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Characterization of the Municipal Plastic and Multilayer Packaging Waste in Three Cities of the Baltic States

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Abstract: The composition of plastic and multilayer packaging waste was assessed in the mixed municipal solid waste (MSW) streams of the Kaunas (Lithuania), Daugavpils (Latvia) and Tallinn (Estonia) municipalities. For the analysis of samples in the mixed MSW streams, the authors used manual sorting and a visual recognition method. Composition analysis of plastic and multilayer packaging waste from separately collected waste of multi-family and single-family households was performed in the Kaunas and Tallinn municipalities. For the analysis of samples in the separately collected waste streams, the research group combined manual sorting and near-infrared (NIR) spectroscopy methods. The findings reveal that the percentage distribution of plastic and multilayer packaging waste within the municipal solid waste (MSW) stream is relatively consistent across the municipalities of Kaunas, Daugavpils and Tallinn, comprising 40.16%, 36.83% and 35.09%, respectively. However, a notable variation emerges when examining separately collected plastic and multilayer packaging waste streams. In this category, the proportion of plastic and multilayer packaging within the total separately collected packaging waste stream ranges from 62.05% to 74.7% for multi-family residential buildings and from 44.66% to 56.89% for single-family residential buildings. The authors provided further insights for the enhanced recycling potential of different plastic materials through improved sorting.

Keywords: municipal waste; plastic packaging waste; multilayer packaging waste; mixed solid waste; separately collected waste; multi-family households; single-family households

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1. Introduction

Since its creation, plastic has become a major commodity in our daily lives due to its remarkable properties [1,2]. The rapid expansion of refineries and plastic manufacturing during the Second World War accelerated its widespread adoption, with global production flourishing from 1950 onward. The extensive utility of this material, attributed to its versatility, low cost, light weight, durability and excellent mechanical properties, has made it vital for a broad range of applications, including food packaging, construction, medical applications and more [3,4].

Plastic production has risen exponentially, peaking in the last decade when global production surpassed that of the entire preceding century, reaching 400.3 Mt in 2022 [5]. Simultaneously, the amount of waste originating from plastics has also seen a surge during the last 20 years, exacerbating plastic pollution and its associated environmental and human health impacts [6]. The average plastic packaging waste generation per person in the European Union (EU) in 2021 was 35.9 kg, with about 40% being recycled [7]. According to Blagoeva et al. [8], the increase in waste generation is associated with improvements in economic conditions and higher purchasing power among the population. Moreover, it is projected that plastic production will double within the next two decades, outpacing the existing waste management capabilities [4]. As a result, plastic pollution has become one of the most urgent environmental challenges today.

The Waste Framework Directive (2008/98/EC) mandates a significant reduction in waste disposal through landfilling across Member States, requiring them to increase municipal waste re-use and recycling to a minimum of 65% of the total municipal waste generated by 2035 [9]. The Directive on Packaging and Packaging Waste (94/62/EC), sets specific recycling targets, requiring at least 50% of all plastic packaging waste to be recycled by 2025, with an increase to at least 55% by 2030 [10]. The Landfill Directive (1999/31/EC) sets a target to limit the disposal of municipal waste in landfills to 10% of the total municipal waste generated by 2035 [11]. These targets underscore the urgent need for ongoing progress and innovation in the plastic and composite packaging waste sector. This commitment not only aims to address environmental sustainability but also plays a crucial role in reducing plastic pollution and conserving natural resources. However, sorting is a critical aspect to recyclability, as proper sorting can considerably improve recycling rates. Low-quality waste streams significantly hinder the overall performance of plastic recycling facilities, reducing the effectiveness of recycling operations [12].

The situation in the Baltic Sea Region (BSR) mirrors the global trend of increasing plastic pollution. Home to approximately 85 million people and surrounded by nine countries, the Baltic Sea supports a unique and vulnerable flora and fauna. However, it is considered one of the most polluted seas, as it receives pollutants through several pathways. Microplastics are becoming increasingly prevalent in its marine ecosystem, making the Baltic Sea a pollution hot spot [13–16]. Inadequate waste management strategies further exacerbate this issue.

Waste management practices vary significantly among the BSR countries, from collection methods to end-of-life alternatives. One of the main challenges is the inefficient collection and sorting of plastic waste, which limits the potential for recycling and resource recovery. In Europe, the effectiveness of waste separation and collection systems differ by country, with extended producer responsibility schemes and deposit systems often playing a role in shaping collection strategies [17,18]. Among the BSR countries, Germany reports the highest plastic collection rate at 73% [19], while Latvia records the lowest at 13% [20].

The different treatment methods employed to manage plastic waste introduce several environmental concerns. Incineration for energy recovery, the predominant method of plastic waste treatment, poses significant challenges, particularly regarding greenhouse gas (GHG) emissions. This process not only exacerbates air pollution but also contributes to climate change. By 2030, GHG emissions from plastics are projected to reach up to 1.34 Gt/y [21,22]. On average, 49% of the plastic waste in the BSR is incinerated, with Sweden leading at 65% and Lithuania reporting the lowest rate at 25%. Recycling rates across the region also show significant variation. The BSR average recycling rate is approximately 27%, with Germany recycling up to 37% of post-consumer plastic waste. In contrast, Finland and Latvia report the lowest recycling rates at around 20%.

Despite its well-documented environmental impacts, landfilling remains a component of plastic waste management in the BSR. On average, 24% of plastic waste is landfilled, with Latvia having the highest rate at 69% and Germany, Sweden and Finland reporting the lowest rates at just 1% [23,24].

Inappropriate or ineffective waste management brings serious challenges. The formation of micro- and nanoplastics is of major concern, which results from the breakdown of larger plastics exposed to ultraviolet light and chemical or physical mechanisms. These small particles are very difficult to recover and manage, threatening aquatic and terrestrial ecosystems, as well as human health by accumulating in food chains [25,26].

Additionally, land and water quality can be adversely affected by the release of harmful substances during the chemical breakdown and decomposition of plastics. Air pollution is also of concern, resulting from the release of hazardous chemicals associated with the chemical composition of plastics. This pollution has detrimental effects on animal life, particularly through the accumulation of microplastics and their associated toxicity. Furthermore, toxic chemicals used in the production of plastics, which are subsequently released into the environment, have been linked to numerous health issues [21,27,28].

