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Influence of Selected Geopolitical Factors on Municipal Waste Management

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Abstract: The collection and transportation of municipal solid waste create a significant energy and carbon footprint, resulting in a significant environmental impact. Proper waste management organization is necessary to minimize this impact. This research aims to identify differences and similarities in waste collection sectors, distinguish affiliation clusters for different waste types, and determine the impact of geopolitical factors on waste production in the analyzed region. Therefore, the similarities of waste production in the separated sectors for different waste types were analyzed. Instead of using the Kolmogorov–Smirnov distance between distributions of waste production, the statistics have been calculated based on L_1 and L_2 norm because they give the scale of differences. The multidimensional scaling method (MDS) and cluster analysis with a Gaussian mixed model (GMM) were used to identify changes in waste production. This technique makes it possible to detect changes between sectors in the analyzed region. Significant differences in cluster membership of sectors by waste type were observed. Geopolitical factors such as the COVID-19 pandemic and the war in Ukraine have caused changes in the sector affiliations of the waste clusters under analysis. The pandemic caused changes in the affiliation of non-segregated waste, plastics, and glass, while no change in waste generation preferences was observed for paper and cardboard waste. The war in Ukraine caused changes in the generation preferences of all waste types in the analyzed region.

Keywords: waste management; waste affiliation clusters; waste production change detection; waste collection planning

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1. Introduction

Economic development and related consumerism contribute to the generation of increasing amounts of municipal waste, i.e., waste related to human activity. Positive trends can be observed in the European Union regarding waste handling methods, such as a decrease in the amount of municipal waste per person or waste reprocessing, i.e., recycling and energy recovery. For example, the amount of municipal waste per person in the European Union in 2022 was 513 kg, which is 4% less waste than in 2021, while it is worth noting that the amount of waste per person in Poland was still below this average (364 kg) although increased compared to the previous years [1]. In addition, the Green Deal provisions adopted by the member countries aim to achieve a circular economy by 2050 [2]. Member countries wishing to comply with EU directives to move toward a circular economy must carefully assess waste management options and use their resources efficiently, considering that one of the priorities is also to reduce energy consumption in all industries in the EU.

The increasing amount of waste in Poland and the rising costs of waste processing make the proper organization of waste collection and management one of the key elements of waste management. The problem on a regional scale is to adapt the separate collection to the region's needs, to avoid causing empty runs of the collection transport and leaving waste uncollected [3]. The collected waste volume depends on many factors that vary in time and space, which can significantly disrupt the entire system's functioning. There are differences in waste composition depending on the season, municipality, climate, population, economy, and other factors [4,5], and waste composition can indicate consumption trends, population behavior patterns, and the number of goods consumed [6,7]. Adequate early detection of changes in waste production in the regions enables more effective waste management. Cases involving critical factors being difficult to predict, are especially complex.

Critical factors such as a pandemic or war had a varying impact on the different transportation types [8]. Moreover, differences were also evident depending on the item being transported [9]. The multidimensional impact of COVID-19 on various transportation types can also be indicated, including public transportation [10] or forwarding trade [11]. Therefore, the aforementioned geopolitical factors may have contributed to changes in waste management. The war's impact on the waste amount and management in a country affected by armed conflict is multidimensional [12], and a particular challenge is the increasing waste volume with the lack of effective management mechanisms [13]. However, this factor can also affect waste management in neighboring countries, directly caused by the refugee influx. The second crisis, the COVID-19 pandemic, directly affected the waste volume by causing an increase in waste generation due to the increased use of single-use products and the panic created during shopping [14]. It was also found that waste volume increased in countries where social distancing rules were observed by staying at home [14]. This is because during the pandemic state, resulting from business and school closures, waste generation shifted from industrial and commercial areas to domestic areas [15]. It is also worth mentioning the change in the waste structure generated in households. Pappalardo et al.'s findings showed that there was a significant change in the overall food waste amount during the isolation associated with the COVID-19 pandemic, with a 12% increase in household waste generation, while the food waste value decreased by 8% as a result of easing healthy eating habits [16]. Amicarelli and Bux's research found that the COVID-19 pandemic changed people's attitudes toward food waste, resulting in a reduction in household food waste generation despite expectations of increased food waste [17]. Simultaneously, the change in habits led to an increase in packaging waste consisting mainly of plastics and cardboard [18]. Limited recycling activities also contributed to the difficulties in organizing waste management during the COVID-19 pandemic [15]. Irregular and improper waste collection, waste recycling withholding, and unsanitary disposal have been important issues in processing and managing the waste generated [19].

Waste management is a key challenge in the fight against energy consumption and greenhouse gas emissions [20–22]. The economy encompasses a range of activities, each reliant on energy for transportation and processing, which impacts various costs. The supply chain can be analyzed in the context of the energy consumption required for waste collection, transportation, handling, and processing [23]. Comparing each process's contribution—waste collection, transshipment, waste processing, and final transportation—the majority of energy consumption goes to transportation, including collection from households and transportation from the waste treatment facility to the final destination [24]. For this reason, actions to optimize energy use in transportation are significant [25,26]. Interestingly, critical phenomena like the COVID-19 pandemic contributed to increased global CO_2 emissions from energy [27]; therefore, measures to optimize the supply chain in such situations become a priority.

Various models for minimizing energy consumption and improving transportation efficiency regarding environmental and social criteria have been proposed in the literature, and the main conclusion for waste collection company managers is to consider revising and verifying collection schedules and timelines [28]. The basic activity regarding this is the appropriate transport scheduling and the adaptation of vehicles, e.g., electrically powered or appropriate transshipment [29]. Another important concern is the reliability of the systems and machinery used not only to transport the waste but also in the waste treatment process [30–33]. Energy recovery from waste is also an important issue in this case, and the concept of converting waste into energy has gained popularity as a solution for achieving environmental sustainability and managing energy shortages [30].

In many cases, the area where waste is collected is divided into sectors. This research aims to identify the differences and similarities of the waste collection in the sectors and to distinguish the sector affiliation to clusters for different waste types. This research also aims to recognize geopolitical impact factors such as the COVID-19 pandemic and the war in Ukraine on waste production in the study region. The aim of this paper is to demonstrate the method for detecting changes in waste production for each sector due to external factors. By comparing cluster membership before and after the geopolitical factor, it is possible to identify changes in waste production within sectors. The presented procedure makes it possible to detect changes across the region. In addition, based on this technique, we can trace the dynamics of change caused by a sequence of geopolitical factors. Considering this, the similarities and differences in waste production in the separated sectors were analyzed for different waste types. The following research questions were formulated:

1. What resident preferences/similarities can be distinguished concerning municipal waste production in distinguished sectors?
2. What changes do critical phenomena such as the COVID-19 pandemic and the war in Ukraine generate in municipal waste production?

