

Article

Studies of the Morphological Composition and the Possibility of Energy Recovery of Residues After Sorting Plastics and Metals

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Abstract

In view of the growing level of the selective collection of plastic waste, the implementation of the CE, as well as the search for alternative, cheap energy sources, the rational management of residues after the sorting of this waste is becoming increasingly important. The article presents the result of studies carried out at the turn of 2024/2025 in four voivodeships in Poland. The aim of the study was to determine the morphological composition of residues after sorting selectively collected plastics and metals. Knowledge of the detailed morphological composition of sorting residues allows for the assessment of the effectiveness of the sorting process and the suitability of these residues for energy recovery. Innovative studies have shown that about 80% of the weight of sorting residues consists of fractions suitable as components of RDF. Another new aspect of this study is a comparison of the results of studies on selected fuel properties of RDF produced from ballast after the sorting of plastics and metals and those of RDF derived from ballast after the sorting of mixed municipal waste. RDF from plastic sorting residues has almost twice the net calorific value, higher chlorine and zinc content, and lower ash and moisture content. The practical part of the article proposes technological solutions to meet the requirements set for these types of fuels by cement and CHP.

Keywords: sorting residue; morphological composition; plastics; fuels from waste; waste-to-energy; RDF; SRF

1. Introduction

The idea of using municipal waste as an alternative source of energy dates back to the 1970s, in the aftermath of the first major fuel crisis. As a result, new energy sources have been sought to replace fossil fuels. At that time, attention was paid to the energy potential of municipal waste. Mechanically processed municipal waste, devoid of the mineral non-flammable fraction, has been called refuse-derived fuel (RDF) and is used in energy and heat generation processes [1–3]. In addition, with the introduction of the CE in waste management in the EU, a number of quantitative policy targets are being pursued to reduce the amount of municipal waste that is landfilled to 10% by 2035 [4]. This requirement was introduced into Polish legislation by the Landfill Directive [5]. In practice, the implementation of this requirement will be impossible without energy recovery from waste. Research has shown that both residual municipal waste of the MSW and selectively collected biological waste are important and complementary sources of renewable energy. These sources support the role of WtE systems in the energy transition, which is



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directed towards a circular economy and the assumed climate neutrality. By optimizing the recovery of energy obtained from waste, it is possible to significantly contribute to the implementation of the assumptions of the European Green Deal and thus to the reduction of greenhouse gas emissions [6].

Energy recovery from waste is consistent with CE principles, particularly in the context of rapid resource depletion and climate change, which require decisive and sustainable solutions [7]. It should be noted that the energy treatment of waste, as part of the WtE technology, is among the technologies used in the CE processes, and the use of residual waste energy completes this process [8,9]. The use of energy from residual municipal waste in energy processes should be subject to the appropriate preparation and removal of, among other things, non-flammable fractions and to preparation for combustion in a cement kiln in a cement plant or in a heating plant using a fluidised bed boiler [10,11].

Fuel produced on the basis of processed municipal and industrial waste is called RDF. Increased production of municipal waste has forced the development of modern technologies for its processing. In the current waste management model, some fractions of municipal waste cannot be recycled; one method of use is to process these into RDF fuel. Such fuel can most often be prepared in the form of flakes (“fluff”—loose shredded mixture), pellets, or briquettes [12]. In accordance with the principles of the CE, fractions are separated in sorting plants for recycling. However, after the sorting process, there is a part that cannot be recycled, as well as that which cannot be separated for recycling, and as a sorting residue, can be used to some degree as a component of RDF fuel [13]. Most often, RDF waste fuel is made from fractions of plastics, textiles, paper, and cardboard that are no longer recyclable. It is produced in most installations for mechanical and biological waste treatment and is also made of a fraction of 0–80 mm, which in most cases does not fit into the CE. SRF solid secondary fuel refers to standardised solid fuel that is not produced from hazardous waste. The most common ingredients from which SRF fuel is produced are paper, used tyres, plastic waste, wood, and textiles [14].

According to the European Committee for Standardisation [15], the classification of SRF fuels is based on three main parameters: net calorific value, chlorine content, and mercury content. The choice of these parameters was dictated by aspects related to assessing the usable value of the fuel in terms of economy, technology, and the environment. However, these are basic parameters that do not fully reflect the properties of RDF. Table 1 shows the technical requirements and classes for SRF fuels. The activities of the CEN/TC Technology Committee were directed at unifying the quality standards for physicochemical parameters relating to SRF; specifications and technical reports were developed, some of which were published as standards.

Table 1. Technical requirements and SRF classes [15].

Parameter	Statistical Measure	Unit	Fuel Class				
			1	2	3	4	5
Net calorific value (NCV)	Mean	MJ/kg (ar)	≥ 25	≥ 20	≥ 15	≥ 10	≥ 3
Chlorine (Cl)	Mean	[%] in mass (d.m.)	≤ 0.2	≤ 0.6	≤ 1.0	≤ 1.5	≤ 3
Mercury (Hg)	Median	mg/MJ (ar)	≤ 0.02	≤ 0.03	≤ 0.05	≤ 0.10	≤ 0.15
	80th percentile	mg/MJ (ar)	≤ 0.04	≤ 0.06	≤ 0.10	≤ 0.20	≤ 0.30

According to the definition contained in the standard [16], SRF is a fuel produced from municipal waste and non-hazardous waste that is used for the purpose of energy recovery

in a suitable installation. In accordance with the PN-EN ISO 21640:2021-10 standard, a classification system has been presented that provides five SRF classes [15].

It should be noted that according to the law, RDF fuels are waste (in Poland, they are listed in the waste catalogue under the code 19 12 10; under the name of alternative fuel), and so far, there are no legal regulations allowing them to be classified as a product [16,17].

