toxicity, and photochemical oxidation. LCA model was developed by considering four core LCA principles such as goal and scope definition, inventory analysis, impact assessment, and improvement assessment. A brief description of the PG technology is given below.

Pyrolysis–gasification of MSW

Pyrolysis–gasification is an emerging technology for MSW treatment (Malkow 2004; McKay et al. 2004; Saft 2007), and the technology is not yet implemented widely in commercial basis. Coal-gasification was used since the early 1800s to produce town gas and the first four-stroke engine ran on produced gas in 1876 (Wheeler and De Rome 2002). In the 1850s, most of the city of London was illuminated by ''town gas'' produced from the gasification of coal (Cherubini et al. 2008a). Pyrolysis–gasification is a hybrid thermo-chemical conversion process (combination of pyrolysis and gasification process) (NSCA and NSFCAAEP 2002) where solid materials are converted to the gaseous products. The gaseous product contains CO_2, CO, H_2, CH_4, H_2O, and traces of hydrocarbons in high amounts of inert gases present in the gasification agent, various contaminants such as small char particles, ash, and tars (Bridgwater 1994). Pyrolysis generally takes place in high temperatures of around 400–1,000 °C. Thermal degradation of waste occurs in the absence of air to produce syngas, oil or char, and slug; however, in reality it is quite impossible to degrade waste in zero air environments. Gasification takes place at higher temperatures than

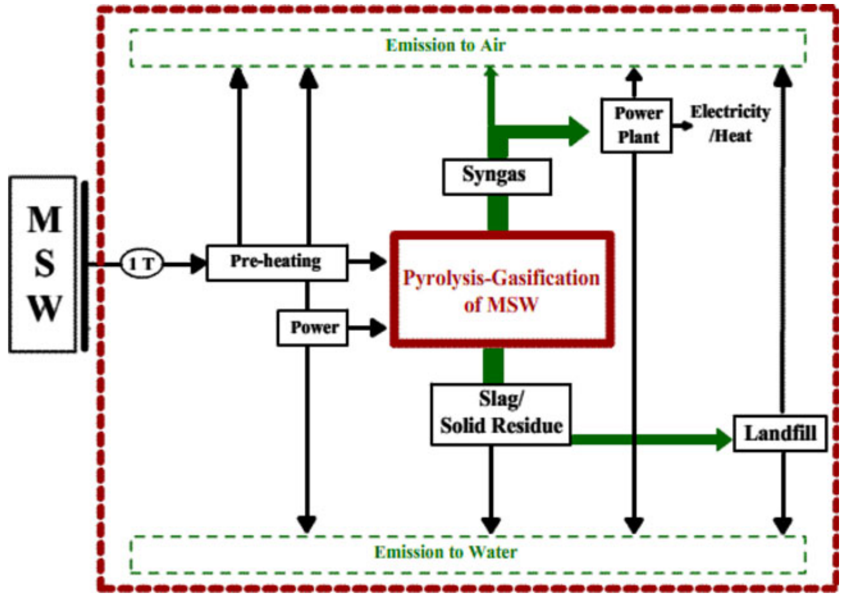


Fig. 1 Scenario (a) system boundary for pyrolysis–gasification of MSW

pyrolysis at around 1,000–1,400 °C in controlled amount of oxygen. The majority of the carbon content in the waste is converted into gaseous form (syngas). For most waste feedstock, the gas produced contains highly toxic and corrosive reduced species and the gas may, therefore, require cleaning before combustion (NSCA and NSFCAAEP 2002).

Goal and scope

The goal of this study was to develop LCA models for PG of waste management process. A comparative LCA model of the emerging waste treatment technology such as PG and the existing waste treatment technology such as incineration was also developed in this study. Two different scenarios such as scenario: (a) LCA of PG of MSW and scenario, (b) comparative LCA model of PG and incineration of MSW were modeled through SimaPro software. One ton of MSW was used as a functional unit for both the scenarios.

System boundaries

Scenario (a) shows the system boundary of the LCA model for PG of the MSW treatment technology. The process start-up energy and 1 ton of MSW are considered as the input materials for the model and slag or solid residue, emission to the air and electricity generation are considered as the output of the model. Figure 1 shows the system boundary for the PG process.