The study was conducted in Lublin, which is a provincial city, one of the largest cities in the eastern part of Poland (population 318,987, as of 31 December 2022 [34]). The chosen city for the study was determined by its proximity to Ukraine, which meant that with the war's outbreak close to this Polish region, the number of people living in the area increased significantly. After the war broke out, the spatial distribution of Ukrainian refugees in Poland could be estimated based on applications for UKR foreigner status. Data from the Chancellery of the Prime Minister indicate that in the period from 14 March 2022 to 31 October 2022, more than 1.43 million applications for UKR status were registered in Poland due to the conflict in Ukraine, including 66.1 thousand in the Lublin province, and 22% of refugees residing in Lublin alone [35].

The amount of municipal waste generated depends not only on population but also on consumption patterns. In 2022, there was a clear differentiation between the provinces in the western part of the country and the eastern provinces, which include Lublin Province [36]. The Lublin area is divided into 27 administrative districts, in which 17,344 inhabited single-family properties and 5644 multi-family properties are located. In 2022, the total mass of municipal waste in Lublin from all properties (residential and non-residential) was 135,093.7411 Mg (analysis of the state of municipal waste management in the city of Lublin for the year 2022, Department of Environmental Protection, Lublin City Hall [37]). Among these wastes were the following fractions:

- Unsegregated waste (municipal/mixed);
- Paper, cardboard;
- Plastics;

- Glass;
- Pomace, plant waste, sawdust, shavings, kitchen waste, biodegradable waste;
- Metal packaging;
- Textiles;
- Electrical devices (electronic waste);
- Sorbents, filter media, brake fluids, car oils, tires;
- Alkaline batteries, rechargeable batteries;
- Concrete waste, rubble, soil, and earth (renovation and construction waste);
- Bulky waste.

In the research conducted, waste generated by households and businesses that are collected not subject to separate collection was accepted for analysis.

In the city of Lublin, 7 waste collection sectors have been distinguished based on administrative districts (Figure 1).

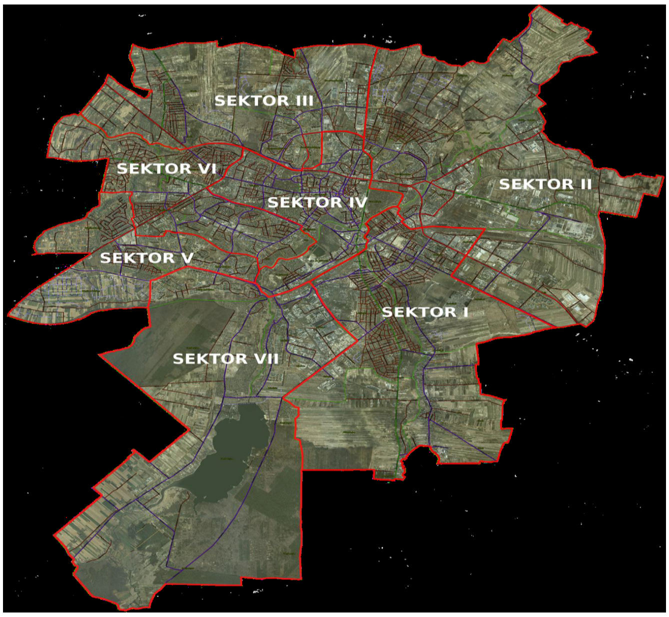

Figure 1. Waste collection sectors in Lublin [37].

2. Materials and Methods

2.1. Distribution Comparison

In many cases, the Kolmogorov–Smirnov test to compare (verify the differences) the distributions of two features, X and Y, is used [32,38]. Based on the realization observations $\{x_1, x_2, \ldots, x_{n_1}\}$ and $\{y_1, y_2, \ldots, y_{n_2}\}$ for these features, we create empirical distributions

$$F_X(t) = \frac{\#\{x_i : x_i \le t, \quad 1 \le i \le n_1\}}{n},$$
$$F_Y(t) = \frac{\#\{y_i : y_i \le t, \quad 1 \le i \le n_2\}}{n}$$

where # denotes the set cardinality. For the Kolmogorov–Smirnov test at the significance level $\alpha \in (0,1)$ the hypothesis is formulated:

H_0. $\forall t \in (-\infty, \infty)$ $F_X(t) = F_Y(t)$ *(the distribution functions of the distributions are identical or differ insignificantly),*

and the alternative hypothesis:

H_1. $\exists t \in (-\infty, \infty)$ $F_X(t) \neq F_Y(t)$ *(the distribution functions of the distributions differ significantly).*

The test statistic is given by the formula:

$$D_{XY}^{KS} = \sup_{t \geq 0} \left| F_X(t) - F_Y(t) \right| \tag{1}$$

The D statistic has a Kolmogorov distribution. From the Kolmogorov distribution tables for the significance level α, we determine the critical value. If $\sqrt{\frac{n+m}{nm}} D_{XY}^{KS} > K_\alpha$, where n and m denote sample sizes, then we reject the null hypothesis H_0 in favor of the alternative hypothesis H_1. The Kolmogorov–Smirnov test can be used to identify differences in the distributions of two characteristics, for example, before and after an event (e.g., before and after a pandemic or before and after the start of a war). Unfortunately, the statistic (1) shows the largest difference for empirical distributions F_X and F_Y (Figure 2), while the statistics

$$D_{XY}^{1} = \int_{-\infty}^{\infty} \left| F_X(s) - F_Y(s) \right| ds, \tag{2}$$

$$D_{XY}^{2} = \int_{-\infty}^{\infty} \left(F_X(s) - F_Y(s) \right)^2 ds \tag{3}$$

show the scale of differences in the norm L_1 and L_2, respectively. The graph below illustrates a comparison of the two empirical distributions. The red line length indicates the Kolmogorov–Smirnov statistic D_{XY}^{KS}, while the black area (differences in empirical distributions) indicates the statistical value D_{XY}^{1}.

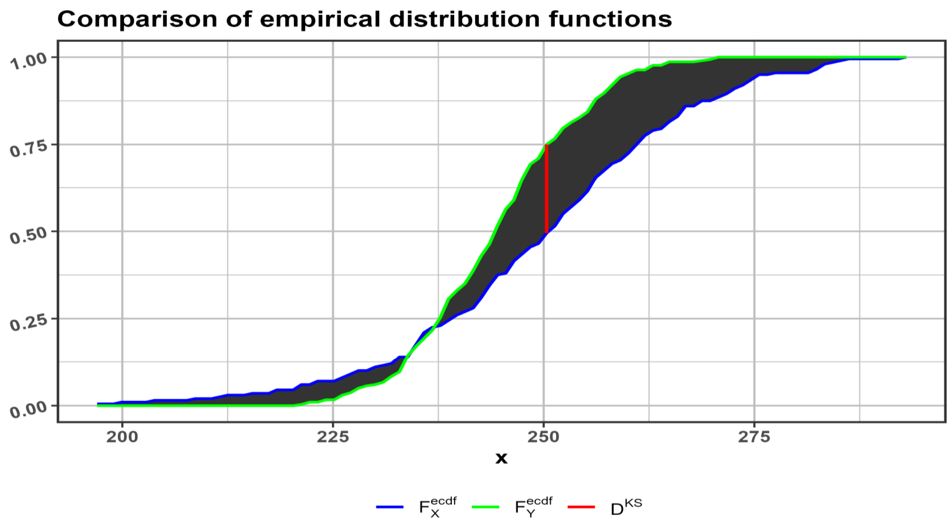

Figure 2. Distribution comparison.

