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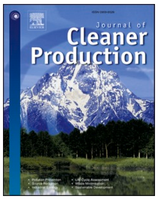

Life Cycle Assessment for the environmental impact assessment of a city' cleaning system. The case of Cracow (Poland)

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ABSTRACT

In large urban agglomerations, the composition and amount of municipal waste are diversified and depend on the level of wealth, season, number of tourists, etc. In city strategies, there is a visible search for solutions that minimize the impact on the environment and optimize costs incurred by residents. One of the municipal waste streams is street sweepings, i.e. waste generated as a result of street cleaning processes, classified under the code 200303 and is not treated as hazardous waste. Their quantity, quality, and seasonal variability have an impact on the natural environment, including air quality. Their removal reduces the amount of PM10 and PM 2.5. They are usually disposed of the landfills. In Cracow, where air emissions have been successfully reduced in recent years via different actions, experimental studies were carried out on the impact of mechanical street cleaning on air quality, and methods of their management were discussed. The article analyzes various technological solutions based on the LCA (Life Cycle Assessment) methodology for assessing the environmental impact of technologies and waste generated in the processes of street cleaning in urbanized areas. It is used to assess the impact of individual products, technologies, strategies or systems on the environment, taking into account emissions "from the cradle to the grave". In the latest documents of the European Commission, the LCA method is recommended for the analysis of environmental performance measurement in the life cycle of products and organizations. The presented calculations in the SimaPro software showed that for the adopted assumptions, on the example of a selected street section, it is possible to reduce the impact by 5 times, as a result of city cleaning processes. The calculations take into account the consumption of water, fuel, and the operation of the machinery as well as the management of sweeping waste and wastewater treatment. The process of managing this type of waste reduces emissions related mainly to toxic effects for humans (carcinogenic and non-carcinogenic effects), reduction of solid particles and ecotoxicity for freshwater. Comparing the analyzed scenarios (scenario 1 - after cleaning the city and scenario 0 - before), scenario 1 is characterized by a much lower impact on the environment. Although there are loads in this scenario 1 in each impact category of EF 3.0, the overall result is still lower than in all scenarios 0 options. In scenario 1, the environmental impact mainly relates to the freshwater ecotoxicity, ionizing radiation and climate change categories, which are qualitatively different. From scenario 0, where the greatest environmental impact is in the particulate matter category.

1. Introduction

LCA is already a widely used technique to assess the potential environmental impact of various municipal waste management options. (Kulczycka et al. in., 2015, 2016). For large urban agglomerations, this often applies to the assessment of the entire system (Zhou et al., 2011; Gao et al., 2018)). From this perspective, LCA (Life Cycle Assessment) results can be the basis for decision-making processes in public entities,

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e.g. central and local administration (de la Rúa Lope et al., 2017; Lewandowska et al., 2013), to eliminate the threats of the so-called hot spot and used in green public procurement GPP (Aghbashlo et al., 2020; Lelek and Kulczycka, 2021). Despite many studies and projects for cities and regions, there are few works on identifying the impact of sweeping management on air condition Generowicz et al., (2019), 2020; Polukarova et al. (2020); and various methods of their disposal (Lloyd et al., 2019; Amato et al., 2014; Alves et al., 2018). Therefore, this article attempts to identify the impact based on real data obtained during street cleaning in Cracow. For many years, Cracow has been intensifying its activities for clean air. It is the first city in Poland that has banned the use of solid fuels for heating purposes by residents (2019) and has also implemented a mechanical city cleaning system consisting in increasing the frequency of sweeping and washing and introducing additional street washing to implement the procedure in the event of a smog alert in Cracow, as a result of air pollution with PM10 dust. As part of the research on the effectiveness of the waste treatment system, studies on the significance of these measures for changes in the quality of the environment and the improvement of the quality of life of the inhabitants were also undertaken.

2. Literature review

Life Cycle Assessment (LCA) is defined according to ISO 14040 (EN ISO 14040 of 2009) as one of the most attractive decision support frameworks for estimating the total environmental impact of a product/process in environmental impact assessment studies (Aghbashlo et al., 2020; Mandegari et al., 2017). The method takes into account all the factors potentially influencing the environment, i.e. emission, energy consumption, quantity and quality of generated waste as well as materials and raw materials used (Zhou et al., 2011; de la Rúa Lope et al., 2017). LCA can perfectly reflect the multiple impacts on natural resources, human health and the quality of ecosystems. LCA life cycle assessment as one of the environmental management techniques is recognized and recommended as a tool for the assessment of environmental projects in many areas of economic activity (Lewandowska et al., 2013; Kulczycka et al., 2015). It is worth noting that the LCA perspective on the environmental performance of products has made it a central concept for both industrial environmental management and environmental policy making in government and public administration (Meyer and Upadhyayula, 2014; Yay, 2015).

LCA is used in many areas to assess technologies, systems or processes for municipal solid waste management systems (Farzad et al., 2017; Kulczycka et al., 2015), as well as to compare waste collection systems, the environmental effects of waste disposal, incineration and other waste management scenarios (Dong et al., 2018; Mayer et al., 2021; Beylot et al., 2018; Pérez et al., 2021; Kulczycka et al., 2015; Lelek and Kulczycka, 2021; Generowicz et al., 2020). It also makes it possible to conduct assessments for waste management in cities. Comparative LCA studies of alternative municipal solid waste management systems in the literature include the use of LCA (Grzesik and Malinowski, 2016; Tunesi, 2011). There are only two articles in the literature comparing the environmental effects of different types of streets sweeping services using the LCA method (Bartolozzi et al., 2018; Gilardino et al., 2017), but they do not focus on air quality. In street cleaning waste, apart from numerous pollutants in the form of hydrocarbons (Mummullage et al., 2016) and heavy metals (Shi et al., 2010; Generowicz et al., 2019), especially in fine fractions below 10 mm (Gronba-Chyła et al., 2021; Ciuła, 2022), where the most common metals are: arsenic, mercury, lead, copper, cadmium, zinc, nickel and chromium (Zhang et al., 2017; Alves et al., 2018; Lloyd et al., 2019). In the publication (Shi et al., 2010) is shown that all metals except arsenic, compared to the background values, are accumulated in significant amounts. These wastes, especially in the winter season, also show a high concentration of chlorides (Gronba-Chyła, 2022). They are also present in nitrates and phosphates (Pearson et al., 2018; Malakootian et al., 2022).

