Environment Protection Engineering

Vol. 43 2017 No. 4

DOI: 10.37190/epe170411

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COMPARATIVE ENVIRONMENTAL IMPACT ASSESSMENT OF THE LANDFILLING AND INCINERATION OF RESIDUAL WASTE IN KRAKOW

The methodology of life cycle assessment (LCA) is a valuable tool for identifying and assessing the environmental impacts caused by waste management scenarios. The aim of this study was to perform a comparative LCA of two scenarios of municipal waste management system in Krakow, Poland. The assessment is limited to residual (mixed) waste. Under the former scenario, residual waste is landfilled at a well-equipped facility, while under the latter scenario, residual waste is incinerated in a thermal treatment plant with energy recovery. Landfilling represents a real situation for 2010, when all residual waste was landfilled, incinerating expresses the plan for 2016. The elements of the scenarios such as collection and treatments of separately collected waste are excluded from the system boundaries. The modeling of the environmental impact is done by the EASETECH model, employing EDIP 2003 methodology. The final results are expressed in person equivalent (PE) units. Both scenarios have negative impacts on the environment, however the impact for incineration is much lower than for landfilling. In respect of landfilling, the significant impact categories are photochemical ozone formation, global warming, eutrophication and human toxicity. Regarding incineration, significant impact categories include eutrophication, photochemical zone formation, acidification and human toxicity.

1. INTRODUCTION

The establishing of affordable, effective and integrated waste management system of increasing quantities of solid waste is one of the major challenges facing municipalities. The methodology of life cycle assessment (LCA) is a valuable tool for identifying and assessing the environmental impacts caused by waste management scenarios. LCA provides a broad overview of the environmental aspects of various waste management scenarios enabling their comparison. However waste management is a large and complex system that is difficult to survey [1]. The systemic approach of LCA provides the

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capacity of evaluating the various waste technologies with different energy consumption and production patterns along with different levels of material recovery [2]. The general purpose of LCA is providing a holistic view of the emissions to the environment and resource uses caused by a waste management system [1].

The functional unit in LCA of waste management is defined as the management of a certain amount of waste with a certain composition. Besides the collecting and treating waste, the system can also provide such products as materials (recyclables), fertilizer (compost) as well as recovered heat and electricity [1].

LCA is a useful tool for comparing alternative waste management scenarios but performing an LCA study for waste management is a complicated task and requires very careful definition of the scope of the study in order to obtain reliable results. Several models have been developed to perform the life cycle assessment of waste management systems: EPIC/CSR, MSW-DST, IWM-2, WISARD, ORWARE, LCA -IWM, WRATE, and EASEWASTE.

The IWM model applies lifecycle thinking and includes a model for calculating life cycle inventories. The model is very user friendly but it is not flexible. The ORWARE model originally focused on organic but was expanded to other waste material fractions. It uses a combination of life cycle assessment and material flow analysis (MFA). This model is very flexible but difficult to use. The WISARD performs a full LCA of a waste system. It handles up to 41 material fractions and many waste treatment methods and technologies that can all be modified by the user. However, the model has been criticized for not being transparent, not clearly defining system boundaries and providing results that cannot be easily interpreted [2].

The EASEWASTE model is a user friendly, well-documented and flexible model, which is able to compare different waste management strategies and waste treatment technologies [2]. A number of studies with EASEWASTE model have been carried out. Some of these studies employed the model to evaluate environmental impacts from municipal waste management systems, for example, in the municipality of Aarhus, Denmark [3], in Beijing City, China [4], while others have used the model to evaluate the environmental performance of treatment technologies: incineration [5, 6] and landfilling [7, 8]. The EASEWASTE model has also been applied to compare the environmental performance of different waste treatment technologies [9, 10].