Appropriate and effective waste management is essential to minimize risks to the environment and human health. To ensure an effective waste management system, it is essential to know the composition of existing waste streams. The literature review revealed that to date, only a limited number of studies have partially examined the morphology of plastic and multilayer packaging waste to assess its distribution within the waste stream according to packaging and polymer types (Table 1).

Table 1. Analysis of previous studies, partially focused on investigations of waste morphological composition.

Country of Study	Year of Study	Main Outcome	Ref.
Austria	2024	This study provides a general quantitative and qualitative analysis of municipal waste in Austria, assessing the quantities of waste generated and its distribution across different waste types (e.g., packaging waste, WEEE, glass, etc.).	[29]
Austria	2024	This study provided an in-depth characterization of non-beverage plastic bottles, including all packaging subcomponents, in mixed MSW as well as separate post-consumer plastic packaging waste collection, including the polymer, product category, decoration technology, filling volume, color and more, to assess the quality of this waste stream and the potential for recovery and recycling.	[30]
Poland	2023	Waste streams were analyzed to investigate the impact of seasonal fluctuations on the quantity and composition of generated municipal waste and separately collected waste.	[31]
China	2023	The study applied a theoretical–practical model to determine the distribution of plastic packaging waste by packaging type and other factors.	[32]
Finland	2017	The sorting study identified the composition of the plastic fraction of MSW by the main polymer types (LDPE, HDPE, PET, etc.). Accordingly, the recycling potential of these plastics has been assessed.	[33]
Lithuania, Russia, Ukraine and Georgia	2014	This study investigates the impact of seasonal variations on the quality and composition of MSW in four Eastern European cities, providing insights from research conducted between 2009 and 2011.	[34]

Plastic waste is integral part of municipal waste management systems; thus, typically, seasonal variations in residential plastic waste are analyzed in the context of municipal waste streams [34]. The authors of the study performed in Denmark state that a waste composition dataset representative of the whole year can be obtained from waste sampled for at least a full week from a representative group of households covering the different socio-economic and geographical conditions of the area. Participation in source-segregating recyclables (i.e., paper, cardboard and plastic packaging and metal) may not be influenced significantly by seasonal variations. Moreover, seasonal variations and household sizes did not significantly influence the percentage of other misplaced recyclable materials (i.e., paper, cardboard, plastic and metal) in household waste [35]. The effect of seasonal fluctuations on the quantity and composition of generated municipal waste and on the quantity and composition of selectively collected waste was analyzed by the authors from Poland. The material composition of selectively collected waste in subsequent measurement series often differed. It is difficult to link the observed changes concerning the quantity and composition of the analyzed waste streams with the seasons of the year, although weather conditions undoubtedly impact the consumption and functioning models of people, thus impacting the size of waste streams [31].

The contamination of plastic waste affects the identification of polymer types and limits further steps in the plastic recycling chain. Visual categorization of contamination levels provides only general view of municipal plastic waste quality; however, it does not provide a solid background for decision making. The literature review revealed only rudimentary efforts for the establishment of procedures related to the assessment of municipal plastic waste contamination. Thus, the development of a standard protocol and techniques for the assessment of municipal plastic waste contamination is one of the urgent tasks for authorities and scientific community.

Several studies outlined economic and environmental benefits, such as that recycling plastic waste reduces carbon emissions by up to 42% compared to producing new plastic through conventional methods [36]. It was also determined that on average, a person can save approximately 219 kWh of energy through recycling. Additionally, recycling resources offers an estimated annual economic benefit of around USD 60 per person, considering that 12% of waste is recycled [37]. Another study examined the chemical recycling of plastics for the production of new materials. The authors concluded that recycled polymers are more economical than virgin materials, offering substantial financial benefits through energy savings, which vary from 40% to 90%, depending on the polymer type [38].

This research contributes to broader policy objectives by exploring solutions that enhance waste sorting and processing, thereby supporting the transition toward a more sustainable and circular economy. Specifically, the research focuses on identifying the types of municipal plastic waste in three cities within the BSR. The study employs a comprehensive sorting assessment to analyze the distribution of plastic waste within municipal waste streams. By evaluating both mixed waste and separately collected packaging waste, the study aims to identify the different types of plastic packaging materials and categorize them into meaningful groups. The collected data were then analyzed to assess the recycling potential of different plastic materials through improved sorting techniques. Finally, this research aims to provide practical insights that can enhance plastic waste treatment and recycling strategies in the Baltic Sea Region.

2. Methods

The present study focused on three Baltic States—Lithuania, Latvia and Estonia—with one municipality selected from each country for detailed analysis. Plastic and multilayer packaging waste compositions were assessed in mixed municipal solid waste (MSW) streams in Kaunas (Lithuania), Daugavpils (Latvia) and Tallinn (Estonia). For these mixed waste samples, the authors employed manual sorting and visual recognition methods. The method is time consuming and prone to human error. Additionally, visual recognition may struggle to differentiate certain types of plastics, especially when they are contaminated, degraded or lack clear distinguishing characteristics. Additionally, the composition of plastic and multilayer packaging waste from separately collected waste of both multi-family and single-family households was analyzed in Kaunas and Tallinn. For these separately collected waste streams, the authors employed a combination of manual sorting and near-infrared (NIR) spectroscopy methods. Despite the fact that a small handheld NIR device was used for the study, there is potential for large-scale industrial NIR applications [39,40].

2.1. Study Area

The three studied Baltic States share similarities in their Gross Domestic Product (GDP) per capita [41], as well as have relatively comparable population sizes [42]. Among the municipalities selected for detailed analysis, the population ranges from approximately 78,900 (2023) in Daugavpils to nearly 319,800 (2023) in Kaunas and more than 447,000 (2023) in Tallinn (Figure 1). In all three municipalities, residents have access to separate packaging waste collection services. However, Daugavpils lacks a 'door-to-door' collection system for plastic packaging waste, meaning that such waste is excluded from its organized waste transport services [43]. In contrast, Kaunas and Tallinn offer door-to-door separate packaging waste collection for single-family households through municipally owned companies. For multi-family houses, separate packaging waste collection is organized collectively for several buildings. Despite these differences, the three countries can be regarded as a single region due to their similar environmental standards, waste management practices and shared development, institutional and economic characteristics [44,45].