It is known that many organic pollutants are emitted in the road environment, e.g. from exhaust gases, fuels, lubricating oils, road construction materials, and vehicle components such as bodywork, brakes and tires (Peikertova and Filip, 2016; Generowicz et al., 2020). The tiniest fractions that constitute the most difficult pollutants consist of minerals, rubber, asphalt, other organic materials and emulsions (Aryal et al., 2017), and they contain a lot of organic pollutants. In street-sweeping materials, a strong correlation was observed between smaller particle sizes and high concentrations of metals and PAHs (Lloyd et al., 2019). Pollution from street sweeping can cause re-suspension of particles of various sizes PM2.5 and PM10 in the air (Kryłów and Generowicz, 2019), which in turn causes high human exposure to heavy metals, metalloids and minerals (Amato et al., 2009). Many articles describe the negative impact of road dust on human health (Tan et al., 2018; Wu et al., 2018), they increase the incidence of people, especially respiratory diseases, allergies and dermatological diseases. Workers directly cleaning streets are particularly at risk (Priyanka and Kamble, 2017; Sobiecka et al., 2010). Non-fuel sources of particulate matter related to road traffic and road dust are an increasingly important source of PM10 air pollution (Gustafsson et al., 2019; Alwaeli et al., 2020). Increased road traffic is a major contributor to the increase in PM levels in cities (Amato et al., 2010, 2014; Bogacki et al., 2018). In addition, the storage of street cleaning waste in landfills significantly contributes to the increase in dustiness in this area with particulate matter (Chalvatzaki et al., 2010; Zhao et al., 2016). It has been shown that frequent sweeping along with street washing effectively reduces the amount of PM10 and PM2.5 in the air (Kryłów and Generowicz, 2019; Karanasiou et al., 2012). Taking into account the above, an attempt was made to assess the life cycle of street cleaning, assuming its deposition on the streets or the processes of removal, cleaning and final disposal (Amato et al., 2010; Bogacki et al., 2018). This is important as most countries lack national regulations for the disposal of street-sweeping waste, so waste is often deposited in landfills, where there is a risk that the pollutants will be released back into the environment (Markiewicz et al., 2019; Polukarova et al. al., 2020; Fan et al., 2019).

3. Goal and methodology of the research

The aim is to compare the potential environmental impacts of waste disposal processes from street cleaning. The assessment was given a reference scenario assuming no waste disposal, and then the obtained results were compared with the scenario assuming the disposal of a certain amount of waste removed from the assumed area and within a specified time frame. This approach allowed the assessment of the potential environmental damage caused under the reference scenario and the environmental benefits of disposing of a given amount of waste. The method used to assess the potential environmental impact was the LCA (Life Cycle Assessment), which enables a holistic analysis of the environmental impact of products, processes, technologies, or entire systems. The functional unit was the evaluation of the mechanical cleaning process of a street section with a defined area in a weekly cycle (7 days, after a 7-day cleaning break). The research on the quantity and quality of waste generated in the cleaning process was carried out during the full annual cycle in 2015, and the 7-day cycle in September was used for the LCA assessment.

As part of the research, methodology development, and sampling preparation, the following tasks were performed:

- Choosing the area and streets for cleaning
- Sampling preparation for quality laboratory tests of waste and sewage from street cleaning
- Gravimetric measurements of cleaning cars to determine the amount of collected waste
- Laboratory tests of waste and sewage collected on the studied routes
- LCA life cycle analysis using SimaPro software with a comparison of potential impacts in variant scenarios for dealing with street cleaning waste