Scenario (b) is the comparative LCA study of PG and incineration process of MSW. A simplified comparative LCA model is shown in Fig. 2. In scenario (b), the both processes handle 1 ton of MSW and as the input of the model, process start-up energy for both technologies and 1 ton waste is considered. Transportation of waste was not considered in the model. The produced energy, heat, emissions to the air, and the final residue from the systems are considered as the output of the systems. For both scenarios, the heat is assumed to be used in the production of electricity. Therefore, as an output of the process only equivalent electricity production was accounted and calculated. Average Swedish national electricity is offset though the system as avoided product by the both waste-to-energy treatment technologies.

Assumptions and limitations

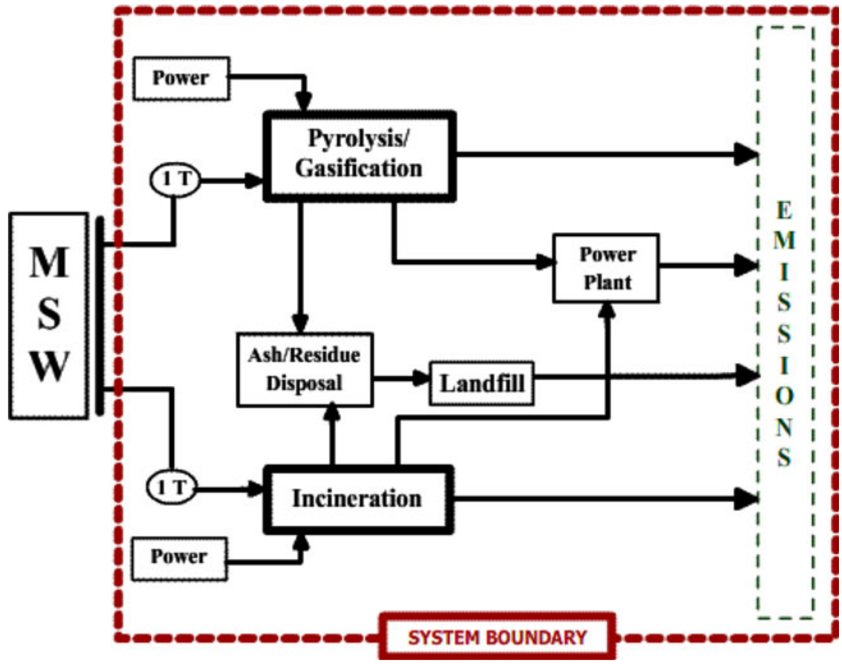
The following assumptions have been made during the LCA model development:

- The so-called “zero burden” assumption means that when the holder discards, life cycle of waste has begun.
- For both scenarios, transportation of waste was ignored by assuming that both the plants were in same distance and transportation has minimum contribution of environmental burden in whole waste life cycle.
- Average energy data (Swedish context) were considered for the model assuming the similar impact on the model for both the processes.
- Inventory data was based on UK’s waste treatment facilities, therefore, waste composition of Sweden was assumed to be similar with the waste composition of UK, which is not 100 % true but due to data unavailability, this assumption was made.

Life cycle inventory and data analysis

Life cycle inventory of the LCA model was conducted based on the available literature, technical reports, and

Fig. 2 Scenario (b) system boundary for PG and incineration of MSW



journal publications including DEFRA (2004), Bridgwater (1994), NSCA andNSFCAAEP (2002), Feo et al. (2003), Halton (2007), Finnveden et al. (2000), Cherubini et al. (2008a, b), Khoo (2009) and Circeo (2009). The LCA model was developed based on the inflow–outflow material data that are available from the reference sources. It was important to understand and interpret the data quality and reliability while developing a comparative model. The related data for PG process was not available in the context of Swedish waste. Moreover, there were no large scale commercial PG plants in Sweden where data can be acquired. Therefore, the data was collected from UK's waste report by assuming that waste composition of emissions would be similar context in Sweden.

Input–output data of the PG model were waste for treatment (1 ton MSW), start-up energy to run the systems (electricity kWh/ton of MSW), emissions from the treatment facility (g/T) to the air, soil or water, energy generated from the systems (kWh/ton of MSW), and residue (kg/ton) produced by the facilities. Most of the data used for the LCA model were based on the waste composition in UK. Both technologies require start-up energy, and both generate energy from the waste treatment facilities and final residues were generated from the processes. Table 1 shows the Inflow–outflow energy and solid waste from the processes.