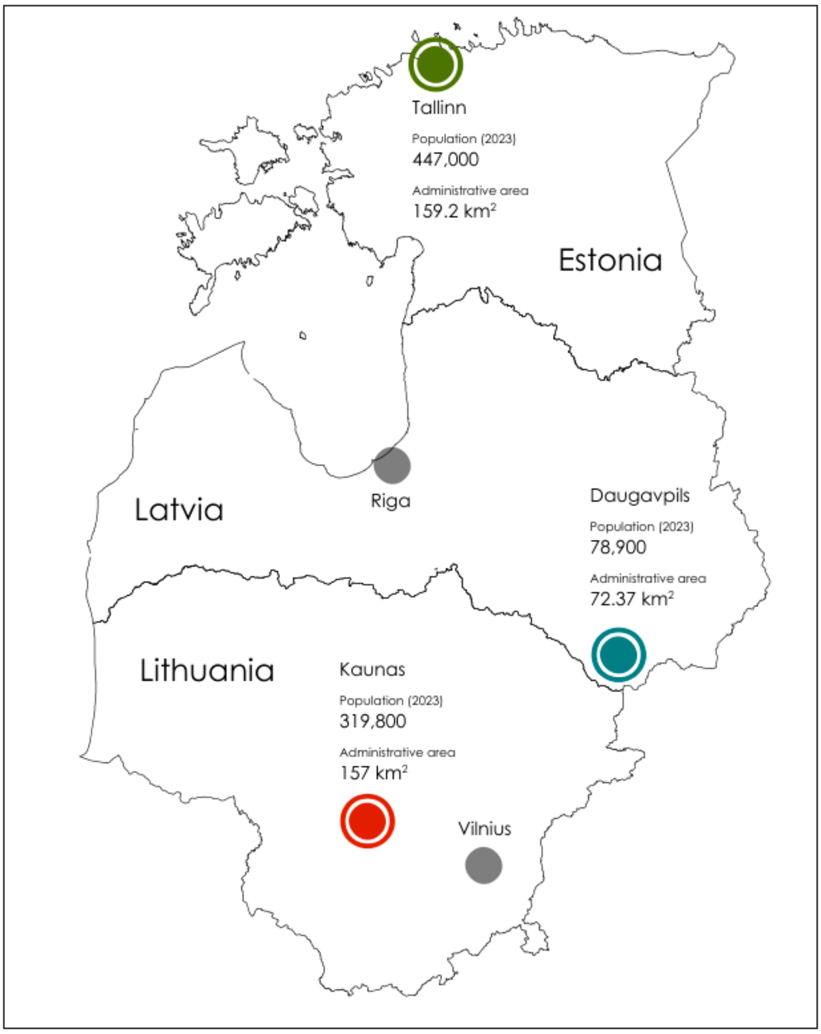

Figure 1. Population and size of administrative territories in Kaunas, Daugavpils and Tallinn municipalities.

The generation of plastic waste in the three countries increased between 2004 and 2022. In Lithuania, it rose from 23,250 tons to 131,918 tons [46]. In Latvia, it increased from 721 tons to 144,808 tons [47], while in Estonia, the amount of collected and generated plastic waste increased from 28,967 tons to 45,631 tons, with peaks of 71,826 tons in 2008 and 65,955 tons in 2014 [48].

2.2. Plastic and Multilayer Packaging Waste Characterization in the Mixed Municipal Solid Waste Stream

The composition of mixed municipal solid waste (MSW) from the three studied cities was determined following the Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste (ASTM D5231-92(2016)) [49]. Mixed MSW samples were collected from both single-family and multi-family households at locations supervised by local waste management operators. The waste collection period was selected to avoid atypical events (for example, holidays) and took one week, including the weekend, to reduce the effect of consumption behavior. In total, the MSW sample was formed from ten subsamples collected at different locations spread over the administrative territories of the selected municipalities. The collection of representative samples of approximately 150 kg was performed from 30 randomly chosen collection points.

A two-step procedure was used for waste characterization. In the first step, plastic and multilayer packaging waste were separated from other categories of mixed municipal waste. In the second step, the plastic packaging waste was manually sorted and categorized visually into the following groups: HDPE jars, LDPE films, PP jars, rigid packaging, PP films, PET bottles, rigid packaging, PS foam, PS jars, rigid packaging, other plastics and multilayer packaging. The items that could not be identified in terms of packaging and/or polymer type were assigned to the 'not-identified' category. The 'multilayer packaging' category was also determined separately. It should be noted that no drying or washing of plastic packaging items was performed, leaving surface contaminants unaccounted for. The entire characterization was held indoors to avoid undesirable effects such as wind. The same weighting scale with an accuracy of 0.001 kg was used for the whole sample, and the weights for each category were documented in a predefined Excel-based protocol.

2.3. Plastic and Multilayer Packaging Waste Characterization in the Separately Collected Municipal Solid Waste Stream

Separately collected plastic waste subsamples from multi-family as well as single-family households were collected from ten households situated in different parts of the municipalities. The same as for the mixed MSW, the waste collection period was one week. Because of different intensities of separate plastic collection for the individual households, the mass of the samples from multi-family households varied from 35.74 kg in Tallinn to 37.23 kg in Kaunas, while the mass of the samples from single-family households varied from 26.53 kg in Tallinn to 40.83 kg in Kaunas.

The characterization of the separately collected waste followed a similar two-step procedure as for the mixed MSW. In the first step, plastic and multilayer packaging waste was separated from other waste categories. In the second step, plastic packaging waste was sorted, and the polymer type was identified on-site using NIR spectroscopy-based technology [50]. This method analyzes diffusely reflected light, enabling the rapid and non-destructive acquisition of spectrograms. A comparison and justification of the primary spectroscopic methods [51,52] that can be used for the identification of plastics (polymers) are presented in Table 2.

Table 2. A comparison and justification of the spectroscopy methods.

