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Life Cycle Environmental Assessment of Municipal Solid Waste to Energy Technologies

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Abstract: The study aimed to analyze potential environmental burdens of different waste-to-energy technologies through LCA model. LCA model is developed by SimaPro software by considering Eco-indicator 99 method. Landfill, Incineration, Pyrolysis-Gasification and Anaerobic Digestion are analyzed by considering emission to the atmosphere per unit electricity generation. Results show that, Landfill and Incineration have the highest climate change impact among the four WTE options. Incineration and P-G has the significant impact on respiratory inorganics and acidification categories. AD has the lowest impacts on respiratory inorganics and acidification. AD and P-G have found as least environmental impact causing technology for waste-to-energy options. therefore, P-G and AD are more favorable waste-to-energy options for municipal solid waste management.

Key words: Municipal Solid Waste (MSW) · Waste-to-Energy (WTE) · Life Cycle Assessment (LCA) · Pyrolysis-Gasification (P-G) · Incineration · Landfill · Anaerobic Digestion (AD)

Acronym Abbreviation:
AD : Anaerobic Digestion, LCA : Life Cycle Assessment, LCIA : Life Cycle Inventory Analysis
MSW : Municipal Solid Waste, P-G : Pyrolysis-Gasification, WTE : Waste-to-Energy

INTRODUCTION

Different waste treatment options are available in the current time with different level of problem solving and resource recovery facilities. All of the waste management options have some benefits, as well as some problems while applying in practical cases. There is no such a single technology that can solve the waste management problem fully. Therefore, it is important to integrate different waste management technology in a strategic way to achieve the sustainable waste management objectives.

However, it is difficult to select a particular technology for sustainable waste management decision or policy making processes without knowing the different technologies and their impacts on the environment. Due to lack of information on impacts from certain technology, sometimes wrong decision has been made and which might arise adverse and critical situation in future. Therefore, it's important to know different technology through comparative study for different options and that might be a guiding tool for decision making processes. Different system analysis tool [1] can be the key tool to analyze different technology and their socio-economic and environmental performance. LCA is one of the important tools that have been considered in the research work for analyzing four different WTE technologies like Landfill, Incineration, Pyrolysis-Gasification and Anaerobic Digestion.

The paper aimed to analyze environmental performance of the waste-to-energy technology based on the energy recovery facilities through LCA model. Therefore, LCA model is developed based on the emissions and the resource recovery from the different waste treatment technologies.

WTE Technologies: Municipal Solid Waste (MSW) to energy conversion has now been considering one of the optimal methods to solve the waste management problem in a sustainable way. Different advanced mechanical biological and thermo-chemical waste-to-energy technologies have now been applying for managing MSW. The primary goal of these technologies is to manage MSW and also recover energy from it. In our research work, we have considered four different

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WTE technologies like (i) Landfill, (ii) Incineration (iii) Pyrolysis-Gasification and (iv) Anaerobic Digestion based on their energy generation perspectives. Brief descriptions of these technologies are given bellow.

Landfill: 'Landfill' is the term to describe the physical facilities used for the disposal of solid wastes and solid waste residuals in the surface soils of the earth [2]. Landfill is very old but still one of the extensively used technologies for MSW management and advance sanitary landfill has the option to collect landfill gas and to use as biofuel or electricity production. Landfill gas is generated from the landfill site. Biogas generation in a landfill has generally five different phases like Initial Adjustment, Transition Phase, Acid Phase, Methane Fermentation and Maturation Phase [3-6].

Incineration: Raw waste can be used as a feed stock in the advanced thermal Incineration process. Incineration processes has taken place in the presence of air and at the temperature of 850°C and waste are converted to carbon dioxide, water and non-combustible materials with solid residue (Bottom ash) [7]. Incineration is very popular technology in Europe due to heat and electricity generation option from the waste management facilities. Primarily, two process stages [8] are involved in Incineration processes like, (a) combustion of the waste where flue gas is produces and (b) cleaning of the flue gas and emitted to the atmosphere.

Anaerobic Digestion (AD): Anaerobic Digestion is one of the favorable organic waste management options which have higher resource recovery potentials. Biological process of the AD is taking place in the absence of oxygen with the help of microbes. Biogas and compost are produces from the anaerobic process. Biogas; consists of methane (ranging 55% to 70%) and carbon dioxide (CO_2) is produced from the process after 2-3 weeks. compost can be used as organic fertilizer based on nutrient content.