RDF fuels can be used through combustion in cement plants or in combined heat and power plants equipped with CFB circulating fluidised bed boilers, provided that they are produced from segregated non-recyclable fractions of municipal waste, for which energy recovery is highly desirable [18,19]. RDF fuels in Poland are mainly used in the cement industry as an additional fuel in the clinker firing process. In addition, RDF fuels are used instead of fossil fuels in the energy sector. Energy recovery using RDF fuels through their co-combustion in a cement plant is an effective form of waste management, supporting the CE. Figure 1 shows the percentage share of heat from RDF fuels in the cement industry in Poland and Europe.

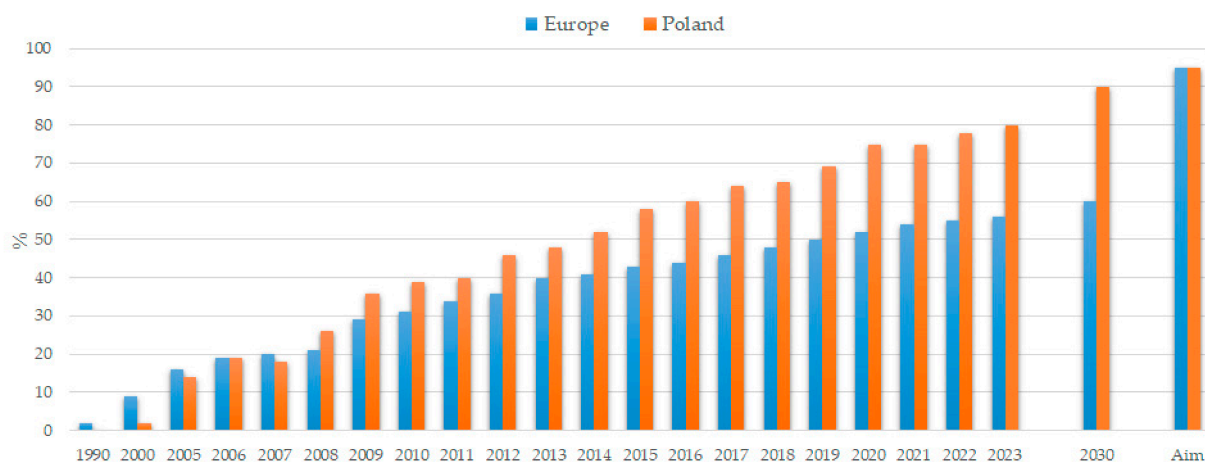


Figure 1. Comparison of the share of heat from RDF fuels in the cement industry in Poland and Europe [20].

For better illustration, the figure covers the period from 1990 to 2022 and shows only an upward trend in the use of fuels for the treatment of municipal waste. The use of waste as a fuel in the cement industry aligns with the idea of WtE, and this type of fuel can be used in waste incineration plants [21]. The advantages of using a rotary kiln in a cement plant for RDF combustion include the following [22]:

- High combustion temperature and long residence time at this temperature.
- A completely waste-free process. Because the ash passes into the clinker product there is the possibility of implementing the R5 material recycling process and issuing a document confirming recycling for the municipal installation where RDF was produced. In order to qualify this process as R5 material recycling, the cement plant should obtain the status of a recycler.
- All energy from waste incineration is used in the process of incineration of clinker (Energy Recovery R1—an recovery confirmation document—is provided for the municipal installation).
- The alkaline atmosphere in the furnace neutralises the acidic gaseous components produced in the RDF combustion process.
- The possibility of dosing RDF into the furnace in various forms.
- The high efficiency of the dust collection equipment.
- The relatively low cost and short adaptation time of the furnace to RDF combustion.

In addition to the technology of rotary kiln using RDF fuels, the industry of managing fuels from waste, the so-called RDF in CHP with modern fluidised bed boilers using a CFB technology, is developing in Europe, and these investments are also being carried out outside Europe, e.g., in Korea or Japan. The advantages of CFB multi-fuel boilers in terms of RDF use are as follows [22]:

- Fuel flexibility—the possibility of the co-combustion of various fuels and resistance to legislative changes.
- Proven technology and positive operating experience.
- Ensures the competitiveness of heat and electricity production thanks to the possibility of changing the type of fuel depending on current costs.
- The possibility of co-combustion of RDF with a net calorific value that does not allow them to be burned independently.

In the available literature, there are no requirements for cement plants and CHP in terms of RDF. As a result, the tested fuel properties of RDF do not have a reference point for a specific requirement.

There is no research on residues from the sorting of selectively collected plastics and metals in terms of their energy use in the available literature. No studies were found in the literature that compare the fuel properties of RDF produced from ballast after the sorting of plastics and metals with RDF that is produced from mixed municipal waste in terms of the possibility of their energy use in the heat and power plant industry, in fluidised bed boilers, or in cement production. Therefore, the purpose of the article is to fill the above gap. The result of the work is also the development of a proposal for a technological line for the production of RDF from the residues of sorting plastics and metals, so that, as a result, the produced RDF meets the requirements of cement plants and CHP.

2. Requirements of the Cement Plant and Combined Heat and Power Plant for RDF

Cement plants in Poland use RDF fuels extensively, and it is the most reliable method of thermal waste transformation, having become a permanent part of waste management. In order for the fuel to be used in the cement industry, it must meet certain requirements, depending on whether it is to be used in the main burner or the calciner. Table 2 shows examples of the requirements of three cement plants for RDF in Europe.

Table 2. Requirements of three example cement plants for RDF in Europe [22]. Cement plant requirements pertain to the quality of RDF going to the calciner and main burner (physicochemical parameters).

Requirements:	Unit	Cement Plant 1	Cement Plant 2	Cement Plant 3
Net calorific value of RDF going to the calciner	[MJ]/kg _{w.m.}]	≥18	≥18.5	≥16
Net calorific value of RDF going to the main burner	[MJ]/kg _{w.m.}]	≥21	≥21	≥21
Ash	%	≤20	-	≤20
Sulphur content	%	≤0.5	<0.5	<0.5
Chlorine content	%	≤0.8	<0.7	≤0.7
Moisture content	%	≤20	<18	≤20

Table 2. Cont.

