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A Life Cycle Assessment of the Municipal Waste Management System in Tarnów***

1. Introduction

One of the essential aspects of sustainable development is establishing an efficient, economically viable and integrated waste management system, which would have a minimal negative impact on the environment. The methodology which allows for the identification and evaluation of the environmental impact is Life Cycle Assessment, considered to be one of the most effective tools of environmental management. Waste management is an extensive and complex system. Besides waste collecting and processing, waste management system can generate products in the form of recovered secondary raw materials, fertilizers (compost), energy and heat. On the other hand, provision of fuel (collection) and energy (processing) are necessary for the operation of the system.

System approach of Life Cycle Assessment covers all environmental impacts related to waste management, including each of the processes, such as waste collection, transportation, sorting, composting, recycling, incineration, landfilling, as well as obtained useful products (raw materials, fertilizers, energy) and supplied fuel and energy.

LCA is a useful tool to assess environmental aspects of waste management systems. However, the LCA procedure is a complex task and, in order to obtain reliable and objective results, it requires a careful definition of the scope of a research, acquisition of a variety of accurate data, as well as a skillful selection of a method for assessing environmental aspects. Several models have been developed for modeling the environmental impact of waste management systems, such as: IWM-2, EPIC/CSR, MSW-DST, ORWARE, WISARD, WRATE, LCA-IWM, EASEWASTE [3].

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In 2011, the first application in the Polish language version was launched, dedicated to evaluate municipal waste management systems [8].

This article aims to analyze the life cycle of the municipal waste management system in Tarnów in 2012, using the IWM-PL model.

2. Methods and Materials

2.1. The Municipal Waste Management System in Tarnów

Tarnów, a city located in the southern part of Poland, in eastern Małopolska, is the second-largest (after Krakow) city in the province of Małopolska. The city covers an area of 72.4 km² and, at the end of 2012, it had a population of 112,952 inhabitants [4]. Tarnów enjoys the records of the highest average temperature in the country, and therefore it is called the "Polish Heat Pole". Tarnów is an important administrative, economic and cultural center, as well as an attractive tourist destination in the region. It is a sub-regional center for neighboring municipalities of administration, education and higher education, health care and trade. It houses plants, which are significant on a national scale, involved in chemical, machinery, metal, construction, glass and food industries [2].

Tarnów has a diversified structure of the development, with a predominant share of multi-family buildings and a significant share of single-family houses. Based on the Report on the state of the city of 2012 [9], it was calculated that 61% of residents live in multi-family buildings, 39% – in single-family houses.

There are no systematic studies on municipal waste carried out for the city of Tarnów, but in 2011 the Department of Municipal Waste Storage (ZSOK) conducted studies on morphological composition of mixed solid waste from single-family and multi-family housing units [1]. Based on the study carried out by the Department of Municipal Waste Storage, the morphological composition of municipal waste for Tarnów has been illustrated in Table 1.

Table 1. Morphological composition of municipal solid waste in Tarnów, produced in single-family houses and blocks of flats

No.	Material	Single-family houses Share [%]	Blocks of flats Share [%]
1	paper	13.95	15.90
2	glass	6.65	8.10
3	metals	2.05	3.00
4	plastics	15.60	14.80
5	textiles	6.60	17.50
6	organic (kitchen and garden)	49.00	39.90
7	others	6.15	0.80

Source: based on [1]

The morphological composition of municipal waste produced in single-family houses differed from the morphological composition of municipal waste produced in blocks of flats. Therefore, it was necessary to calculate the weighted average, with the weights for the percentage shares for each type of buildings were assigned subject to the percentage of residents occupying a given type of development, that is, the weight of 0.39 for single-family houses and 0.61 for multi-family housing. The morphological composition of mixed solid waste in Tarnów is presented in Table 2.