Pyrolysis-Gasification (PG): Pyrolysis-Gasification is a advanced hybrid thermal waste treatment processes and is an emerging technology since the processes has been used for MSW management system from the very recent time. Thermal degradation (between 400-1000°C) of the Pyrolysis process is taking place in the absence of air and it produces syngas, oil and char. Gasification takes place at higher temperatures than pyrolysis (1,000-1,400°C) in a controlled amount of oxygen [9]. The gaseous product contains CO_2, CO, H_2, CH_4, H_2O, trace amounts of higher hydrocarbons [10]. Pyrolysis is favorable to reduce heavy metal emission [11] and also sulphur di-oxide and particulates however, oxides of nitrogen, VOCs and dioxins emissions might be similar with the other thermal waste treatment technology [12]. Thermal waste to energy conversion has the higher energy conversion potentials that the other technology [13].

MATERIALS AND METHODS

Life Cycle Assessment (LCA): Life cycle assessment (LCA) is one of the effective and principal decision support tools [14] to assess environmental burdens per functional unit of waste generated [15]. LCA is uses for assessing environmental performances of certain product or service and LCA is very common for evaluating waste management system analysis. Many research has already been done for waste management system and some of the work is done by Psomopoulos *et al.* [16]; Consonni *et al.* [17]; Pavlas and Tous [18]; Manfredi and Christensen [19]; Gheewala and Liamsanguan [20]; Bilitewski and Winkler [21]; Ekvall and Finnveden [22]; Björklund [23]; Diaz and Warith [24]; Matuto [25]; Björklund and Finnveden [26]; Cherubini *et al.* [27]; Pennington and Koneczny [28]; Barton and Patel [29]; DEFRA [12]; Feo *et al.* [30]; Bridgwater [10]; NSCA [9]; Halton EFW Business Case [31]; Cherubini *et al.* [27]; Finnveden *et al.* [32]; Circeo [33] and Khoo[34] for assessing MSW management methods, technology, strategy, policy and costing.

Most of the study that cited in the paper, have been analyzed the environmental performance of the WTE option individually and not considering only based on the energy generation efficiency and environmental performance. However, this study is done only based on the electricity generation rate from the different WTE system and environmental performance while managing municipal solid waste. Even though, the study has limitation while considering only emissions data for comparative resource recovery option but the study is important from the analytical point of view to identify the environmentally favorable waste treatment option while considering resource recovery option in waste management system.

Goal and Scope: The goal of the study is to analyze different waste-to-energy facilities based on energy generation and environmental impact potentials. The study is carried out by considering the energy recovery

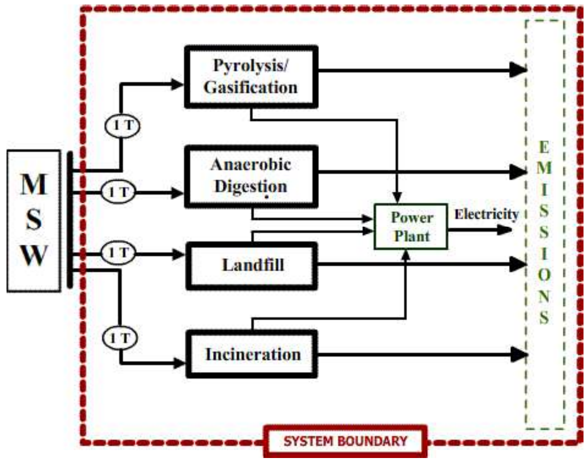

Fig. 1: System boundary of the LCA model

Table 1: Emissions to air from waste management facilities (grams per ton of MSW)