Requirements:	Unit	Cement Plant 1	Cement Plant 2	Cement Plant 3
Total metal content: Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V	mg/kg d.m.	<2500	<2500	≤1000
Mercury content	mg/kg d.m.	<5	<2	≤0.5
Contents Cd + Th + Hg	mg/kg d.m.	-	<10	-
Total metal content: Cd + Tl	mg/kg d.m.	<50	-	<30
Granulation for calciner	mm	<40	<35	≤30
Granulation for the main burner	mm	<25	<25	<25
Average bulk density	Mg/m ³	-	-	0.15–0.20
PCB + PCT (polychlorinated biphenyls + polychlorinated terphenyls)	mg/kg	-	<50	-
Scrap content		-	-	to the 0.5%
Other:		**	-	*

** The fuel should not contain PCDD/F, biologically active substances, medical waste and components such as radioactive or emitting ionising radiation, explosive, tearing, substances that might react with each other, or those containing pathogenic or toxic compounds. The fuel should be homogeneous and should not contain impurities exceeding the required granulation. * Fluorine to 100 ppm, cadmium to 20 ppm, Tal to 10 ppm, arsenic to 10 ppm, cobalt to 50 ppm, nickel to 50 ppm, antimony to 50 ppm, lead to 250 ppm, chromium to 250 ppm, copper to 250 ppm, manganese to 250 ppm, and vanadium to 250 ppm.

Table 3 presents selected fuel properties of the RDF used in selected CHP plants in Europe.

Table 3. Selected fuel properties of RDF used in selected CHP plants in Europe [22].

Location of the CHP Plant (Multi-Fuel Fluidised Bed Boilers)		RDF I (Data from 2016)	RDF II (Data from 2016)	RDF III (Data from 2026)
		Norrköping in Sweden	Lomellina II/Lomellina Energia/Parona, Italy	One of the CHP Plants Located in Central Europe
Moisture	%	27	20–35	10–25
Ash	%d.m.	14.3	4–20	10–20
Chlorine	%d.m.	1.0	0.6–1.2	<0.7
Net calorific value	MJ/kg	12.9	10.5–16.8	10–15
Mercury	ppm d.m.	n.a.	n.a.	<0.6
Zinc	ppm d.m.	n.a.	n.a.	<250
Sulphur	%d.m.	n.a.	0.25	<0.8

d.m.—dry matter; n.a.—not available.

3. Industrial Research—Sampling for Testing

Tests of selectively collected plastics and metals were carried out in four sorting plants. Each of them was located in a different voivodeship (Łódzkie, Silesian, Lubusz, Greater Poland). The waste sent to the sorting plant came from the following cities: Łódź, Katowice, Nowa Sól, and Grodzisk Wielkopolski. The morphological composition of residues after sorting plastics and metals was studied in the period November 2024–January 2025, before

the entry into force of the deposit system in Poland. In each of the designated sorting plants, representative samples weighing about 100 kg each were taken from the residues of sorting plastics and metals. After the sorting process, the fractions were sent to containers or baler-containers, from where research samples were taken. According to the adopted research assumptions, each sample analysed came from a different batch of waste from a specific city with a known housing type.

Samples of waste remaining after the sorting process from Grodzisk Wielkopolski were taken in January 2025. The weights of the samples taken were as follows: sample 1—90.82 kg, sample 2—71.2 kg, sample 3—69.81 kg, sample 4—88.5 kg.

Samples of waste remaining after the sorting process from Łódź were taken in November 2024. The weights of the samples taken were as follows: sample 1—71.26 kg, sample 2—86.3 kg, sample 3—92.4 kg, sample 4—82.3 kg.

Samples of waste remaining after the sorting process from Katowice were taken in December 2024. The weights of the samples taken were as follows: sample 1—83.43 kg, sample 2—92.4 kg, sample 3—77.54 kg, sample 4—86.1 kg.

Samples of waste remaining after the sorting process from Nowa Sól were taken in January 2025. The weights of the samples taken were as follows: sample 1—112.2 kg, sample 2—89.4 kg, sample 3—101.2 kg, sample 4—79.9 kg.

A total of 1374.76 kg of waste from the sorting process of plastics and metals was tested.

Samples of waste residues from the sorting of plastics and metals from the cities of Łódź, Nowa Sól, and Grodzisk Wielkopolski came from single-family and multi-family housing. Waste from Knurów came exclusively from single-family housing.

Obtaining representative and reliable results of testing the morphological composition of waste requires the adoption of an appropriate test methodology. The adopted methodology takes into account the method of sampling, its weight, and the number of samples taken. In addition, an important factor is the place and time of sampling, taking into account the type of buildings, the size of the city, and the season, each of which affects the possibility of the variability of the morphological composition of waste.

The criterion used in the research presented in this paper is to ensure the representativeness of the results obtained. These are the established and proven sampling procedure, the size and weight of the sample, the repeatability of the test results obtained, and the number of samples taken.

Measurement uncertainties resulted from possible misclassification, or difficulties in identifying plastics without markings, which was very rare. Additional uncertainties include the accuracy of the scale or soiling of the packaging with an organic or mineral fraction. Packaging with contents (residues of a beverage or other liquid) were classified as contaminants.

Two scales were used to study the morphological composition: a platform scale and a hook scale with a weighing accuracy of ± 20 g. Samples for testing weighing approximately 100 kg were taken in accordance with the procedure set out below. This is to ensure the representativeness and repeatability of the tests carried out.