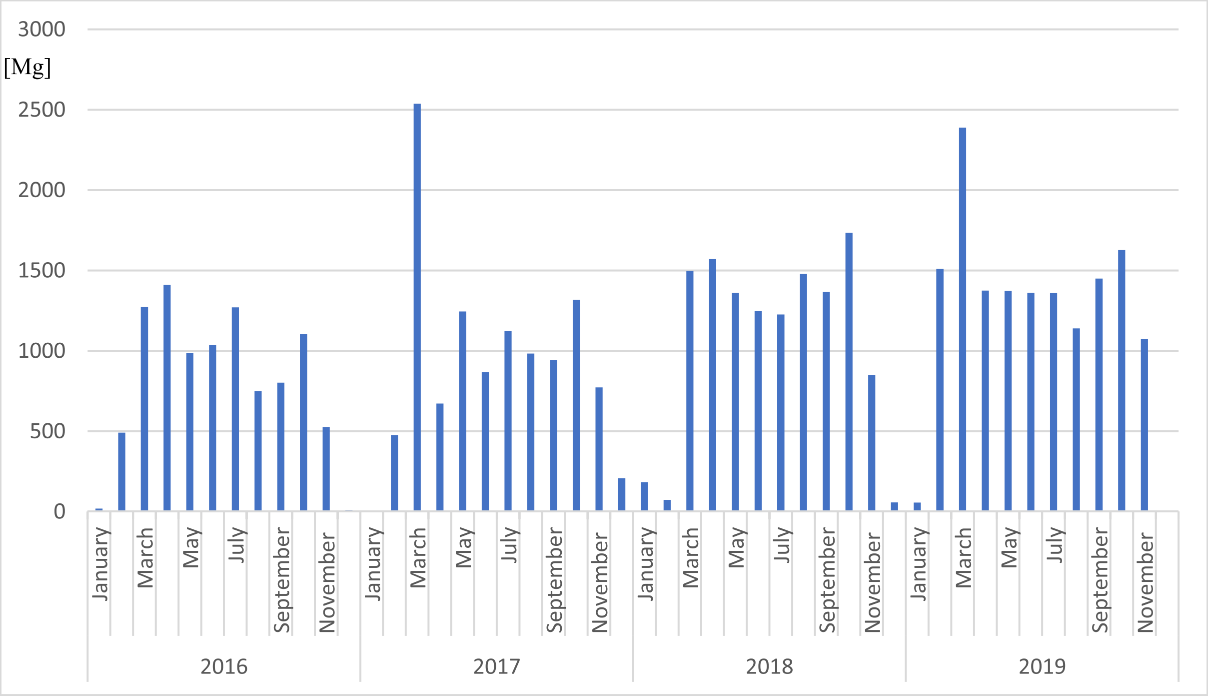

Fig. 1. Accumulation of sweeping waste collected in Cracow in 2016–2019 (Generowicz et al., 2020).

4. Description of the research

The research was conducted in Cracow (Poland) with 1 million inhabitants. In 2019, as part of the Integrated Municipal Waste Management System and collection points, 388,926.11 Mg of all municipal waste was collected, which is an increase of 6.41% compared to the amount of municipal waste collected in 2018 (363,988.72 Mg). Street cleaning generates an additional waste stream-sweepings, the amount of which varies depending on the season **(**Generowicz et al., 2020). This accumulation is presented in a chart showing the accumulation of sweepings in 2016–2019, because the full cleaning and washing cycle started in 2016.

According to Fig. 1, in the following years, the distribution of the amount of waste collected from the streets is quite stable. The accumulation increases are characteristic in the early spring period when street cleaning and washing activities begin after winter, and in the fall (October), when leaves falling from the trees on the streets and sidewalks (Generowicz et al., 2020). The accumulation of waste in the early spring, in comparison to the entire year, is the highest, reaching even 2, 500 Mg per month (in 2017 and 2019).

The research was carried out on a street located in a high-rise residential estate, inhabited by approx. 20 thousand people. Streets and roads undergoing cleaning processes are primarily access routes to housing estates and flats. The measured section of the street was over 1.1 km (in both directions), it is an access road for residents with a variable width of 9–10 m (with bays for buses +3 m), no parking spaces along the streets, no green belt between the lanes the road and the sidewalk (2 m wide pavement along the entire street on both sides of the road). On one side of the street there is high-rise, modern multi-family residential buildings, on the other side also residential buildings and greenery. The area of the cleaned street was 12,100 m^2. The research was conducted over 7 consecutive days. Every day in the evening, both sides of the street were swept, and then washed in such a way that it was possible to sample the sewage at the curb, and the collected sewage would run off the entire width of the road. The car road sweeper was weighed before and after cleaning in order to determine the amount of sweepings collected. After weighing, samples were taken straight from the car for chemical analysis. During the experiments, sweepers MPO Sp. z o. o. in Cracow, which meet the highest ecological standards concerning emissions (EURO 6) were used. All devices were PM10 certified. The sweepers worked in a wet system with recirculation of water, which means that the water was used many times during the sweeping process. The collected samples of sweeps and sewage were sent for laboratory tests. The following determinations were made in the sweeping waste: total dry weight; dry matter, mineral and organic matter, heavy metals (Cr, Zn, Cd, Mn, Ni, Pb). Wastewater was analyzed in terms of total, mineral and organic suspended solids, nitrates (V), nitrates (III), ammoniacal nitrogen, total Kjeldahl nitrogen, sulphates (VI), chlorides and heavy metals (Cr, Zn, Cd, Mn, Ni, Pb).

The results of the laboratory and gravimetric tests were used for LCA. The assessment was given the reference scenario 0, assuming no waste disposal, and then the obtained results were compared with scenario 1, assuming the disposal of a certain amount of waste removed from the planned area. In order to remove waste, it is necessary to use an appropriate cleaning infrastructure, which was also included in the analysis. The boundaries of the system assessed under Scenario 1 assume that waste will be neutralized by sweeping urban surfaces and washed them with water. The waste was collected and stored. Some part in the form of sewage ended up in the municipal sewage system and another part was transported to the municipal sewage treatment plant for disposal. The period for cleaning processes was assumed to be 7 days.

Life-cycle assessment was performed using SimaPro software (9.3.0.3. Developer) and the EF 3.0 Method (adapted) v. 1.02. SimaPro is one of the most popular and commonly used software for life cycle analysis. It has been in the market for more than 15 years. It has many advantages. It is flexible, equipped with many LCI datasets, user friendly and generates transparent results. It provides impact assessment results but also shows the contributors of the impacts. SimaPro enables creation of various scenarios and models comparison. The EF method is the impact assessment method adopted in Environmental Footprint transition phase of the European Commission. The implementation is based on EF method 3.0 published for use during the EF transition phase. It includes the normalization and weighting factors published in November 2019 by EC (European Commission, 2019).

Table 1
The amount of accumulated waste in 7 days without cleaning, for analyzed area (Generowicz et al., 2020).

