

Article

A Detailed Analysis of the Morphological Composition of Selectively Collected Plastics and Metals: A Case Study of Four Voivodeships in Poland

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Abstract

This article presents the results of research on the morphological composition of selectively collected plastics and metals conducted in four voivodeships in Poland from late 2024 to early 2025, before the introduction of the deposit-return system. A very detailed classification of the morphological composition of the studied plastics and metals into 29 groups was adopted, which distinguishes this study from other research and makes it possible to assess the quality of selectively collected waste. A detailed analysis of morphological composition enables an in-depth assessment of the potential of individual fractions for mechanical recycling, chemical recycling, or energy recovery. The results show that contamination in selectively collected plastics and metals, i.e., fractions not covered by this collection scheme, accounted for approximately 22% of the total mass. The largest share among the studied fractions consisted of films of various types, which accounted for approximately 24% of the mass of selectively collected waste. Assuming an 85% sorting efficiency for marketable plastics and metals, a maximum of approximately 57% of the mass of selectively collected plastics and metals can be directed to mechanical recycling. The remaining fraction, excluding PVC and glass, can be used for energy recovery or, in the future, partly directed to chemical recycling. The article also discusses factors that will affect changes in the morphological composition of selectively collected waste, including the deposit-return system, extended producer responsibility, and packaging eco-design.

Keywords: morphological composition; plastic waste; reuse; recycling; selective collection of plastics and metals; circular economy



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1. Introduction

In the modern world, changing consumption patterns, population growth, increasing urbanisation, and the use of primary raw materials have made the management of plastics a major challenge in waste management [1]. In Europe, in 2022, 40.7% of generated plastic packaging waste was recycled, while 35% was used in energy recovery [2]. Energy recovery means the thermal treatment of waste and waste-derived fuels to generate energy, most often through combustion, provided that the process meets specific energy-efficiency criteria.

According to data [2], the recycling rate of plastic packaging waste in the EU is increasing, from 25.2% in 2005 to 40.7% in 2022. Recycling rates for plastic waste vary

considerably between EU countries: In 2022, the highest rates were recorded in Slovakia (59.6%), Belgium (54.2%), and Germany (51.1%). In Poland, the rate was 46.3%. The lowest plastic recycling rates were recorded in Malta (16.4%), Denmark (23.5%), and France (25.2%) [2]. In 2023, 79.7 million tonnes of packaging waste were generated in the European Community, of which plastics accounted for 15.8 million tonnes (19.8%) and metals for 3.9 million tonnes (4.9%).

In recycling processes, it is essential to identify precisely the waste stream and the fractions it contains. This is particularly important for selectively collected plastics, which represent a valuable source of secondary materials for many areas of the economy. Nevertheless, its effective management requires waste-processing technologies that improve resource efficiency and reduce environmental impacts. For environmental technology designers and packaging manufacturers, the key challenges therefore include increasing recycling rates and reducing treatment costs.

Recycling is a priority in the waste hierarchy, but large-scale plastic recycling is currently not achievable in the EU. This is due to technological factors, as not all plastics are recyclable, and economic factors, including high labour and electricity costs, the availability of cheap primary raw materials, the quality of separate waste collection, sorting efficiency, and other factors. For these reasons, energy recovery is a necessary step towards closing the material loop in the municipal sector and is currently the only option that can sufficiently reduce landfilling [3]. The results of a previous study [4] showed that approximately 90% by mass of the residue from plastic sorting consists of a high-calorific fraction suitable for use as a component in waste-derived fuel production.

It should be noted that the morphological composition of selectively collected waste changes over time and also depends on the collection location. Since plastics, their collection, and their processing are now subject to the principles of the circular economy [5], the full potential contained in plastics can be realised only if the challenges of eco-designing packaging and plastic products, as well as their effective collection, sorting, and processing, are taken seriously.

Advanced sorting technologies do not fully eliminate the material heterogeneity of packaging waste, which remains a major barrier to high-quality recycling, particularly for flexible packaging. This is largely associated with the extensive use of multilayer laminates and packaging composed of materials that cannot be mechanically separated. Detailed information on the composition of sorted packaging waste streams is therefore necessary to improve the quality of post-consumer recyclate and support the development of improved recycling processes.

The authors of [6] analysed in detail the sorting fractions of polyolefins in flexible packaging waste from three European countries. The mass of recyclable fractions collected in the yellow-bag system and delivered to the Polish sorting plant in Marszów in 2019 accounted for approximately 40% of the total mass [7].

The morphological composition of municipal waste strongly influences the design of sorting plants, which aim to recover clean, homogeneous secondary raw materials for recycling. Fuel for energy recovery is also often produced from sorting residues. This composition varies depending on the season, housing type, waste origin, the character of a given locality (e.g., tourist or industrial), and residents' wealth and environmental awareness. Knowledge of the variability in the morphological composition of municipal waste characteristic of particular seasons or housing types, combined with proper management of the waste stream entering the installation and optimal retrofitting of the sorting facility, makes it possible to obtain good-quality secondary raw materials for recycling and repeatable parameters of waste-derived fuels that meet customer requirements. Studying

morphological composition should be one of the first and basic tools for determining the suitability of waste for recycling processes [8].

The recycling of problematic and environmentally polluting plastics is one of the main challenges for the European circular economy. The quality and quantity of selectively collected plastics, as well as their effective sorting, are indispensable components of the waste management system and are of key importance for increasing recycling rates [9].

At present, Poland lacks national-level data on packaging placed on the market, broken down in detail by individual polymers; on the morphology of packaging waste; and on the amount of packaging waste processed in recycling plants, also broken down by polymer. This makes it difficult to plan and develop plastics processing in Poland [10]. Therefore, the research conducted and the results obtained partly address these gaps by providing detailed morphological analysis of selectively collected plastics and metals and demonstrating their real potential for recycling.