A sample for morphological composition studies from the selective collection of plastics and metals was taken from a container or a press-container after the sorting process. The sample was taken from a container/baler-container (usually with a volume of 32 m³) when there was at least 10 m³ of collected waste in it. After gaining access to the container with a snow shovel, the waste was collected from various places (if possible) until a test sample weighing about 100 kg was obtained. In the case of bulk (not bagged) sample, a 1100 L container on wheels was used for this purpose. This container was filled with waste until the weight of about 100 kg was reached.

After preparing the sample, the waste was divided into 29 groups. During the work, a sorting table (own initiative) was used, on which individual fractions were separated and systematically weighed. The mass of each individual fraction was recorded on measurement cards. The analysis of the morphological composition of the waste was carried out manually and the identification of the individual types of plastics consisted in the verification of the markings found on the waste and on the experience of the test performers. To make it easier to distinguish ferrous metals from non-ferrous metals, a neodymium magnet was used. During the research, photographic documentation was made, showing the tested samples, as well as each of the 29 separated fractions. A fine fraction of less than 20 mm was extracted on a manual sieve.

The research on the morphological composition of waste was based on the recommendations of the methodology recommended by the former Department of Economy of the Ministry of the Environment, which is based on the developed research methodology Solid Waste Analysis Tool [23,24].

In the modification of the recommended research methodologies adopted in this study, it was decided to divide the resulting waste stream into 29 material categories. Such a division allows for a more accurate recognition of fractions that can be subjected to energy recycling. In addition, the result of the research will be information on the residues of the sorting process of plastics and metals, how effectively the sorting process is carried out and the assessment of the usefulness of this fraction as fuel.

Below, the individual groups into which the resulting waste stream was divided during the morphological composition research are compiled.

The films were divided into the following groups:

- PP foil;
- PP film (metallized);
- LDPE film divided into LDPE transparent, LDPE light, white/yellow, coloured or printed, and black;
- LDPE and HDPE films—all colours except black;
- Plastic films with a layer of aluminium (e.g., coffee bags);
- PP film—multi-material with a layer of metal (e.g., chip packaging).

Other material fractions:

- Rigid plastics: PE, PP, PS divided into black and non-black;
- Foamed plastics containing expanded PS and foamed PE in the form of foam;
- PET bottles divided into transparent, opaque and black bottles and PET trays in colours other than black and black;
- PVC—all types;
- fillers (including mastic, acrylic and any other filling except silicones);
- beverage carton;
- magnetic metals;
- non-magnetic metals;
- paper and cardboard—constituting “contamination”, i.e., materials not intended for collection under the adopted rules of the selective collection of plastics and metals in Poland;
- others—including paper-based laminates, organic waste, textiles, glass, disposable nappies—that constitute “contamination”, i.e., materials not intended for collection under the adopted rules of the selective collection of plastics and metals in Poland;
- “other (7)/other” packaging;
- fine fraction < 20 mm.

Fuel samples generated from the sorting residues of selectively collected plastics and metals, as well as from mixed municipal waste, were collected in different months of 2024 and March 2025 in accordance with the PN-EN ISO 21645:2021-09 standard [25]. Several primary samples were taken from the fuel pile, mixed, and reduced to a laboratory sample using the quartering method. The laboratory sample was then submitted for testing. First, the total moisture content was determined. The separated sample was subsequently ground and subjected to further analyses.

The technological lines for the production of RDF included grinding, metal separation and air separation processes. The standards used in the study of selected fuel properties of RDF produced from sorting residues of separately collected plastics and mixed municipal waste are presented in Table 4.

Table 4. Standards according to which samples of fuels from waste were tested.

Name of Determination	Standard
Sample preparation	PN-EN ISO 21646: 2022-11 Sample Preparation [26]
Net calorific value	PN-EN ISO 21654: 2021-12 Net Calorific Value [27]
Chlorine	PN EN 15408: 2011 Chlorine Content [28]
Ash	PN EN ISO 21656: 2021-08 Ash Content [29]
Moisture	PN EN ISO 21660-3:2021-08 Moisture Content [30]
Zinc, mercury	PN-EN ISO 3884: 2025-10 Methods for the determination of elements [31]

Waste fuel samples were taken as follows: a certain number of primary samples were taken from different places in the waste fuel pile and then combined, and the amount of material was reduced to the volume of the laboratory sample by the quartering method. The sample prepared in this way is crushed in a laboratory knife grinder to grain sizes below 1 mm. Before the shredding process, the moisture content is determined by the total weight method in a laboratory dryer. The remaining analyses were performed after the sample was fragmented. The heat of combustion was determined in a calorimetric bomb, the chlorine content by the potentiometric method and the ash content by the weight method in a muffle furnace. Mercury was determined using the CVAAS (atomic absorption) technique using an MA-3000 analyser (Nippon Instruments Corporation, Kyoto, Japan). Zinc was determined by atomic absorption spectrometry (ASA) using an atomic absorption spectrometer. All devices are periodically inspected and properly calibrated in accordance with manufacturers’ requirements and standards.

4. Research Results

Table 5 presents the results of the morphological composition of residues after sorting selectively collected plastics and metals. The research was carried out on the premises of four waste sorting plants in Poland, where the waste stream was divided into 29 morphological groups.

Table 6 presents the results of studies on the selected fuel properties of RDF produced from residues after the sorting of selectively collected plastics and metals. The fuel samples taken came from various production plants, and the technological lines for the production of RDF included shredding, metal separation, and air separation processes.

Table 7 compares selected fuel properties of RDF produced from the sorting of residues of selectively collected plastics and metals with RDF produced from residues from mixed municipal waste sorting. The results presented are the average of seven measurements, and the fuel samples came from various fuel production installations located in Poland.

Table 5. Comparison of the average values of the morphological composition of residues after sorting selectively collected plastics and metals from four sorting plants in Poland.