The start-up energy which was required for the system was taken from the average country electricity grid, and Sweden's average energy mix was considered and the data were used from the SimaPro software database. Both processes produce electricity from the systems, therefore, avoided electricity production was also considered for the systems as average country (Sweden) mix from the database. For both technologies, process data were used for the LCA model, so the model is process-based LCA. No transportation emission was considered for both the models. All the emissions data that are taken into account for the LCA model was the average emissions rate. This means that it is not any plant specific emissions data rather than average treatment plant's emissions data. Therefore, average emissions data from PG and incineration of MSW were used for the LCA model. Table 2 shows the emissions data for two waste treatment facilities.

The carbon emissions for both thermal facilities were assumed to be the same. Since the carbon dioxide is the content of biogenic and fossil carbon, therefore, to identify environmental burdens, only fossil carbon dioxide is considered for the model. From the eco-invent database, MSW contributes 39.5 % of fossil carbon, therefore, 39.5 % of total carbon emission i.e., 395,000 g/ton is considered for both processes in the LCA model.

Table 1 Input–output (energy and residue) in different MSW treatment processes

Input/output	Pyrolysis–gasification	Incineration
Start-up energy (kWh/T)	339.3[c]	77.8[a]
Energy generated (kWh/T)	685[d]	544[d]
Solid residue (kg/T)	120[b]	180[b]

[a] Finnveden et al. (2000), [b] DEFRA (2004), [c] Khoo (2009), [d] Circeo (2009)

Table 2 Emissions to the air from waste management facilities (grams per ton of MSW)

Substances	Emissions of MWS treatment processes (g/T)	
	Pyrolysis–gasification	Incineration
Nitrogen oxides	780	1,600
Particulates	12	38
Sulphur dioxide	52	42
Hydrogen chloride	32	58
Hydrogen fluoride	0.34	1
VOCs	11	8
Cadmium	0.0069	0.005
Nickel	0.040	0.05
Arsenic	0.060	0.005
Mercury	0.069	0.05
Dioxins and furans	4.8×10^{-8}	4.0×10^{-7}
Polychlorinated biphenyls	No data	0.0001
Carbon dioxide	10,00,000	10,00,000
Carbon monoxide	100	No data

DEFRA (2004)

Results and discussions

Impact assessment for scenario (a): pyrolysis–gasification of MSW

Impact assessment of the PG model was presented in characterization and normalization methods. The characterization results represent the contribution of the potential environmental burdens through ten different impact categories. Inventory of the characterization gave the idea not only on the specific polluting substances that is responsible, but also the process phases for the environmental burdens. Results are present in ten different impact categories in the both characterization and normalization of LCA model. Characterization values are presented in the Table 3. Negative value of the model represents the savings of environmental burdens, therefore, negative value of the impact categories were in fact positive for the environment. The positive values show the environmental burdens imposed by the technology, therefore, positive value of certain impact categories represents environmental degradation on certain impact categories.

From Table 3, characterization data showed that the energy recovery facility and final disposal were the significant parts of the PG processes. Environmental burdens were less from the process emission compared to the disposal of final residue. For PG process, volume of final residue was important for environmental burdens and was responsible for almost every impact categories. Since, the assumption was made based on the fact that the final residue will be disposed to the landfill, higher volume of inert residue will impose higher burden on the environment. However, different research shows the possibilities of secondary use of inert residue as construction material. If the final residue can be used as construction materials, then the environmental burden will reduce tremendously on the PG processes.

Electricity generation was one of the most environmental beneficial factors for PG process. Model showed the environmental saving for the energy generation in different impact categories, especially, in the global warming, acidification, and photochemical oxidation. From Table 3, output energy from the PG was considered as the avoided product and average country mix was considered for this model. If the avoided value is taken as the marginal of country electricity production, then the model would show more environmental favorable output for the process. Because marginal value was taken from the most possible substitution energy option, i.e., if Sweden has coal power plant for electricity production, then assumption made for marginal value was that electricity produced from the PG will replace the coal power plant.