The novelty of this article lies in the detailed division of the morphological composition of selectively collected plastics and metals into 29 groups. This enables an assessment of the recyclability of individual fractions and provides essential information for those placing packaged products on the market and for those responsible for packaging eco-design in the context of the PPWR regulations being implemented in Poland.

Based on detailed studies of the morphological composition of selectively collected plastics and metals used as input material in waste sorting facilities, facility operators can therefore make informed decisions on modernisation pathways and efficiency improvements. This may include the separation of new fractions for recycling, thereby increasing recycling rates and improving economic performance.

2. Theoretical, Legal, and Statistical Background

The structure of packaging waste generation in the EU in 2023 is shown in Figure 1 [11].

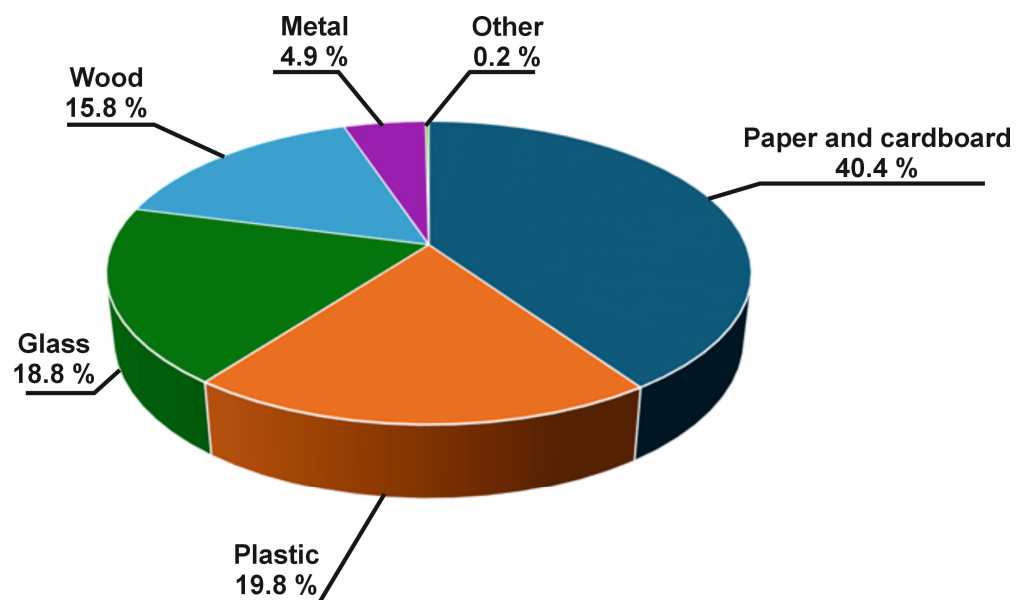


Figure 1. Packaging waste generated in the EU in 2023 (own elaboration based on Eurostat data [11]).

Figure 2 presents the recycling rates for plastic packaging waste in all EU Member States in 2023.

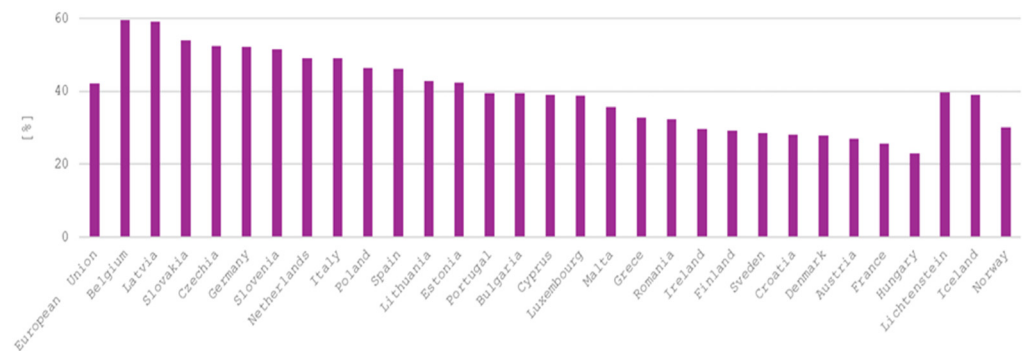


Figure 2. Recycling rates for plastic packaging waste in all EU Member States in 2023 (own elaboration based on Eurostat data [12]).

The reuse of plastics presents a challenge in proper management and resource recovery while also aiming to minimise the negative environmental impact of plastic waste [13]. Plastics of various types and colours, in the form of packaging, containers, and other post-consumer waste, are collected in bags or container systems, depending on the housing type. In line with the principles of the circular economy and the waste hierarchy, plastics should first be directed to recycling processes.

An important factor in the effectiveness of selective plastic collection is how it is organised, especially in terms of proximity and accessibility for residents. For example, kerbside collection results in less packaging waste in residual waste, which indicates better separate collection quality. In densely populated city centres, where space for additional bins is limited, coloured plastic bags can be an effective solution. Waste collection close to households is effective and is one way to accelerate the transition towards more resource-efficient management and a circular economy [14]. Another study [8] also showed that the quality and cleanliness of selectively collected plastics in single-family housing using the bag system are significantly better than in block housing using the container system, mainly because collection in multi-family housing is anonymous. Figure 3 schematically presents the organisation of the collection, sorting, and processing of selectively collected plastics and metals.