The Voivodeship in Which the Waste Sorting Plant Was Located The City from Which the Waste Came		Łódź	Silesian	Lubusz	Greater Poland	Mean with SEM	SD
		Łódź	Katowice	Nowa Sól	Grodzisk Wielkopolski		
Type of Housing/Month in Which the Research Was Conducted		Single-Family/ November 2024	Single-Family/ December 2024	Mixed/ January 2025	Single-Family/ January 2025		
Fraction Name/Unit		[%]	[%]	[%]	[%]	[%]	
1	PP-film	0.89	1.76	1.32	2.81	1.69 ± 0.41	0.82
2	PP-film—metallised	0.98	0.35	0.1	0.05	0.37 ± 0.22	0.43
3	LDPE-film—transparent	3.32	1.93	5.26	4.8	3.83 ± 0.76	1.51
4	LDPE-film—bright, white and yellow coloured or printed (transparent based and >20% printed with white/yellow)	3.09	1.97	1.37	1.85	2.07 ± 0.37	0.73
5	LDPE and HDPE-film—coloured, excluding black	7.96	5.96	8.36	8.04	7.58 ± 0.55	1.09
6	LDPE-film—black	0.9	0.73	1.68	1.11	1.1 ± 0.21	0.41
7	Plastic film, with an aluminium layer (e.g., coffee bags)	0.36	0.35	0.29	0.33	0.34 ± 0.02	0.03
8	Plastic-film—multimaterial, including multimaterial where one of the layers is metallised PP (e.g., crisp bags)	0.58	0.51	0.51	0.93	0.63 ± 0.10	0.2
9	PE-rigid—Non-black	2.83	4.5	2.55	3.22	3.27 ± 0.43	0.86
10	PE-rigid—Black	0.02	0.32	0.11	0.15	0.15 ± 0.07	0.13
11	PP-rigid—Non-black	6.67	5.13	3.78	7.51	5.77 ± 0.83	1.65
12	PP-rigid—Black	0.67	0.8	0.5	0.87	0.71 ± 0.08	0.16
13	PS-rigid—Non-black	0.8	0.49	0.71	0.48	0.62 ± 0.08	0.16
14	PS-rigid—Black	0.23	0.41	0.15	0.17	0.24 ± 0.06	0.12
15	Foamed plastics—All, includes expanded PS and foamed PE	1.24	0.67	1.18	1.1	1.05 ± 0.13	0.26
16	PET bottles—Transparent	4.27	10.52	5.15	8.2	7.03 ± 1.44	2.87
17	PET bottles—Opaque	1.67	2.07	0.66	7.12	2.88 ± 1.45	2.89
18	PET bottles—Black	0.22	0.21	0.1	0.05	0.14 ± 0.04	0.08
19	PET trays—Non-black	0.67	0.79	0.92	2.21	1.15 ± 0.36	0.72
20	PET trays—Black	0	0.11	0.15	0.31	0.14 ± 0.07	0.13
21	PVC—All	1	1.03	2.01	0.9	1.23 ± 0.26	0.52
22	Fillers (including also mastic, acrylic and any other filling besides silicones)	0.1	0.34	0.16	0.02	0.15 ± 0.07	0.14
23	Beverage carton	2.52	1.92	1.88	2.24	2.14 ± 0.15	0.3
24	Metals—Magnetic	4.8	2.3	3.1	4.55	3.69 ± 0.60	1.19
25	Metals—Non-magnetic	1.43	0.8	1.65	1.38	1.32 ± 0.18	0.36
26	Paper and cardboard	20.35	24.57	23.14	10.07	19.54 ± 3.28	6.55
27	Others, including paper-based laminates, organic waste, textiles, glass, nappies	24.32	25.12	18.9	21.06	22.3 ± 1.45	2.89
28	“Other”(7) type of packaging	3.19	2.03	3.8	2.9	2.98 ± 0.37	0.74
29	Fines < 20 mm	4.92	2.31	10.51	5.57	5.84 ± 1.71	3.42
SUM		100.0	100.0	100.0	100.0	100.0	

Table 6. Results of studies of selected fuel properties of RDF produced from residues after the sorting of selectively collected plastics and metals.

No.	Date of Sampling	Net Calorific Value kJ/kg	Chlorine % d.m	Ashes % d.m.	Moisture Content %	Zinc ppm d.m.	Mercury ppm d.m.
1	13 March 2025	24,563	0.21	7.5	9.4	497	0.09
2	19 September 2024	24,650	0.70	11.5	15.8	514	0.12
3	20 June 2024	20,790	0.32	10.9	11.7	431	0.36
4	12 December 2024	19,230	2.08	13.2	22.1	411	0.26
5	9 August 2024	20,413	1.06	14	16.8	772	0.10
6	20 November 2024	20,666	1.58	9.2	10.2	663	0.2
7	16 April 2024	21,750	1.32	7.5	15.6	233	0.30
Average value with SEM		21,723 ± 736.13	1.04 ± 0.24	10.5 ± 0.91	14.5 ± 1.55	503 ± 61.39	0.20 ± 0.04
SD		1947	0.63	2.4	4.1	162	0.10

Table 7. Comparison of selected fuel properties of RDF produced from residues after the sorting of selectively collected plastics and metals with RDF produced from residues after the sorting of mixed municipal waste.

Unit	Net Calorific Value	Chlorine	Ash	Moisture	Zinc	Mercury
	kJ/kg	%d.m.	%d.m.	%	ppm d.m.	ppm d.m.
RDF * from sorting ballast after separate collection of plastics and metals	21,723	1.04	10.5	14.5	503	0.20
RDF * from sorting ballast from mixed municipal waste	12,624	0.42	17.2	35.3	386	0.56

* The process lines for the production of RDF included the processes of shredding, metal separation and air separation.

5. Discussion of Results

Detailed studies of the morphological composition of residues after sorting selectively collected plastics and metals fill the gap in the available literature in this area. Such a thorough analysis allows for the assessment of the effectiveness of the sorting processes carried out and, on this basis, it is possible to make a decision on the appropriate modernisation strategy of the sorting plant, as well as to assess the suitability of this fraction for the production of RDF.