Table 3 Characterization value of pyrolysis–gasification process

Impact category	Unit	Total	Pyrolysis–gasification process	Energy used (input)	Energy generated (output)	Disposal to landfill
Abiotic depletion	kg Sb eq	−0.04597	0	0.151243	−0.30534	0.108122
Acidification	kg SO_2 eq	0.24779	0.4524	0.266826	−0.53868	0.067249
Eutrophication	kg PO_4 eq	1.129403	0.1014	0.007164	−0.01446	1.035303
Global warming (GWP100)	kg CO_2 eq	1,017.135	1,000.153	22.63846	−45.7039	40.04723
Ozone layer depletion (ODP)	kg CFC-11 eq	−1.4E−05	0	1.6E−05	−3.2E−05	1.95E−06
Human toxicity	kg 1,4-DB eq	805.5721	24.69638	6.879374	−13.8885	787.8848
Fresh water aquatic eco-toxicity	kg 1,4-DB eq	215.3661	0.053575	0.492722	−0.99474	215.8145
Marine aquatic eco-toxicity	kg 1,4-DB eq	1,87215.3	431.519	1,404.988	−2,836.48	188,215.3
Terrestrial eco-toxicity	kg 1,4-DB eq	2.507963	2.054501	0.055803	−0.11266	0.510317
Photochemical oxidation	kg C_2H_4	−0.00244	0.005196	0.010058	−0.02031	0.002607

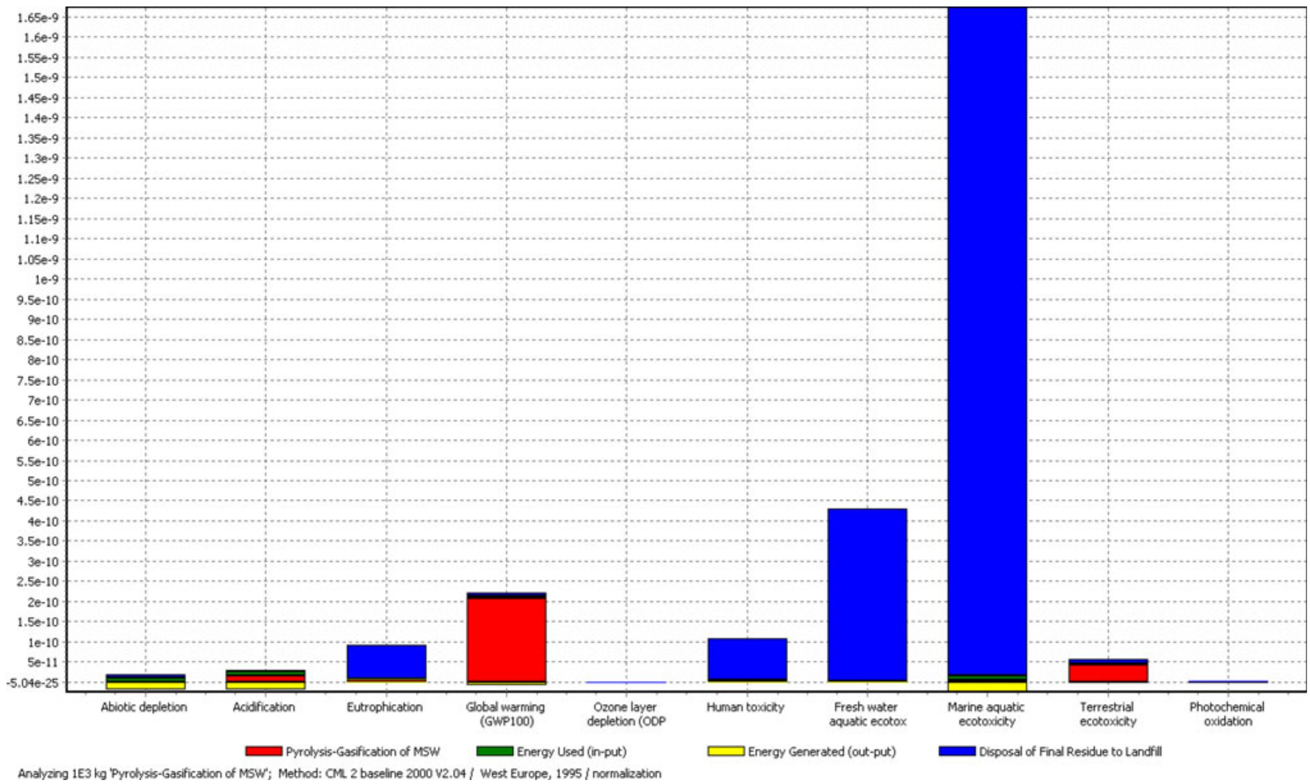


Fig. 3 Normalization graph of the LCA model of the pyrolysis–gasification

The PG model showed that PG of MSW contributes in the acidification, eutrophication, human toxicity, marine eco-toxicity, and terrestrial eco-toxicity impact categories. Emission from the process was responsible for the environmental burdens since the PG process occurs in limited amount of air. The volume of syngas being less, was one of the key benefits of PG process. If more air was used in the process, higher volume of syngas was produced and more environmental burden would be imposed.