Also other models or methodologies have been used to compare the municipal waste scenarios or waste treatment technologies. The study by Arena [11], compares three scenarios: 1) landfilling; 2) refuse derived fuel (RDF) production and then its combustion; 3) incineration of non-pretreated residual waste, for the Campania region in Italy, with a functional unit of 1 kg of residual waste. As the principal indicators of environmental impact, the following impact categories were adopted: air pollution; water pollution, resources consumption (water consumption, net energy consumption, non-renewable resource consumption), quantities of final waste generated (requirements for landfill volume). In the study by Cherubini [12], four waste management scenarios are discussed: 1) landfilling with biogas utilization to produce electricity; 2) landfilling without biogas utilization, 3) incineration; 4) a sorting plant separating waste into an inorganic fraction (refuse derived fuel to produce energy) and an organic fraction (to produce biogas). This evaluation was performed applying the SPI (sustainable process index) methodology, which measures the potential impact of processes on the ecosphere and compares mass and energy flows entailed by human activities with natural flows. The life cycle assessment methodology was employed to compare the environmental impact of incineration and landfilling of municipal solid waste in the city of São Paulo, Brazil in the study by Mendes [13]. The paper by De Feo and Malvano [14] examines several municipal waste management scenarios operating in southern Italy with eleven environmental impact categories, applying WISARD (waste integrated system assessment for recovery and disposal) model. The paper by Moberg [15] tests the validity of the waste hierarchy by employing the LCA methodology for recycling, incineration with heat recovery and landfilling of recyclable waste in Sweden. Assamoi and Lawryshyn [16] assessed the environmental impacts and discounted costs of the incineration versus landfilling of municipal waste in Toronto.

Only few studies of LCA of municipal waste management systems have been performed for cities or regions in Poland. Den Boer and Szpadt [17] carried out an the LCA of three waste management scenarios for the Wrocław city, with the end point of time horizon set for year 2020. The LCA-IWM model was applied for this analysis. In the study by Cholewa and Kulczycka [18], municipal waste scenarios for the Świętokrzyski Region were evaluated for years 2006 and 2008. A preliminary analysis was performed by the IWM-2 model, and then the outputs from the IWM-2 application were modeled with SimaPro software. In the study by Kulczycka [19], the environmental impact of a small number of Polish landfills and three incinerators was evaluated employing the IWM-2 model and SimaPro software.

The environmental impact of the municipal waste management system in Krakow was evaluated using the IWM-PL model [20–22], a Polish-language application. The IWM-PL application is based on the IWM-2 model, and applies the Eco-Indicator 99 method for performing life cycle impact assessments. Another model, EASETECH, was applied for evaluating the environmental impact of three municipal waste scenarios in Krakow. Despite announcing preliminary results of this evaluation [23, 24], in the present study a thorough analysis for two scenarios of landfilling and incineration of residual waste in Krakow has been presented, with detailed discussion of results. The landfilling represents a real situation for 2010, when all residual waste was landfilled, the incinerating scenario expresses the plan for 2016. The modeling is performed for municipal waste generated in Krakow, which parameters were thoroughly determined at the examination conducted in 2010–2011 [25]. The modeling is done with the EASETECH application, based on the concept of the EASEWASTE, which was developed by the Technical University of Denmark.

2. MATERIALS AND METHODS

Waste generation and composition. Krakow, the capital of Małopolska Province in southern Poland, in 2010 was inhabited by 756 183 residents, with additional significant number of temporary residents: tourists (8.15 million) and students (206 549). The structure of the city is very diverse, as Krakow dates back to 7th century, being nowadays one of the most important academic, cultural, artistic, economic and industrial centers in Poland. The medieval, densely-populated, central part of the city covers 18.7% the city area, multi-family houses occupy 62.5% and single-family houses cover 18.8%.