Table 2. Morphological composition of municipal solid waste generated in Tarnów, taking into account the structure of the development

No.	Material	Share [%]
1	paper	15.14
2	glass	7.53
3	metals	2.63
4	plastics	15.11
5	textiles	13.25
6	organic (kitchen and garden)	43.45
7	others	2.89

Source: [11]

In 2012 in Tarnów, 33,041 Mg of mixed municipal solid waste was collected. Besides mixed municipal solid waste, there is also selective collection of recyclable materials carried out.

Selective collection of waste is carried out through:

- properly labeled containers available for some real properties,
- public points of selective collection of municipal solid waste spaced throughout the city,
- garbage bags with well-defined colors in the single-family housing.

Selective collection includes the following waste fractions: paper and cardboard, glass, plastics, metals. The collected recyclable materials are transported to entities involved in recycling. In addition, several times a year, bulky waste is collected. Biodegradable waste (only the so-called green waste) from green areas is collected immediately after it is generated, and it is sent for composting. Table 3 summarizes the amount of selectively collected waste in 2012.

Table 3. Selectively collected waste in Tarnów in 2012

No.	Code	Types of collected waste	Mass [Mg]
1	200101	paper and cardboard	1444.0
2	200102	glass	1194.9
3	200139	plastics	427.0
4	200140	metals	6.6
5	200201	biodegradable waste (garden and park)	584.0
6	20 03 07	bulky waste	649.4

Source: based on [10]

Mixed (residual) municipal solid waste from the area of Tarnów is stored at landfills in Tarnów-Krzyż (Municipal Waste Storage Site) and "Za Rzeką Białą".

The Municipal Waste Storage Site contains four closed landfill sectors (6.5 ha), open landfill (2.5 ha) and composting sector for biodegradable waste. Landfill gas from closed sectors is collected through pipelines and degassing wells, sent to the collection station, and then converted into electricity in generator sets. Leachate water is collected by drainage system, which flows into concrete tanks divided into two chambers. The first chamber serves as a settling tank, where the separation of solid contaminants is carried out; in the second chamber, aeration of leachate is performed, aimed at its treatment. Aerated leachate from the tanks is directed to the municipal sewage treatment plant through a sanitary sewage system.

2.2. The Functional Unit and System Boundaries

The functional unit is the total amount of municipal waste in the waste management system, i.e. the amount of mixed solid and selectively collected municipal waste, collected in Tarnów in 2012, and transported to materials recovery facility or for neutralization. The functional unit includes: mixed solid waste collected from households and public buildings, with averaged morphology specified in Table 2, selectively collected recyclable materials (glass, paper, plastics, metals), bulky waste, green waste from parks and gardens. The system boundaries include the processes of recovery and neutralization carried out in recovery facilities, as well as transportation of waste to these facilities. The construction of recovery and neutralization facility is excluded from the system boundaries. The boundaries of the system for municipal waste management in Tarnów in 2012 is illustrated in Figure 1.

2.3. IWM-PL Model to Perform LCA of Waste Management Systems

Life Cycle Assessment (LCA) is a difficult and complicated process, requiring multiple, highly accurate data (databases), as well as methodologies for modeling environmental mechanisms and effects caused by released emissions. Therefore, Life Cycle Assessment is carried out using specially developed models. The application to perform Life Cycle Assessment and cost analysis, published in the Polish language version, is the IWM-PL model, which enables the quantification of potential environmental impacts as well as of economic aspects of the analyzed municipal waste management system [8].

The IWM-PL model requires the input of a wide variety of data in 24 steps, 18 of which relate to the environmental aspects, and the remaining ones – to the economic evaluation. 18 steps of the environmental data input have been grouped into nine sections [8]:

1) waste collection,
2) sorting,
3) production of alternative refuse-derived fuel (RDF),

4) biological treatment,
5) thermal treatment,
6) combustion of alternative fuels,
7) landfilling of non-hazardous waste,
8) landfilling of hazardous waste,
9) recycling.