By directly analyzing only the Kolmogorov–Smirnov statistic values D_{XY}^{KS} or statistics D_{XY}^{1} and D_{XY}^{2} for the sectors in which municipal waste is collected, it is difficult to determine the similarities and differences for all sectors or the occurrence of changes following the occurrence of two geopolitical events in succession. Using the Kolmogorov–Smirnov test, it is only possible to determine whether there were significant changes in the distributions of waste volumes before and after the geopolitical shock occurred. A better picture of the differences between distributions is provided by the statistics defined by Formulas (2) and (3), which capture the scale and shape of the differences between the distribution functions. The problem is not in capturing the significance of the changes for each sector, just having a specific fleet and considering the changes that have occurred in the waste generation in all sectors at the same time; it is necessary to reallocate transport resources and change the waste collection schedule to ensure the residents' sanitary safety. To solve the problem, the similarities and differences in waste generation were analyzed simultaneously for all sectors. To determine the similarities and differences in municipal waste disposal amounts between sectors, it is necessary to group them into clusters that present similar characteristics for the groups in the cluster. To define the clusters, first multidimensional scaling and then K-means cluster analysis were used.

2.2. Multidimensional Scaling Method

Consider a set containing m objects. For these objects, a distance matrix $\{D_{ij}\}_{1\leq i,j\leq m}$ is determined. In the considered case, the distance matrix values are defined as the deviations between the waste collection volume distributions; therefore, the quantities $D_{i,j}$, $1 \leq i,j \leq m$ are determined using (1), (2), or (3). To determine similarities and differences between distributions, the Multidimensional Scaling Method is first used [38–40]. This technique allows for similarities and differences visualization of certain object groups. Using this technique, the $j-$ th object is assigned a point $z_j \in \mathbb{R}^n$, $1 \leq j \leq m$ and the distance between points $\|z_i - z_j\|$ corresponds to D_{ij}—differences between objects i, j. The quantity $\|\|$ denotes the Euclidean norm. The coordinates of points z_j in some cases are strongly correlated with factors influencing the behavior of the object [38,39]. Using MDS, objects for which the differences are small are closer to each other, while objects with larger differences are farther apart.

Determining points $z_i \in \mathbb{R}^n$, $1 \leq i \leq m$ involves solving the assignment

$$\min_{z_1,\ldots,z_m} S(z_1, z_2, \ldots, z_m), \tag{4}$$

where the objective function is given by the formula

$$S(z_1, z_2, \ldots, z_m) = \sum_{1\leq i,j\leq m} \left(D_{ij} - \|z_i - z_j\|\right)^2. \tag{5}$$

2.3. Cluster Analysis

Cluster analysis involves grouping a dataset into subsets. The elements belonging to these subsets have certain patterns and similarities in data structures. In other words, cluster analysis involves dividing a set into clusters (groups) characterized by certain patterns. The division into groups enables the detection of patterns, identical features, or regularities in a group [38]. However, using clustering methods, it is possible to identify outliers, which is very helpful in detecting anomalies or the occurrence of feature changes due to events. Unusual outliers can be useful for identifying abnormalities, disorders, uniqueness, and deviations. This paper will use k-means clustering analysis and Gaussian mixture models to detect similarities and changes in waste collection across sectors.

2.3.1. K-Means Cluster Analysis

We consider a set of points $C = \{z_j\}_{1\leq j\leq m}$, where each point $z_j \in \mathbb{R}^n$ corresponds to an object. In the considered case, after applying the multidimensional scaling method, it corresponds to the distribution of collected waste from the sector. First, the number of groups K, $K << m$ is determined, into which the entire set C should be divided. Using the K-means clustering method (see, e.g., [37,39] the entire set of unlabeled objects C is divided into disjoint groups (clusters) $C_1, \ldots, C_K$, where $C_1 \cup \ldots \cup C_K = C$ and $C_i \cap C_j = \emptyset$ for $i \neq j$ and $1 \leq i,j \leq K$. Objects belonging to a group are characterized by similarities and the differences are small and are located closer to each other. Objects belonging to the group have similarities and the differences are not large and are more closely located next to each other.

To divide a set of objects into groups, we define an intra-group variation

$$W(C_k) = \frac{1}{\#C_k} \sum_{i,j \in C_k} \|z_i - z_j\| \tag{6}$$

where $\#C_k$—number of objects belonging to the $k-$ th cluster.

We divide the entire set into clusters in such a way that the sum of intra-group variations is as small as possible. Solving the task

$$\min_{C_1,\ldots,C_K} \sum_{k=1}^{K} W(C_k) \tag{7}$$

enables the set C to be divided into groups, with the differences between the objects in the group being as small as possible (i.e., the objects belonging to the group are located next to each other).

2.3.2. Gaussian Mixed Models

Mixed models [38] are a tool for identifying distributions. The distribution of the studied characteristic X is represented as a linear combination of different distributions. For Gaussian mixed models, we define the distribution

$$f(x) = \sum_{j=1}^{K} w_j \psi(x, m_j, \Sigma_j), \quad \text{for} \quad x \in \mathbb{R}^n \tag{8}$$

where $w_j \geq 0$ for $1 \leq j \leq K$ and $\sum_{j=1}^{k} w_j = 1$, whereas

$$\psi(x, m, \Sigma) = \frac{1}{\sqrt{(2\pi)^n \det(\Sigma)}} \exp\left(-\frac{1}{2}(x-m)^T \Sigma^{-1}(x-m)\right)$$

where $m \in \mathbb{R}^n$ and $\Sigma \in \mathbb{R}^{n \times n}$.

When the entire set C is divided into clusters $C_1, \ldots, C_K$, where the weights are calculated as follows: $w_j = \frac{\#C_j}{\#C}$, $1 \leq j \leq K$. The probability of an observation z_i belonging to cluster C_j is defined as

$$p_j(z_i) = \frac{w_j \psi(z_i, m_j, \Sigma_j)}{\sum_{s=1}^{K} w_s \psi(x, m_s, \Sigma_s)} \tag{9}$$

for $1 \leq i \leq m$, $1 \leq j \leq K$.