The latest study on generation, composition and parameters of municipal waste in Krakow was performed from November 2010 to October 2011 [25]. The results of this study shows that the average annual generation of municipal waste from households per capita was 324.3 kg for Krakow; for the city center 563 kg, for single-family houses 329.3 kg and for multi-family houses 268.1 kg. In 2010, the amount of residual waste generated in households was estimated at 245 215 Mg and commercial activity produced 36 457 Mg of such waste. The study by Sieja [29] demonstrated that mixed (residual) waste had a water content of 41.1%, volatile solids in dry matter 78.3%, heat combustion 13.82 MJ/kg, lower heating value 7.94 MJ/kg, Cl content in dry matter 0.297%, F content in dry matter 0.0031% and S content in dry matter 0.168%. The composition of residual waste in Krakow is shown in Table 1.

Table 1

Material composition [wt. %]
of household residual (mixed) waste [25]

Material fraction	Content
Bio-waste (food and garden waste)	29.22
Wood	0.99
Paper and cardboard	20.48
Plastics	14.59
Glass	8.53
Textiles	2.93
Metals	2.25
Hazardous waste	0.72
Composites	4.6
Inert waste	1.96
Others	4.89
Fine fraction (below 10 mm)	8.84

In Krakow, selective collection systems have been established for recyclables (glass, paper, plastics, metal), textiles, garden waste, bulky waste, construction and demolition waste, and hazardous waste. Selectively collected recyclables are sorted at the sorting station and sent to recycling plants. Bulky waste is dismantled into secondary raw materials and remaining waste is processed into RDF. Separately collected green waste is composted at two plants. In 2010, the residual (non-selectively collected) waste was deposited at the modern and well-equipped landfill.

Scenarios. Two scenarios for residual waste management in Krakow are modeled in this study:

- Scenario I describes the real situation in 2010. Under this scenario, residual (non--separately collected) waste is transferred to be landfilled at the facility, where landfill gas is collected and subsequently converted into heat and electricity. Leachate through a drainage system is collected, then via sewerage reaches a municipal wastewater treatment plant.
- Scenario II represents a strategic plan for the municipal waste management system in Krakow for 2016. Under this scenario mixed waste is transferred to a thermal treatment plant, where non-separately collected (residual) municipal waste is incinerated with energy recovery.

The aim of this study is to perform a comparative LCA of landfilling and thermal treatment of residual waste, therefore the elements of the scenarios such as collection and treatments of separately collected waste are excluded from the system boundaries. Those elements are identical for both scenarios. The transport distance for both treatment plants (landfill and incinerator) is assumed to be comparable, because both plants are located in Krakow, with similar distance to the city center.

Functional unit and system boundaries. Functional unit of this LCA study is the total quantity of mixed (non-separately collected) waste introduced into the municipal waste management system in 2010 in Krakow city (that is, 281 672 Mg), with the composition shown in Table 1. System boundaries for scenario I are given in Fig. 1, while those for scenario II in Fig. 2.

The LCA method for waste management systems. The scenarios are modeled with EASETECH application, based on EASEWASTE model [3]. The modeling with EASETECH starts from the point where municipal waste is collected and ends at the point of final waste treatment, therefore the model tackles a whole waste management system. A database includes waste treatment options as well as external processes such as material production, electricity and fuel production and consumption, transportation, operations of heavy working machineries. The model calculates emissions to the environment (air, water, soil) and resources consumption. Recycled materials and energy resulting from the waste treatment are regarded as substitutes for virgin materials or energy. The list of exchanges (emissions and resources consumption) is translated into environmental impacts with the life cycle impact assessment (LCIA) methodologies. One of these methodologies employed by EASETECH is EDIP 2003, a newer version