Method	Purpose	Strengths	Limitations
Near-infrared spectroscopy (NIR)	For identifying plastics by polymer type and sorting them in waste recycling systems	Rapid, non-destructive and ideal for sorting	Less detailed, limited material types and difficult to apply on dark-colored samples
Fourier-transform infrared spectroscopy (FTIR)	For polymer identification and functional group analysis	Accurate, provides detailed molecular information and suitable for microplastic analysis	Requires sample preparation, is slower and is difficult to apply on dark-colored samples
Raman	For detailed chemical composition and impurity detection	Non-destructive, analyzes small and complex samples and is suitable for microplastic analysis	Lower signal intensity, relatively slow method and sensitive to environmental components
Laser-induced breakdown spectroscopy (LIBS)	For elemental composition of plastic materials	Rapid and non-destructive and can be performed in situ (i.e., without removing the material from its environment); it can simultaneously detect multiple elements in a single measurement	The composition of the material may affect the accuracy of the measurements, especially for complex or heterogeneous samples

Summarizing the choices of spectroscopy methods, it can be stated that NIR is most effective for the rapid sorting and identification of plastics in large-scale or automated systems, such as recycling plants. FTIR and ATR-FTIR are excellent for detailed analysis and the identification of plastics, especially in laboratory or controlled environments. Raman spectroscopy provides complementary information to FTIR and is valuable for analyzing small or complex polymer samples. LIBS, while useful for elemental analysis and detecting contaminants or additives, does not provide the molecular or structural insights needed to identify and distinguish between different polymers effectively.

After activation, the device was paired with a mobile application for setup, and calibration was performed to minimize any influence of the light source or detector on the measurements. The obtained NIR spectra enabled the highly accurate identification of the polymer type in the plastic packaging. Using the trinamiX plastic pack plus solution (trinamiX GmbH, Ludwigshafen, Germany), the authors were able to identify more than 30 types of polymers, including bio-based ones. Despite its speed and high degree of confidence, the NIR spectroscopy method has limitations, as heavily contaminated and black colored items were categorized as 'not identified'.

Each identified item was assigned to one of the following categories: jars, bottles, rigid packaging, foam, films and combined packaging. As with the mixed MSW stream, no drying or washing of the plastic packaging was performed. The entire characterization was held indoors to avoid undesirable effects such as wind. The same weighting scale with an accuracy of 0.001 kg was used for the whole sample, and the weights for each category were documented in a predefined Excel-based protocol.

2.4. Calculation Procedure

To determine the required sample size n, the authors applied the following formula:

$$n = \frac{Z^2 p(1-p)}{E^2} \quad (1)$$

where the following hold true:

Z—the score corresponding to the desired confidence level (95% confidence);
p—the estimated proportion of plastic waste in the total waste stream;
$\overline{E}$—the margin of error or acceptable level of precision (±5%).

In addition, a finite population correction (FPC) formula was used:

$$n_{adjusted} = \frac{n}{1 + \left(\frac{n-1}{N}\right)} \quad (2)$$

Here, N—the total number of waste items.

3. Results

3.1. Plastic and Multilayer Packaging in the Mixed Municipal Solid Waste Streams

The identification and categorization of plastics and multilayer packaging in the mixed MSW streams were performed during the summer–autumn period of 2023. Three municipalities/waste management operators were involved in the plastic waste composition analysis: Kaunas MBT facility (Lithuania), Daugavpils Recycling Center (Latvia) and Tallinn Recycling Center (Estonia). The results of the plastic and multilayer packaging waste composition assessment in the mixed MSW streams are presented in Table 3.

Table 3. Composition of plastic and multilayer packaging waste in the mixed MSW streams in Kaunas, Daugavpils and Tallinn (mass percentages).

Type of Polymer and Categories of Plastic and Multilayer Packaging	Kaunas (LT)		Daugavpils (LV)		Tallinn (EE)	
	In the Total Sample Mass, %	In the Category 'Plastics and Multilayer Packaging', %	In the Total Sample Mass, %	In the Category 'Plastics and Multilayer Packaging', %	In the Total Sample Mass, %	In the Category 'Plastics and Multilayer Packaging', %
HDPE jars	0.51	1.32	5.63	15.24	0.87	2.00
LDPE film	20.88	53.86	14.19	38.53	7.24	17.88
PP jars, rigid packaging	5.98	11.97	2.96	8.04	6.14	15.16
PP film	6.33	16.20	2.46	6.68	2.37	5.87
PET bottles, rigid packaging	1.74	4.48	0.88	2.40	2.26	5.58
PS foam	0.93	2.50	1.51	4.11	0.35	0.86
PS jars, rigid packaging	0.14	0.36	-	-	6.54	16.16
Other plastics *	1.25	3.22	2.46	6.68	6.49	16.02
Multilayer packaging tetra packs, blisters	2.40	6.09	6.74	18.32	2.83	7.01
Total, %	40.16		36.83		35.09	

* Unidentified category and/or type of polymer.

The percentage distribution of plastic and multilayer packaging waste in the mixed MSW streams was similar across all three municipalities, ranging from 35.09% in Tallinn, 36.83% in Daugavpils and 40.16% in Kaunas. The largest proportion of plastic waste was LDPE films, with significant variation across municipalities: Kaunas with 20.88%, Tallinn with 7.24% and Daugavpils with 14.19% of the total waste mass. The second largest group consisted of PP packaging, including jars, rigid packaging and films, contributing 12.31% in Kaunas, 8.51% in Tallinn and 5.42% in Daugavpils. A notable exception was found in Daugavpils, where HDPE jars accounted for 5.63% of the total sample mass, while in Tallinn, it was 0.87% and 0.51% in Kaunas. Other types of plastics were identified in smaller quantities, with varying distributions across the municipalities. Multilayer packaging (such as tetra packs and blisters) represented up to 2.40% in Kaunas, 2.83% in Tallinn and 6.74% in Daugavpils. Overall, the mass percentage of plastics and multilayer packaging in Daugavpils was three times higher (18.32%) compared to Kaunas (6.09%) and Tallinn (7.01%).

In all three municipalities, waste management operators use manual or partly manual sorting of plastic waste. This process, which relies heavily on the experience of the technicians, does not always provide reliable classification by polymer type. This study highlights the challenge of identifying the polymer type through visual recognition of labels on plastic items. As expected, many plastic items in the mixed MSW flow were contaminated, deformed or crushed, making label identification not possible. As a result, the proportion of non-readable labels was significant, with 56.02% in Kaunas, 47.56% in Daugavpils and 68.32% Tallinn. These findings suggest that the implementation of technological means for polymer type identification could significantly improve sorting of plastic waste in mixed MSW flows.