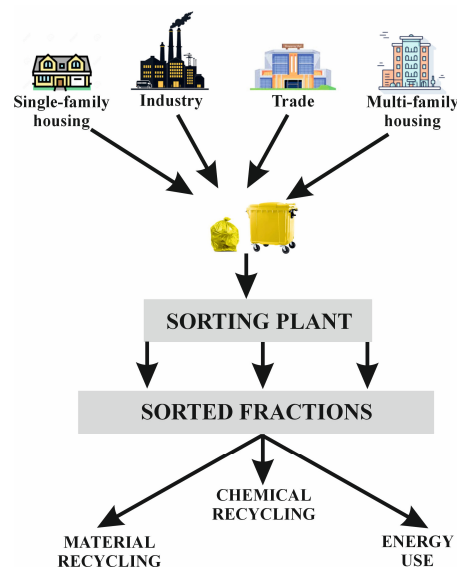


Figure 3. Processes of waste stream separation and utilisation (drawing: A.J. Wandrasz).

Table 1 presents the quantities of plastics and metals collected selectively in Poland from 2020 to 2024, according to statistical data [15].

Table 1. Quantities of selectively collected plastics and metals according to statistical data [15].

Year	The Amount of Waste Generated in Poland [thousand tons]	Amount of Selectively Collected Plastics [%]	Amount of Selectively Collected Metals [%]	Amount of Selectively Collected Plastics [thousand tons]	Amount of Selectively Collected Metals [thousand tons]
2020	13,117	9.9	0.1	1298.6	13.1
2021	13,674	9.6	0.2	1312.7	27.3
2022	13,420	10.1	0.1	1355.4	13.4
2023	13,448	10.4	0.1	1398.6	13.4
2024	14,158	10.3	0.1	1458.3	14.1

The morphological composition of selectively collected plastics and metals in Poland will change significantly in the near future, mainly due to the introduction of the deposit-return system and requirements of the PPWR Regulation and SUP Directive. Regulation (EU) 2025/40 of the European Parliament and of the Council of 19 December 2024 on packaging and packaging waste, adopted in 2024/2025, entered into force in 2025 and will be applied by EU countries from mid-2026 [16].

Selected PPWR objectives and assumptions that will lead to future changes in the morphological composition of selectively collected plastics:

- Waste minimisation by reducing the amount of packaging material and banning unnecessary packaging (e.g., double walls), as well as by prohibiting certain types of single-use packaging (e.g., for fresh fruit and vegetables in the HoReCa sector).
- Ensuring that, in line with the objectives of the circular economy (CE), by 2030, all packaging on the EU market is recyclable and reusable.
- Improving design sustainability by requiring packaging to be lighter, less material-intensive, and to have limited empty space (an empty-space ratio of no more than 50% from 2030).
- Harmonising regulations: alignment of rules across all EU Member States to facilitate the functioning of the single market and provide clear requirements for businesses.
- Introducing new labelling: a standardised packaging label indicating recyclability and handling instructions.

For businesses, this will require adapting packaging designs to the new standards and eco-design principles, as well as reducing packaging mass and volume. It will also involve introducing more reusable packaging, for example, in the e-commerce sector, and ensuring a higher content of recycled materials (recyclates) in packaging. In addition, attention should be paid to the provisions of the SUP Directive [17], adopted in May 2019. This directive is one of the EU's most significant steps towards reducing the use of single-use plastic products.

According to the PPWR, packaging recyclability is expressed in performance classes A, B, and C. From 2030 onwards, recycling performance will be based on design-for-recycling criteria. These criteria ensure the closed-loop use of secondary raw materials of sufficient quality to replace primary raw materials [16]. An assessment based on these design-for-recycling criteria is conducted for each packaging category. Once the criteria have been weighted for each packaging unit, the unit is classified as category A, B, or C. If the recycling performance class of a packaging unit is below 70%, the unit is considered not to meet the requirements of the recycling performance classes. As a result, the packaging is deemed technically non-recyclable, and its place on the market is restricted.

From 2035, a new factor will be added to the assessment of packaging recyclability: the assessment of recycling at scale. A new assessment will therefore be conducted based on the actual amount (mass) of material recycled from each packaging category.

3. Research Methodology

The research was conducted in four voivodeships in Poland, in the following cities: Łódź (Łódzkie Voivodeship), Katowice (Silesian Voivodeship), Nowa Sól (Lubusz Voivodeship), and Grodzisk Wielkopolski (Greater Poland Voivodeship), from November 2024 to January 2025.

Four independent samples were taken from each city. Each waste sample came from a different batch of waste from a given city and housing type.

Waste samples from Łódź were collected on 27–29 November 2024. The masses of the individual samples were 74.46 kg, 83.2 kg, 86.4 kg, and 88.7 kg.

Waste samples from Katowice were collected on 12, 13, and 16 December 2024. The masses of the individual samples were 75.34 kg, 77.8 kg, 79.8 kg, and 85.4 kg.

Waste samples from Nowa Sól were collected on 7–9 January 2025. The masses of the individual samples were 85.78 kg, 89.6 kg, 93.4 kg, and 83.7 kg.

Waste samples from Grodzisk Wielkopolski were collected on 21–23 January 2025. The masses of the individual samples were 89.06 kg, 67.2 kg, 78.5 kg, and 89.9 kg.

The total mass of the analysed waste samples was 1328.24 kg. The representativeness of the results was ensured by several criteria, including an established and verified sampling procedure, sample size and mass, repeatability of results, and the number of samples collected. Possible measurement uncertainties resulted from scale accuracy, classification errors due to difficulties in identifying unmarked plastics (which occurred very rarely), and contamination of packaging with organic or mineral fractions. Packaging containing residues was classified as contamination.

The results are expressed as the mean $\pm$ standard error of the mean (SEM).

The collected waste samples primarily originated from single-family houses and were obtained through the so-called “yellow bag” collection system, under which plastics and metals are collected jointly in Poland. Only the samples from Nowa Sól (Lubusz Voivodeship) came from both single-family and multi-family residences.

Obtaining reliable and representative data on the morphological composition of waste requires an appropriate research methodology. Such a methodology should take into account the sampling method, sample mass, number of samples collected, and the time and location of sampling while also considering variations in waste composition depending on season, housing type, city size, and other relevant factors.