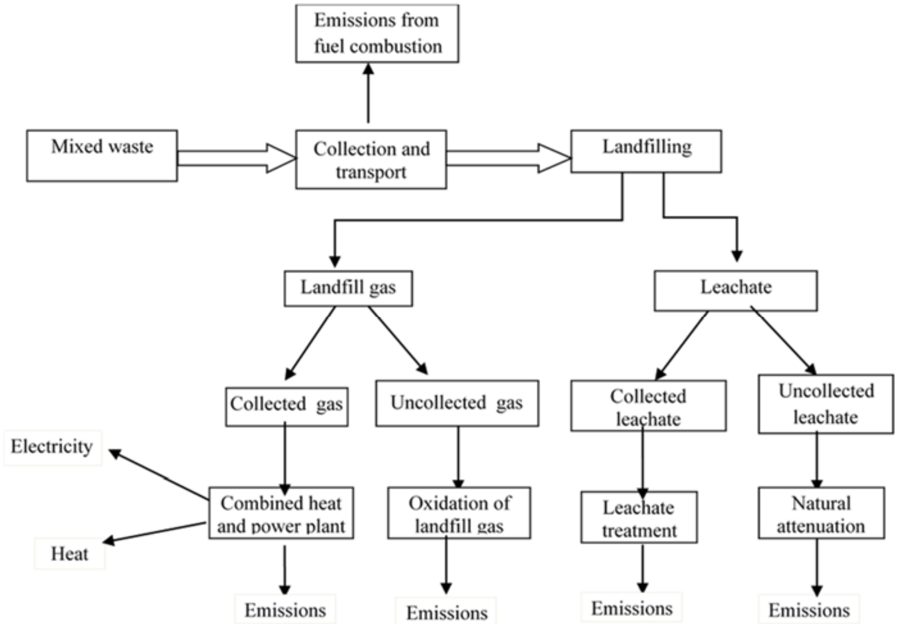

Fig. 1. System boundaries for scenario A: landfilling mixed waste

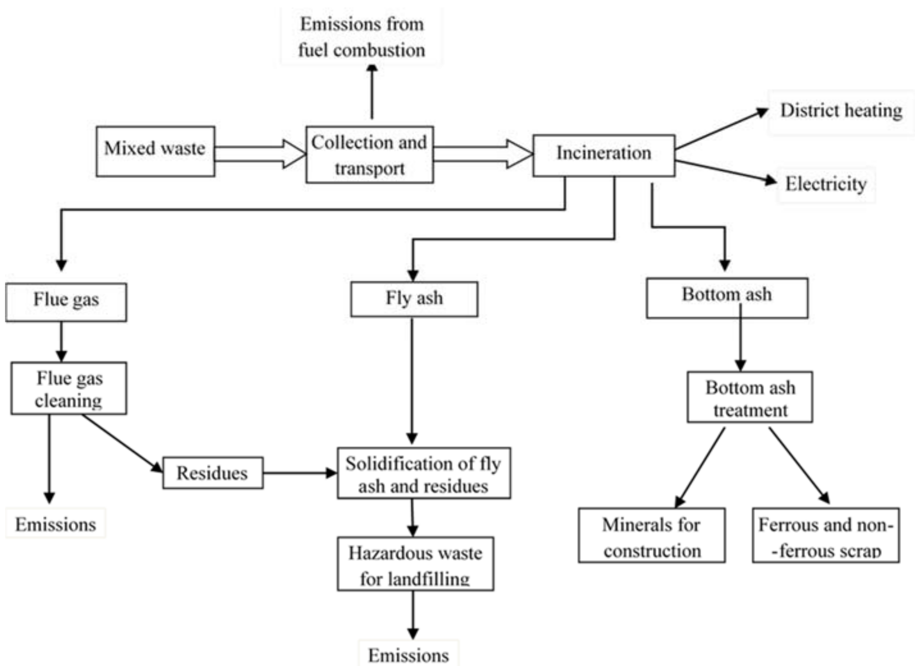

Fig. 2. System boundaries for scenario B: incineration of mixed waste

of EDIP 1997 with following impact categories: acidification, ecotoxicity acute in water, ecotoxicity chronic in soil, ecotoxicity chronic in water, eutrophication combined potential, eutrophication separate N potential, eutrophication separate P potential, terrestrial eutrophication, global warming, human toxicity via air, photochemical ozone formation impacts on human health, photochemical ozone formation impacts on vegetation, stratospheric ozone depletion.