Figure 3 shows the normalization graph of the model representing the level of significance for different impact categories. From Fig. 4, PG had the significant contribution in marine aquatic eco-toxicity (MAE), and MAE was the highest burden categories among ten different impact categories. The second most significant burden from the PG process was the fresh water eco-toxicity. The human toxicity, eutrophication, terrestrial eco-toxicity, and acidification were also major burden categories for PG of MSW. From the inventory data of the model, it was evidenced that the environmental burdens of the PG of MSW were primarily caused by the disposal of final residue. Therefore, volume and treatment of the final residue are one of the key concerns to promote PG as an effective waste treatment technology for WMS in Sweden. Major significant environmental impact categories are discussed below.

Aquatic depletion

PG had significant impacts on marine and fresh aquatic categories. Disposal of final residue was the primary cause for aquatic quality depletion. Vanadium copper (ion) and selenium was the main disposal degrading aquatic environment and nickel, zinc, and antimony were the primary pollutants for the aquatic depletion. Therefore, metallic substances in the waste composition were the primary concerns for the aquatic depletion from the process.

Global warming potential

Pyrolysis–gasification had potential global warming impacts. Global warming can be caused by the disposal of the residue as it contains harmful gaseous by-products and particles which can increase the greenhouse gases. Carbon dioxide and carbon monoxide were the primary reason for GWP, and these emissions mainly occur during decomposition of final residue.

Acidification

The disposal of final residue in the environment causes acidification. However, the acidification can be avoided by

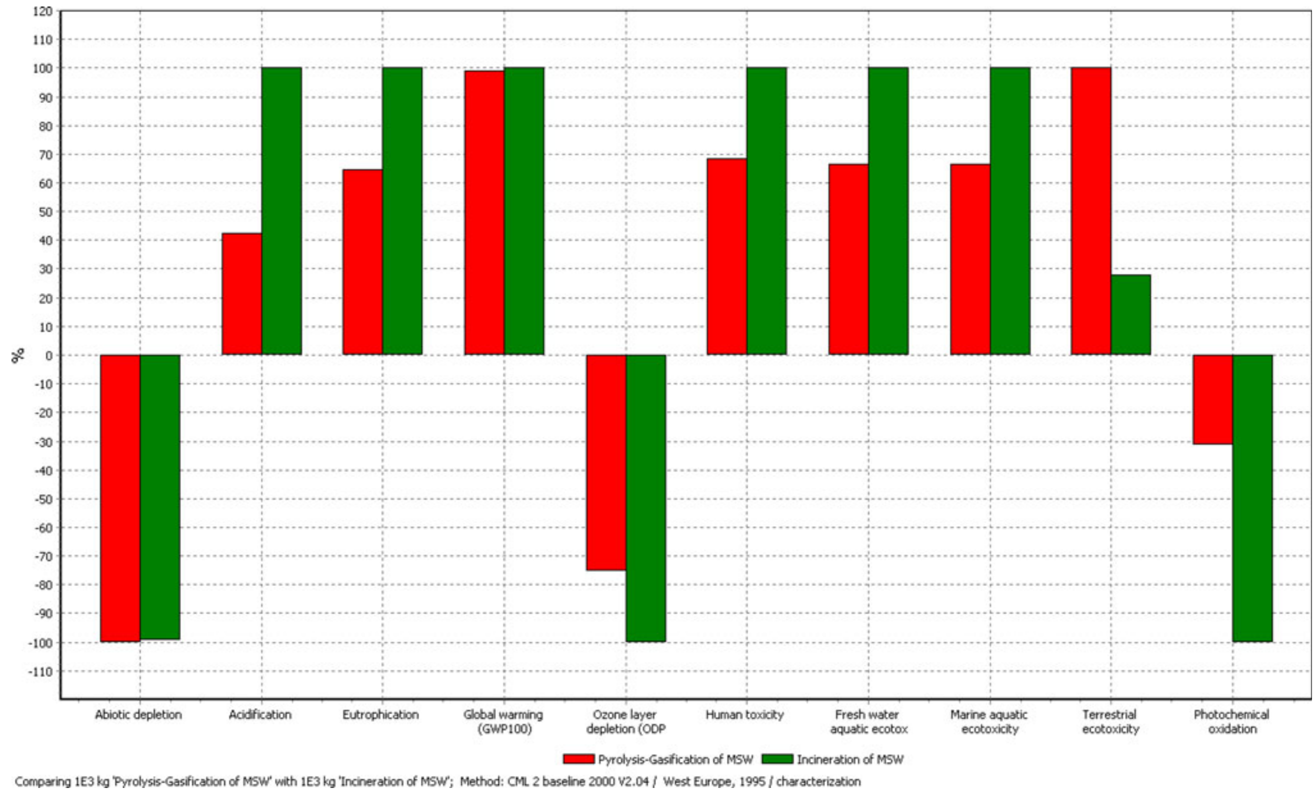


Fig. 4 The characterization graph for the comparative LCA model for pyrolysis–gasification and incineration