3.2. Separately Collected Plastic and Multilayer Packaging Waste

The MSW management systems in Kaunas and Tallinn provide facilities for the separate collection of specific types of waste (plastics, metals, paper and cardboard) from multi-family and single-family households. Conversely, the waste management system in Daugavpils does not offer separate collection for specific waste from multi- and single-family households; thus, the research of separately collected plastic and multilayer packaging waste was only conducted in the Kaunas and Tallinn municipalities. In Kaunas, plastic and multilayer packaging waste from multi-family households is collected using underground containers, while plastic and multilayer packaging together with paper, cardboard and metal from single-family households are collected in 0.12, 0.14 or 0.24 L volume containers.

In Tallinn, the plastic waste coming from multi-family households is collected in dedicated containers, while single-family households collect plastics and multilayer packaging together with paper, cardboard, metal and glass in 150 L volume yellow plastic bags. As mentioned within Section 2, the handheld Plastic Plus NIR spectroscopy device (trinamiX GmbH) was applied for the identification of the polymer type. In addition, plastics were categorized in the following groups: jars, bottles, rigid packaging, foam and films.

3.2.1. Separately Collected Plastic and Multilayer Packaging Waste from Multi-Family and Single-Family Households in Kaunas

The total mass of the separately collected waste sample from multi-family households in Kaunas was 49.84 kg. Of this, 37.23 kg was plastic and multilayer packaging, while 12.26 kg consisted of non-plastic items. Thus, plastic and multilayer packaging accounted for 74.70% of the total sample mass. The composition of the separately collected and multilayer packaging waste sample from multi-family households in Kaunas is presented in Table 4.

The major groups of plastic items were LDPE film (18.45%), PET bottles and rigid packaging (12.59%), films (7.46%) and PP bottles and rigid packaging (4.43%). Surprisingly, the sample did not contain any kind of jars. Multilayer packaging made up 11.45% of the total sample mass. A reduced number of bio-based plastics (PVDF, 6.53%) was also found in the sample. The distribution of plastic and multilayer packaging waste by the type of polymer (mass percentages) is presented in Figure 2. The major groups of packaging waste were LDPE (24.25%), PET (20.06%), PS (7.93%) and HDPE (7.89%). For around 10.96% of the items, the polymer type was not identified.

Table 4. Composition of separately collected plastic and multilayer packaging waste sample from multi-family households in Kaunas (mass, kg).

KAUNAS, Multi-Family Households											
Packaging Categories	**Polymer Type**								**Multi-Layer Packaging**	**Not Identified**	**Mass by Packaging Type**
	HDPE	**LDPE**	**PP**	**PVC**	**PS**	**PET**	**PA**	**PVDF**			
	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
Jars											
Bottles	1.04	1.21	0.78			3.39		1.30		0.78	8.50
Rigid packaging	1.21	0.95	0.87		1.04	1.30		1.13			6.50
Foam					1.91						1.91
Films	0.69	6.87	0.69	0.78		2.78	0.95			3.30	16.06
Combined packaging									4.26		4.26
Mass by polymer type, kg	2.94	9.03	2.34	0.78	2.95	7.47	0.95	2.43	4.26	4.08	37.23

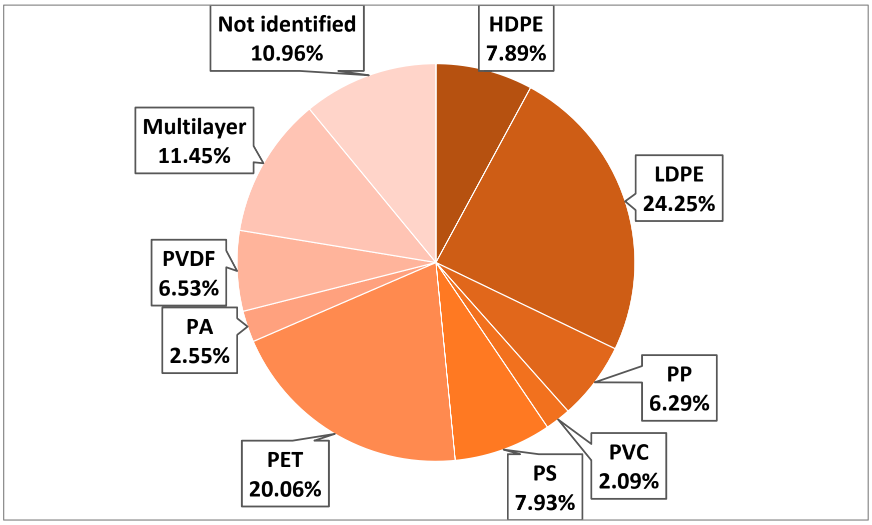

Figure 2. Distribution of plastic and multilayer packaging waste by the type of polymer in the samples collected from multi-family households in Kaunas (mass percentages).

The total mass of the separately collected waste sample (plastic and multilayer packaging, paper, cardboard and metal) from single-family households in Kaunas was 91.42 kg. Of this, 40.83 kg was plastic and multilayer packaging, while non-plastic items made up 50.59 kg. Thus, plastic and multilayer packaging accounted for 44.66% of total sample mass. The composition of plastic and multilayer packaging in the separately collected waste sample from single-family households in Kaunas is presented in Table 5.

Table 5. Composition of plastic and multilayer packaging in the separately collected waste sample from single-family households in Kaunas (mass, kg).