Waste accumulated	Following days of maintaining cleanliness in Cracow, on selected street						
	1	2	3	4	5	6	7
after 7 days without surface cleaning [kg]	340,00	180,00	140,00	140,00	140,00	140,00	140,00

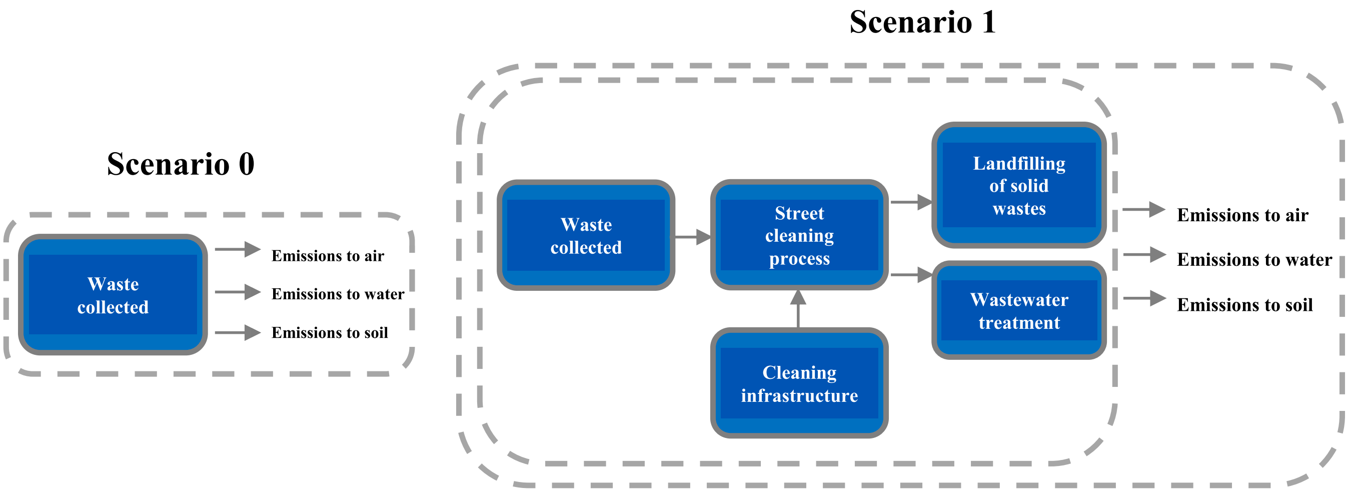

Fig. 2. System boundaries for Reference Scenario 0 and Scenario 1.

Table 2
Composition of waste from the first day of testing, after 7 days without cleaning and emissions from uncollected waste in scenario 0 (Generowicz et al., 2020).

	Indicator	Unit	Sample 1	Sample 2	Sample 3	Average	Emissions to air	Emissions to water	Emissions to soil
Option I	Dry matter	[g/kg s.m.]	75,96	77,9	82,1	78,65	55,06	11,80	11,80
	Mineral dry matter (550 °C)	[g/kg s.m.]	96,97	98	98,2	97,72	68,41	14,66	14,66
	Organic dry matter (550 °C)	[g/kg s.m.]	3,03	1,96	1,8	2,26	1,58	0,34	0,34
	Cadmium	mg/g s.m.	4,46	5,18	5,74	5,13	3,59	0,77	0,77
	Nickel	mg/kg s.m.	22,36	24,57	27,82	24,92	17,44	3,74	3,74
	Copper	mg/kg s.m.	123,86	212,87	177,19	171,31	119,91	25,70	25,70
	Lead	mg/kg s.m.	40,36	38,53	61,37	46,75	32,73	7,01	7,01
	Zinc	mg/kg s.m.	307,77	320,02	373,4	333,73	233,61	50,06	50,06
	Chromium	mg/kg s.m.	109,6	125,56	131,33	122,16	85,51	18,32	18,32
	Manganium	mg/kg sm	751,57	741,84	873,45	788,95	552,27	118,34	118,34
Option II	Dry matter	[g/kg s.m.]	75,96	77,9	82,1	91	39,33	19,66	19,66
	Mineral dry matter (550 °C)	[g/kg s.m.]	96,97	98	98,2	97,72	48,86	24,43	24,43
	Organic dry matter (550 °C)	[g/kg s.m.]	3,03	1,96	1,8	2,26	1,13	0,57	0,57
	Cadmium	mg/g s.m.	4,46	5,18	5,74	5,13	2,56	1,28	1,28
	Nickel	mg/kg s.m.	22,36	24,57	27,82	24,92	12,46	6,23	6,23
	Copper	mg/kg s.m.	123,86	212,87	177,19	171,31	85,65	42,83	42,83
	Lead	mg/kg s.m.	40,36	38,53	61,37	46,75	23,38	11,69	11,69
	Zinc	mg/kg s.m.	307,77	320,02	373,4	333,73	166,87	83,43	83,43
	Chromium	mg/kg s.m.	109,6	125,56	131,33	122,16	61,08	30,54	30,54
	Manganium	mg/kg sm	751,57	741,84	873,45	788,95	394,48	197,24	197,24
Option III	Dry matter	[g/kg s.m.]	75,96	77,9	82,1	91	25,96	25,96	25,96
	Mineral dry matter (550 °C)	[g/kg s.m.]	96,97	98	98,2	97,72	32,25	32,25	32,25
	Organic dry matter (550 °C)	[g/kg s.m.]	3,03	1,96	1,8	2,26	0,75	0,75	0,75
	Cadmium	mg/g s.m.	4,46	5,18	5,74	5,13	1,69	1,69	1,69
	Nickel	mg/kg s.m.	22,36	24,57	27,82	24,92	8,22	8,22	8,22
	Copper	mg/kg s.m.	123,86	212,87	177,19	171,31	56,53	56,53	56,53
	Lead	mg/kg s.m.	40,36	38,53	61,37	46,75	15,43	15,43	15,43
	Zinc	mg/kg s.m.	307,77	320,02	373,4	333,73	110,13	110,13	110,13
	Chromium	mg/kg s.m.	109,6	125,56	131,33	122,16	40,31	40,31	40,31
	Manganium	mg/kg sm	751,57	741,84	873,45	788,95	260,35	260,35	260,35

5. Development of life cycle assessment

5.1. Functional unit and system boundaries

The main assumptions of each scenario are:

- Scenario 0- leaving streets without cleaning and accumulating waste for 7 days, and in consequence causing emissions to soil, water, and air,
- Scenario 1 - removal of waste for 7 consecutive days, using appropriate cleaning infrastructure (sweepers and washing trucks), disposal of collected waste at a landfill and wastewater at a

Table 3
The inventory data for scenario 1.