Samples of approximately 100 kg were collected according to an established procedure designed to ensure the representativeness of the material analysed. Sampling methods differed depending on the collection system. For selectively collected plastics and metals from single-family housing, one sample consisted of 40–50 full “yellow bags” randomly selected from various locations in the reception hall for bagged selectively collected waste. For waste from multi-family housing, collected in containers, the sample was taken from a pile with a volume of at least 10 m³. Using a snow shovel, waste was collected alternately from the top, middle, and bottom layers and from different sides of the pile until the required sample mass was obtained. The morphological composition of the waste was then determined using two weighing devices, a hook scale and a platform scale, both providing measurements with an accuracy of 20 g.

Studies of the morphological composition of waste were conducted in accordance with the recommendations of the methodology previously endorsed by the Waste Management

Department of the Ministry of the Environment. This methodology is based on the Solid Waste Analysis Tool methodology developed as part of an EU research project [18,19].

In this study, the recommended research methodology was modified by dividing waste into as many as 29 material categories. As a result, the findings provide valuable insights into the quality of selective collection and the potential for further use of selectively collected plastics and metals.

The waste was separated into 29 groups on a sorting table. The fractions were systematically weighed, and their masses were recorded on measurement sheets. A neodymium magnet was used to make it easier to distinguish ferrous from non-ferrous metals. During the study, photographic documentation was prepared showing the collected samples and the 29 separated fractions. Fine particles below 20 mm were separated using a sieve.

The individual groups into which the collected waste samples were divided during the morphological composition study are presented below.

Films were divided into the following groups:

- PP;
- Metallised PP;
- LDPE divided into transparent LDPE, light white/yellow LDPE, coloured LDPE or LDPE with print (transparent base and >20% white/yellow print), and black LDPE;
- LDPE and HDPE—coloured, excluding black;
- Plastic film with an aluminium layer (e.g., coffee bags);
- Multi-material PP plastic film with a metallised layer (e.g., crisp bags).

The other groups were:

- Rigid PE, PP, and PS, divided into black and non-black fractions;
- All foamed plastics, including expanded PS and foamed PE;
- PET, divided into transparent, opaque, and black bottles, and PET trays in colours other than black and black trays;
- PVC—all types;
- Fillers (including mastic, acrylic, and any other filler except silicones);
- Beverage cartons;
- Magnetic metals;
- Non-magnetic metals;
- Paper and cardboard—constituting “contamination”, i.e., materials not intended to be collected under the adopted rules for the selective collection of plastics and metals in Poland;
- Other materials, including paper laminate, organic waste, textiles, glass, and diapers—constituting “contamination”, i.e., materials not intended to be collected under the adopted rules for the selective collection of plastics and metals in Poland;
- “Other (7)/other” packaging;
- Fine fraction <20 mm.

Morphological analysis of waste was carried out manually, and the identification of specific types of plastics was based on verification of markings found on waste items and on the researchers’ previous experience. The researchers did not have access to a portable FTIR/NIR device for identifying unmarked plastics whose type was uncertain. Such cases occurred very rarely and had only a minor effect on measurement errors and study results.

Figure 4 shows an example view of one of the research-station locations and the sieve used to obtain the sub-sieve fraction with a particle size below 20 mm.

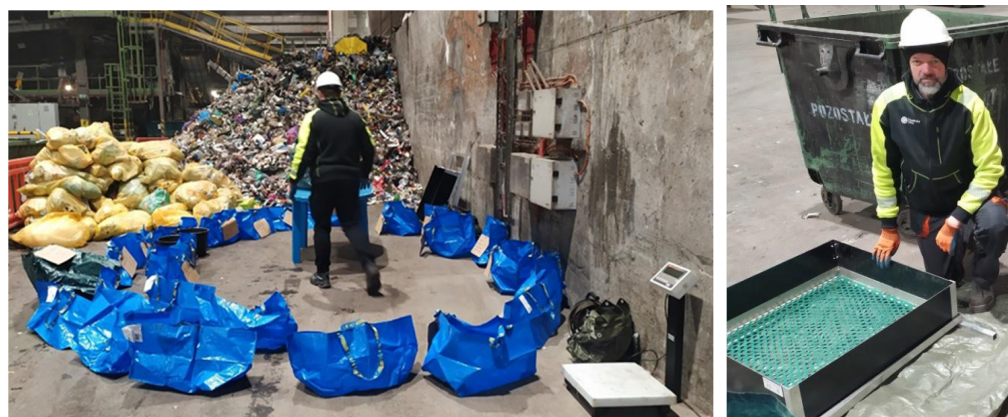


Figure 4. Research station (left) and sieve used in the study (right) (photo by W. Hryb).

4. Results

The results of the study of the morphological composition of selectively collected plastics and metals, divided into 29 morphological groups and accounting for housing type, collection method, location, and month of sampling, are presented in Table 2.

Table 2. Average morphological composition of selectively collected plastics and metals in four cities located in different voivodeships in Poland.

L.p.	Voivodeship/City:	Łódź	Silesian	Lubusz	Greater Poland	Mean with SEM	SD
		Łódź	Katowice	Nowa Sól	Grodzisk Wielkopolski		
	Type of Housing	Single-Family	Single-Family	Single-Family/ Multi-Family	Single-Family		
	The Month in Which the Research Was Conducted	November 2024	December 2024	January 2025	January 2025		
	Fraction Name:/Unit	[%]	[%]	[%]	[%]	[%]	
1	PP-film	0.76	2.56	1.53	3.78	2.16 ± 0.66	1.31
2	PP film—metallised	0.33	0.23	0.10	0.08	0.19 ± 0.06	0.12
3	LDPE film—transparent	5.85	5.58	5.58	5.28	5.57 ± 0.12	0.23
4	LDPE film, bright, white and yellow coloured or printed (transparent-based and >20% printed with white/yellow)	3.46	3.26	2.18	3.15	3.01 ± 0.29	0.57
5	LDPE and HDPE film—coloured, excluding black	11.12	10.22	9.16	11.28	10.45 ± 0.49	0.98
6	LDPE film—black	2.55	1.48	0.91	0.42	1.34 ± 0.46	0.92
7	Plastic film, with an aluminium layer (e.g., coffee bags)	0.44	0.54	0.28	0.30	0.39 ± 0.06	0.12

Table 2. Cont.