KAUNAS, Single-Family Households										
Packaging Categories	**Polymer Type**							**Multilayer Packaging**	**Not Identified**	**Mass by Packaging Type**
	HDPE	**LDPE**	**PP**	**PVC**	**PS**	**PET**	**PLA**			
	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
Jars			2.81			0.70			0.79	4.3
Bottles	3.43					5.45				8.88

Table 5. *Cont.*

KAUNAS, Single-Family Households										
Packaging Categories	**Polymer Type**							**Multilayer Packaging**	**Not Identified**	**Mass by Packaging Type**
	HDPE	**LDPE**	**PP**	**PVC**	**PS**	**PET**	**PLA**			
Rigid packaging	7.21	1.14	3.28		0.93	2.37			0.88	15.81
Foam					0.97					0.97
Films	0.96	3.60	0.88	0.96		0.61	1.05		0.7	8.76
Combined packaging								2.11		2.11
Mass by polymer type, kg	11.60	4.74	6.97	0.96	1.90	9.13	1.05	2.11	2.37	40.83

The major groups of plastic items were HDPE rigid packaging and bottles (26.06%), PET jars, bottles and rigid packaging (20.87%) and PP jars and rigid packaging (14.91%). Multilayer packaging made up 5.15% of the total mass. Notable, a small proportion of bio-based films (PLA, 2.56%) was also identified. The distribution of plastic and multilayer packaging waste by the type of polymer (mass percentages) is presented in Figure 3. The major groups of packaging were HDPE (28.50%), PET (22.35%), PP (17.06%) and LDPE (11.60%). For around 5.80% of items, the polymer type was not identified.

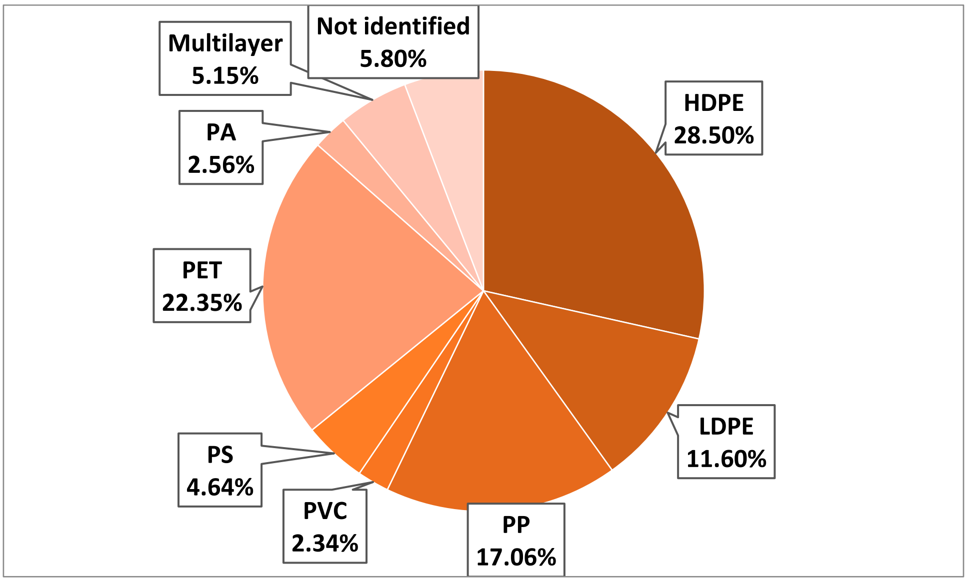

Figure 3. Distribution of plastic and multilayer packaging waste by the type of polymer (mass percentages) in the samples collected from single-family households in Kaunas.

The comparison of the data on the collected plastic and multilayer packaging waste from single- and multi-family households in Kaunas revealed that the consumption and collection habits of citizens in these two groups differed. Bottles and rigid packaging from HDPE (26.06%) made up the major group of plastics for single-family households, while in multi-family households, they accounted for only 6.04%. The second major category of plastic packaging waste from single-family households was PET bottles and rigid packaging (19.15%), while PET films made up only 1.49%. On the other hand, the percentage of PET bottles and rigid packaging collected from multi-family households was lower (12.57%); however, it contained a considerably higher percentage of PET films (7.45%). The third major category of plastic waste from single-family households was PP jars and rigid packaging (14.92%), while for multi-family households, this category constituted only 4.43%. The percentage of collected LDPE films from single-family households was

8.82%, while LDPE films collected from multi-family households comprised 18.45% of the sample mass.

A comparison of the percentages of multilayer packaging showed that multi-family households collect over twice the amount of these items (11.45%) compared to single-family households (5.15%). The share of not-identified plastic waste from single-family households was 5.80% and for multi-family households was 10.96%, almost twice as high. The obtained percentages of plastic items with a not-identified polymer type, combined with the visual observations, support the assumption that separately collected plastic waste from single-family households is better separated and cleaner compared to plastic waste from multi-family households.

3.2.2. Separately Collected Plastic and Multilayer Packaging Waste from Single-Family and Multi-Family Households in Tallinn

The total mass of the separately collected waste sample from multi-family households in Tallinn was 57.60 kg. The mass of non-plastic items constituted 21.86 kg, while plastic and multilayer packaging accounted for 35.74 kg, meaning 62.05% of the total sample mass. The composition of plastic and multilayer packaging in the separately collected waste sample from multi-family households in Tallinn is presented in Table 6.

Table 6. Composition of plastic and multilayer packaging in the separately collected waste sample from multi-family households in Tallinn (mass, kg).

TALLINN, Multi-Family Households										
Packaging Categories	**Polymer Type**							**Multi-Layer Packaging**	**Not Identified**	**Mass by Packaging Type**
	HDPE	**LDPE**	**PP**	**PVC**	**PS**	**PET**	**PA**			
	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
Jars	0.65	0.01	0.88		0.10		0.12		0.10	1.86
Bottles	0.42		0.38			0.60				1.40
Rigid packaging	1.96	0.08	2.17	0.10	0.20	2.65	0.08		0.15	7.39
Foam					0.10					0.10
Films	0.83	5.77	0.87				0.02		1.33	8.82
Combined packaging								16.17		16.17
Mass by polymer type, kg	3.86	5.86	4.30	0.10	0.40	3.25	0.22	16.17	1.58	35.74

The major groups of plastic items were LDPE films (16.14%), followed by jars, bottles and rigid packaging from PP (9.59%) and HDPE (8.48%). Unexpectedly, the sample contained an exceptionally high percentage of multilayer packaging (45.24%). The distribution of plastic and multilayer packaging waste by the type of polymer (mass percentages) is presented in Figure 4. The major groups of packaging waste were LDPE (16.39%), PP (12.03%), HDPE (10.80%) and PET (9.09%). For 4.42% of the analyzed items, the polymer type was not identified.