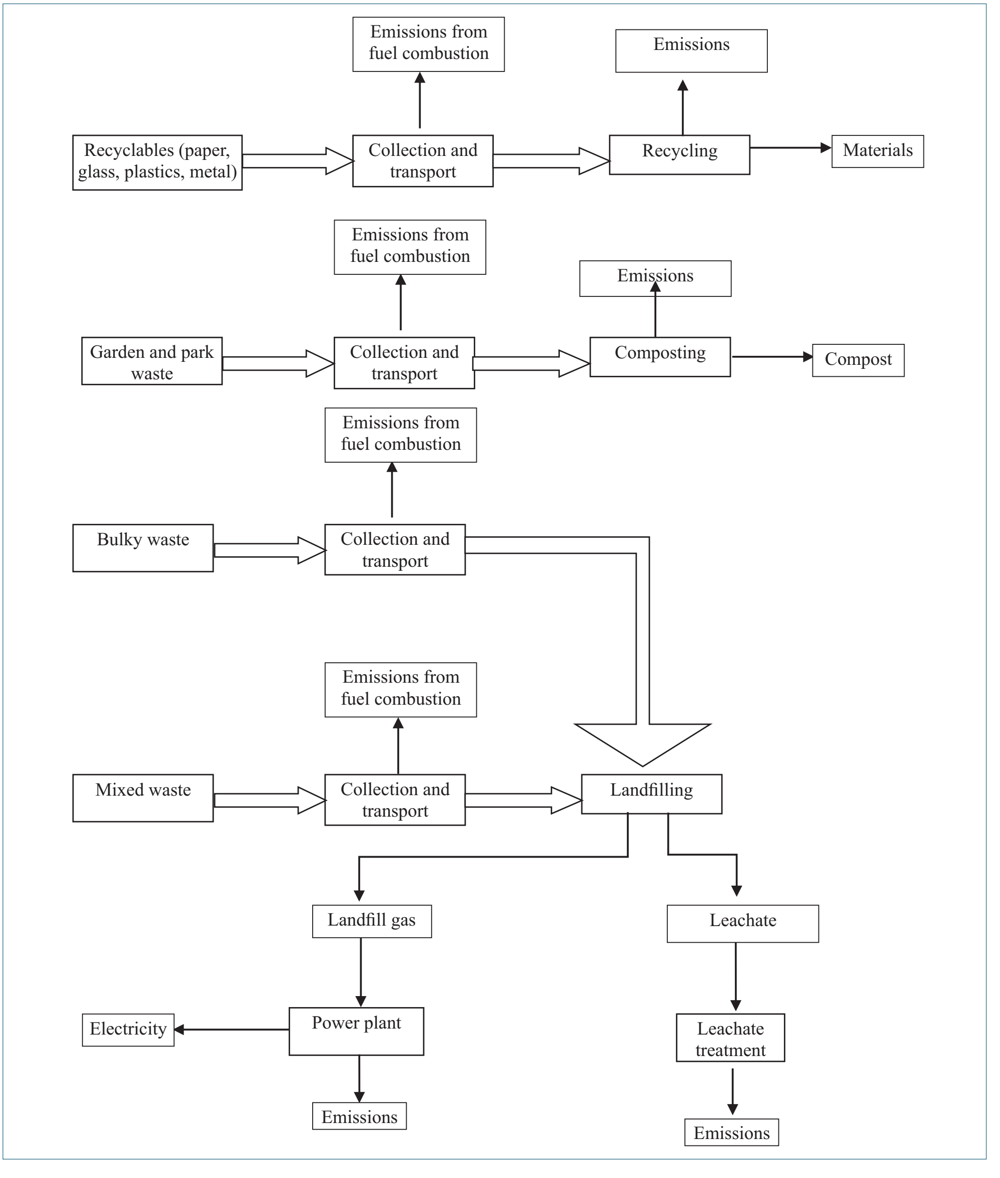

Fig. 1. System boundaries

The exact process of data input, calculation, data estimation for modeling the waste management system in the IWM-PL application, has been described in [6]. Below are the essential data entered into the model for the purposes of this analysis.