The representative samples taken for testing came from four waste sorting plants located in Poland with basic technical and technological equipment. The separation of secondary raw materials in the sorting plants was mainly based on manual sorting; in one of the installations, there were two opto-pneumatic separators.

The research was conducted in four voivodeships: Łódź, Lubusz, Silesian, and Greater Poland in the period November 2024–January 2025. The selectively sorted, collected plastics and metals came from the following cities: Łódź, Katowice, Nowa Sól, and Grodzisk Wielkopolski.

The sorted waste came mainly from single-family buildings, collected as part of the so-called “yellow bags” and includes plastics and metals collected jointly in Poland. Only samples from Nowa Sól (Lubusz Voivodeship) came from mixed buildings.

In the residues of sorting plastics and metals, there were tradeable materials—valuable secondary raw materials suitable for mechanical recycling in the form of ferrous and non-ferrous metals, PET beverage bottles, as well as PE and PP packaging, totalling about 20% of the ballast weight. These raw materials were not separated in the sorting plant due to the following factors: size (low efficiency of separation of small elements), degree of soiling, difficulties with identification in the case of manual sorting, and, above all, limited efficiency of the sorting process, as there are currently no technologies allowing one to achieve 100% efficiency of the separation process of a given fraction.

Undesirable fractions in RDF include PVC, fillers (including also mastic, acrylic and any other filling besides silicones), metals, disposable nappies, hazardous waste, hazardous waste packaging, and fine fractions. PVC should be eliminated from RDF due to its very high chlorine content. Fillers (including mastic, acrylic, and any other filling except silicones) due to the presence of additives (plasticisers, pigments, biocides), which will affect the emission and high content of mineral fillers, which in turn will increase the ash content and reduce the net calorific value, and which should not be a component of RDF. Ferrous and non-ferrous metals are valuable raw materials for recycling and should not be a component in RDF. Used disposable nappies should not be sent to RDF due to their very high moisture content and nitrogen content. Hazardous waste and the packaging of hazardous substances should not be sent to RDF due to their chemical composition. The fine fraction is characterised by higher moisture content (originating from the organic fraction), mineral content (originating from the mineral fractions), increased zinc and other undesirable elements compared to other fractions. The study used one sieve at the researchers' disposal, with a hole diameter of 20 mm. A fraction with a granulation of 0–20 mm contains organic substances, characterised by high moisture content and mineral fractions, so it is undesirable in RDF, as it will reduce its calorific value.

The total proportion of undesirable fractions in RDF is approximately 19.2% of the weight of the ballast after the sorting process for the separately collected plastics and metals, and consists of PVC 1.23%; fillers 0.15%; metals 5.01%; glass and disposable nappies 7%; and fines < 20 mm 5.84%. This means that around 80% of the residue weight of the sorted separately collected plastics and metals is suitable as a fuel component from waste.

It is worth noting that about 19.5% of paper and cardboard is found in the residue after sorting plastics and metals. Theoretically, this fraction should not be found in selectively collected plastics but, in reality, the quality of selective plastic collection in Poland leaves much to be desired. Paper and cardboard have a much lower net calorific value than plastics, but this fraction is legally qualified as biomass. The poor quality of the selective collection of plastics and metals is evidenced by the high share of the other group (22.3%), which includes, among other things, textiles, glass, used disposable nappies, organic waste, and laminated papers. The results of the research presented in [32] showed a significant difference in the quality of selectively collected plastics and metals, which shows that selectively collected waste from single-family buildings (collection in yellow bags) has a much better quality—a lower content of contaminants, i.e., waste not covered by collection, than that from multi-family buildings (collection in yellow containers).

The various types of films are also worth noting (their total share was 17.61%). Their share in ballast is significant and most of them are characterised by high heat of combustion. This is a fraction that is easy to separate with an air separator and the separated light fraction can become a component of RDF. Beverage cartons (2.14%) are also suitable for energy use as a component of RDF fuel in cement plants [33].

It should be remembered that the morphological composition of residues from the process of sorting separately collected plastics and metals will depend on the quality of selective waste collection in a given area, as well as the degree of mechanisation/automation

of the sorting plant. Morphological composition studies were carried out before the introduction of the deposit system in Poland, which means that the composition of this ballast has now changed. Another factor that will change the morphological composition of selectively collected plastics will be the introduction of requirements resulting from the PPWR, according to which all packaging placed on the EU market is recycled on a large scale. In the coming years, the recycling sector will have to invest in solutions for packaging groups that are not processed today, or these packaging types will be modified to be more recyclable, hence the growing importance of ecodesign [34].

As part of the conducted research, the results associated with selected fuel properties of RDF produced from ballast after sorting plastics and metals were compared with those associated with RDF derived from ballast after sorting mixed municipal waste. RDF from plastic sorting residues has almost twice the net calorific value (21.7 MJ/kg) compared to RDF produced from mixed municipal waste sorting residues (12.6 MJ/kg). This is due to the higher content of high-calorific-value plastics and the lower ash and moisture content of the ballast fuel produced after sorting plastics. The net calorific value of RDF from ballast after sorting mixed municipal waste is too low to be used in the cement industry, but is sufficient to be used in a fluidised bed boiler in a combined heat and power plant. The moisture content of RDF generated from residues from the sorting of mixed municipal waste is too high for the current requirements of CHP plants.