The total mass of the sample of separately collected waste from the single-family households in Tallinn was 46.63 kg. The mass of non-plastic items constituted 20.10 kg, while plastic and multilayer packaging was 26.53 kg, meaning it comprised 56.89% of the total sample mass. The composition of plastic and multilayer packaging in the separately collected waste sample from single-family households in Tallinn is presented in Table 7.

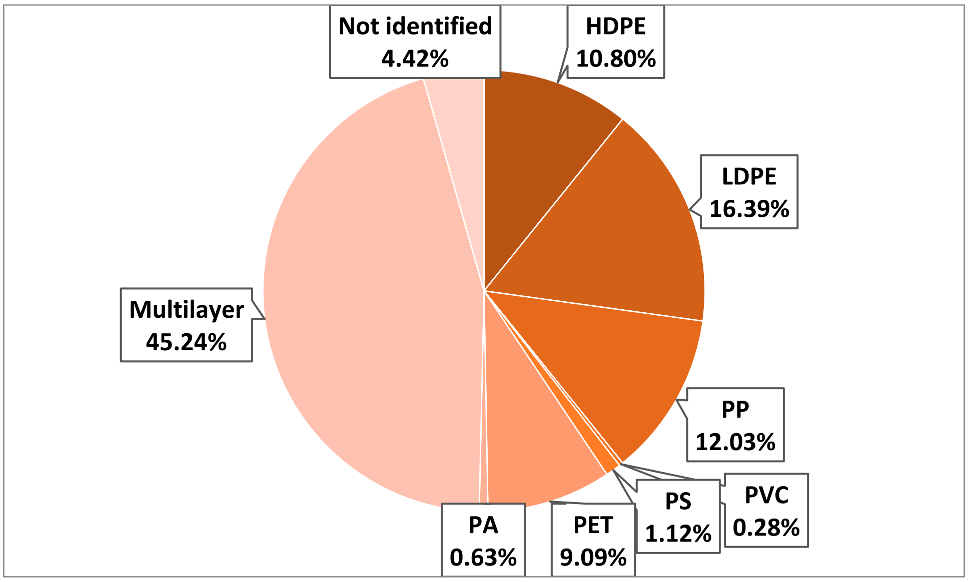

Figure 4. Distribution of plastic and multilayer packaging waste by the type of polymer (mass percentages) in the samples collected from multi-family households in Tallinn.

Table 7. Composition of plastic and multilayer packaging in the separately collected waste sample from single-family households in Tallinn (mass, kg).

TALLINN, Single-Family Households												
Packaging Categories	Polymer Type									Multilayer Packaging	Not Identified	Mass by Packaging Type
	HDPE	LDPE	PP	PVC	PS	PET	PA	ABS	PVDF			
	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
Jars	0.47		0.19			0.48						1.14
Bottles	0.24		0.21			1.30						1.75
Rigid packaging	1.57		5.07	0.28	0.26	2.99		0.08				10.25
Foam												
Films	0.99	4.71	1.62			0.28	0.11		0.04		0.27	8.02
Combined packaging										5.37		5.37
Mass by polymer type. kg	3.27	4.71	7.09	0.28	0.26	5.05	0.11	0.08	0.04	5.37	0.27	26.53

The major groups of plastic items were jars, bottles and rigid packaging from PP (21.37%), PET (17.98%) and HDPE (8.59%) and LDPE films (17.75%). Multilayer packaging made up 20.24% of the total mass. It is important to note that small amounts of bio-based films (ABS: 0.31% and PVDF: 0.15%) were also identified. The distribution of plastic and multilayer packaging waste by the type of polymer (mass percentages) is presented in Figure 5. The major groups of packaging waste were PP (26.72%), PET (19.03%) and LDPE (17.75%). For 1.03% of items, the polymer type was not identified.

A comparison of the data on the collected plastic and multilayer packaging waste from single-family and multi-family households in Tallinn revealed that the consumption and collection habits of citizens in these two groups differ considerably. Jars, bottles and rigid packaging from PP (23.29%) constituted the major group of plastics from single-family households, while in multi-family households, it was only 9.60%. The second major category of plastic waste from single-family households was PP jars, bottles and rigid packaging (20.62%), while for multi-family households, this category made up only 9.59%. The third major category of plastic packaging waste from single-family households was PET bottles and rigid packaging (17.98%), while PET films made up only 1.05%. The percentage of PET bottles and rigid packaging collected from multi-family households was lower (9.09%), and no items from PET film were identified.

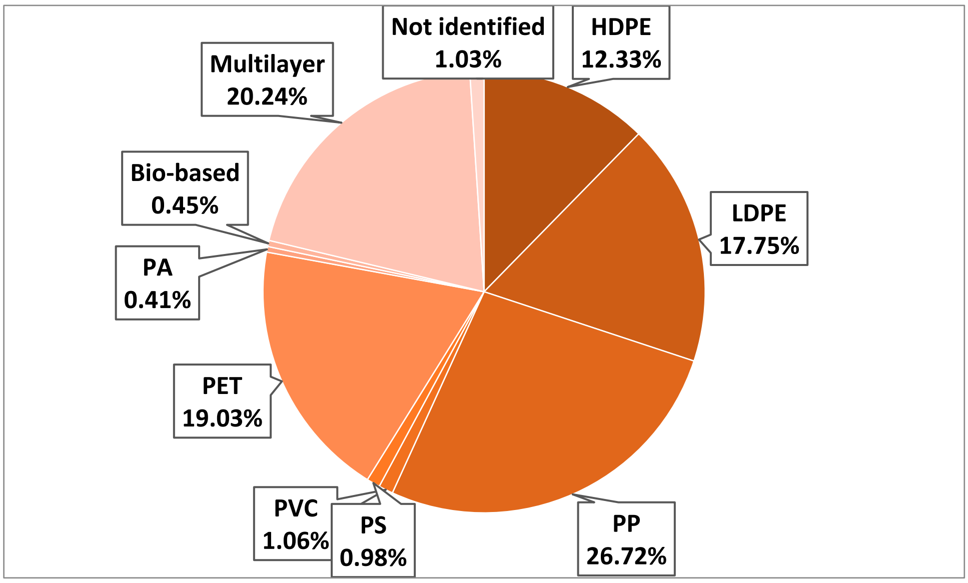

Figure 5. Distribution of plastic and multilayer packaging waste by type of polymer (mass percentages) in the samples collected from single-family households in Tallinn.

