



Article

Hazardous Waste Advanced Management in a Selected Region of Poland

Przydatek Grzegorz ¹, Moşneguţu Emilian ^{2,*}, Cabała Adrian ¹ and Irimia Oana ^{2,*}

¹ Engineering Institute, State University of Applied Sciences in Nowy Sacz Zamenhofa 1a, 33-300 Nowy Sacz, Poland

² Department of Environmental Engineering and Mechanical Engineering, Faculty of Engineering, Vasile Alecsandri University of Bacau, 157 Calea Marasesti, 600115 Bacau, Romania

* Correspondence: emos@ub.ro (M.E.); oana.tartoaca@ub.ro (I.O.)

Abstract: This article presents a study on hazardous waste management in the Malopolskie region of Poland. The study was based on the information obtained during three years from 2016 to 2018, and following analysis, it was found that in 2016 there was the highest amount of 24,872.13 tons of hazardous waste produced, of which only a three-fold lower amount was disposed of. In this study, various types of hazardous waste were analyzed, including the waste from construction materials and asbestos. The predominant share of 50% of the mass of analyzed hazardous waste was felt on the generated one. Waste recovered in installations had a lower share of 43%, with a significant and favorable increase of over 5000.00 tons. In the context of the correctness of environmental aspects, it was considered an advisable solution that would optimize treatment conditions, and at the same time minimize the costs of hazardous waste management.

Keywords: hazardous waste; generation; recovery; disposal; installation



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1. Introduction

Efficient waste management often involves harnessing the potential of man-made waste and reusing it through recycling [1]. The management of hazardous waste is an important problem that requires attention. Hazardous waste is the most difficult waste to manage, because in the treatment process it produces, among other things, heavy metals and dioxins. Hazardous waste can come from a variety of sources, such as agriculture, industry, commerce, and even households [2,3]. By definition, hazardous waste is waste with properties that make it hazardous or potentially harmful to human health or the environment, which is why it is listed in the European Waste Catalog [4] and in Council Directive 91/689/EEC [5].

The Municipal Solid Waste Management System (MSWM) covers the production, collection, recovery, processing, management, and disposal of solid waste [6]. Waste treatment includes recovery and disposal. According to the provisions of the Polish Act on waste 14.12/2012 [7], recovery is defined as a process of which the main result is that the waste serves a useful use by replacing other materials. Recycling, on the other hand, is part of recovery, where waste is reprocessed into products, materials, or substances, for primary or secondary use. Then again, processing (inside and outside the installation) is treated as a recovery or disposal process. The latter process includes incineration of waste and landfilling as a final waste management [8].

Hazardous waste management is still a problem in the European Union. To be able to better control waste management, it is necessary to improve the mechanisms for managing records and identification [9–11].

Typical elements of hazardous waste management include collection, transport, recycling, and disposal [12]. The recovery of raw materials from hazardous waste requires

specialized equipment and installations that require large financial outlays, and the most important result of this is the recovery of metals from hazardous waste.

Inappropriate treatment, storage, and disposal of hazardous waste has potentially adverse effects on human health and on environmental impacts [13]. The severity of environmental pollution caused by hazardous waste can be reduced by proper disposal or recycling [14]. Chen et al. [15] demonstrated, in the environmental aspect, the adsorption capacity of biochar, which can minimize the content and pollutants of hazardous waste at the same time.

Waste neutralization consists of processing waste in such a way as to eliminate most of the hazardous compounds present in it, by converting these into non-hazardous components. Incineration is a common method for neutralizing hazardous waste and guarantees a relatively high level of decomposition. For this neutralization method, devices such as combustion chambers with a fluidized bed furnace, combustion chambers with the possibility of injection of liquid waste, hearth furnaces, and rotary furnaces with an afterburner are used [16].

The treatment and disposal of hazardous waste in a centralized facility should depend on the types of waste that are received. Disposal of waste is the last process and an important issue in the overall hazardous waste management plan [17]. To ensure the effective utilization of municipal solid waste (MSW), long-term processing technologies should be applied in well-targeted circular economy implementations [18].

This study's aim was to assess the process management of hazardous waste management in one of the regions, located in the southern part of Poland, for the period 2016–2018, taking into account all the cases in which we can analyze the hazardous waste, respectively, in the generated, recovered, and disposed-of stages.