The environmental impacts are calculated as normalized potential impacts and expressed in the unit of person equivalent (PE). A calculated positive value of normalized impact potential presents a contribution to the impact, while a negative one indicates an avoidance of the impact or resource consumption [3].

Modeling of landfills in a life cycle assessment perspective is challenging. LCA calculates the summed potential impacts from the total emissions during the defined time frame, but emissions from a landfill normally occur at very low concentrations over a very long time, and risks of damaging human health or the environment may thus be lower than an LCA may indicate. The main emissions associated with landfills are gas produced by the organic content in the landfilled waste and leachate produced by precipitation entering the landfill. The potential landfill gas generation is calculated by the content of volatile solids of each material fraction, the potential methane production for each material fraction and the methane concentration in the landfill gas. The collection efficiencies are 88%, and all collected gas is directed to a turbine producing electricity with an energy recovery of 30% of the energy content in the landfill gas. Treatment efficiencies for all substances in collected landfill gas are assumed to be between 98% and 99% [7].

Leachate generation depends on yearly average precipitation and the type of landfill covers. The leachate emissions, in addition to leachate quantity and composition, also depend on the efficiency of the leachate collection system and the treatment facilities. Treatment of the collected landfill leachate operates with individual removal efficiencies for each substance as a percentage of the incoming substance in the leachate. Treated leachate is thereafter led to fresh surface water with the remaining amount of each substance [7].

Assessment of the environmental aspects of waste incineration must include both the actual emissions from the incinerator and the emissions saved, because the energy produced and the materials recovered substitute for the production of energy and materials by other processes. The actual emissions, primarily air emissions, depend on the waste incinerated, the combustion and flue gas cleaning technology, and the actual operation of the plant [5].

3. RESULTS AND DISCUSSION

The results of environmental impact of two scenarios of municipal waste management in Krakow are expressed in several universal impact categories discussed above. The normalized impacts for Krakow waste management systems have been calculated in person equivalent (PE) units.

3.1. LANDFILLING

The calculated results of the modeling of the environmental impact potentials of residual waste landfilling in Krakow showed that methane emission is the most domi-