the PG process due to energy generation. Nitrogen oxide and sulphur dioxide are the primary reason for the acidification impact, and these gases are emitted in the atmosphere during the process stages.

Pyrolysis–gasification primarily contributes to the water and air emissions. Emission control of the PG process mainly involves the volume of the final residue and alternative use of final residue rather than landfill. For sustainable WMS, these problems should be corrected in the near future. Since PG is an emerging technology, there is scope for further improvement in these areas to promote the technology as a proven technology.

Impact assessment for scenario (b): comparative LCA model for PG and incineration

In scenario (b), comparative study between PG and incineration was done. In this case, transportation impacts were not considered for any of the processes. From the impact assessment result, both treatment facilities have positive environmental impacts on abiotic and ODP due to the electricity generated by the processes. Incineration had the higher value in ODP than the PG process.

Figure 4 shows the characterization graph of the comparative LCA model. Characterization value does not show the significance of the impact rather it highlights the contribution of emission by the processes. Thus, higher contribution value does not mean most adverse environmental impact.

From the characterization graph, it can be said that the incineration of MSW had higher environmental burdens than the PG and particularly, in the acidification, eutrophication, global warming, human toxicity, and aquatic toxicity categories. However, PG has higher potential environmental impacts in terrestrial eco-toxicity and photochemical oxidation categories. Incineration contributed the highest GWP among the two facilities and PG had the least GWP.

Normalization graph (Fig. 5) shows the significance of impact and comparative impact level in different impact categories. Normalization graph shows that aquatic life can get significantly vulnerable by both processes. The significant impact categories are further discussed below based on the inventory data of the comparative model.

Aquatic depletion

Incineration had significantly higher contribution in aquatic depletion both marine and fresh water rather than PG of MSW. Emission from the leachate of the final residue disposal to landfill was the main reason for aquatic depletion both for fresh and marine system. Heavy metal