2. Materials and Methods

Based on information obtained from Polish Statistics and the Marshal's Office in Krakow, the annual number of inhabitants and qualitative and quantitative data concerning hazardous waste were obtained, covering the years 2016–2018, in the scope of:

- Generation;
- Disposal;
- Recovery during installation;
- Outside of the installation, recovery
- The mass of generated and processed waste (recovery and disposal) is broken down by counties.

In addition, calculations of the relationship between hazardous waste-processing categories and the quantity of produced hazardous waste were needed.

Under the Regulation of the Minister of Climate from 2 January 2020, on the Waste Catalogue, waste was categorized by type, groups, and subgroups [19].

The analysis includes the generated hazardous waste, broken down into nine types:

- Asbestos-containing insulation materials (170601 *);
- Other insulation materials containing dangerous substances (170603 *);
- Insulating materials other than those mentioned in 170601 and 170603 (170604);
- Asbestos-containing construction materials (170605 *);
- Other wastes (including mixed substances and objects) from the mechanical treatment of waste containing hazardous substances (191211 *);
- Fluorescent lamps and other mercury-containing waste (200121 *);
- Devices containing freons (200123 *);
- Medicines other than those mentioned in 200131 (200132);
- Batteries and accumulators, including batteries and accumulators mentioned in 160601, 160602, or 160603 and unsorted batteries and accumulators containing these batteries (200133 *).

The nine wastes listed below types of hazardous waste were included in the installation as part of the recovery process:

- Insulating materials other than those mentioned in 170601 and 170603 (170604);
- Other wastes (including mixed substances and objects) from the mechanical treatment of waste containing hazardous substances (191211 *);
- Solvents (200113 *);
- Fluorescent lamps and other mercury-containing waste (200121 *);
- Devices containing freons (200123 *);
- Oils and fats other than those mentioned in 200125 (200126 *);
- Paints, inks, printing inks, adhesives, adhesives and resins containing dangerous substances (200127*);
- Medicines other than those mentioned in 200131 (200132);
- Batteries and accumulators, including batteries and accumulators mentioned in 160601, 160602, or 160603 and unsorted batteries and accumulators containing these batteries (200133 *);
- Discarded electrical and electronic equipment other than those mentioned in 200121 and 200123 containing hazardous ingredients (200135 *).

Only one is included for off-site recovery:

- Medicines other than those mentioned in 200131 (200132).

Concerning the disposal of hazardous waste, the following 9 types of waste have been included:

- Asbestos-containing insulation materials (170601 *);
- Insulating materials other than those mentioned in 170601 and 170603 (170604);
- Asbestos-containing construction materials (170605 *);
- Solvents (200113 *);
- Oils and fats other than those mentioned in 200125 (200126 *);
- Paints, inks, printing inks, adhesives, adhesives, and resins containing dangerous substances (200127 *);
- Cytotoxic and cytostatic drugs (200131 *);
- Medicines other than those mentioned in 200131 (200132);
- Wood containing dangerous substances (200137 *).

For the results of the studied hazardous waste management, the following statistical parameters were determined: minimum and maximum value, arithmetic mean, and standard deviation.

2.1. Hazardous Waste Management

At the national level, the National Waste Management Plan [20] for 2022 defines the main solutions for waste management, including hazardous waste. The analysis of the waste management process reveals that the primary priorities are to reduce waste generation, increase waste recovery, and reduce the number of landfills [21]. It is very important that hazardous waste be managed appropriately to minimize serious negative effects on human health and the environment. In Poland, hazardous waste in the form of used solvents is recycled, incinerated, and recovered in the form of energy. Waste oil and other oil-containing wastes are refined in refineries. Regarding the recovered plant protection products packaging, this is subjected to an energy recovery process in incineration and co-incineration plants. The energy is obtained and then used in various technological processes, replacing the consumption of coal, oil, and gas. Asbestos-containing waste is deposited in dedicated landfills and in special underground plots [20].

2.2. Characteristics of the Małopolskie Region Area

The Małopolskie region is located in the southeastern part of Poland. It borders the following regions: Świętokrzyskie in the north, Śląskie in the west, Podkarpackie in the east, and Slovakia in the south (Figure 1). This region covers part of the Western Carpathians

and the Małopolska Upland. Two main Polish rivers flow through its area: the Vistula and the Warta, which are the longest rivers in Poland. The capital of the region is Krakow, the second-largest city in terms of area and population, which was once the capital of Poland. In terms of administration, the voivodeship is divided into two levels: the county into 22 counties and communally into 182 communes. Analyzing the area of individual counties, the largest is Nowosądecki, at 1549 km², and the smallest is Chrzanów, at 372 km². It is one of the smaller regions in Poland (12th place in the country), and is forth in terms of the number of inhabitants [22].