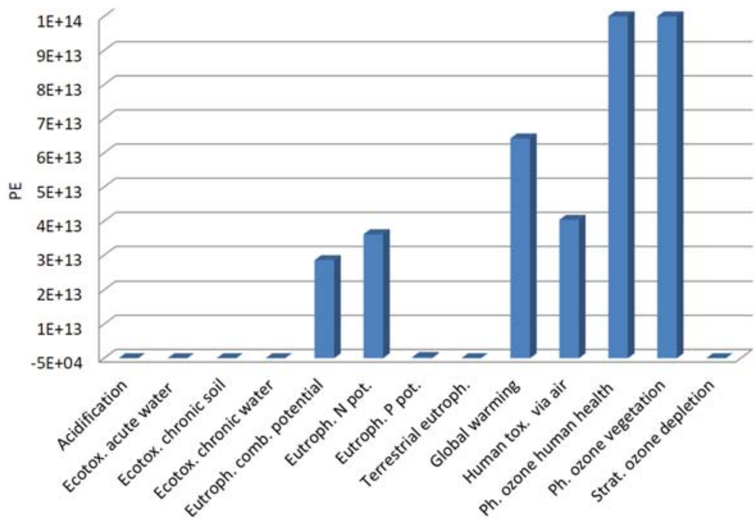

Fig. 3. Normalized impact of landfilling of residual waste in Krakow

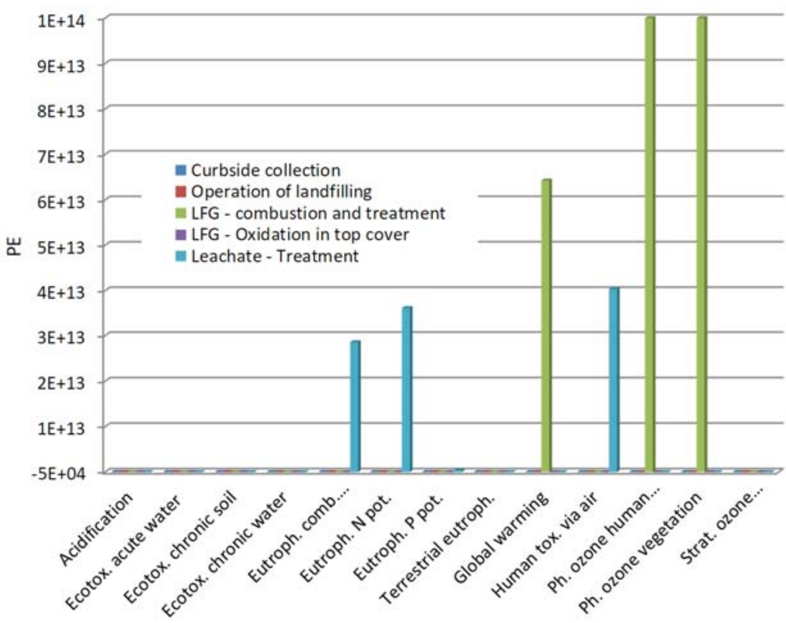

Fig. 4. Normalized impact per process of landfilling of residual waste in Krakow

nant contributor to global warming and to photochemical ozone formation, with an annual amount of 2.16×10^{16} kg. Air emissions of trichlorofluoromethane (CFC-11) at 8.16×10^{6} kg contribute mostly to stratospheric ozone depletion. Nitrogen oxides emitted annually at 9.67×10^{5} kg contribute to terrestrial acidification and to eutrophication potential. Emission to water of phosphate at 3.61×10^{11} kg contributes to freshwater eutrophication. Emissions to water of chromium(VI), xylene and selenium as well as emission to air of nickel and polychlorinated biphenyls contribute to ecotoxicity. The normalized potential impacts of the waste management system were calculated employing EDIP 2003 methodology and are shown in Figs. 3 and 4.

The normalized results showed that landfilling contributes mostly to global warming and to photochemical ozone formation (impacting both human health and vegetation), mainly due to methane emission and landfill gas treatment and combustions. High normalized impact values are observed also for eutrophication and human toxicity, and result from leachate and its treatment.

3.2. INCINERATION

Further calculated results of the modeling presented in Fig. 5 showed that incineration of residual waste generates a positive effect in respect of some of the impacts.