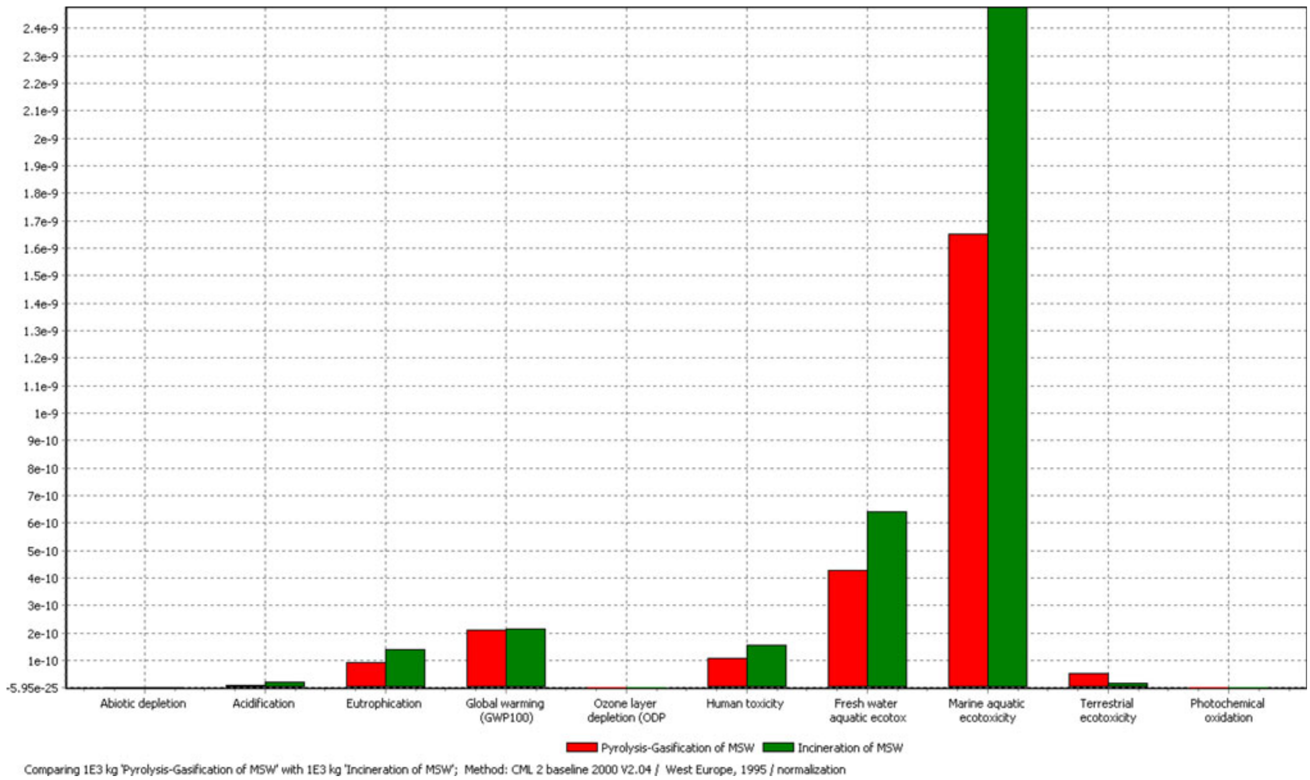


Fig. 5 The normalization graph for the comparative LCA model of the pyrolysis–gasification and incineration

pollution such as vanadium, nickel, zinc, and copper and the emission of selenium, antimony, and molybdenum to air were the main polluters for the aquatic depletion.

Human toxicity

Pyrolysis–gasification has lower contribution in human toxicity impact compared to incineration. Impact mainly contributes from the disposal of final residue. Arsenic, cadmium, mercury, nickel, nitrogen oxide, and hydrogen fluoride are the primary pollutants for the human toxicity which are emitted to atmosphere and water by the PG process. Antimony and selenium mainly caused human toxicity by the incineration process through groundwater pollution.

Global warming potential

Incineration had significantly higher contribution in the GWP, however, carbon emission was assumed same for both technologies. The treatment principles of the two technologies were the main reasons for this difference. Incineration was done under uncontrolled airflow that produces higher CO_2 emission to the atmosphere, whereas PG was done in controlled volume of air, and therefore, CO_2 emission was significantly lower in the PG process.

Terrestrial eco-toxicity

The only impact category where PG had higher contribution than incineration process. Heavy metals such as mercury, cadmium emission to the atmosphere were the main reason for terrestrial eco-toxicity. It is important for both global as well as trans-boundary issues while taking decision for waste facilities in certain technology.

Sensitivity analysis

Avfall Sverige (2010) report shows that significant improvement in the emissions of incineration process was achieved from 2003 to 2007. The emissions (per ton) of HCl, SO_x, NO_x, and dioxin were reduced to 66, 73, 15 and 87 %, respectively from 2003 to 2007. For the sensitivity analysis, assumption was made that 30 % of emissions can be improved for PG process for next 5 years. Electricity generation and its use can be more efficient during that duration and efficiency can be gained by 5 %. A comparative analysis was done by taking consideration of efficiency of PG for the next 5 years' time. Figure 6 shows the characterization results of the sensitivity analysis.

From the sensitivity graph, most of the impact categories had shown the expected results except abiotic and acidification. Since assumption has been made of 30 %