Figure 1. Location of Małopolska region in Poland (Poland in middle-eastern Europe, Małopolska southeastern Poland).

2.3. Qualitative and Quantitative Analysis of Hazardous Waste

2.3.1. Produced Hazardous Waste

In the Małopolska region, the largest amount of hazardous waste generated was asbestos-containing construction materials, with the highest weight of 24,872.13 tons in 2016 but the lowest amount of solvents, at 0.005 tons. The highest value of standard deviation occurred in that same year (Table 1). This type of waste also had the largest share (80.22%) of the total amount of hazardous waste.

Over the three years, the indicator of hazardous waste accumulation per capita per year showed a decline of 0.009 kg and accumulation of 1.32 tons per km² with the average, respectively, of 0.007 kg per cap. and 1.15 tons per area.

The second-largest share of 10.47% was for insulation materials other than those listed in 170601 and 170603, with the highest amount of 2508.10 tons recorded in 2016.

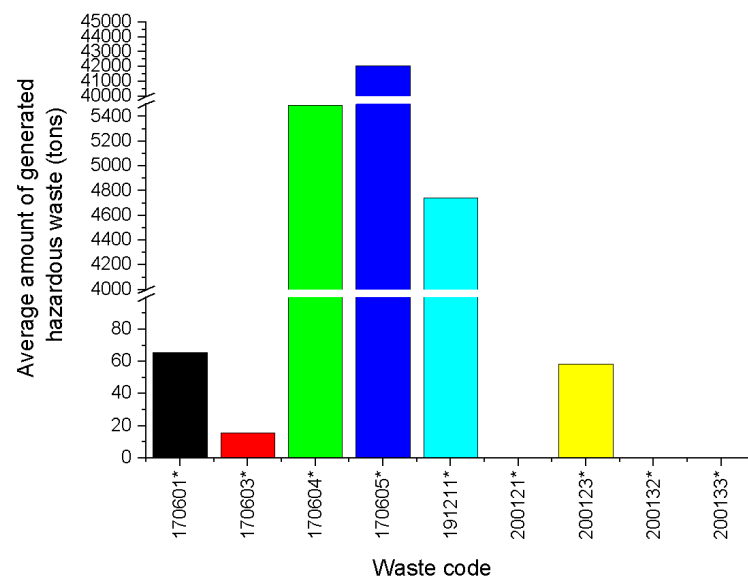
On the other hand, the smallest amount, of 0.005 tons, corresponds to the unsorted batteries and accumulators containing these batteries for the year 2018. Overall, analyzing the amount of hazardous waste, which is the subject of this study, the highest average value of 3161.34 tons was recorded in 2016, and the lower value of 931.16 tons was recorded in 2018. Additionally, the result of standard deviation was the highest in 2016 and amounted to 7717.09 tons. This confirmed the greatest diversification of the results.

From the analysis of the graphical representation in Figure 2, it shows that the largest amount of waste generated, of all the types of hazardous waste studied, is that of construction material waste, which contains asbestos, namely 42,058.27 tons. The lowest amount of hazardous waste corresponds to medicinal waste and was 0.054 tons, other than those mentioned in 200131.

Table 1. Amount of generated hazardous waste in 2016–2018.

Code of Waste	Amount of Waste [tons]			Contribution [%]
	2016	2017	2018	
170601 *	63.04	0.61	1.95	0.13
170603 *	0.25	0.71	14.66	0.03
170604	2508.10	1026.78	1955.50	10.47
170605 *	24,872.13	13,143.38	4042.77	80.22
191211 *	1004.87	1427.39	2310.83	9.05
200121 *	0.009	0.08	-	0.00
200123 *	3.63	-	54.76	0.11
200132	-	0.05	-	0.00
200133 *	-	0.05	0.005	0.00
Total	28,452.02	15,599.04	8380.47	100.00
Max.	24,872.13	13,143.38	4042.77	
Min.	0.009	0.05	0.005	-
Average	3161.34	1733.23	931.16	
Standard deviation	7717.09	4066.17	1402.68	-
Indicator of hazardous waste accumulation [kg cap. ⁻¹ year ⁻¹]	0.012	0.006	0.003	-
Waste accumulation per area [tons km ⁻²]	1.87	1.03	0.55	-

* Hazardous waste in the waste catalog is waste marked with an upper index in the form of an asterisk "*" next to the waste type code, apart from the provisions of Art. 7 of the Act of 14 December 2012, on waste [7].