Inputs	Unit	Amount
Fuel (diesel)	litre	637
Tap water	m3	336
Landfilled waste	kg	1220
Wastewater	m3	336
including:		
Suspension	[g/dm^3]	5,107
Mineral suspension (550 °C)	[g/dm^3]	4,474
Suspension, organic (550 °C)	[g/dm^3]	0,633
Nitrate	[mgN/dm^3]	4,29
Nitrite	[mgN/dm^3]	0,143
Nitrogen	[mgN/dm^3]	11,35
Kiejdahl's total nitrogen	[mgN/dm^3]	6,918
Ammonium nitrogen	[mgN/dm^3]	0,2939
Organic nitrogen	[mgN/dm^3]	6,6241
sulfates	$mgSO_4/dm^3$]	45,7
chlorides	[mg/dm^3]	44,5
Nickel	[mg/dm^3]	0,034
Copper	[mg/dm^3]	0,092
Cadmium	[mg/dm^3]	0,008
Lead	[mg/dm^3]	0,029
Zinc	[mg/dm^3]	0,359
Chromium	[mg/dm^3]	0,05
Manganium	[mg/dm^3]	0,353

Table 4
Cumulative environmental impact indicator for Scenario 0, with option analysis.

No.	Unit process	Eco-indicator points [Pt]	Change in the indicator in relation to option III
1.	Option I	0,5862	101,9%↑
2.	Option II	0,4294	47,9%↑
3.	Option III	0,2904	–

municipal treatment plant. This scenario takes into account the cleaning processes including the infrastructure required for the process in the form of sweepers, the fuel and water they consume (without cleaning agents), as well as the disposal of the collected waste at the municipal landfill and the wastewater from the cleaning process at the municipal wastewater treatment plant;

- In order to reflect the life cycle of the cleaning infrastructure, the transportation data was taken from the Ecoinvent database on a truck with a load of 3.5–7.5 tons, i.e. reflecting the payload of the aforementioned sweeper (5 tons), and meeting EURO6 emission standards.
- For Scenario 0, 3 variants of pollutant distribution between air, water and soil were assumed due to the lack of literature data to simulate pollutant distribution

In order to clearly and measurably define the scope of the analysis, a functional unit was defined. For this purpose, quantitative data on the disposal of waste from an area of land equal to 12100 m2, for a period of 7 days, was adopted.

In order to clearly and measurably determine the scope of the analysis, a functional unit was defined. For this purpose, quantitative data on the disposal of waste from an area of 12100 m2, for a period of 7 days were used (Table 1). According to Table 1, the weight of accumulated waste is 1220 kg. The system boundaries for Scenario 0 and Scenario 1 are shown in Fig. 2.

5.2. *Inventory data*

Data on the amount of waste accumulated in the analyzed area, over the next 7 days, are shown in Table 1.

In the analyzed cases, the environmental impact is related to the streams and flows presented in Tables 2 and 3. Among them are elementary streams, i.e., entering or exiting directly into the environment (e.g., emissions), as well as human-processed products/goods (exchanges between the product system and the technosphere/systems of other products, e.g., tap water, fuel). Each material already processed, e.g. electricity, has its technological history implying consumption of further materials and generation of emissions and waste, which translate into a burden on the environment.

Due to the difficulty of modeling the distribution of pollutants among environmental components (air, water, soil), three variants of Scenario 0 were assumed, using different distributions of individual pollutants across air, water and soil.

5.2.1. *Scenario 0*

The analysis for scenario 0 includes 3 different emission variants, assuming different distribution of pollutant emissions to the environment:

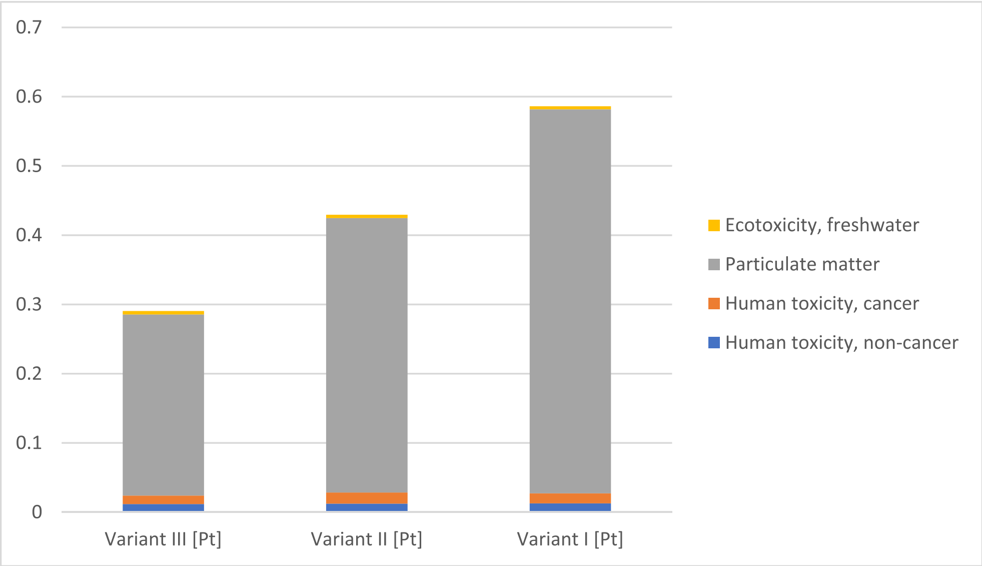

Fig. 3. Impact assessment for Scenario 0, along with its option analysis.

Table 5
Characterization results for 3 options in scenario 0.