The identifications of density (8) involve estimating both the weights $w = \{w_1, \ldots, w_K\}$ as well as the parameters of the normal distribution $m = \{m_j\}_{1 \leq j \leq K}$ and $\Sigma = \{\Sigma_j\}_{1 \leq j \leq K}$. To determine the normal distribution parameters, the likelihood function is defined as

$$L(w, m, \Sigma) = \prod_{i=1}^{m} f(z_i) = \prod_{i=1}^{m} \left(\sum_{j=1}^{K} w_j \psi(z_i, m_j, \Sigma_j) \right). \tag{10}$$

By solving the tasks

$$\max_{w,m,\Sigma} L(w, m, \Sigma) \tag{11}$$

a sequence of weights $w = \{w_i\}_{1 \leq i \leq K}$ and parameters $m = \{m_j\}_{1 \leq j \leq K}$ and $\Sigma = \{\Sigma_j\}_{1 \leq j \leq K}$ corresponding to clusters $C_1, \ldots, C_K$ are both obtained.

Based on the logarithm property, we solve the auxiliary task instead of task (11), where the logarithm of the objective function (10) is maximized, and therefore we are solving the following task

$$\max_{w,m,\Sigma} \sum_{i=1}^{m} \log(w_1 \psi(z_i, m_1, \Sigma_1) + \ldots + w_K \psi(z_i, m_K, \Sigma_K)) \quad (12)$$

To solve the task (12), the Expectation-Maximization (EM) algorithm [38] is used.

3. Results

To identify changes due to geopolitical factors for each sector and each waste type before and after the geopolitical shock, distributions of the waste amount generated were determined. The D^1_{XY} statistic given by Equation (2), which more accurately describes the scale of differences between distributions than the Kolmogorov–Smirnov statistic, was used to capture differences in waste quantity distributions. Using MDS, the position in the Cartesian coordinate system was determined for each sector, while the Gaussian mixture model was used to estimate the probability of belonging to clusters. Then, the sector membership of the corresponding cluster for which the probability is highest was determined. All calculations were performed in the R 4.4.1 programming language.

3.1. Impact of COVID-19 on the Distribution of Collected Waste

The lockdown began in Poland on 10 March 2020. The impact of COVID-19 on the change in the affiliation of sectors to clusters was analyzed. Below is the application of the GMM method to detect changes in sector waste generation.

Sectors with the letter C added at the beginning indicate the same sector only for data after 10 March 2020. The affiliation of sectors S_i and CS_i, $i \in \{1, 2, ..., 7, N\}$ to different clusters indicates the change in the waste amounts received until and after the start of the lockdown.

3.1.1. Non-Segregated Waste

The collection, processing, and transportation of mixed waste consumes the largest amount of energy in the waste management chain [24]. Regarding mixed municipal waste, it is important to schedule the collection of this waste type properly. Figure 3 presents the changes in the Lublin city sector's affiliation to clusters 1, 2, and 3 using the GMM.

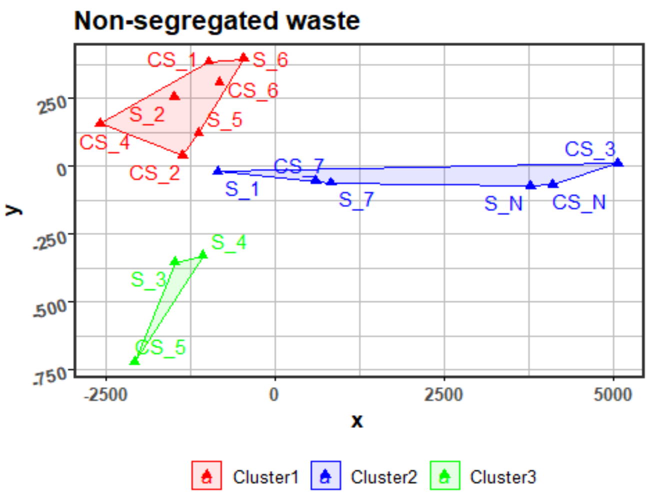

Figure 3. Grouping of non-segregated waste collection sectors using GMMs.

The results indicate changes in the preference for generating non-segregated waste in individual clusters (Table 1). Pandemic conditions caused a change in the affiliation of non-segregated waste in the following sectors: S1 from cluster 2 to 1, S3 from cluster 3 to 2, S4 from cluster 3 to 1, and S5 from cluster 1 to 3 (Table 2). This means these waste groups may need to be rescheduled, or the number of vehicles serving the sectors changed.

Table 1. Probability of sector affiliation for non-segregated waste.

i	S_i			CS_i		
	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 1**	**Cluster 2**	**Cluster 3**
1	0. 665	0.55556	0.01779	0.99999	0.00000	0.00001
2	0.99975	0.00000	0.00025	0.95557	0.01838	0.02605
3	0.00012	0.00000	0.99988	0.00000	1.00000	0.00000
4	0.00058	0.00000	0.99942	0.99912	0.00000	0.00088
5	0.99762	0.00000	0.00238	0.00000	0.00000	1.00000
6	1.00000	0.00000	0.00000	0.99998	0.00000	0.00002
7	0.00035	0.99965	0.00000	0.00144	0.99856	0.00000
N	0.00000	1.00000	0.00000	0.00000	1.00000	0.00000

Table 2. Cluster affiliation to sector for non-segregated waste.

	Cluster 1	**Cluster 2**	**Cluster 3**
Before COVID-19	S_2, S_5, S_6	S_1, S_7, S_N	S_3, S_4
After COVID-19	CS_1, CS_2, CS_4, CS_6	CS_3, CS_7, CS_N	CS_5

Observed changes suggest the need to adapt the waste collection system to new conditions. Changing the sectors' affiliation with the clusters may require optimizing waste collection schedules to adjust frequency to new waste generation patterns. It may also mean a change in the number or distribution of vehicles serving each sector to provide operational efficiency and minimize costs.

3.1.2. Paper and Cardboard Waste

The results indicate that no change in the preference for generating paper and cardboard waste occurred (Tables 3 and 4 and Figure 4) resulting from the COVID-19 pandemic. Pandemic conditions did not change paper and cardboard waste type affiliation, meaning that the COVID-19 pandemic did not affect the collection grouping of this waste type. The lack of change in the generation of paper and cardboard waste during the period under review indicates the consistent nature of this waste stream despite pandemic constraints. This may indicate that the level of paper product consumption in households and commercial sectors has remained constant despite changing socioeconomic conditions.

Table 3. Probability of sector affiliation for paper/cardboard waste.

i	S_i			CS_i		
	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 1**	**Cluster 2**	**Cluster 3**
1	1	0	0	1	0	0
2	1	0	0	1	0	0
3	1	0	0	1	0	0
4	0	1	0	0	1	0
5	1	0	0	1	0	0
6	1	0	0	1	0	0
7	1	0	0	1	0	0
N	0	0	1	0	0	1

Table 4. Cluster affiliation to sector for paper/cardboard waste.