	Per kWh Emissions from WTE facilities (gm/kWh)			
Substances	Pyrolysis/Gasification	Anaerobic Digestion (AD)	Incineration	Landfill
Nitrogen oxides	1.22	0.57	2.75	0.369
Particulates	0.019	No data	0.065	0.03
Sulphur dioxide	0.081	0.009	0.072	0.443
Hydrogen chloride	0.049	6.1e-5	0.1	0.0689
Hydrogen fluoride	5.29e-4	2.1e-5	0.0017	0.0133
VOCs	0.017	No data	0.014	0.037
1,1-Dichloroethane	Not likely to be emitted	No data	Not likely to be emitted	0.0033
Chloroethane	Not likely to be emitted	No data	Not likely to be emitted	0.0013
Chloroethene	Not likely to be emitted	No data	Not likely to be emitted	0.0014
Chlorobenzene	Not likely to be emitted	No data	Not likely to be emitted	0.0029
Tetrachloroethene	Not likely to be emitted	0,0004	Not likely to be emitted	0.0041
Benzene	Not likely to be emitted	No data	Not likely to be emitted	2.96e-7
Methane	Not likely to be emitted	No data	Not likely to be emitted	93.6
Cadmium	1.08e-5	3.02e-7	8.6e-6	3.5e-4
Nickel	0.000062	9.1e-7	8.6e-5	4.7e-5
Arsenic	9.35e-5	1.51e-6	8.6e-6	5.9e-6
Mercury	1.1e-4	1.81e-6	8.6e-5	5.9e-6
Dioxins and furans	7.5×10^{-11}	No data	6.9×10^{-10}	2.7×10^{-10}
Polychlorinated biphenyls	No data	No data	1.72e-7	No data
Carbon Dioxide	No data	No data	1721	985
Carbon Monoxide	0.16	No data	No data	---

Source: Adapted from DEFRA, Department for Environment, Food and Rural Affairs (2004) report,

and emissions potential from the each WTE technology. LCA model consider from the cradle to death impact analysis from the waste generation, transportation storage, treatment and disposal of final residue. However, in this study is considered only electricity generation potentials and environmental impact associated with the emissions from the system. Therefore, a small part of the waste management system is analyzed in this study.

Functional unit of the study is considered as 1kWh electricity and the environmental impact of generating 1kWh energy. All output data i.e. emission from the different WTE facilities are adapted to the per unit (kWh) electricity generation rate. The study is done to analyze environmental impact from different waste treatment facilities to produce 1kWh electricity production.

Fig. 1 shows the system boundary of the LCA model. 1 ton of wastes have been treated by different

Table 2: Emission to water from AD facilities

Emission to water	Emission rate (g/kWh)
Dissolved solid	0.242
Total nitrogen	0.03
Ammonical nitrogen	0.022
Nitritite nitogen	1.21e-4
COD	0.3
BOD	0.076

Table 3: Emission to the water from the Landfill

Substances	Emission to water (surface and ground) from landfill (g/kWh)*
Aniline	1,29e-8
Chloride	0.147
Cyanide	6,4e-6
Fluoride	8,1e-5
Nitrogen (Total)	0.046
Phenols	3.8e-8
Phosphorus	3.7e-4
Toluene	9.4e-7
Arsenic	3.01e-7
Chromium	4.431e-6
Copper	6.89e-7
Lead	5.9e-6
Nickel	5.9e-6
Zinc	4.93e-6

Source: DEFRA [12] * total emission of water has been counted by adding up the surface and ground water emission

Table 4: Normalization and weighting value for Europe 99 method

Normalization/ Weighting set	DamageCategories	Normalization	Weighting
Europe EI 99 E/A	Human Health	64.7	400
	Ecosystem Quality	1.95E-4	400
	Resources	1.68E-4	200

Source: Pré Consultants, [36]

WTE technology and as output of the system, energy generation (kWh) and emissions (gm/kWh) from the system have been considered.

Assumptions

Following assumptions have been made for the LCA model:

- The study have been done based on the electricity generation and emission rates but not considering transportation and final disposal impact from the each treatment options.
- Electricity produces from the different WTE option has not been considered as avoided materials since the aim of the study is to analyze environmental impact per kWh electricity generation from WTE facilities.
- Electricity produced from Sanitary landfill is considered to add electricity to the national grid system, however, this type of advanced and high cost facilities are not common.

Life Cycle Inventory and Data: Life cycle inventory of the LCA model is made primarily based on the Department for Environment, Food and Rural Affairs [12] 'Review of Environmental and Health Effects of Waste Management: Municipal Solid Waste and Similar Wastes' report. The report is analyzed different waste management technology based on their potential benefit, impact and problem solving capacity. Table 1, shows the emission data for 1 kWh electricity generation from WTE facilities which is adapted from the 1ton of waste emission to the electricity generation by each facilities while treating 1 ton of MSW. Therefore, total emission value for 1 ton of MSW is divided by the total electricity generation for getting per kWh emission data.

Table 3, shows the water emission from the landfill and here surface water and ground water emission are considering as total waster emission.