**Figure 2.** Average amount of generated hazardous waste in 2016–2018.

2.3.2. Recovery of Hazardous Waste in Installations

According to the data analyzed, it can be observed that in Małopolska region the largest amount of recycled waste from the facilities (Table 2) was the equipment that contained freons, at a proportion of 42.51%. Referring to this type of waste, it can be seen that its quantity increased from 3321.23 tons in 2016, to 4983.91 tons in 2018.

Table 2. Recovery of hazardous waste in installations in 2016–2018.

Code of Waste	Amount of Waste [tons]			Contribution [%]
	2016	2017	2018	
170604	1407.45	1347.85	484.43	11.42
191211 *	-	1750.08	4489.46	22.00
200113 *	-	-	0.003	0.00
200121 *	23.71	68.26	54.81	0.52
200123 *	3321.23	3754.34	4983.91	42.51
200126 *	-	-	0.04	0.00
200127 *	0.67	0.61	-	0.03
200132	0.05	-	0.005	0.00
200133 *	121.28	113.590	141.72	1.33
200135 *	2160.69	2055.85	2080.50	22.20
Total	7041.11	9090.58	12,234.87	100.00
Max.	3321.23	3754.34	4983.91	
Min.	0.05	0.61	0.003	-
Average	704.12	909,058	1223.48	
Standard deviation	1128.62	1222.90	1860.41	-

For this analysis, the standard deviation amounted to 1128.61 tons. The smallest amount of hazardous waste was 0.003 tons, and corresponds to the waste with the code 200132. In 2018, the highest value was obtained for the average amount of waste, with a value of 1223.48 tons, which confirms an increase in the amount of hazardous waste recovered in the installations for the years under analysis. The value of the standard deviation of 1860.41 tons was the highest in the last year. Analyzing the data from 2016 to 2018, it was discovered that the amount of waste recovered in facilities increased by over 5000 tons.

2.3.3. Recovery of Hazardous Waste Outside Installations

Based on the analysis of the waste recovery outside the installation, it was possible to demonstrate only the medicines other than those mentioned in 2001 (Table 3). Analyzing the amount of waste sent for recovery outside of installations, it can be noticed that the highest mass was 0.6 tons, a value which was obtained in 2016 and 2018, and the lowest value was 0.4 tons, obtained in 2017.

Table 3. Recovery of hazardous waste outside installations in 2016–2018.

Code of Waste	Amount of Waste [tons]		
	2016	2017	2018
200132	0.60	0.40	0.60

2.3.4. Disposal of Hazardous Waste

In 2016, in the Małopolska region, the largest amount of condition waste was related to construction materials, particularly waste that contained asbestos (Table 4). The quantity of this type of waste was 7402.27 tons. Overall, the highest share (91.47%) of this type of waste was recorded. The smallest amount, however, was 0.005 tons, which occurred in the case of solvents. The value of the standard deviation reached 2315.19 tons. The highest amount of waste disposed of, 7717.04 tons, was recorded in 2016, and it was found that this amount had a decreasing tendency, reaching its lowest quantity in 2018 at 4042.77 tons. It was observed that the difference between the maximum and minimum value of deposited waste represented a significant value of 3000 tons. This means there was a positive reduction in the quantity of deposited waste. The highest differentiation of the results based on the value of the standard deviation of 2315.19 tons is noticeable in the first analyzed year.

Table 4. Amount of assembled hazardous waste in 2016–2018.

Code of Waste	Amount of Waste [tons]			Contribution [%]
	2016	2017	2018	
170601 *	47.38	-	11.38	0.31
170604	248.90	474.65	746.46	7.73
170605 *	7402.27	6735.51	3254.16	91.47
200113 *	0.10	-	0.005	0.00
200126 *	0.057	-	-	0.00
200127 *	0.23	0.52	3.22	0.02
200131 *	0.25	-	-	0.00
200132	14.59	38.30	17.20	0.37
200137 *	3.26	5.40	10.34	0.10
Total	7717.04	7254.38	4042.77	100
Max.	7402.27	6735.51	3254.16	
Min.	0.057	0.52	0.005	-
Average	857.45	806.04	449.20	
Standard deviation	2315.19	2101.50	1018.24	-

2.3.5. The Amount of Hazardous Waste Broken down by Counties

Analyzing the data presented in Figure 3 for individual counties, it was found that the highest quantity of hazardous waste, 37,173.25 tons, was generated in the city of Krakow; the county where the most waste was processed was the Chrzanów county (northwestern part of the region), 17,633.33 tons.