	Cluster 1	Cluster 2	Cluster 3
Before COVID-19	S_1, S_2, S_3, S_5, S_6, S_7	S_4	S_N
After COVID-19	CS_1, CS_2, CS_3, CS_5, CS_6, CS_7	CS_4	CS_N

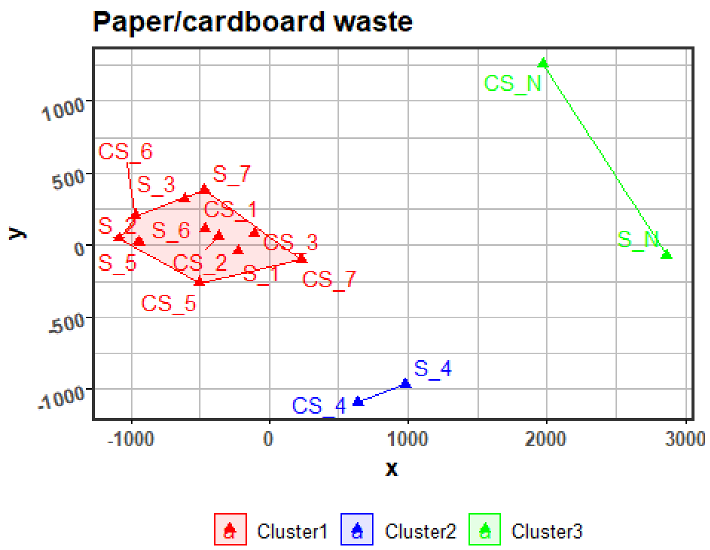

Figure 4. Grouping of paper and cardboard waste collection sectors using GMMs.

3.1.3. Glass Waste

The results indicate changes in glass waste generation preferences in individual clusters (Table 5 and Figure 5). Pandemic conditions resulted in a change in the glass waste affiliation in the unoccupied sector from cluster 3 to 2 (Table 6), meaning it may be necessary to reschedule the collection of these waste groups in this sector or change the number of vehicles serving the sectors. The research showed that pandemic conditions caused significant changes in glass waste generation in the non-residential sector. Changes in the affiliation of glass waste in the non-residential sector may be the result of restrictions on economic activity, such as the shutdown of catering establishments, hotels, or cultural institutions. The observed changes may be due to a shift in the dominant glass waste sources in the non-residential sector, such as from the service sector to the industrial sector or other economic units with less sensitivity to pandemic restrictions. These changes generate certain logistical consequences, including the need to optimize glass waste collection schedules in the non-residential sector and adjust the number and location of glass waste containers to better match current waste generation sources. The results indicate that glass waste in the non-residential sector is more susceptible to fluctuations caused by emergencies, such as a pandemic, compared to other waste streams. This is due to the strong link between glass waste production and the operations of the food service and catering sectors, which were affected by pandemic restrictions. This indicates the need for flexible waste management systems, especially in the context of unpredictable emergencies.

Table 5. Probability of sector affiliation for glass waste.

i	S_i			CS_i		
	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 1**	**Cluster 2**	**Cluster 3**
1	1	0.00000	0.00000	1	0.00000	0.00000
2	1	0.00000	0.00000	1	0.00000	0.00000
3	1	0.00000	0.00000	1	0.00000	0.00000
4	1	0.00000	0.00000	1	0.00000	0.00000
5	1	0.00000	0.00000	1	0.00000	0.00000
6	1	0.00000	0.00000	1	0.00000	0.00000
7	1	0.00000	0.00000	1	0.00000	0.00000
N	0	0.00002	0.99998	0	0.99998	0.00002

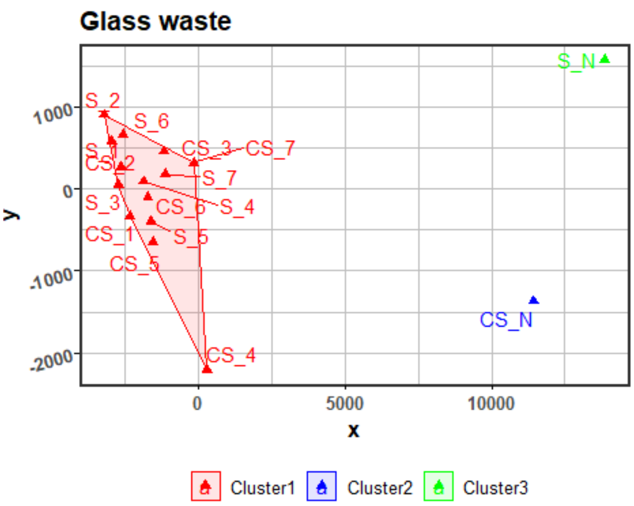

Figure 5. Grouping of glass waste collection sectors using GMMs.

Table 6. Sector affiliation to clusters for glass waste.

	Cluster 1	Cluster 2	Cluster 3
Before COVID-19	S_1, S_2, S_3, S_4, S_5, S_6, S_7	-	S_N
After COVID-19	CS_1, CS_2, CS_3, CS_4, CS_5, CS_6, CS_7	CS_N	-

3.1.4. Plastic Waste

Results analysis indicates that pandemic conditions significantly affected changes in artificial waste generation, changing its affiliation with the waste stream structure. The obtained results allow noticing changes in the preference of plastic waste generation in each cluster (Table 7 and Figure 6). Pandemic conditions changed the artificial waste affiliation in the following sectors: S3 from cluster 2 to 3 and S7 from cluster 1 to 3 (Table 8). This may indicate the need to change the schedules for the collection of these waste groups or change the number of vehicles serving the sectors. The sectors where the change was observed (3 and 7) are mainly single-family households. It is worth noting that during the pandemic period, households generated a different waste structure. There was a significant 53% increase in the amount of plastic packaging waste [41]. This may be related to the increasing use of disposable packaging, protective materials (e.g., masks, gloves), and the intensification of online shopping, requiring additional plastic packaging. The change in artificial waste's affiliation may be due to a shift in its generation between sectors as a consequence of an increase in artificial waste generation in households due to changing consumer habits (online shopping, greater consumption at home) and a decline in the generation of this waste in the commercial and service sectors due to reductions in business activity. The indicated changes require waste management adaptation systems, including the need to change the timing of collection of these waste groups, change the number of vehicles serving the sectors, and improve segregation systems to effectively process the growing volume of plastic waste, especially packaging.