L.p.	Voivodeship/City:	Łódź	Silesian	Lubusz	Greater Poland	Mean with SEM	SD
		Łódź	Katowice	Nowa Sól	Grodzisk Wielkopolski		
	Type of Housing	Single-Family	Single-Family	Single-Family/ Multi-Family	Single-Family		
	The Month in Which the Research Was Conducted	November 2024	December 2024	January 2025	January 2025		
	Fraction Name:/Unit	[%]	[%]	[%]	[%]	[%]	
8	Plastic film— multimaterial, including multimaterial where one of the layers is metallised PP (e.g., crisp bags)	0.40	0.87	0.56	0.78	0.65 ± 0.11	0.21
9	PE rigid—non-black	3.20	4.03	2.77	3.50	3.38 ± 0.27	0.53
10	PE rigid—black	0.59	0.39	0.13	0.11	0.31 ± 0.12	0.23
11	PP rigid—non-black	7.53	7.80	4.08	6.13	6.39 ± 0.85	1.7
12	PP rigid—Black	0.59	0.68	0.32	0.18	0.44 ± 0.12	0.23
13	PS rigid—non-black	0.95	1.87	0.35	0.75	0.98 ± 0.32	0.64
14	PS rigid—black	0.11	0.16	0.13	0.27	0.17 ± 0.04	0.07
15	Foamed plastics—all, includes expanded PS and foamed PE	0.37	1.51	0.66	0.36	0.73 ± 0.27	0.54
16	PET bottles—transparent	20.88	17.15	12.93	26.67	19.41 ± 2.92	5.83
17	PET bottles—opaque	3.10	2.09	2.16	2.22	2.39 ± 0.24	0.47
18	PET bottles—black	0.12	0.07	0.22	0.20	0.15 ± 0.04	0.07
19	PET trays—non-black	0.21	1.56	0.99	2.82	1.40 ± 0.55	1.1
20	PET trays—black	0.10	0.13	0.32	0.48	0.26 ± 0.09	0.18
21	PVC—all	1.67	1.23	1.38	0.60	1.22 ± 0.23	0.45
22	Fillers (also including mastic, acrylic, and any other filling besides silicones)	0.00	0.13	0.11	0.08	0.08 ± 0.03	0.06
23	Beverage carton	3.76	5.44	3.46	5.69	4.59 ± 0.57	1.14
24	Metals—magnetic	5.33	5.35	4.21	3.80	4.67 ± 0.40	0.79
25	Metals—non-magnetic	1.75	2.74	2.00	3.07	2.39 ± 0.31	0.62
26	Paper and cardboard	8.20	4.31	15.19	1.86	7.39 ± 2.91	5.82
27	Others, including paper laminate, organics, textile, glass, diapers	12.24	14.04	20.91	11.09	14.57 ± 2.20	4.4
28	“Other” (7) type of packaging	3.42	4.02	2.76	4.40	3.65 ± 0.36	0.72
29	Fines < 20 mm	0.97	0.56	4.68	0.71	1.73 ± 0.99	1.97

5. Discussion of Results

The study of the morphological composition of waste is distinguished by the division of waste into as many as 29 material fractions. To date, the available literature on the morphological composition of selectively collected waste has not yet presented such a detailed classification. This level of analytical detail makes it possible to determine the actual quality of selective collection and the options for waste management.

At present, Poland lacks national-level data on packaging placed on the market, with a detailed breakdown by individual polymers; on the morphology of packaging waste; and on the amount of packaging waste processed in recycling plants, also broken down by polymer. This makes it difficult to plan and develop plastics processing in Poland [20]. Therefore, the research conducted and the results obtained partly address these gaps by providing detailed morphological analysis of selectively collected plastics and metals and demonstrating their actual recycling potential.

The research was conducted in four voivodeships in Poland, in the following cities: Łódź (Łódzkie Voivodeship), Katowice (Silesian Voivodeship), Nowa Sól (Lubusz Voivodeship), and Grodzisk Wielkopolski (Greater Poland Voivodeship), from November 2024 to January 2025.

The collected waste samples mainly originated from single-family housing and from collection in the so-called “yellow bags”, which in Poland cover plastics and metals collected jointly. Only the samples from Nowa Sól (Lubusz Voivodeship) came from both single-family and multi-family housing.

The fraction with the largest mass share (23.8%) consisted of films of various types and colours (the sum of all film types), which accounted for nearly one quarter of the mass of selectively collected waste. The results are consistent with studies conducted in Poland by the Institute of Environmental Protection, where, in the stream of selectively collected municipal waste in the so-called yellow-bag system, LDPE and HDPE films were the fraction with the largest share, together accounting for over 25% of the total mass of the stream [20].