Impact category	Unit	Option III (33%, 33%, 33%)	Option I (70%, 15%, 15%)	Option II (50%, 25%, 25%)	Option III (33%, 33%, 33%)	Option I (70%, 15%, 15%)	Option II (50%, 25%, 25%)
Human toxicity, non-cancer	Pt	0,0117	0,0128	0,0123	4,03%	2,86%	2,18%
Human toxicity, cancer	Pt	0,0123	0,0144	0,0162	4,24%	3,77%	2,46%
Particulate matter	Pt	0,2615	0,5546	0,3962	90,05%	92,27%	94,61%
Ecotoxicity, freshwater	Pt	0,0049	0,0044	0,0047	1,69%	1,09%	0,75%
Total	**Pt**	**0,2904**	**0,5862**	**0,4294**	**100%**	**100%**	**100%**

Table 6
Sources of environmental impact for the five most significant impact categories for Scenario 0, with an option analysis.

The most important emissions affecting the environment in a given impact category	Flow contribution in impact categories OPTION I [%]	Flow contribution in impact categories OPTION II [%]	Flow contribution in impact categories OPTION III [%]
Human toxicity, cancer			
Emissions to air: Chromium	71,3	63,2	39,4
Emissions to water: Chromium	10,3	15,2	26,6
Emissions to soil: Chromium	9,8	14,6	25,4
Total	91,4	93,0	91,4
Human toxicity, non-cancer			
Emissions to air: Lead	43,7	35,5	22,5
Emissions to air: Cadmium	20,0	14,9	10,3
Emissions to soil: Lead	14,4	25,0	34,7
Emissions to soil: Cadmium	7,2	12,5	17,3
Total	95,3	87,9	82,8
Particulate matter			
Emissions to air: Particulates, < 10 μm (mobile)	100	100	100
Ecotoxicity, freshwater			
Emissions to air: Copper	54,2	36,1	22,8
Emissions to water: Copper	15,8	24,6	31,1
Emissions to soil: Copper	16,7	26,0	32,9
Total	86,7	86,7	86,8

Table 7
Characterization results for 3 variants in scenario 0.

Impact category	Unit	Option III (33%, 33%, 33%)	Option I (70%, 15%, 15%)	Option II (50%, 25%, 25%)
Human toxicity, non-cancer	CTUh	0,00015	0,000159	0,000153
Human toxicity, cancer	CTUh	0,00001	0,000011	0,000013
Particulate matter	disease inc.	0,00174	0,003685	0,002632
Ecotoxicity, freshwater	CTUe	11000,22	9817,44	10534,06

- Option I - 70% of dry matter waste are emissions to the air, other pollutants, including heavy metals, stand for emissions to soil (15%) and water (15%)
- Option II - 50% of dry matter waste are emissions to the air, other pollutants, including heavy metals, stand for emissions to soil (25%) and water (25%)
- Option III - 33% of dry matter waste are emissions to the air, other pollutants, including heavy metals, stand for emissions to soil (33%) and water (33%)

The final emissions modeled in the environmental impact assessment, calculated in accordance with the above-mentioned assumptions are presented in Table 2.

5.2.2. Scenario 1

As part of the research and analysis of cleaning processes, the equipment used for this purpose requires the consumption of 91 dm3 of diesel and 48 m3 of water per day for analysed area. The resulting environmental impact was divided into 3 aspects:

- impact related to water consumption and fuel combustion,
- impact related to the storage of collected waste,
- impact related to the disposal of wastewater at the city's wastewater treatment plant.

The inventory data for scenario 1 is shown in Table 3.

5.3. LCA results

The analysis was carried out in Sima Pro (version 9.3.0.3 Developer). All datasets used for the process modelling come from Ecoinvent database (version 3.8). Analysis of 3 variants of Scenario 0 showed that Option I has the highest environmental impact (70% of dry matter waste are emissions to air, 15% to soil 15% to water reaching 0.5862 Pt (Table 4). The lowest environmental burden arises in the ecotoxicity category. The different magnitudes of individual emissions (in a given variant) only cause differences within the same impact categories. Thus, qualitatively for all of the analyzed variants, the impacts are associated with the following impact categories: human toxicity (carcinogenicity), human toxicity (non-carcinogenicity), particulate matter and freshwater ecotoxicity (Fig. 3). Results in Table 5 and Fig. 3 show that the highest negative environmental impact is related to particulate matter emissions, which stands for more than 90% of all impact categories in each option.

Emissions responsible for the impact in these 4 impact categories, as well as their share in the overall category index are presented in Table 6. According to the data presented for the category of carcinogenic effect, the most significant pollutant is chromium accounting in all analyzed options for more than 90% in the overall category index. For the non-carcinogenic effect, the dominant impact is due to emissions of lead (to soil and air) and cadmium (to soil and air). The combined impact of these emissions accounts for more than 80% percent of the total impact of the impact category, per option. In the case of freshwater ecotoxicity, the highest negative environmental impact is caused by copper (emissions to soil, water and air), which stands for than 85%. Particulates <10 μm (mobile) are responsible for 100% of impact in particulate