Table 7. Probability of sector affiliation for plastic waste.

i	S_i			CS_i		
	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 1**	**Cluster 2**	**Cluster 3**
1	1.00000	0.00000	0.00000	1.00000	0.00000	0.00000
2	0.00000	0.99835	0.00165	0.00000	0.99888	0.00112
3	0.00000	0.96991	0.03009	0.00000	0.00000	1.00000
4	1.00000	0.00000	0.00000	1.00000	0.00000	0.00000
5	0.99999	0.00000	0.00001	1.00000	0.00000	0.00000
6	0.00000	0.99810	0.00190	0.00000	0.99788	0.00212
7	1.00000	0.00000	0.00000	0.00000	0.00000	1.00000
N	0.00000	0.00000	1.00000	0.00000	0.00000	1.00000

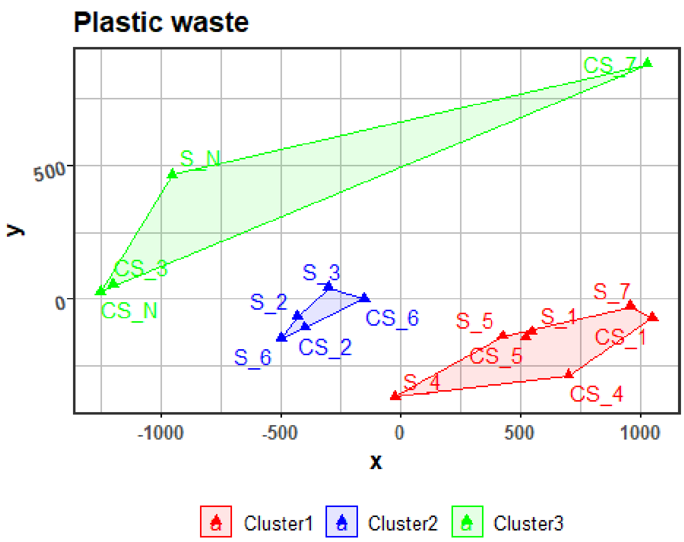

Figure 6. Grouping of plastic waste collection sectors using GMMs.

Table 8. Sector affiliation to clusters for plastic waste.

	Cluster 1	**Cluster 2**	**Cluster 3**
Before COVID-19	S_1, S_4, S_5, S_7	S_2, S_3, S_6	S_N
After COVID-19	CS_1, CS_4, CS_5	CS_2, CS_6	CS_3, CS_7, CS_N

3.2. Impact of War in Ukraine on Waste Collection Volumes

The war in Ukraine has influenced migration processes, potentially also affecting the volume, redistribution, and municipal waste structure in European countries [13]. The war in Ukraine has significantly affected waste generation and management in Europe. The arrival of displaced Ukrainians in other European countries has increased the burden on their waste management systems [42].

This research analyzed the impact of the war in Ukraine on the change in the sectors' affiliation to clusters. The GMM method was used to analyze the impact. Sectors with the letter N added at the beginning indicate the same sector only for data after 2022-02-24 (the start of the war in Ukraine). The affiliation of sectors S_i and WS_i, i ∈ {1, 2, . . ., 7, N} o different clusters signifies a change in the waste volumes received until and after the start of the war in Ukraine. The figures below (Figures 7–10) present changes in cluster membership using GMM. To better capture the changes caused by successive geopolitical shocks in the case under consideration, we analyze the sequence of changes caused first by the COVID-19 pandemic and then by the war in Ukraine. The dynamics of change reveal the need for adaptation of collection schedules and logistical changes related to waste collection.

3.2.1. Non-Segregated Waste

The results suggest changes in the preference for generating non-segregated waste in each cluster (Table 9 and Figure 7) as a result of the war in Ukraine. With the outbreak of war, population migration affected the general trend related to waste volume, and due to reallocation, the waste production volume in the sectors also changed. This resulted in a change in the affiliation of non-segregated waste in sectors S3, S4, S5, and S7 (Table 10). Sector S3 was located before the pandemic in cluster 1, after the pandemic in cluster 2, and after the outbreak of the war in cluster 3. S4 and S5 sectors before the pandemic were in cluster 1, while after COVID-19 and the outbreak of war, they were in cluster 3. Meanwhile, the S7 sector went from cluster 1 in the pre- and post-pandemic period to cluster 2 after the outbreak of war. Changes in the cluster affiliation of sectors make it necessary to focus on scheduling the collection of this waste group and the efficiency of using the available fleet. The war in Ukraine has caused significant population displacement, which has affected the cluster's unsegregated waste generation structure. The refugee influx into certain regions may have increased the amount of waste generated in residential sectors, especially in areas receiving significant migrant populations. Results showed changes in waste generation preferences, which has implications for logistics and waste management. Therefore, it may be necessary to reallocate logistics resources such as vehicles and personnel to meet changed waste generation patterns.

Table 9. Probability of sector affiliation for non-segregated waste.

i	S_i			CS_i			WS_i		
	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 1**	**Cluster 2**	**Cluster 3**
1	0.99094	0.00000	0.00906	0.98373	0.00000	0.01627	0.98759	0.00000	0.01241
2	0.97371	0.00000	0.02629	0.96063	0.00000	0.03937	0.94924	0.00000	0.05076
3	0.95661	0.00000	0.04339	0.00000	0.99997	0.00003	0.00000	0.00000	1.00000
4	0.95444	0.00000	0.04556	0.05129	0.00000	0.94871	0.00007	0.00000	0.99993
5	0.97732	0.00000	0.02268	0.00029	0.00000	0.99971	0.00000	0.00000	1.00000
6	0.98986	0.00000	0.01014	0.99108	0.00000	0.00892	0.98925	0.00000	0.01075
7	0.93773	0.00000	0.06227	0.96599	0.00000	0.03401	0.00000	0.99992	0.00008
N	0.00000	0.99985	0.00015	0.00000	0.99992	0.00008	0.00000	0.99987	0.00013

Table 10. Sector affiliation to clusters for non-segregated waste.

	Cluster 1	**Cluster 2**	**Cluster 3**
Before COVID-19	S_1, S_2, S_3, S_4, S_5, S_6, S_7	S_N	-
After COVID-19	CS_1, CS_2, CS_6, CS_7	CS_3, CS_N	CS_4, CS_5
After the war started	WS_1, WS_2, WS_6	WS_7, WS_N	WS_3, WS_4, WS_5

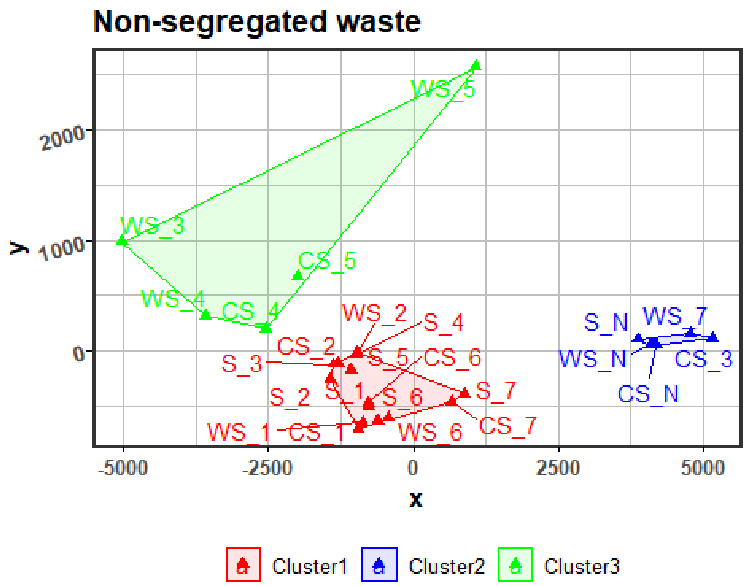

Figure 7. Grouping of non-segregated waste collection sectors using GMMs.