Films were divided into 8 groups: PP, metallised PP, transparent LDPE, light white/yellow LDPE, coloured LDPE or LDPE with print (transparent base and >20% white/yellow print), coloured LDPE and HDPE excluding black, black LDPE, films with an aluminium layer (e.g., coffee bags), and multi-material PP films with a metallised layer (e.g., crisp bags). From a mechanical recycling perspective, transparent LDPE film is the most valuable film fraction. Its average mass share was 5.6% of selectively collected plastics and metals; there is a market demand for it, and in Poland, it usually has a positive value as a secondary raw material. Light white/yellow LDPE, coloured LDPE, or LDPE with print (transparent base and >20% white/yellow print) accounted for 3% of the mass of selectively collected plastics and metals, while coloured LDPE and HDPE (excluding black) accounted for approximately 10.5%. These films most often have a negative value, meaning that waste sorting plants in Poland must pay recyclers to accept them. The mass share of PP film was 2.16%; demand for this secondary raw material on the Polish market is very low due to the very low price of primary raw materials from China.

Films that are not marketable for mechanical recycling in Poland, although they are technologically recyclable, include metallised PP film, plastic film with an aluminium layer (e.g., coffee bags), and multi-material PP plastic film with a metallised layer (e.g., crisp bags). The total mass share of these films was 1.23%. In Europe, approximately 81% of PE films are used in packaging production, of which 41% are non-food-contact packaging films, and 17% are bags and flexible packaging [21].

The results presented in [8] showed a significant difference in the quality of selectively collected plastics and metals. Selectively collected waste from single-family housing

(collected in yellow bags) was of much higher quality, with a lower content of contaminants, i.e., waste not covered by the collection scheme, than waste from multi-family housing (collected in yellow containers).

The results of this study confirm this pattern, as the lowest quality, i.e., the highest contamination rate, was observed in selectively collected plastics and metals from multi-family housing blocks in Nowa Sól, Lubusz Voivodeship.

Contamination represented a high mass share in the examined samples of selectively collected plastics and metals from four voivodeships in Poland. Its average share was 22% and ranged from 13% to 36%. Contamination, i.e., waste not covered by selective collection, consisted of paper and cardboard, organic waste, textiles, glass, diapers, and paper laminate. The best quality was recorded in selectively collected waste from Grodzisk Wielkopolski, where contamination accounted for 13%, whereas the poorest quality was found in waste samples from Nowa Sól, where contamination accounted for 36%. The total share of plastics in selectively collected plastics and metals was approximately 70% on average.

Transparent PET bottles, including transparent colourless bottles and bottles with blue or green tints, had a high mass share, averaging 19.41%. Approximately 15% of the bags collected from Grodzisk Wielkopolski may have come from businesses or offices, as their content consisted almost exclusively of transparent PET bottles. This contributed to a high proportion of transparent PET bottles in the analysed material.

PET beverage bottles with a capacity of up to 3 litres have been covered by the deposit-return system in Poland since October 2025; in practice, the system began operating in Poland in January 2026. This will remove the most valuable secondary raw material from the stream of selectively collected plastics, i.e., the material that generates the highest revenue for sorting plants from the sale of secondary raw materials, and will significantly change the morphological composition of selectively collected waste. Opaque PET bottles (white, red, and brown) accounted for 2.39% of the mass of the studied waste. This fraction is recyclable, but its marketability in Poland is severely limited due to low interest among recyclers; therefore, it is usually not separated in sorting plants or directed to recycling.

PET trays are less standardised in terms of shape and chemical composition than PET bottles, which makes automatic sorting and recycling difficult. As a result, PET trays are very rarely separated and recycled in Polish sorting plants.

Ferrous metals accounted for 4.7% and non-ferrous metals for 2.4% of the mass of the examined waste. Aluminium beverage cans dominated among the non-ferrous metals and have also been covered by the deposit-return system in Poland since October 2025.

Non-black rigid PP plastics accounted for 6.4% of the mass of selectively collected plastics. They are a valuable secondary raw material for mechanical recycling, as is rigid non-black HDPE, with a share of 3.4%.

The share of beverage cartons (Tetra Pak-type packaging) was 4.59%. They are separated in Polish sorting plants and then sent to paper mills, where cellulose fibres are recovered after shredding in a hydropulper. The residue of polyethylene combined with aluminium in the form of a laminate, known as PolyAl (aluminium (ALU) and polyethylene (PE)), is also recyclable.

The residue from the separation of cellulose fibres from beverage cartons in paper mills is also suitable for energy recovery as an alternative fuel (RDF) in cement plants [22].

The total share of all types of black plastics was 2.67%, with film predominating. When carbon black is used as a pigment, these plastics cannot be identified by opto-pneumatic separators and therefore will not be directed to the recycling process.

The share of non-black rigid PS was close to 1%. Only one recycler on the Polish market processes PS from municipal packaging waste; therefore, the possibilities for recycling this fraction are severely limited.

Foamed polystyrene (expanded polystyrene, including trays and other items) accounted for approximately 0.7%. In most sorting plants in Poland, it is not separated due to its large volume and low mass. As a result, only clean expanded polystyrene, after compaction in a special briquetting machine, can find a market among recyclers.

“Other (7)/other” packaging accounted for 3.65% of the mass of selectively collected waste. This category often consists of so-called barrier packaging composed of various types of plastics. For this reason, it is not separated in sorting plants and is not recycled. It can be used as feedstock for waste-derived fuel for energy recovery in cement plants or combined heat and power plants and, in the future, may be directed to chemical recycling.

The fine fraction (<20 mm) accounted for 1.73% of the mass of selectively collected waste. This fraction mainly contained organic waste, mineral waste, and small pieces of plastic that could not be identified due to their size and lack of markings. This fraction is not recyclable due to its particle size and the limitations of sorting processes for such a fine fraction.

PVC plastics accounted for approximately 1.22% of the mass of selectively collected waste. They are not recycled and cannot be used as components of waste-derived fuels for energy recovery in combined heat and power plants or cement plants due to their high chlorine content.