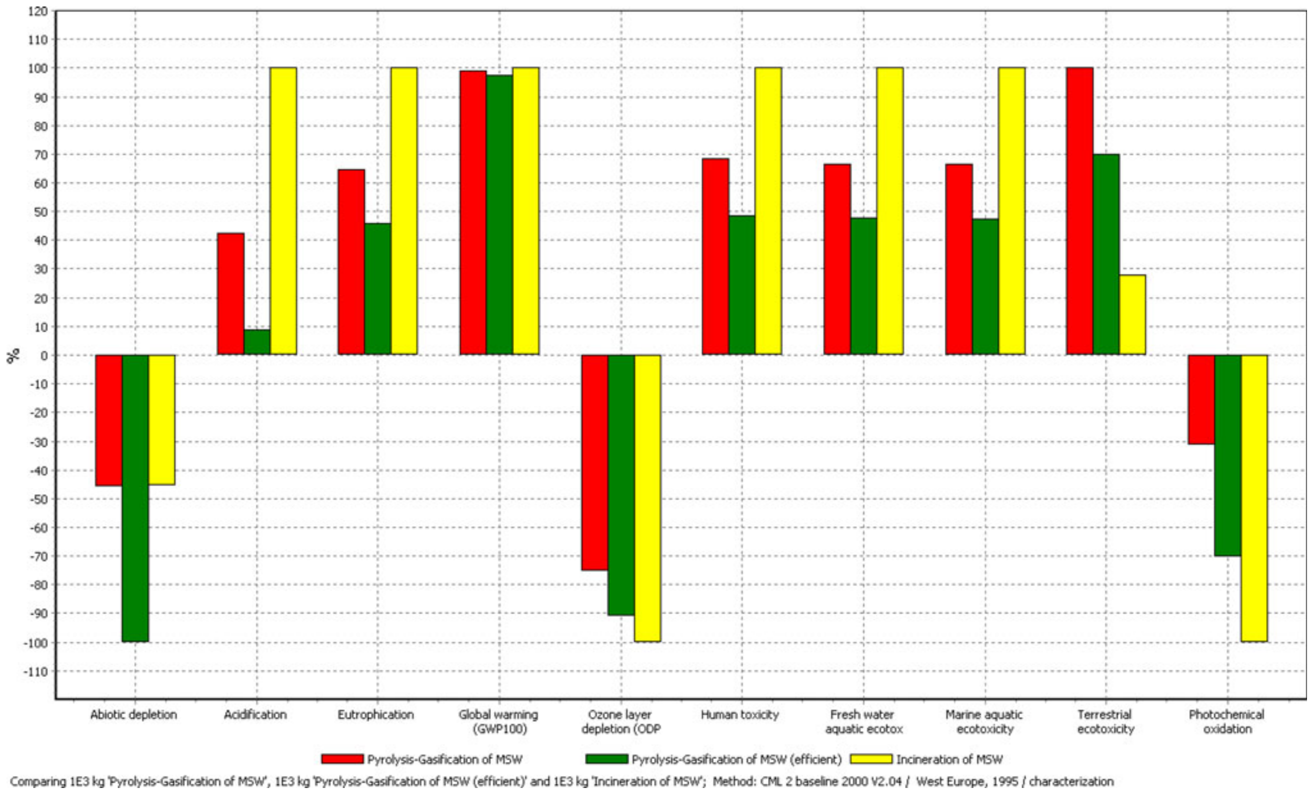


Fig. 6 Characterization of efficient PG with the previous study

efficiency in emissions reduction and 5 % improvement of the energy productions, and for both improvement, SO_x and NO_x emissions will be improved which are the primary pollutants for acidification. Therefore, the total acidification has higher positive value than other impact categories. Abiotic depletion was also offset significantly due to the improvement of the technology for the next 5 years. The sensitivity study was based on assumptions of efficiency in emissions reduction and improvement of the energy productions, therefore the sensitivity study do not represent accurate prediction if the assumptions are not fulfilled.

Uncertainty and limitations of the results

Different WMS analysis tools have different contexts of analytical capabilities and therefore, output results may vary. Even the LCA model which is used in many countries has varied baseline assessment methods such as per person impact equivalent or per year impact equivalent and so on. Moreover, un-harmonized analysis tools in different socio-economic and environmental context lead to a complex decision-making process for the decision makers. The study was done by considering only the air emissions and the final disposal from the PG and incineration processes, but other emissions such as water and soil has not been considered which might have significant environmental impacts too. Lack of information and data make the model more difficult to assess.

Conclusion and further studies

According to LCA model, PG reflects the lower environmental burdens compared to the incineration of MSW. Particularly, the emissions and the final disposal of the residue were the most problematic areas for PG technology. One of the main reasons for lower environmental burdens from PG process was the controlled uses of air during the combustion. The other reason was PG produces higher amount of heat and electricity than incineration. This study did not necessarily try to identify the best technology among the two processes. However, LCA models helped to understand the different technologies through comparative models. PG is an important emerging technology for Sweden. Air Particulate Cleaning residues (APC) that trapped in the syngas cleaning process the solid residue from the combustion and the emission still needed to be improved for sustainable waste management.

Further studies can be done to analyze the life cycle costing of the PG of MSW. For the decision-making of the waste management policies, it is also important to consider socio-economic benefit from the certain waste-to-energy technologies. For long-term sustainability, context resource recovery through thermal waste treatment may need a holistic social, economic, and environmental study.

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