33,041 Mg of collected unsorted solid municipal waste was entered. Its morphological composition has been presented in Table 2. The weight of collected bulky waste was 649.4 Mg. The amount of waste which was selectively collected to individual containers was entered as follows: paper – 1,444 Mg, glass – 1,194.9 Mg, plastics – 427 Mg, metals – 6.6 Mg, organic waste – 584 Mg. Average fuel consumption (diesel) during the collection and transportation of the selectively collected waste was calculated at 1.6 L/Mg of waste. Composting was adopted as the process of biological treatment of organic waste, the loss of weight during the decomposition of organic matter was adopted at the level of 50%, the consumption of electricity per 1 Mg of organic waste was adopted at 30 kWh. In the process of landfilling mixed (residual) municipal waste, electricity consumption was calculated at 5.74 kWh/Mg of waste, the consumption of fuel (diesel) was calculated at 3.10 L/Mg of waste. The effectiveness of landfill gas collection was adopted at the level of 65%, and the recovery of energy from landfill gas at 40%. The amount of energy in the IWM-PL model was adopted at the level of 1.5 kWh/Nm^3 of the collected landfill gas. The efficiency of collecting leachate was adopted at 90%, the efficiency of treatment of leachate at 85%. The transportation distances for secondary raw materials for recycling were estimated based on the location of the recycling plant closest to Tarnów. The following values were entered into the model: paper – 88 km, glass – 9 km, ferrous metals – 180 km, plastics – 70 km.

After all the data and parameters of waste treatment plant have been entered, the model calculates emissions to water and air. For all pollutants, the quantities of emitted pollutants are given in kilograms per one functional unit, i.e. the total amount of municipal solid waste entered into the system. The emission values of individual substances can be positive or negative. Negative values stand for "avoided impacts", when municipal waste management system generates environmental benefits, i.e. useful products, such as secondary raw materials recovered from recycling or energy from incineration.

During the next stage of LCA, the results of the inventory (emission values) are converted into environmental impact categories. Different methodologies of LCIA (Life Cycle Impact Assessment) are used for this purpose. The IWM-PL model is based on the methodology of the Eco-indicator 99, which considers three damage categories: human health, ecosystem quality and resources. Several impact categories are assigned to the damage categories. For each impact category, a category indicator is calculated. Since indicators of individual categories are incomparable, during the normalization stage of individual values, the impact category indicators are divided by a common reference value. In the methodology of the Eco-indicator 99, such a reference value is the averaged annual environmental impact made by one European citizen. The results obtained in this procedure are expressed in eco-points (Pt), where one eco-point is interpreted as one-thousandth of the total environmental impact caused by the statistical European citizen per year.

The IWM-PL model does not use the full methodology of the Eco-indicator 99, but only its limited extent. The damage category of natural resources has not been included. The other two damage categories are limited. The precise description of the Eco-indicator 99 methodology and the methodology used in the IWM-PL model has been provided in [5].

The IWM-PL model converts the calculated values of emissions to air and water into 6 impact categories: carcinogens (Carcinogenic effects on humans), Respiratory organics (Respiratory effects caused by organic substances), Respiratory inorganics (Respiratory effects caused by inorganic substances), climate change, acidification/eutrophication, ecotoxicity.

3. Results and Discussion

The results of the inventory (LCI), which are emissions to air and water, have been converted into values of impact category indicators. Figure 2 illustrates the environmental impact of emissions to air, and Figure 3 presents the environmental impact of emissions to water, in six impact categories. Figures 2 and 3 show the results after the normalization stage.