Life Cycle Impact Assessment (LCIA): Life cycle impact assessment of the WTE technologies has been done by the Eco-indicator (Europe 99) method. Eco-indicator has account three different impact area like human health, ecosystem quality and resource depletion. Eco-indicator is a damage oriented end point [35] analyzing tool.

Eco-indicator methods has the option to analyze environmental burden under three impact areas and eleven different impact categories like carcinogens, respiratory organics, respiratory inorganic, climate change, radiation, ozone layer, eco-toxicity, acidification/eutrophication, land use, minerals and fossil fuels. In the inventory, impacts are analyzed by different effect categories then damage assessment has been measured by human health, ecosystem and resource categories. Then the impact values are normalized based on regional perspectives. In this study European value have been considered and normalization and weighting value are given bellow.

There are Three Damage Categories:

- Human Health, (unit: DALY= Disability adjusted life years; this means different disability caused by diseases are weighted)

- Ecosystem Quality (unit: PDF*m2yr; PDF= Potentially Disappeared Fraction of plant species)
- Resources (unit: MJ surplus energy Additional energy requirement to compensate lower future ore grade)

RESULTS AND DISCUSSION

Characterized Results: Ecoindicator has the option to analyze eleven different impact categories however, in the study LCA model has been developed based on emissions per kWh electricity recovery data so the results have been shows with 'no impact' value for radiation, ozone layer, land use, mineral and fossil fuels. Table 5 and Figure 3, show the characterization results and graph respectively of the different WTE facilities and 'zero impact' values are not considered in the report. Characterization graph shows that, landfill has the higher impact on carcinogen, respiratory organic climate change and eco-toxicity and incineration has the significant impact on respiratory organic, acidification/eutrophication and climate change. Incineration has the high impact in respiratory inorganics, climate change and acidification impact categories. However, Pyrolysis-Gasification and Anaerobic Digestion has the significantly lower potential impact in carcinogenic, respiratory organics and climate change categories. Moreover, AD has zero potential impact on respiratory organics and climate change. Nitrogen oxides, Nickel, Cadmium, Sulfur dioxide are the primary pollutants that have potential environmental impact on the ecosystem services.

From the inventory analysis cadmium, arsenic and dioxin have been found as the primary polluters causing carcinogen impacts for WTE options, NOx, SOx and particulates matters are responsible for respiratory inorganics and acidification problem. Methane, carbon dioxide and carbon monoxide have been found as the prime polluters for climate change impact.

Characterization results show the contribution of emissions in different impact categories. Since the model is developed from the average emission value of the WTE options, therefore, the model is limited to explain the consequences of the diverse waste streams. Different waste fractions will change the emissions value for the model.