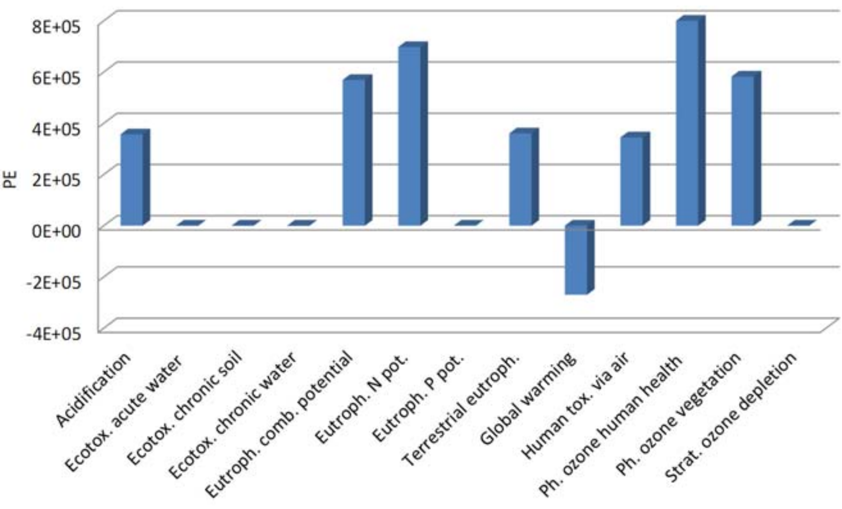

Fig. 5. Normalized impact of incineration of residual waste in Krakow

Positive effects to the environment (values below zero) are observed for global warming (-2.70×10^{5} PE), stratospheric ozone depletion (–38.5 PE) and for all types of ecotoxicity. These values for ecotoxicity are: -3.73×10^{2} PE for ecotoxicity acute in water, -2.50×10^{2} PE for ecotoxicity chronic in soil, -6.66×10^{2} PE for ecotoxicity chronic in water. The avoided impacts in relation to global warming are mainly caused by reduced coal combustion for electricity production in Poland.

However, most of the impact categories for incineration have values above zero, which means that incineration impacts negatively on the environment. The highest effect is observed on photochemical ozone formation, impacts on human health (8.15×10^5 PE) and on vegetation (5.82×10^5 PE) mainly due to the emission of nitrogen oxides from the high stack of the incinerator. Emitted nitrogen oxides are also responsible for high values of eutrophication and human toxicity in the air.

3.3. COMPARISON OF THE TWO SCENARIOS FOR RESIDUAL WASTE TREATMENT

The environmental effects of two residual waste treatment methods, incineration and landfilling, were compared in the EASETECH model using the EDIP2003 methodology and assuming the same quantity and quality of waste for both scenarios. The normalized results of the environmental impact are presented in Table 2.

Table 2

Normalized environmental impact for incineration and landfilling of residual waste in Krakow in PE units

Impact category	Incineration	Landfilling
Acidification	3.57×10^5	4.72×10^5
Ecotoxicity acute in water	-3.73×10^2	2.17×10^8
Ecotoxicity chronic in soil	-2.50×10^2	3.08×10^7
Ecotoxicity chronic in water	-6.66×10^2	3.98×10^8
Eutrophication combined potential	5.69×10^5	2.86×10^{13}
Eutrophication separate N potential	6.98×10^5	3.61×10^{13}
Eutrophication separate P potential	7.53×10^1	3.72×10^{11}
Terrestrial eutrophication	3.60×10^5	-2.67×10^4
Global warming GWP 100a	-2.70×10^5	6.42×10^{13}
Human toxicity via air	3.45×10^5	4.04×10^{13}
Photochemical ozone formation, impacts on human health	8.15×10^5	2.20×10^{14}
Photochemical ozone formation, impacts on vegetation	5.82×10^5	1.30×10^{14}
Stratospheric ozone depletion, ODP total	-3.85×10^1	2.03×10^9

In all but one impact category, the normalized values are lower for incineration than for landfilling. The most severe disparity in values is observed for global warming: for incineration the value is below zero (-2.70×10^5 PE), while for landfilling it far exceeds zero (6.42×10^{13} PE); put differently, the quantity of the difference is 18 orders of magnitude. For this impact category the most significant contributing substances from landfilling is methane of non-fossil origin. On the other hand, landfilling of organic substances also has a positive impact on the environment, because some quantities of carbon dioxide of fossil origin are stored in the landfill and not emitted into the atmosphere; this positive impact is, however, quite low.

The values below zero for incineration indicate a positive impact on the environment, which is mainly due to avoided emissions of carbon dioxide of fossil origin. Incinerated waste is a source of energy, therefore lower quantities of fossil fuels are burnt to produce energy; in other words, emissions of carbon dioxide of fossil origin are avoided.

For all types of ecotoxicity impact categories, incineration values are below zero while those for landfilling are significantly above zero (10^7, 10^8 PE). Negative values for incineration for acute ecotoxicity in water result from avoided emissions of strontium and aluminum; for chronic ecotoxicity in water they result from avoided emissions of strontium and selenium; for chronic ecotoxicity in soil they are the result of avoided emissions of formaldehyde and selenium. Ecotoxicity values significantly above zero for landfilling are the result of emissions of zinc, copper and nickel ions into ground water (acute ecotoxicity in water) as well as toluene, xylene, tetrachloroethane into the air (ecotoxicity in soil).