Taking into account the future PPWR requirement that all packaging placed on the EU market be recycled at scale, in the coming years, the recycling sector will have to invest in solutions for packaging groups that are not currently processed or redesign packaging to improve its compatibility with recycling. This underlines the growing importance of eco-design. According to analysis [10], the largest processing capacities of plants in Poland are found in plants processing LDPE/HDPE films (46%), rigid PE, PP, and PS polyolefins (29%), and PET (17%), which shows how far Poland still is from implementing large-scale recycling as defined by the PPWR regulations.

6. Conclusions

The study of the detailed morphological composition of selectively collected plastics and metals from four cities, each located in a different voivodeship in Poland, was conducted in the autumn and winter of 2024 and 2025. It enabled the determination of shares of 29 material fractions. This level of detail distinguishes this study from other research and enables an assessment of the potential of the analysed waste for material, chemical recycling, or energy recovery. A detailed understanding of waste morphology is also important for organising the technological process of waste sorting.

In the analysed stream of selectively collected plastics and metals, the fine fraction below 20 mm accounted for 1.7%, while black plastics accounted for 2.67%. Plastics containing carbon black as a pigment are not visible to opto-pneumatic separators; therefore, they are not separated by these devices and do not enter the recycling process.

The contamination share in selectively collected plastics and metals, i.e., fractions not covered by this collection scheme, was approximately 22% by mass, indicating poor selective-collection quality. The contaminants mainly consisted of paper, cardboard, organic materials, textiles, glass, and diapers. Since most samples came from single-family housing using the bag system, and only part of the samples from Lubusz Voivodeship came from multi-family housing, it can be assumed that contamination in container collection from multi-family housing will be even higher and of even poorer quality. This tendency is confirmed by the results presented in [8]. For this reason, environmental education and social

responsibility should be continuously strengthened to enhance the quality of selectively collected waste. Intelligent and automated collection systems should also be considered, as they may help monitor residents of multi-family housing, reduce anonymity, and improve collection quality. Their implementation should be accompanied by economically justified fee and penalty systems without applying collective liability.

Plastics and metals, theoretically suitable for material or mechanical recycling, accounted for approximately 66.8% of the mass of selectively collected waste. Plastics and materials suitable for mechanical recycling in demand on the Polish market include LDPE, HDPE, and PP films (with limited marketability); PE, PP, and PS packaging (with limited marketability); PET bottles; beverage cartons; and ferrous and non-ferrous metals. Assuming an 85% sorting efficiency for marketable plastics and metals, approximately 57% of the mass of selectively collected plastics and metals will be directed to mechanical recycling. The remaining fraction, excluding PVC and glass, may be used for energy recovery or, in the future, partly directed to chemical recycling. The 85% sorting efficiency was assumed based on the authors' unpublished studies conducted in waste sorting plants, information from manufacturers of opto-pneumatic sorters, and general contractors of waste sorting plants in Poland.

Rigid plastics made of PP, PE, and PS accounted for 11.7% of the mass of the studied waste, while films of various types accounted for 23.8%, with PE film predominating at 20.4%. Films separated in Polish sorting plants are sent to recyclers for a surcharge and constitute a cost for sorting plants; in January 2026, sorting plants had to pay an additional PLN 100–400/Mg.

The research was conducted before the deposit-return system became operational in Poland. The system began operating in practice in January 2026 and will significantly affect the morphological composition of selectively collected plastics and metals. It covers PET beverage bottles with a capacity of up to 3 litres and metal beverage cans with a capacity of up to 1 litre, which together accounted for approximately 20% of the analysed stream. These fractions are among the most valuable secondary raw materials and, before the introduction of the deposit-return system, accounted for up to 50% of sorting plants' revenue from the sale of secondary raw materials. Ferrous metals accounted for 4.7%, almost twice the share of non-ferrous metals at 2.4%; this disproportion is expected to increase, as aluminium beverage cans constitute the main share of non-ferrous metals.

Among the plastic fractions not directed to recycling, the largest share was represented by "other" packaging marked with the number 7, accounting for approximately 3.65%. These are often multi-material packages, which makes mechanical recycling technologically difficult and economically unviable. Therefore, producers of short-life-cycle packaging and everyday-use materials should design products so that recycling is technologically feasible, available at scale, and economically and environmentally viable. Otherwise, support mechanisms, for example, from EU funds, may be needed to improve the competitiveness of recycling compared with production from primary raw materials derived from crude oil.

Plastic packaging intended for direct food contact must first ensure consumer safety by preventing contamination with chemical substances or microplastics. It should also extend shelf life, thereby reducing food waste.

In the coming years, the PPWR Regulation will reduce packaging waste by limiting excessive packaging materials, minimising empty spaces, banning unnecessary packaging, and prohibiting certain types of single-use packaging. It will also promote recycling and reuse by introducing uniform, stringent packaging standards across the EU that cover design, labelling, production, and life-cycle management.

The introduction of EPR, packaging eco-design, and PPWR requirements in Poland will change the types of plastic packaging used for various products. Consequently, the

morphological composition of selectively collected plastics and metals in yellow-bag and container systems will also change, as will the possibilities for recovery and recycling. However, low economic profitability remains a serious obstacle to achieving high recycling rates in Europe and Poland, as evidenced by numerous bankruptcies in the plastics recycling sector. This is related, among other factors, to high energy, labour costs, and the availability of cheap primary raw materials from China.

The development of chemical recycling in Europe is an opportunity and should complement mechanical recycling. It enables the production of high-quality plastics and offers a solution for hard-to-recycle waste, including waste intended for food-contact applications. PPWR regulations are closely linked to the need for a legal framework for chemical recycling technologies, as these technologies are necessary to achieve the assumed recycle content levels.

Overall, studies on waste morphology should serve as a basis for designing effective waste-treatment processes and for assessing the suitability of individual fractions for specific recovery methods. Future research should focus on seasonal variability in the morphology of selectively collected plastics and metals and on the effects of the deposit-return system, the PPWR Regulation, and the planned implementation of EPR in Poland, as these factors will significantly shape the waste composition and recovery potential.