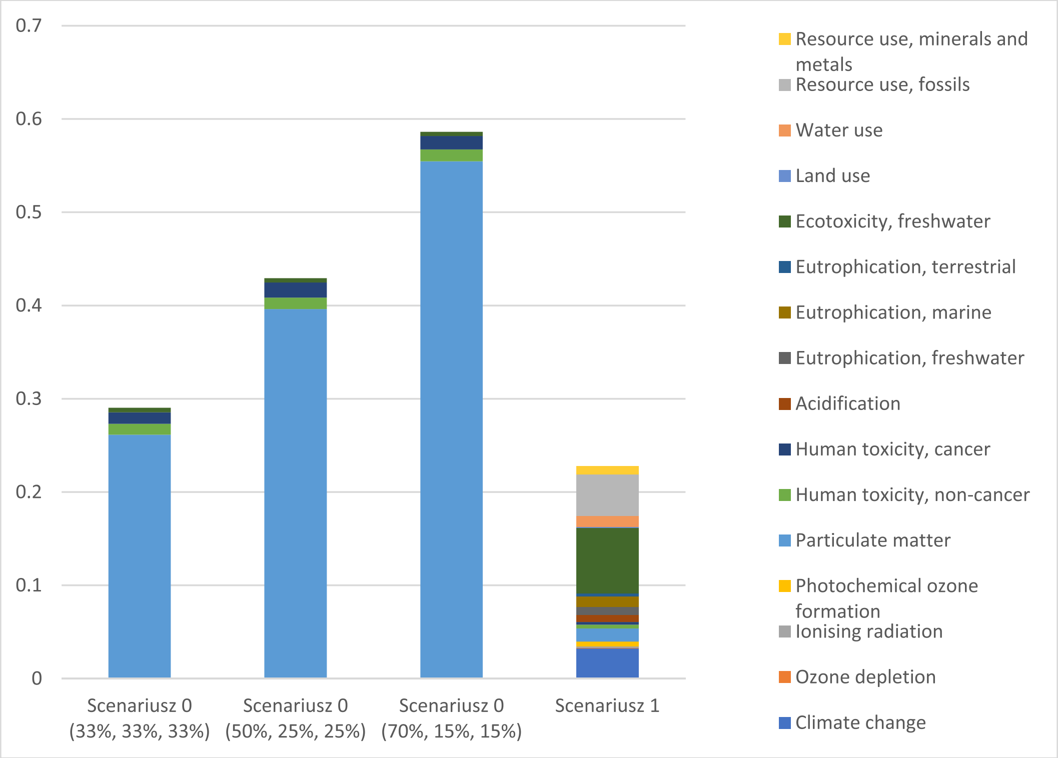

Fig. 4. Comparison of impact assessment for Scenario 0 and all variants of Scenario 1.

Table 8
Cumulative environmental impact index for Scenario 0 (Option III) and Scenario 1.

No.	Unit process	Eco-indicators [Pt]
1.	Scenario 0 (Option III)	0.2904
2.	Scenario 1	0.2257

Table 9
Impact assessment for Scenario 0, with its variant analysis. The results of the cumulative indicator for individual impact categories [Pt].

Impact category	Eco-indicator Pt			
	Scenario 0 (Option III)	Share [%]	Scenario I	Share [%]
Climate change	0	0	0.0349	14.14
Ozone depletion	0	0	0.0008	0.31
Ionising radiation	0	0	0.0023	0.94
Photochemical ozone formation	0	0	0.0057	2.31
Particulate matter	0.2615	90.05	0.0150	6.07
Human toxicity, non-cancer	0.0117	4.02	0.0042	1.71
Human toxicity, cancer	0.0123	4.23	0.0029	1.16
Acidification	0	0	0.0093	3.75
Eutrophication, freshwater	0	0	0.0058	2.35
Eutrophication, marine	0	0	0.0118	4.8
Eutrophication, terrestrial	0	0	0.0033	1.34
Ecotoxicity, freshwater	0.0049	1.7	0.0728	29.49
Land use	0	0	0.0012	0.48
Water use	0	0	0.0118	4.79
Resource use, fossils	0	0	0.0559	22.64
Resource use, minerals and metals	0	0	0.0092	3.72
TOTAL	**0.2904**	**100**	**0.2257**	**100**

matter category.

For a detailed analysis of individual impact categories, the results were also presented after the characterization stage, i.e. in units characteristic for a given impact category (not cumulated to a common Pt unit). The results presented in this way (Table 7) cannot be compared between the given impact categories, nor can they be summed up within the different categories.

However, the most interesting result is the comparison of scenarios 0 and 1, which makes it possible to see the impact of street cleaning process The results of this comparison are shown in Fig. 4.

It is visible that scenario 1 is characterized by the lowest environmental impact. Although in this scenario 1 there are loads in each impact category of the EF 3.0 method the overall result is still lower than in all variants of scenario 0. In scenario 1, environmental impact is mainly related to the categories of freshwater ecotoxicity, ionizing radiation and climate change, which is qualitatively different from scenario 0, where the highest environmental impact is found in the particulate matter category. In scenario 1, this impact is due to processes from the technosphere, namely mainly from the use of road sweepers. The comparison of the cumulative environmental impact indicator for the best variant in scenario 0 (option III) and Scenario 1 is presented in Table 8. The share of individual impact categories in the overall impact of individual scenarios is presented in Table 9.

Based on the data presented in the process tree, it can be concluded that water consumption for street cleaning, transport and fuel consumption for road sweepers have a dominant impact on the environmental outcome of Scenario 1 (98.2% of the overall impact), while impacts related to waste and wastewater have a secondary impact, accounting for 0.55% and 1.25% of the overall impact rate for Scenario 1, respectively (Fig. 5). The process tree for Scenario 0 (Option III) is shown in Fig. 6. Due to the lack of unit sub-processes coming from the technosphere, the total impact of Scenario 0 is assigned only to the elementary streams constituting emissions to air, water and soil. Therefore, this process tree only consists of one block.