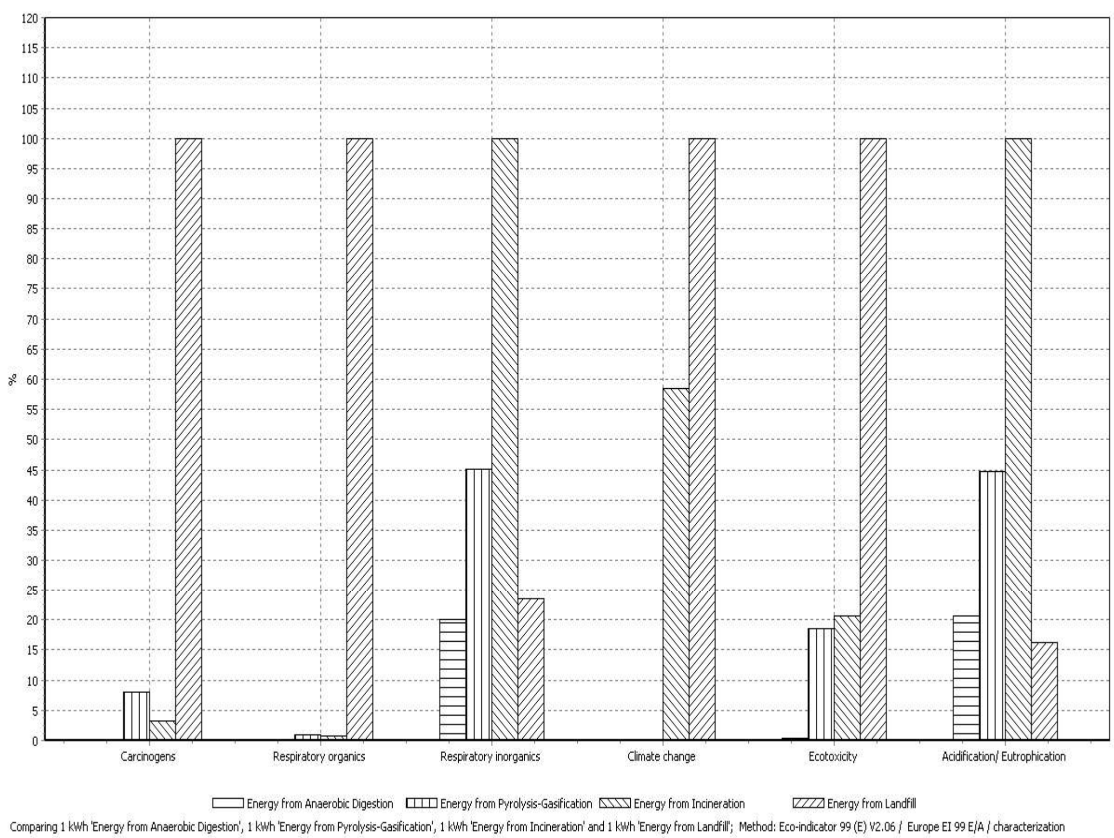

Fig. 3: Comparative LCA characterization results of the WTE facilities

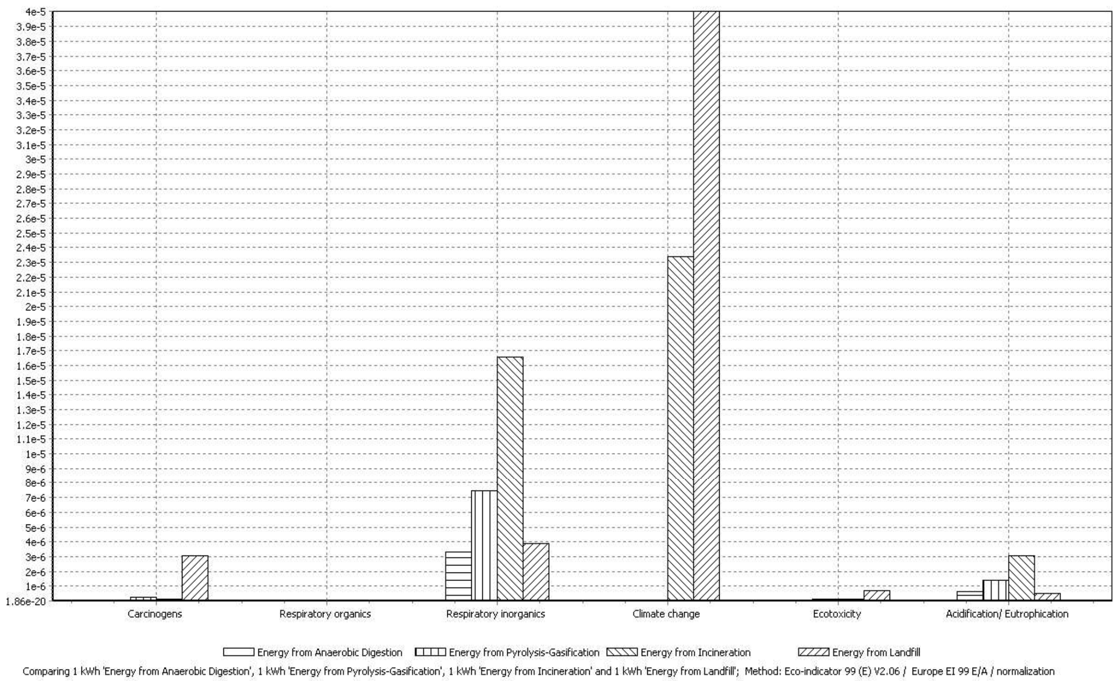

Fig. 4: Normalization graph for different WTE options

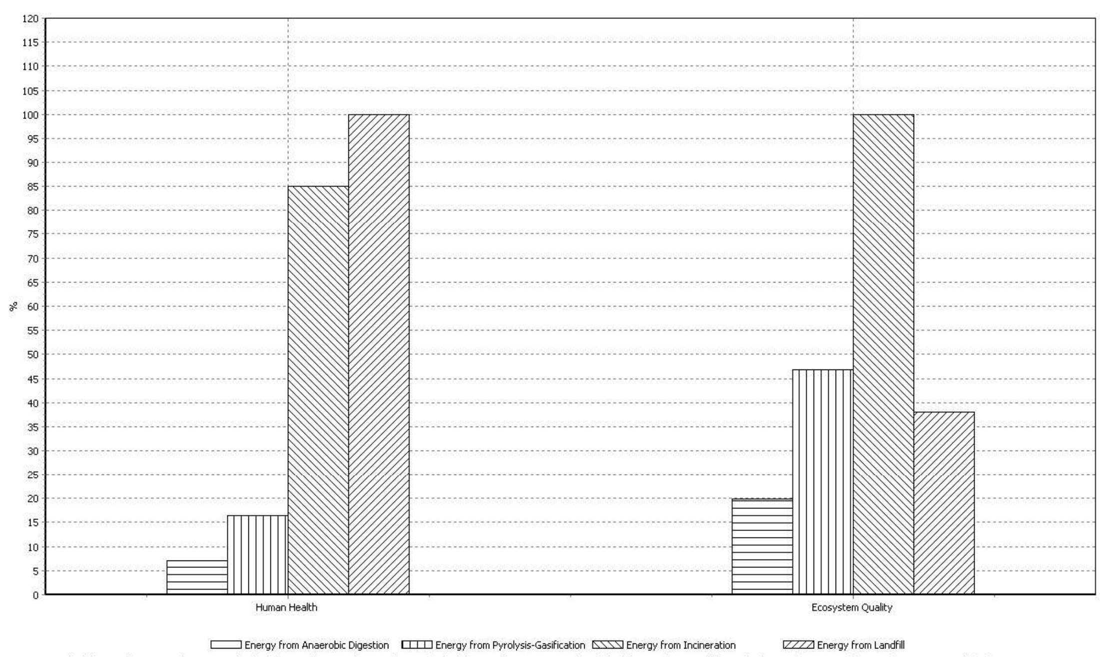

Fig. 5: Damage assessment result of different WTE options

Normalized and Weighting Results: Figure 4, shows the normalization graph of different WTE facilities. Normalization graph shows that, climate change and respiratory inorganic are the significant impact categories in regional perspectives (Europe). Landfill and Incineration are the two WTE technologies that contribute environmental burdens and P-G and AD has the lowest impact in the country impact level. Methane and carbon dioxide emission from landfill and incineration are mainly responsible for Climate change impact.

Table 5: Characterization results of the WTE facilities

Impact category	Unit	Landfill	Incineration	Pyrolysis-Gasification	Anaerobic Digestion
Carcinogens	DALY	4.73E-08	1.5E-09	3.77E-09	7.8E-11
Respiratory organics	DALY	1.22E-09	9.04E-12	1.1E-11	0
Respiratory inorganics	DALY	6.04E-08	2.56E-07	1.15E-07	5.13E-08
Climate change	DALY	6.19E-07	3.61E-07	5.15E-11	0
Ecotoxicity	PAF*m2yr	0.037168	0.007701	0.00691	0.000118
Acidification/ Eutrophication	PDF*m2yr	0.002569	0.015786	0.007054	0.003266