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Abbreviations

PET	Polyethylene terephthalate
PS	Polystyrene
PP	Polypropylene
PE	Polyethylene
PVC	Polyvinyl chloride
PC	Polycarbonate
LDPE	Low-density polyethylene
HDPE	High-density polyethylene
PPWR	Packaging and Packaging Waste Regulation
HoReCa	Hotels, restaurants, catering/cafés
EPR	Extended producer responsibility
SUP	Single-use plastics
CE	Circular economy
SEM	standard error of the mean
SD	Standard deviation

References

- Godfrey, L. Waste Plastic, the Challenge Facing Developing Countries—Ban It, Change It, Collect It? *Recycling* **2019**, *4*, 3. [CrossRef]
- European Parliament. *Recykling Odpadów Z Tworzyw Sztucznych W UE: Fakty I Liczby*; European Parliament: Strasbourg, France, 2025.
- Den Boer, E.; Banaszkiewicz, K.; den Boer, J.; Pasiecznik, I. Energy Recovery from Waste—Closing the Municipal Loop. *Energies* **2022**, *15*, 1246. [CrossRef]
- Hryb, W. Pozostałości z sortowania tworzyw sztucznych jako składnik paliw z odpadów. *Przemysł Chem.* **2019**, *98*, 117–121.
- Plastics Europe. *Circular Economy for Plastics*; Plastics Europe: Brussels, Belgium, 2022.
- Freitag, N.; Schneider, J.; Decottignies, V.; Fell, T.; Kucukpinar, E.; Schlummer, M. Waste Study on Flexible Food and Non-Food Packaging: Detailed Analysis of the Plastic Composition of European Polyethylene-Containing Waste Streams. *Materials* **2024**, *17*, 3202. [CrossRef] [PubMed] [PubMed Central]
- Połomka, J.; Jędrzak, A.; Myszograj, S. Risk and Opportunity of Using Plastics from Waste Collected in a Yellow Bag. *Polymers* **2020**, *12*, 1815. [CrossRef] [PubMed]
- Hryb, W.; Wandrasz, A.J. Research on the Morphological Composition and Recovery Possibilities of Selectively Collected Plastics and Metals—A Case Study. *Appl. Sci.* **2025**, *15*, 11227. [CrossRef]
- Jędrzak, A.; Den Boer, E.; Kamińska-Borak, J.; Szpadt, R.; Krzyśków, A.; Wielgosiński, G. *Gospodarka Odpadami Komunalnymi w Polsce. Analiza Możliwości i Barier Zagospodarowania Odpadów z Tworzyw Sztucznych, Pochodzących z Selektynego Zbierania Odpadów Komunalnych, a Kwestie GOZ*; Instytut Ochrony środowiska Państwowy Instytut Badawczy: Warszawa, Poland, 2021.
- Polish Plastics Pact. Available online: <https://www.paktplastikowy.pl> (accessed on 22 March 2026).
- Eurostat—Packaging Waste Statistics. Available online: <https://ec.europa.eu/eurostat/data/database> (accessed on 30 March 2026).
- Eurostat—Env_waspac. Available online: <https://ec.europa.eu/eurostat/data/database> (accessed on 23 March 2026).
- Kibria, M.G.; Masuk, N.I.; Safayet, R.; Nguyen, H.Q.; Mourshed, M. Plastic Waste: Challenges and Opportunities to Mitigate Pollution and Effective Management. *Int. J. Environ. Res.* **2023**, *17*, 20. [CrossRef] [PubMed]
- Sörme, L.; Voxberg, E.; Rosenlund, J.; Jensen, S.; Augustsson, A. Coloured Plastic Bags for Kerbside Collection of Waste from Households—To Improve Waste Recycling. *Recycling* **2019**, *4*, 20. [CrossRef]
- GUS. *Statistical Analysis: Environment 2020–2025, Warsaw 2020–2025*; GUS: Warsaw, Poland.
- Packaging and Packaging Waste Regulation. 2024. Available online: <https://www.europarl.europa.eu/doceo/document/TA-9-2024-0318-EN.html> (accessed on 15 March 2026).
- Ministerstwo Klimatu I Łódzki Instytut Technologiczny Realizują Dyrektywę SUP. Available online: <https://www.gov.pl/web/klimat> (accessed on 2 March 2026).
- Development of a Methodological Tool to Enhance the Precision and the Comparability of Solid Waste Analysis Data. Deliverable 8—Demonstration Part, Methodology for the Analysis of Solid Waste (SWA-Tool) Version User, European Commission, Project No. EVK4-CT-2000-00030, 2001–2004. Available online: <http://www.mos.gov.pl> (accessed on 25 July 2025).
- Szpadt, R.; Jędrzak, A. *Określenie Metodyki Badań Składu Sitowego, Morfologicznego i Chemicznego Odpadów Komunalnych, na Zlecenie Ministerstwa Środowiska*; Kamieniec Wrocławski: Zielona Góra, Poland, 2006.
- Morfologia Odpadów Komunalnych Wytwarzanych W Polsce, Ioś-Pib Report. 2022. Available online: <https://ios.edu.pl/raporty-i-analizy/odpady-pl/morfologia-odpadow-komunalnych-wytwarzanych-w-polsce-w-systemie-gminnym-2/> (accessed on 20 April 2026).
- Plastics Recyclers Europe. *Flexible Films Market in Europe: State of Play, Production, Collection and Recycling Data*; Plastics Recyclers Europe: Brussels, Belgium; Eunomia: Bristol, UK, 2022.
- Umweltbundesamt. Available online: <https://www.umweltbundesamt.de> (accessed on 12 April 2026).

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