3.2.2. Paper and Cardboard Waste

The results confirm the changes in paper and cardboard waste generation preferences in each cluster (Table 11 and Figure 8) as a result of the war in Ukraine. The outbreak of the war caused population migrations, resulting in a change in the affiliation of paper and cardboard waste in the following sectors: S3 from cluster 1 to 2 and S7 from cluster 1 to 2 (Table 12). This could mean changes in the waste collection schedule and the number of vehicles used. The results highlight the need for dynamic management of paper and cardboard waste streams in emergency situations. In particular, these systems must be able to adapt quickly to the demographic and economic variables in each cluster. Prospectively, it is also worth noting that in regions hosting refugees, it is necessary to develop paper waste recycling infrastructure to meet the increased volume of this stream [43].

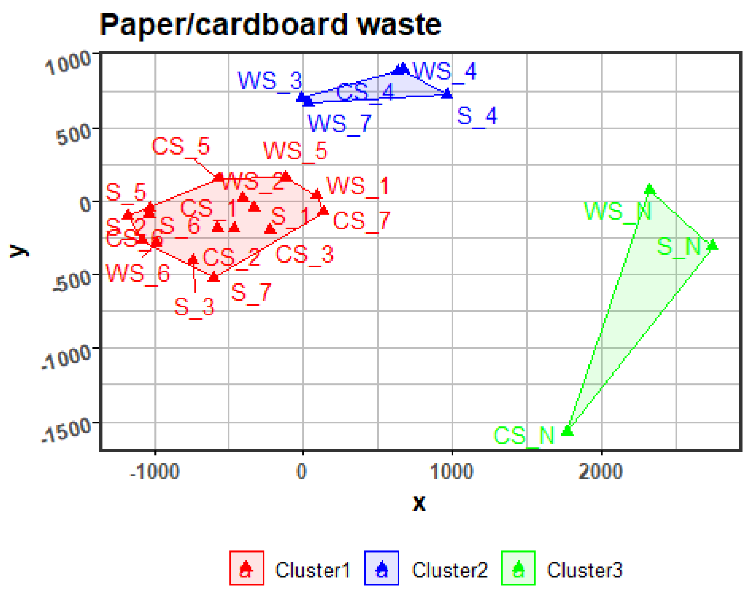

Figure 8. Grouping of paper and cardboard waste collection sectors using GMMs.

Table 11. Probability of sector affiliation for paper and cardboard waste.

i	S_i			CS_i			WS_i		
	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 1**	**Cluster 2**	**Cluster 3**
1	1.00000	0.00000	0	1.00000	0.00000	0	0.99993	0.00007	0
2	1.00000	0.00000	0	1.00000	0.00000	0	0.99997	0.00003	0
3	1.00000	0.00000	0	1.00000	0.00000	0	0.00009	0.99991	0
4	0.00004	0.99996	0	0.00000	1.00000	0	0.00000	1.00000	0
5	1.00000	0.00000	0	0.99887	0.00113	0	0.99816	0.00184	0
6	1.00000	0.00000	0	1.00000	0.00000	0	1.00000	0.00000	0
7	1.00000	0.00000	0	1.00000	0.00000	0	0.00025	0.99975	0
N	0.00000	0.00000	1	0.00000	0.00000	1	0.00000	0.00000	1

Table 12. Sector affiliation to clusters for paper and cardboard waste.

	Cluster 1	**Cluster 2**	**Cluster 3**
Before COVID-19	S_1, S_2, S_3, S_5, S_6, S_7	S_4	S_N
After COVID-19	CS_1, CS_2, CS_3, CS_5, CS_6, CS_7	CS__4	CS_N
After the war started	WS_1, WS_2, WS_5, WS_6,	WS_3, WS_4, WS_7	WS_N

3.2.3. Glass Waste

The results show changes in glass waste generation preferences by cluster (Table 13 and Figure 9) following the war in Ukraine. A change in the glass waste affiliation was observed in the following sectors: S3 from cluster 1 to 2 and S4 from cluster 2 to 1 (Table 14). This makes it necessary to pay attention to the scheduling of collection of this waste group and the efficiency of using the available fleet.

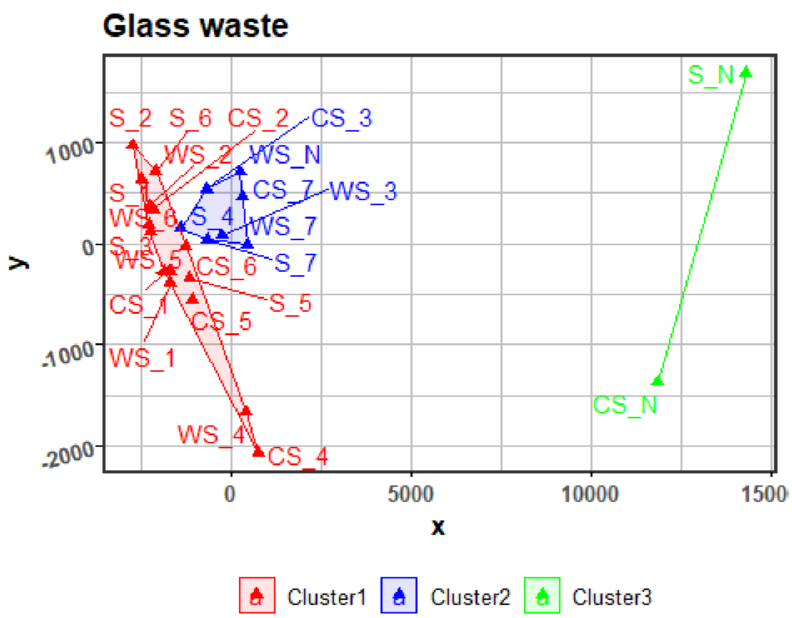

Figure 9. Grouping of glass waste collection sectors using GMMs.

Table 13. Probability of sector affiliation for glass waste.

i	S_i			CS_i			WS_i		
	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 1**	**Cluster 2**	**Cluster 3**
1	0.99734	0.00266	0	0.84233	0.15767	0	0.95376	0.04624	0
2	1.00000	0.00000	0	0.90440	0.09560	0	0.92819	0.07181	0
3	0.69337	0.30663	0	0.00000	1.00000	0	0.00001	0.99999	0
4	0.35653	0.64347	0	1.00000	0.00000	0	1.00000	0.00000	0
5	0.97021	0.02979	0	0.99878	0.00122	0	0.90676	0.09324	0
6	0.99207	0.00793	0	0.50744	0.49256	0	0.77678	0.22322	0
7	0.00379	0.99621	0	0.00000	1.00000	0	0.00000	1.00000	0
N	0.00000	0.00000	1	0.00000	0.00000	1	0.00000	1.00000	0

Table 14. Sector affiliation to clusters for glass waste.