A comparison of the percentages of multilayer packaging showed that multi-family households collect more than twice as much of these items (45.24%) compared to single-family households (20.24%). The share of non-identified plastic waste from single-family households was 1.02% while from multi-family households was 4.42%, more than four times higher. As in Kaunas, the percentage of non-identified polymer type items, combined with the visual observations, supports the assumption that separately collected plastic waste from single-family households is better separated and cleaner in comparison to plastic waste from multi-family households.

4. Discussion

The analysis of the data obtained from the three cities in the Baltic States showed that the composition of the polymer type and packaging category among the cities differed considerably. The high variation in the data was also acknowledged based on the results reported from other cities in the Baltic Sea Region. Several factors, such as national legislation; local regulations; waste collection systems; seasonality; the production and import of food products, beverages and packaging and the habits of citizens, among others, have an impact on the composition of municipal waste. This implies that the development and implementation of a plastic and multilayer packaging waste collection–sorting–recycling system requires location-specific reliable data.

A comparison of the results obtained in this study with the findings of the other authors revealed similar trends. Globally, the proportion of plastic in mixed MSW streams ranges from 7% to 22% [53]. For instance, in the USA, plastic constitutes 13% of mixed MSW, with the majority being LDPE, then HDPE, other and PP (2.9%, 2.5%, 2.5% and 1.8% of total waste mass, respectively) [54]. Similarly, in a Swedish city, the plastic share in mixed MSW was 13.8%, with the distribution of the total waste mass by type as follows:

LDPE, 26%; PP, 24.9%; others, 22%; PET, 14% and HDPE, 8.9% [55]. Another example from Finland illustrates quite similar trends in the prevalence of plastic packaging waste in the overall MSW stream, with the distribution by type of polymer as follows: LDPE, 27.6%; PP, 21.7%; PET, 13.4% and HDPE, 6.9% [33]. According to Delgado et al. [56], the composition of the plastic fraction in MSW by polymer type within the EU according to the data from 2017 varies as follows: LDPE, 38–43%; HDPE, 15–20%; PET, 12–17%; PS, 12–17% and PP, 5–10%. Based on various scientific and practical sources, it is worth noting that the morphological composition of waste strongly correlates with the geographical, economic, social and other situations of countries [57]. Our research provides insights into the current state of the plastic and multilayer packaging waste system in a specific geographic region.

After examining plastic and multilayer packaging waste in the mixed MSW and separately collected waste, samples from multi- and single-family households revealed a clear trend, indicating that the mass share of plastic and multilayer packaging waste in the mixed MSW samples was lower compared to the separately collected samples, where higher values were observed. The highest mass share was observed in the samples from multi-family households.

As expected, a large proportion of plastics in the mixed MSW streams were contaminated, deformed or smashed, making the identification of the polymer type by manual reading of the labeling not possible. Polymer type identification by visual recognition of labeling revealed that in the MSW flows, more than half of the items had labeling that was unreadable. The obtained data combined with the visual observations confirmed the assumption that separately collected waste from single-family households were cleaner and better preserved in its original shape compared to the waste from multi-family households.

A composition of plastics from multi-family and single-family households in Kaunas and Tallinn partially align with the results obtained at the municipality of Copenhagen. For source-separated plastic waste, the composition of plastics was as follows: PET, 31%; PE, 27%; PP, 34% and others, 5% [58]. Another study analyzed categories of plastics from different Danish recycling centers: hard plastics, plastic films and PVC. For hard plastic, PP items dominated (48%), and other types of plastics were present in minor amounts: HDPE (22%), PVC (8%), PS (6%) and PET (3%). For polymeric films, the following results were obtained: LDPE (63%), PP (25%), HDPE (7%) and PET (5%) [59]. Another study dealt with plastic packaging contaminated with food residues. It analyzed several waste streams, one of which was cleaned mixed plastics (CMPs) for anaerobic digestion (AD). The composition of different types of plastics was as follows: LDPE (64%), PP (12%), PET (2%) and a mixture of other polymers (9%) [60].

5. Conclusions

The study demonstrated significant differences in the composition of municipal plastic and multilayer packaging waste among three Baltic cities (Kaunas, Daugavpils and Tallinn). This argues that the development of an effective packaging waste management system at the specific municipality should be based on reliable and localized data.

The main results showed that separately collected plastic and multilayer packaging waste system ensures higher amounts and better quality of waste in comparison to waste collected from mixed municipal solid waste (MSW) streams. This implies that better and more harmonized separately collected packaging waste systems are prerequisites for the enhancement of polymer type identification and increase in plastic waste recycling rates.

Single-family households generally produce cleaner and better-separated waste compared to multi-family households, enhancing the efficiency of sorting and recycling processes. The share of unidentified plastic waste at multi-family households is higher (e.g., 4.42% in Tallinn and 10.96% in Kaunas) compared to single-family households (e.g., 1.03% in Tallinn and 5.80% in Kaunas). This highlights the need for targeted interventions and awareness programs in multi-family households to improve waste quality and sorting practices.

The use of technologies such as near-infrared (NIR) spectrometry significantly improves polymer type identification, reducing the percentage of unidentified plastics in comparison to visual recognition method. However, plastic waste contamination limits polymer type identification and further steps in the plastic recycling chain. The literature review revealed rudimentary efforts for the establishment of procedures related to the assessment of municipal plastic waste contamination. Thus, the development of a standard protocol and techniques for the assessment of municipal plastic waste contamination is one of the urgent tasks for authorities and scientific community.

The findings of this study emphasize the need for improvements in the systems for separately collected plastic waste and the application of advanced technological methods to increase plastic sorting capacities. At the same time, better recognition of polymer types during the sorting process, as well as more accurate characterization of plastic materials, will increase the number of materials ready for recycling. It will also assist decision makers in selecting the most appropriate treatment options for each type of polymer.

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Abbreviations

The following abbreviations are used in this manuscript:

MBT	Mechanical biological treatment
MSW	Municipal solid waste
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
PP	Polypropylene
PS	Polystyrene
PA	Polyamide
PET	Polyethylene terephthalate
PLA	Polylactic acid
ABS	Acrylonitrile butadiene styrene
PVDF	Polyvinylidene fluoride or polyvinylidene difluoride

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