According to Bartolozzi et al. (2018) the details of the process

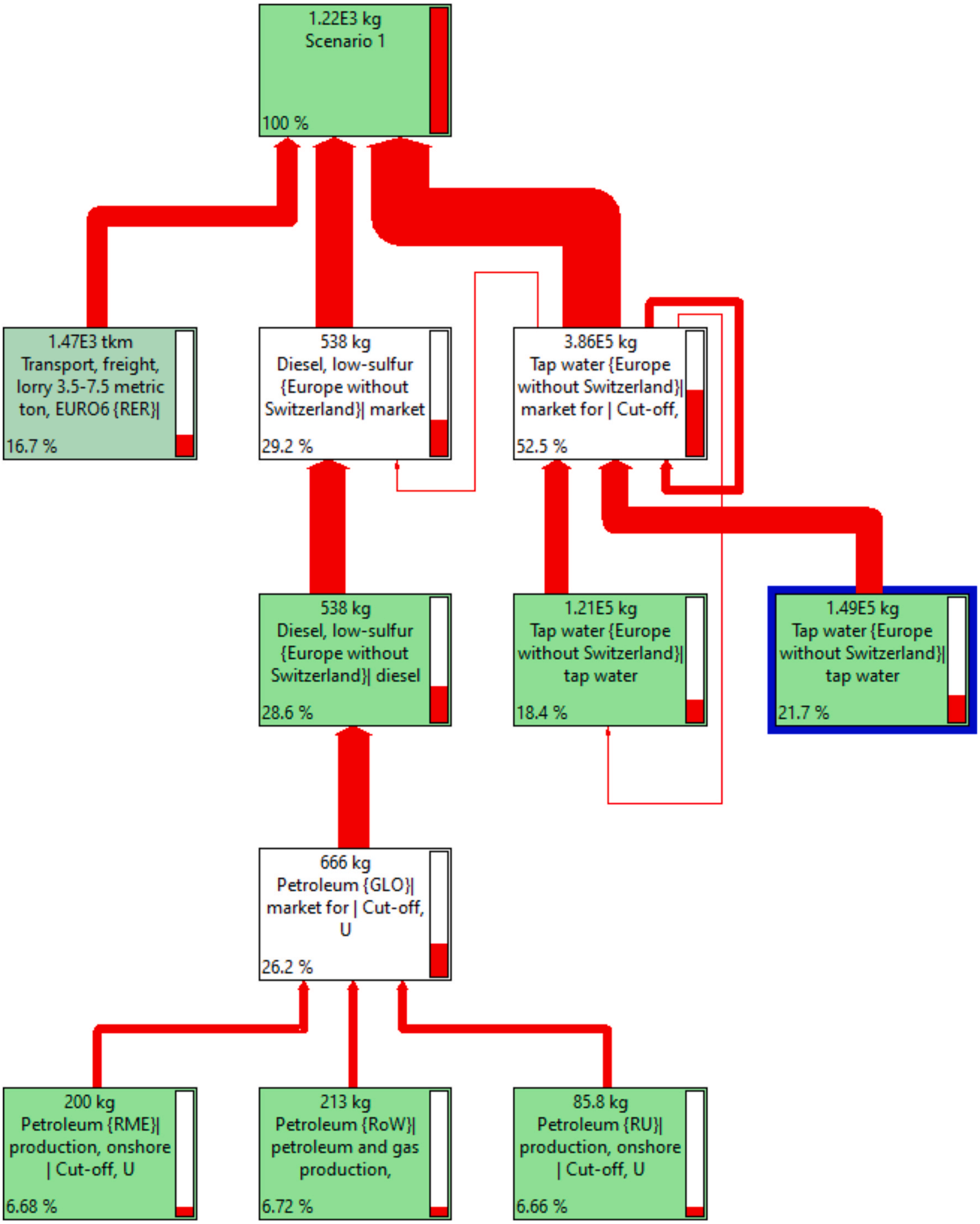

Fig. 5. Process tree for Scenario 1, presenting the share of individual unit processes in the overall impact indicator.
* cut-off 5.69% - processes affecting the overall impact index below 5.69% were cut from the above list.

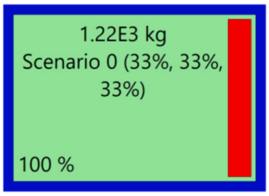

Fig. 6. Process tree for Scenario 0 (Option III), presenting the share of individual unit processes in the overall impact indicator.

contributions analysis shows that the predominant impact is due to the fuel consumption in the vehicle pool, which contributes about 93% to Mineral fossil and renewable. The details show that the main impact of the process unit contributions is due to the fuel consumption in the vehicle pool, which contributes over 80% to all the impact categories, with over 90% to Photochemical ozone formation and Mineral fossil and renewable resources.

The differences in the results of the calculations show that the assumptions of the assessment are important, and in the presented example the results of chemical analyzes were used for the first time to assess the quality of the environment.

6. Conclusions

Life Cycle Assessment (LCA) defined in accordance with ISO 14040 as a technique for assessing environmental aspects and potential environmental impacts over the entire life cycle of a product, i.e. from cradle to grave, takes into account all factors potentially affecting the environment, i.e. emissions, energy consumption, quantity and the quality of the generated waste and the materials used and indicates the result of the actual impact, constituting an environmental management tool. In the article, an attempt to assess the life cycle of street sweepings was implemented taking into account two scenarios.

- For the purposes of the research, a methodology was developed that took into account: the selection of the area and routes for washing streets, sampling of waste and sewage for laboratory tests and gravimetric measurements of road sweepers, laboratory tests of waste and sewage collected allowing to assess the quality and chemical composition of the tested samples, LCA using SimaPro software to compare potential impacts in variant scenarios,
- The scenario assuming the deposition of waste in the urban environment was considered in three variants, due to the modeling of the distribution of pollutants to various elements of the environment: water, soil, air. The variant analysis showed that the worst results are obtained for III variant (33% of dry matter waste are emissions to the air, other pollutants, including heavy metals, stand for emissions to soil (33%) and water (33%))
- Comparing the scenarios in which waste is deposited on the street or is removed and neutralized, it is possible to indicate the introduction of a street cleaning system and waste neutralization can guarantee a 29% reduction in environmental pollution. It can be observed that there has been a reduction in the impact in terms of human, non-cancer, and cancer categories, and the particle matter index has decreased significantly.
- The LCA analysis for the street cleaning system gave an unambiguous result of reducing emissions to the environment as a result of technological processes and can be used as a procedure for quality assessment

CRediT authorship contribution statement

A. Generowicz: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **A. Gronba-Chyła:** Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Data curation, Supervision, Funding acquisition. **J. Kulczycka:** Conceptualization, Software, Formal analysis, Resources, Writing – original draft, Visualization. **P. Harazin:** Conceptualization, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Funding acquisition. **K. Gaska:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **J. Ciuła:** Conceptualization, Methodology, Software, Data curation, Writing – review & editing. **P. Ocłoń:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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