The mercury content for the two types of analysed fuels is at an acceptable level from the point of view of the requirements set by cement and CHP. Much more mercury (0.56 ppm d.m.) is found in RDF from ballast derived from sorted mixed municipal waste, as material containing this harmful element is much more common in this type of waste. Presented in [35] are the results of the testing of the mercury content in waste types that are characterised by the great variation in the parameters that depend on the origin of the waste combustible fractions, as well as on their possible contact with waste containing mercury. Depending on the fuel origin (ballast from the selective collection of waste, residue from mixed municipal waste sorting, bulky waste, car industry waste, sewage sludge), the average content of mercury in the fuels under analysis is included in the range of 0.1–1.15 ppm d.m. This results from the fact that these waste types include elements such as worn-out fluorescent lamps, batteries, and mercury thermometers, etc., which are thrown into rubbish bins by residents who do not care about sorting waste. In plants producing RDFs where drying is applied to reduce the moisture content of the fuel and to increase the net calorific value, an added effect is a reduction in the mercury content because the higher temperature involves evaporation of volatile mercury compounds.

The zinc content in both tested fuels exceeds the requirements of cement plants and CHP. A high zinc content is characterised by a fine fraction of 10–40 mm of municipal waste, as well as plastics (zinc used as a technological additive, filler and white dye), i.e., the basic component of RDF. The carriers of zinc in quantities not accepted by CHP plants (250 ppm) and, increasingly, cement plants (300 ppm) are flammable fractions of municipal waste, which are the basic components of RDF emitted by the air separator, i.e., plastics, artificial textiles, paper and cardboard [36].

Therefore, the production of alternative fuel from municipal waste with a zinc content below 300 ppm is unlikely. In order to solve the problem of excessive zinc content in RDF, it is recommended to obtain homogeneous combustible industrial waste with low zinc content and, after shredding, mix it with RDF from municipal waste.

The authors' unpublished studies of cotton textiles indicate that the zinc content in cotton clothes is below 50 ppm. Therefore, cotton waste can be collected and, once shredded, can be mixed with RDF obtained from municipal waste to reduce its zinc content.

As for the possibility of reducing zinc in RDF fuels, it is worth mentioning separators for ferrous and non-ferrous metals, as well as opto-pneumatic separators that separate waste containing a high zinc content. Installing an eddy current separator in the RDF production line will have a slight impact on the reduction of zinc in the alternative fuel, because zinc in solid form as scrap does not occur in the light fraction of municipal waste (zinc and aluminium very commonly co-occur in the same waste (ZnAl), which is an alloy of zinc with aluminium and other elements).

The chlorine content of 1.04% in RDF obtained from ballast after sorting plastics exceeds the requirements for SRF class 3 fuel and is close to the value for class 4 according to PN-EN ISO 21640: 2021-10 [15].

Therefore, in order to reduce the chlorine content in SRF, it is recommended to add a flammable fraction with a low chlorine content, e.g., RDF from ballast after mixed municipal waste sorting. Another way to reduce the chlorine content in SRF fuel produced this way is to separate PVC waste through opto-pneumatic separators. Their appropriate effectiveness should allow for the maintenance of class 3 for this parameter on a permanent basis.

To sum up, RDF obtained from ballast after plastics sorting differs significantly not only in net calorific value and moisture content, but also in ash, chlorine, and mercury content, so it is recommended to mix these two fuels in appropriate proportions to meet recipient requirements.

The mixing process in an RDF production plant is most commonly carried out by feeding two different combustible waste fractions in appropriate quantitative proportions onto a feed conveyor; these materials then enter a shredder, where they are mixed and homogenised. Another method involves mixing using a loader in storage bays or a dedicated mixer. At the cement plant, the process of mixing combustible fractions stored in various silos and dosed in appropriate proportions is carried out in conjunction with a weighing system.

Figure 2 proposes a schematic of the technological line of the RDF ballast generation plant after sorting plastics and metals, meeting the requirements of cement plants and CHP. The manual sorting station will allow the separation of hazardous waste, disposable nappies and other waste that is particularly undesirable in RDF. Then, the shredder (200 mm sieve) will enable preliminary coarse shredding of waste, which will have a positive effect on the throughput of the line, and the pre-shredded waste can be more effectively subjected to PVC and metal separation processes. Then, the opto-pneumatic separator (NIR) will separate a large part of the PVC, which is a carrier of chlorine that is undesirable in RDF. Next, a ferrous and non-ferrous separator will allow the separation of metals. The star separator will allow the separation of the undesirable fine fraction (0–20 mm) characterised by an increased content of moisture, mineral fraction, zinc, and other undesirable elements. The final device will be a high-speed shredder (40 mm sieve), into which other pre-crushed homogeneous low-zinc combustible fractions will also be dosed in appropriate proportions, so that the produced RDF meets the requirements of cement plants and CHP in terms of zinc content.

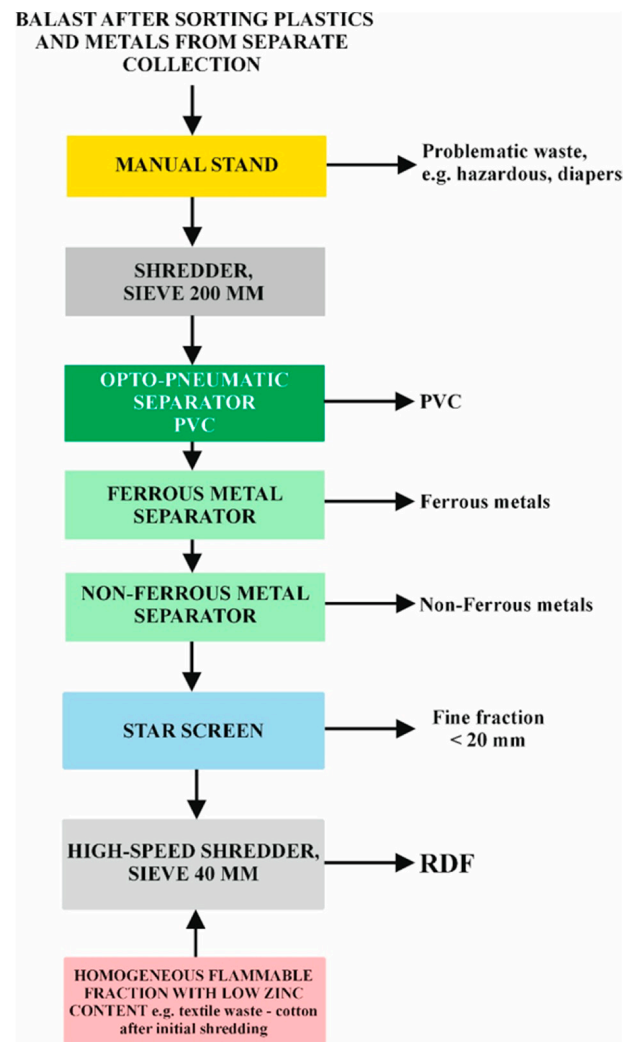


Figure 2. Proposal of a technological line for the installation of RDF production from ballast after sorting plastics and metals, meeting the requirements of cement plants and CHP [drawn by: W. Hryb and A.J. Wandrasz].