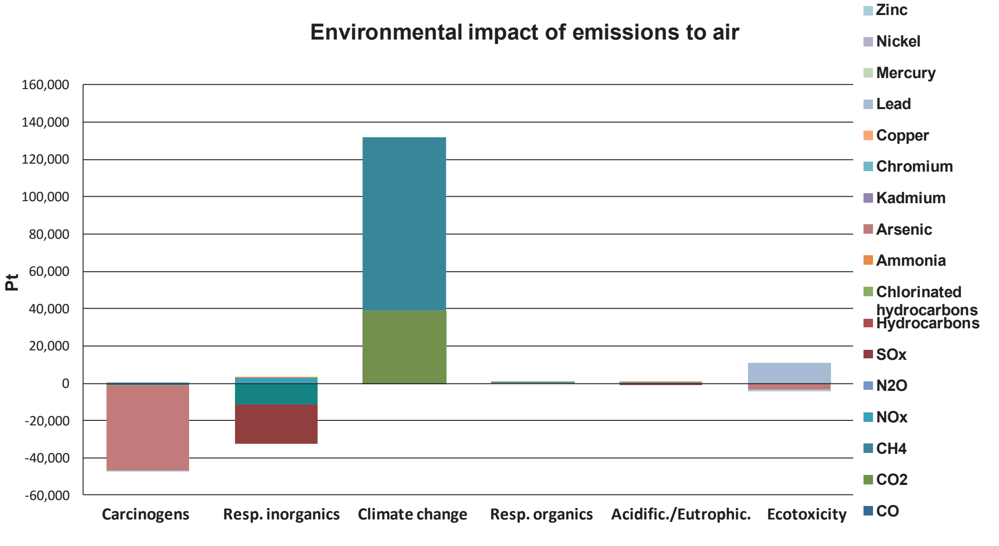

Fig. 2. Environmental impact of emissions to air of the waste management system in Tarnów, after the normalization stage, in six impact categories

Source: [11]

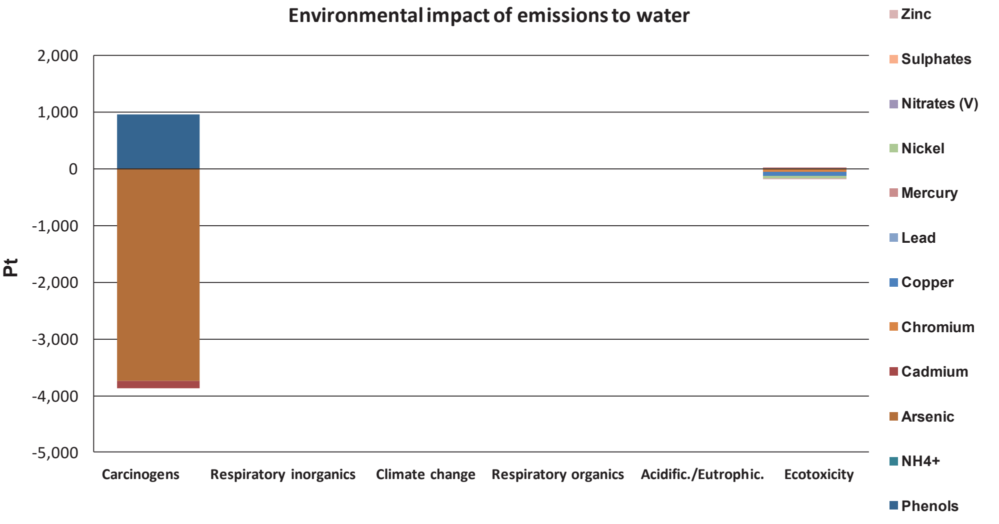

Fig. 3. Environmental impact of emissions to water of the waste management system in Tarnów, after the normalization stage, in six impact categories

Source: [11]

For the environmental impact of emissions to air, the highest value is reached by the climate change indicator, which is circa 131,000 Pt. The main substances which contribute to the high value of the climate change category indicator are emissions of CH_4 and CO_2. The emission value of these substances per functional unit amounts to 811,991.68 kg of CH_4 and 7,076,540.71 kg of CO_2. Both substances are the main components of landfill gas obtained from the decomposition of organic matter under anaerobic conditions during the landfilling of mixed municipal solid waste. The positive value of the indicator is observed in the ecotoxicity category, where lead (Pb) has the greatest share. The negative values of the indicators are observed in the categories of carcinogens and respiratory inorganic. "Avoided" emissions of arsenic (As) in the category of carcinogens and "avoided" emissions of nitrogen oxides and particulate matter in the category of respiratory inorganic contribute to the negative values in these categories. The avoided impacts are associated with the generation of electricity from landfill gas as an alternative to fossil fuels burned in conventional power plants.