In respect of eutrophication impact categories, values for both scenarios of incineration and landfilling of residual waste are above zero, but they are much lower for incineration (10^5 PE) than for landfilling (10^{13} PE). Regarding incineration, the values of eutrophication combined potential and eutrophication N potential result from nitrogen oxides emissions from the high stack of the incinerator. For landfilling, eutrophication is caused by nitrate and phosphate emission into surface water.

The impact category human toxicity shows values above zero for incineration and landfilling, much higher in the case of the latter. This impact category is associated with nitrogen oxides emissions from the high stack of the incinerator; and with nitrate emission to surface water from the landfill. Concerning photochemical ozone formation, both incineration and landfilling exhibit values above zero, and the values for landfilling are much higher than for incineration. This impact category is associated with nitrogen oxides emissions from the high stack of the incinerator, while for landfilling it is linked with methane, toluene, xylene and benzene emissions. Values for stratospheric ozone depletion categories are below zero for incineration, yet above zero for landfilling. This impact category is associated with emissions of chlorofluoromethanes (CFC-s), though for incineration these are avoided emissions (values below zero) while for landfilling these substances are emitted into the air. For the acidification impact category, values for incineration and landfilling are almost equal (both above zero, approx. 10^5 PE). This category is linked with emissions of nitrogen oxides and hydrogen chloride from the high stack of the incinerator; for landfilling, it is associated with emissions of hydrogen chloride, hydrogen fluoride and nitrogen oxides from landfill gas combustion and treatment.

Determinants affecting the results for landfilling are those which influence landfill gas potential generation and its quantity, i.e. the composition of residual waste and particularly the content of biodegradable waste and its characterization. The results for incineration are affected significantly by the water content and heating value. Lowering water content and increasing heating value (for example, expelling kitchen waste) could improve the environmental performance of a municipal waste incinerator, which has been demonstrated in the study by [4].

Higher environmental impacts for landfilling than for incineration are also recognized in other studies. Arena [11] noted the poor environmental performances of landfilling in spite of applying a series of advantageous hypotheses in that study. An even worse overall assessment for this option was thus predictable, considering that LCA does not address odor or visual pollution, destruction of the natural habitat, etc. According to a study by Mendes [13] landfilling presents the highest environmental impact. Energy recovery (via biogas utilization) slightly reduced the environmental impact compared to landfilling without energy recovery. Incineration demonstrated the lowest environmental burden. Assamoi and Lawryshyn [16] state that the incineration scenario contributed in general to a significant reduction in greenhouse gas emissions. The incineration facility produced considerably more electricity compared to the landfilling facility, therefore the waste management option assuming incineration performed better environmentally. Results of a study by Cherubini [12] demonstrate that landfill scenarios are the worst waste management options. Significant environmental savings could be achieved from undertaking energy recovery. The higher the yields of energy from waste treatment processes, the greater the savings. The incineration alternative also seems to be better than landfilling in respect of environmental impact.

4. CONCLUSIONS

- Modeling results show that both scenarios – landfilling and incineration of residual waste – exert a negative impact on the environment. However, the negative impact of incineration is much lesser than that of landfilling.
- Significant impact categories for landfilling are: photochemical ozone formation, global warming, eutrophication, human toxicity; for incineration, significant impact categories include eutrophication, photochemical zone formation, acidification and human toxicity.
- Further research is necessary to obtain a detailed impact assessment for the entire municipal waste management system in Krakow, including separate collection of recyclables, sorting of separately collected waste, dismantling of bulky waste, composting of garden waste, etc.

ACKNOWLEDGEMENTS

The work was completed within the scope of AGH University of Science and Technology statutory research for the Faculty of Mining Surveying and Environmental Engineering No. 11.11.150.008.

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