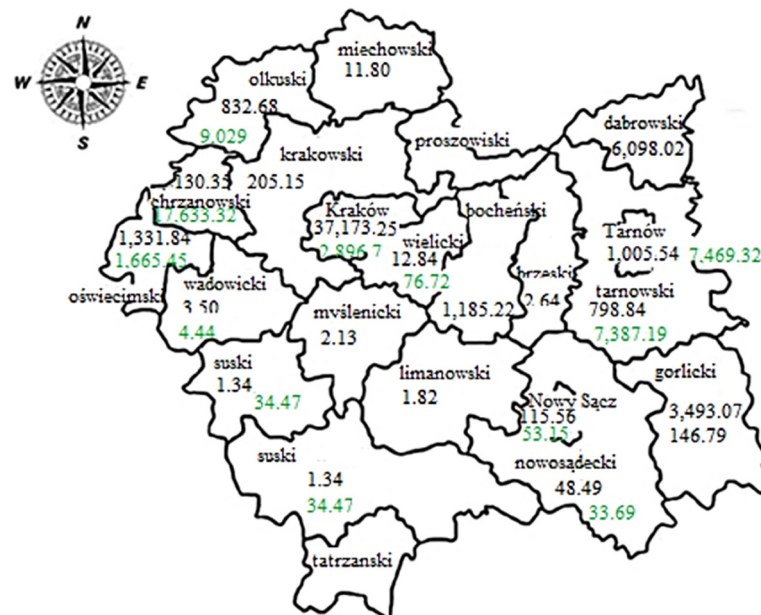


Figure 3. Quantity of produced and processed hazardous waste in individual counties in Małopolska region: produced waste and processed waste [tons].

Aiming to obtain an overview of how to manage hazardous waste within the Małopolska region, the following analysis was performed, using the following calculation relationship:

$$\text{fraction} = \frac{\text{hazardous waste processes categories}}{\text{quantity generated of hazardous waste}} \quad (1)$$

$$\frac{\text{recovered}}{\text{generated}} = \frac{28,366.56}{52,431.53} = 0.54$$

$$\frac{\text{assembled}}{\text{generated}} = \frac{19,014.19}{52,431.53} = 0.36$$

52,431.53 represents the amount of hazardous waste generated in 2016–2018 (tons);
28,366.56 represents the recovery of hazardous waste in installations and recovery outside
the facilities in 2016–2018 (tons);

19,014.19 represents the amount of assembled hazardous waste in 2016–2018 (tons).

The indicators show that the ratio of recovered waste to generated waste of 0.54 was the highest. On the other hand, the lowest value of 0.36 was obtained for the quotient of assembled and generated waste. In 2016–2018, the largest share of 53% was generated by waste. Recovery waste remained at a slightly lower share of 28%, while the lowest share was for assembled waste (Figure 4).

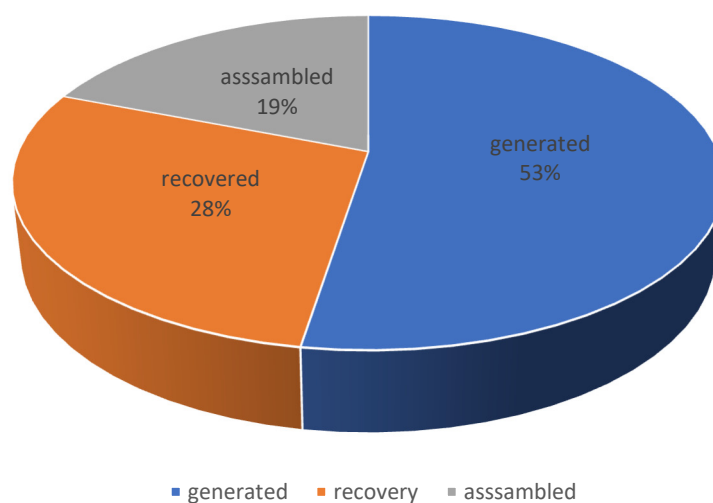


Figure 4. In 2016, and again in 2018, the Małopolskie region’s hazardous waste management was effective.