6. Conclusions

Detailed studies of the morphological composition of residues after the sorting of selectively collected plastics and metals, as well as a comparison against selected properties of RDF produced from ballast derived from the sorting of various materials, fill the gap in the available literature in this area. The article contains quality requirements, as the RDF parameters required by cement plants and CHP differ significantly. Cement plants require a much larger number of parameters and fuel with a much higher net calorific value than CHP, which most often use multi-fuel fluidised bed boilers with a CFB boiler. This provides some logistical possibilities for the production and use of RDF, depending on its properties.

Some parameters are very restrictive, e.g., the required zinc content in RDF is difficult to meet, because it occurs in most flammable fractions forming an excessive amount of RDF. Therefore, the production of RDF from municipal waste with a zinc content below 300 ppm is unlikely. In order to solve the problem of excessive zinc content in RDF, it is recommended to obtain homogeneous combustible industrial waste with low zinc content and mix it with RDF from municipal waste.

Studies of the morphological composition of residues after the sorting of selectively collected plastics and metals showed that, due to the limited efficiency of the sorting process, the degree of mechanisation, and the automation of the process, there was still a proportion

of about 20% of valuable and marketable secondary raw materials useful for mechanical (material) recycling in the ballast. The share of undesirable fractions in RDF in this ballast was also determined due to their chemical composition, moisture content, and other factors affecting the risk of exceeding the selected parameters required by the recipients of these fuels. The total proportion of undesirable fractions in RDF is approximately 19.2%, which means that approximately 80% of the sorting residue from separately collected plastics and metals is suitable as a component of RDF.

The issue of variable chlorine content in RDF and unstable quality parameters of the finished fuel is related to the presence of polyvinyl chloride (PVC) waste in the ballast fraction. The morphological composition of waste is subject to constant fluctuations, which directly translate into difficulties maintaining a consistent chemical profile for RDF. The content of pure chlorine in the structure of PVC materials ranges from 30% to as much as 50%, depending on the amount of additives used. Such a high concentration means that even trace amounts of these plastics in the production stream immediately disqualify the fuel from the user's perspective, as they exceed the relevant standards. In order to meet the stringent quality requirements set for cement or CHP, PVC components must be removed. This can be done in two ways: by cutting off this stream before entering the plant, which is difficult to implement, or by advanced separation directly on the RDF production line. Traditional separation based on an air separator is insufficient in the case of PVC, because the density and aerodynamics of these plastics make them too close to other plastics desired in RDF. The only effective solution for the selective removal of polyvinyl chloride is to implement a high-performance opto-pneumatic separator that identifies PVC particles using near-infrared (NIR) and rejects them using compressed air nozzles. Although opto-pneumatic systems guarantee the chemical purity of the fuel, their purchase and maintenance generate enormous capital (CAPEX) and operating (OPEX) costs. The decision to retrofit the line must be preceded by a reliable financial justification.

The presence of waste paper drastically reduces the energy efficiency of the produced RDF, as the paper is characterised by a low net calorific value. In addition, this raw material has the ability to accumulate moisture, which further reduces the net calorific value and increases the costs of possible fuel drying. The mass occurrence of paper in the yellow bag (intended for metals and plastics) clearly indicates serious mistakes in segregation made by residents in households. This waste should be directed to blue bins, which would relieve the RDF line and allow for the recycling of pure cellulose fibre.

The conducted studies have shown that RDF obtained from ballast derived from sorted plastics differs significantly from RDF obtained from ballast obtained from mixed municipal waste in net calorific value, ash content, chlorine content, mercury content, and moisture content, so it is recommended to mix these two fuels in appropriate proportions in order to meet the requirements of recipients.

The quality of separately collected waste and mixed municipal waste, as well as the eco-design of packaging, is crucial not only in terms of recyclability, but also, as studies have shown, on the quality of RDF fuels produced.

Proper selective collection by residents will help reduce the content of undesirable elements in RDF, especially in terms of mercury content.

Eco-design should reduce the zinc content of packaging, and packaging made of polyvinyl chloride, which is a carrier of chlorine, should be eliminated as undesirable packaging, both in recycling processes and in the production of fuels from waste.

The waste hierarchy in force in the European Union puts recycling ahead of energy recovery. In reality, however, the choice of waste management method is often determined by the economic and technological aspects of sorting and recycling capabilities.

As part of future research, following the introduction of the deposit return system and the implementation of the requirements arising from the PPWR in Poland, the analysis of RDF produced from sorted residues is planned to be repeated. The effectiveness of the technological solutions proposed in this article will also be verified in cooperation with an industrial partner at a reference RDF production facility.

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Abbreviations

The following abbreviations are used in this manuscript:

RDF	Refuse-derived fuel
SRF	Solid recovered fuel
CHP	Combined heat and power plant
CFB	Circulating fluidised bed
CE	Circular economy
WtE	Waste-to-energy
SD	Standard deviation
SEM	Standard error of the mean
PPWR	Packaging and packaging waste regulation
d.m.	Dry matter
w.m.	Wet matter
ar	As received

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