	Cluster 1	Cluster 2	Cluster 3
Before COVID-19	S_1, S_2, S_3, S_5, S_6	S_4, S_7	S_N
After COVID-19	CS_1, CS_2, CS_4, CS_5, CS_6	CS_3, CS_7	CS_N
After the war started	WS_1, WS_2, WS_4, WS_5, WS_6	WS_3, WS_7, WS_N	-

3.2.4. Plastic Waste

The results reveal changes in artificial waste generation preferences by cluster (Table 15 and Figure 10) following the war in Ukraine. A change was observed in the artificial waste affiliation in sector S3 from cluster 2 before the pandemic and cluster 3 after the COVID-19 pandemic to cluster 1 (Table 16), making it necessary to focus attention on the scheduling of collection of this waste group and the efficiency of using the available fleet.

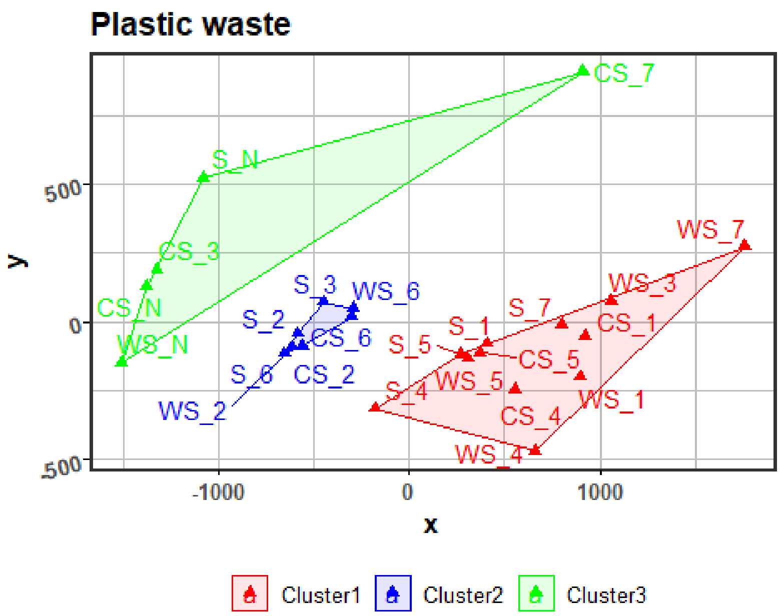

Figure 10. Grouping of plastic waste collection sectors using GMMs.

Table 15. Probability of sector affiliation for plastic waste.

i	S_i			CS_i			WS_i		
	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 1**	**Cluster 2**	**Cluster 3**
1	0.99996	0.00000	0.00004	1.00000	0.00000	0.00000	1.00000	0.00000	0.00000
2	0.00001	0.99712	0.00287	0.00006	0.99780	0.00214	0.00003	0.99752	0.00245
3	0.00002	0.94834	0.05163	0.00000	0.00000	1.00000	1.00000	0.00000	0.00000
4	0.99988	0.00000	0.00012	1.00000	0.00000	0.00000	1.00000	0.00000	0.00000
5	0.99993	0.00000	0.00007	0.99998	0.00000	0.00002	0.99997	0.00000	0.00003
6	0.00005	0.99638	0.00357	0.00016	0.99643	0.00341	0.00009	0.99514	0.00477
7	1.00000	0.00000	0.00000	0.00000	0.00000	1.00000	1.00000	0.00000	0.00000
N	0.00000	0.00000	1.00000	0.00000	0.00000	1.00000	0.00000	0.00000	1.00000

Table 16. Sector affiliation to clusters for glass waste.

	Cluster 1	**Cluster 2**	**Cluster 3**
Before COVID-19	S_1, S_4, S_5, S_7	S_2, S_3, S_6	S_N
After COVID-19	CS_1, CS_4, CS_5,	CS_2, CS_6	CS_3, CS_7, CS_N
After the war started	WS_1, WS_3, WS_4, WS_5, WS_7	WS_2, WS_6	WS_N

4. Conclusions

The increasing waste volume in Poland and the rising costs of waste processing make the proper organization of waste collection and management one of the crucial aspects of waste management. In the research area, seven waste collection sectors were identified for households and enterprises and one non-residential sector, for which similarities in the production of different waste types were analyzed. Significant differences in cluster sector affiliation by waste type were observed. The analysis also considered the influence of geopolitical factors like the COVID-19 pandemic and the war in Ukraine on the change in the affiliation groups of different waste categories. This means that adjustments to the collection schedule of certain waste groups may be needed in practice.

The COVID-19 pandemic had a significant impact on human behavior, causing changes in health, relationships, lifestyles and education [44]. Particularly during the lockdown, work and learning regulations changed, with a consequent increase in the time spent at home and, therefore, a reduction in that time at work and other facilities [45]. This caused an increase in the waste amount generated in households [45] and also changes in its structure [46,47]. The COVID-19 pandemic resulted in a change in the sector affiliation of non-segregated waste, plastics, and glass clusters, whereas no change in waste generation preference was observed for paper and cardboard waste.

The results suggest that the paper and cardboard waste stream is less susceptible to short-term changes in social and economic behavior compared to other waste types, such as non-segregated waste or biowaste. This could be due to a more stabilized demand for products that generate this waste type and their long-term presence in the consumption cycle.

However, the war in Ukraine resulted in population migration, which affected the overall trend related to waste volume due to the reallocation of the change in waste production volumes in the sectors. This resulted in changes in the generation preferences of all waste types in the surveyed region. This means adjusting the waste collection schedule to the new conditions. Since collection distances are constant, the variable that managers can operate on is proper scheduling so that the designated waste collection route does not result in empty or incomplete loads. Therefore, the presented analysis can be useful in waste collection management, especially when arranging waste collection schedules and using the available fleet. This research also reveals that it is necessary to constantly monitor the waste disposal volume and make adaptations to the waste disposal schedule. This is particularly important given that waste transportation is considered one of the most important elements of waste management, which integrates the entire system and consumes the most energy in the process. Therefore, an inadequate waste collection schedule results in higher fuel consumption, resulting in negative environmental and economic impacts.

Optimizing waste collection routes can significantly reduce travel distances, fuel consumption, and CO2 emissions [48]. Together with time savings and the elimination of empty transport runs, this translates into economic savings. In addition, an inadequate waste collection schedule increases the likelihood of waste self-disposal [49], which has negative environmental effects. The need to optimize waste collection in emergencies avoids economic and environmental problems, and rapid model adjustment can take place using artificial intelligence [50].

The research results indicate that waste management systems are vulnerable to changes caused by geopolitical crises, such as war or pandemics [51]. These situations can significantly change the demographic and economic regions' structures, leading to disruptions in legacy systems. The findings highlight the need for an integrated approach to waste management that considers changing social and economic conditions. Therefore, it is necessary to invest in a more resilient and flexible waste management infrastructure, which may include regular monitoring of changes in waste generation to adjust management strategies quickly or incorporate scenarios related to geopolitical crises into long-term waste management planning.

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