3. Discussion

The analysis of the advancement efficiency of management selected hazardous waste for the Małopolskie region shows that the largest amount of hazardous waste generated was related to asbestos-containing construction materials (24,872.13 tons) with a share of 80.22%. According to Duan [23], the level of economic development and the structure of the industry affects the volume of their production. The highest average amount of waste occurred in 2016, which showed a decrease. The same situation, concerning the indicator hazardous waste accumulation per capita, had the highest value of 0.012 kg. This confirms a significant drop in collected waste of 70%. Akpan et al. [24] obtained a higher value of this indicator, of 0.198 kg per cap. per year. In accordance to Przydatek and Ciągło [25], the indicator of waste accumulation per area is important in the assessment of waste management. In the Małopolska region, such an indicator amounted to an average value of 1.15 tons per km², with a decreasing trend.

On the other hand, devices containing 42.51% freon accounted for the largest share of recycled waste in installations. An important process, from an environmental point of view, is the recovery of waste in installations. The quantity of waste recovered from installations only showed an increase of over 5000 tons in the analyzed years. Balde [26] found that most waste has a typical value, and can be recovered and reused to create valuable goods. In the opinion of some researchers [27], the most hazardous waste was used as alternative fuel and raw material in cement kilns. According to Alvarez [28], recycling hazardous waste may involve the use of by-products from the coke oven process as a binder for the production of briquettes.

It should be noted that the recovery of waste outside the installation includes only drugs, other than those mentioned in 200131, in an amount not exceeding 0.60 tons. Some

researchers [29] reported that improper treatment and disposal of medical waste might expose people to potentially harmful microorganisms.

One of the methods of hazardous waste management is the storage of hazardous waste in underground landfills [30,31]. In 2016, the highest amount of 7402.27 tons of waste subjected to neutralization was recorded, which was attributable to construction materials and asbestos, with a share of 91.47%. However, within three years, the region has seen a significant decrease in treated waste of over 3000 tons. This year, the data also varied significantly.

In waste management, it is important to finance this process, regardless of the type of waste, in accordance with the polluter pays environmental principle [32]. Therefore, Aleksandrowicz et al. [33] showed that the costs of hazardous waste management in Poland will increase, and will include expenditure on the organization of the hazardous waste collection system.

Generated waste dominated in the region, the sum of which exceeded the amount of waste generated, with an index of 0.54. The value of the remaining ratio was below 0.40 in the case of assembled waste.

It should be noted that the most hazardous waste was generated in Krakow City in the amount of 37,173.25 tons, and the processed waste in Chrzanów County had a smaller amount of 10,000 tons. Counto [2] confirmed that larger amounts of hazardous waste are especially generated in greater cities. In general, generated waste received the greatest share (53%) while the process of waste recovery stated a lower share (28%). In turn, Sabbas [34] showed that waste recycling processes are the best waste management strategy within an integrated system.

Common methods of hazardous waste disposal are incineration, neutralization, and new technologies, such as solar detoxification [35]. Application is advisable for rational waste management because it provides the best technologies at tolerable costs, providing a viable solution for each type of waste, to optimize the treatment conditions and minimize the costs at the same time [2]. Hu et al. [36] showed that the total reverse logistics costs for the applications cases can be reduced by more than 49%, by using the proposed model consisting of four critical activities in hazardous waste management: (1) collection, (2) storage, (3) treatment, and (4) distribution.

With local trends in waste management, this can promote reuse and valorization, contributing to the industrial adoption of circular economy models as well as environmental protection [37].

4. Conclusions

Based on the analysis of hazardous waste management in a selected region of Poland, it was found over three years that:

- The largest amount of hazardous waste generated was recorded in 2016 and comprised asbestos-containing construction materials (24,872.13 tons), with an overall significant share of over 80%.
- The largest amount of generated waste, 37,173.25 tons, occurred in the Krakow City area.
- Generated waste accounted for the overwhelming share, while processed waste remained at a lower share of 28%. The highest index of 0.54 concerned the ratio of processed to generated waste.
- The largest share, 43%, of waste recovered in installations was constituted by equipment containing freons, and the amount of recovered waste increased favorably by over 5000 tons.
- In 2016, there was the largest amount of treated waste (construction materials) asbestos, which was three times lower than that produced, with the highest share exceeding 90%, and a noticeable decrease occurred at the same time.

- The downward trend of recovered and managed hazardous waste by more than 700 tons on average indicates the need to identify the sources of its generation. On the other hand, this may indicate a reduction in impact on the natural environment.
- The suggested solution would be to optimize the treatment conditions and minimize the costs of hazardous waste management, while maintaining the correctness of environmental aspects.

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