In assessing the environmental impact of emissions to water, the negative value of the indicator appears in the category of carcinogens. It is associated with the avoided emissions of arsenic As. The positive value in this category is caused by emissions of phenols to water.

The final result of Life Cycle Assessment of the municipal solid waste management system in Tarnów has been presented in Figure 4, where the values of the indicators are calculated for two damage categories: ecosystem quality (6,193.77 Pt) and human health (52,676.57 Pt). Municipal solid waste management system has a negative impact on the environment in both damage categories: ecosystem quality and human health, with a significantly higher negative impact observed for human health than for ecosystem quality. The high value of the indicator in the damage category "human health" is determined primarily by the very high value of the indicator in the impact category of climate change, which is 131,000 Pt. The substances which are responsible for such a high value of the indicator in this category are emissions of methane and carbon dioxide. Therefore, the process of waste landfilling and emissions of greenhouse gases from the decomposition of organic matter under anaerobic conditions determine the negative impact of the municipal waste management system on the environment.

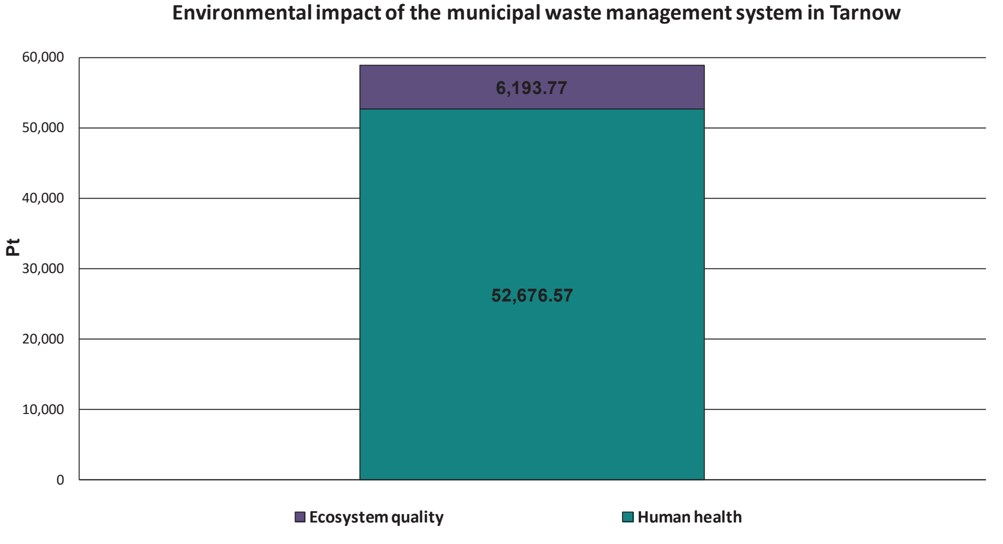

Fig. 4. Environmental impact of the municipal solid waste management system in Tarnów, in two damage categories

Source: [11]

4. Conclusions

1. The performed Life Cycle Assessment for the waste management system in Tarnów in 2012, using the IWM-PL model, revealed a negative impact on the environment. The final result expressed in eco-points (Pt) in two damage categories: "human health" and "ecosystem quality", is much higher for the "human health" category than for the "ecosystem quality".
2. The high indicator value of the damage category "human health" is caused by a huge value of the climate change indicator (131,000 Pt). Emissions of methane and carbon dioxide from waste storage processes contribute primarily to this impact category.

3. The process of waste storage generates useful products in the form of recovered electricity from landfill gas, however, adverse effects of landfilling outweigh the benefits.
4. Changes to the waste management system and abandoning landfilling of mixed municipal solid waste (including bio-waste) can reduce the negative impact on the environment.

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