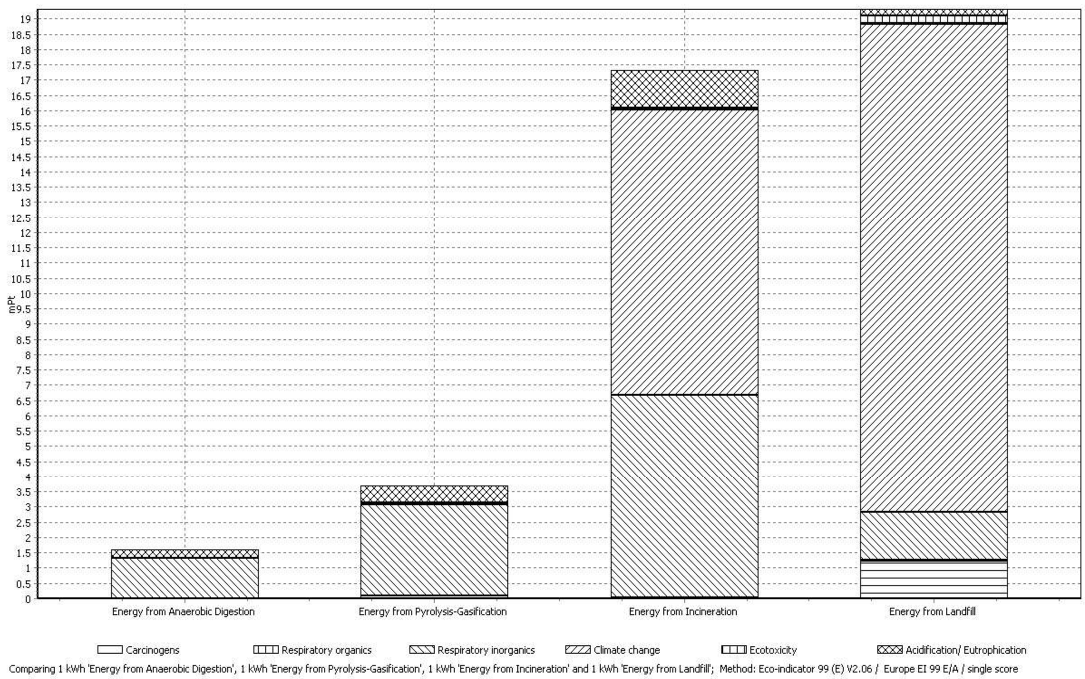

Fig. 6: Single Score result of the different WTE options

Since, climate change issues are now been discussing as the prime global problem for sustainable development so climate change issues is very important while designing or planning waste management system. Landfill and Incineration have significantly higher impact on climate change than P-G and AD due to higher carbon dioxide, methane and carbon monoxide emission to air from the processes. Incineration has the higher impact in respiratory inorganic and acidification impacts due to SOx, NOx and heavy metal emission from the process.

Depending on waste treatment technology, environmental burdens are also varies for different technology. Landfill shows the highest climate change impact due to significant CO2 emission to the atmosphere. P-G shows the lower climate change impact than Incineration of waste; however, both technologies are thermal waste treatment technology. One of the main reason is, P-G is done with the limited volume of air therefore, sysgas that produce from the system is lower in volume. On the other hand, Incineration of waste is done in the present of air, therefore syngas that produce from the system is higher than P-G. it is important to select waste treatment technology for MSW management based on the treatment methodology.

Damage Assessment and Single Score: Since, the study has not been considered the resource uses by the processes so the impacts of recourse have not been showed in the damage assessment graph. Figure 5 shows the damage assessment result of WTE technologies in two different areas like human health and ecosystem support. From the damage assessment results, we can say that, landfill, incineration has the high impact on human health and Incineration has the significantly higher impact than others WTE options on ecosystem support function.

Single score results showed in Figure 6 and the result shows that, landfill has the highest potential impact than the other WTE options and climate change is the primary impact category for landfill which is one of the main reason for banning landfill for waste management system due to significant climate change impact and contributing global environmental problems. Incineration has significant impact on climate change, respiratory inorganic and acidification impact categories. P-G and AD has significantly lower potential impact however, respiratory impact and acidification may cause due to these WTE options. From the inventory analysis, methane, carbon dioxide, cadmium, nitrogen oxide, sulfur dioxide and particulates are the primary pollutants to cause environmental impacts from the different WTE options. Total impact value from the single score method combining human health and ecosystem quality shows that, total value for Landfill, incineration, P-G and AD have found as 0,0147pt, 0,0136 pt, 0,00307 pt and 0,00132pt.

Uncertainty and Limitations of the Results: The study have been done to analyze potential impact due to energy production from different waste treatment options through emission rates, so, in the research other factors like input energy, waste type or disposal of final residue didn't consider which might have significant influence in the overall results. However, this is an effort to measure environmental burden by per kWh electricity generation from different WTE options.

CONCLUSION

Resource recovery especially energy and heat recovery is one of the prime objectives while planning or designing waste management system now a day. Since, different waste treatment options has the waste to energy options, for making strategy or planning decision maker should have to know the right information about the waste-to-energy technology and environmental burden associated with the technologies. From the study, we can conclude that, considering energy production potential and environmental impact, landfill has the highest impact on environmental and mainly in climate change, Incineration has also climate change and respiratory inorganic impacts. P-G is comparatively favorable due to lower environmental impact and AD has the lowest potential impact among the four WTE options. However, different WTE options have different level of problem solving capacity and socio-economic issues are also varied for different WTE options.

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