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Recycling of Polyethylene Terephthalate (PET) Bottles in the Logistics Supply Chain – Overview

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Abstract: A great deal of packaging made of PET is observed in logistics supply chains, and the article is mainly concerned with food – bottles. Implementing the EU's "zero-waste" guidelines implies action on the part of producers of packaging and food for B2C distribution to find new solutions to enable the above-mentioned stakeholders in the logistics supply chain to balance the business mentioned above parties – taking into account environmental protection. The article discusses the tasks and possibilities under the above conditions of a new type of "RECYCLER" companies, which, at the end of the life of PET packaging, i.e. after the foodstuffs in PET bottles have been consumed, produce a recyclate and return it to re-production. In several journals, including, e.g. (Połednik et al. 2016, Topiarzová et al. 2011), respecting good recycling practices – there is an ongoing discussion on the sense of introducing reusable packaging, deposits, etc. This article discusses the barriers to recovery in a multi-level plastics recovery system, with specific reference to the operation of a PET bottle recycling line, and presents a pre-verified concept for a method to increase the efficiency of separating PET bottles from the plastics fraction in a multi-level waste separation system.

Keywords: bottles, PET, recycling, recovery, reverse logistics, waste

1. Introduction

Plastics sourced from recycling and subjected to recycling (PCR – Post-Consumer Recycled) mostly come from plastic packaging disposed of in the bin with separated waste as a "plastics" fraction. The "plastics" fraction consists of waste such as packaging from food products, cosmetics, household chemicals, and medicines. As such, they are a mixture of materials such as LDPE, HDPE, PP, PS, PET, laminates and other plastics. There is now a strong emphasis in the EU on increasing the use of recycled plastics, including PCR plastics for packaging, to reduce waste in landfills and their environmental impact (Gabryelewicz et al. 2021). It takes 1.9 kg of oil to produce 1 kg of PET; globally, this equates to 47.5 trillion kilograms of oil (352 million barrels). This amount of oil covers about two years of Poland's oil demand (Vest 2003), with full-grade PET granules, referred to as "virgin", used most frequently in the production of PET bottles in Poland.

According to (Directive (EU) 2019/904), from 2025 on, PET beverage bottles will contain at least 25% recycled plastic. From 2030, the requirements are increasing, and PET beverage bottles will have at least 30% recycled plastic. At the same time, the food and cosmetics packaging market is striving to produce packaging with as much share of PCR material as possible. It is a trend that has continued for several years. Packages made of 100% PCR are now available on the market. According to (Regulation (EC) No 1935/2004), any food contact material must be safe for the end user/consumer under foreseeable conditions of use. Regulation (Regulation (EC) No 1934/2004) defines this safety as:

- no release of chemicals beyond safe limits,
- no change in food composition,
- no change in the organoleptic characteristics of the food (Zajac & Poznański 2021).

Recycled plastics for food contact should also meet the requirements of (Commission Regulation no. 282/2008). Work is currently underway to amend this regulation. The above requirements also apply to packaging intended for cosmetics. The packaging manufacturer must ensure continuous monitoring of the entire production process and the composition of the final product. For this reason, using PCR plastics involves additional risks discussed further in the article.

Approximately 200,000 Mg PET are consumed annually in Poland, and its consumption per Polish inhabitant per year is more than 3 kg. On average, Polish households produce 1.5 million Mg of plastic waste per year (of which more than 55% is packaging waste), of which 65% was recycled (recycling and energy recovery) in 2012. It means that in Poland, considering the amount of packaging waste landfilled each year, there is approximately 300 000 Mg of new packaging waste each year that could be managed through recycling (Zajac et al. 2020).

According to EU law, waste management should meet the criteria of separation and reuse of secondary raw materials (Chamier-Gliszczyński 2010, Chamier-Gliszczyński 2011). The re-sourcing and reuse of secondary raw materials from post-consumer waste are more complicated and labour-intensive than from postmanufacturing waste and automotive recycling (Chamier-Gliszczynski & Krzyzynski 2005), e.g. end-of-life vehicles (Chamier-Gliszczyński 2011a, Chamier-Gliszczyński 2011b), as the sources are more dispersed and the raw materials from these sources are usually a mixture of different components and are often contaminated. The recovery of PET packaging is increasing in terms of tonnage, but in percentage terms, it is almost at the same level. In the classification of EU countries with the highest percentage rate of PET packaging recovery, Poland ranks 14th. Germany has the highest rate at 93%, followed by Norway (91%), Switzerland (87%), Sweden (85%), Denmark (82%) and Estonia (81%). Poland has been recovering an average of around 30% of PET packaging in recent years. The ever-increasing volume of PET packaging being put into circulation is associated with an increasing range of uses. Still, it is also causing adverse environmental impacts in the form of increased deposition in landfills. In the Polish market, packaging waste accounts for 814,000 Mg per year and amounts to 55% of total plastic waste, of which 39.2% is recycled, 25% is incinerated, and 35.8% is landfilled.

2. Identification of a Logistical Transport and Storage System for PET bottles

The PET bottle is characterised, among other things, by its high strength, resistance to breakage (important in the processes of transport and storage of goods), high degree of transparency, and the possibility of forming any bottle shape. The most favourable option for the recycling process is to make the packaging from a valuable, uncoloured, homogeneous polymer and to use additional elements and components (labels, adhesives, closures) that will not hinder secondary processing. The smaller the number of these components, the easier it is to remove them and recycle the waste into valuable materials.

The raw material and auxiliary materials that make up the PET bottle should favour the recycling process, e.g. recommendations (van Dongen et al. 2011) not to print/write directly on the packaging wall and, for multilayer bottles, not to use any other plastic than PET.

The introduction of a new generation of packaging fulfilling several different functions, such as marketing, utility or logistics, the main purpose of which is, in addition to protecting the packaged product, to protect against microbiological and chemical spoilage. Active and intelligent packaging can include:

- Packaging with sensors – markers of information on the state of the product (indicators of humidity, temperature and optimum consumption temperature);
- Product protection measures (oxygen absorbers, oxygen indicators, laminates containing silicones as drying agents, metallised containers);

- Metal components or packaging – whose corrosive capacity has been considerably reduced through the use of sheets with a low content of contaminants from harmful metals and double-sided painting, packaging made of doubly recrystallised aluminium and steel allowing thin wall thickness;
- Glass bottles made from cullet, thin-walled, multilayer plastic bottles with high barrier capacity and heat resistance.

Active packaging is the packaging of food products that have additional functions to the basic protection of the product against external influences. The main principle of active and intelligent packaging is that it interacts with the packaged product based on changing the conditions inside the packaging, thus extending the product's shelf life. In addition, intelligent packaging (PET in particular) has applications in transporting and storing materials in temperature regimes (e.g. reduced temperature, which characterises transport processes for organs for transplantation, and other goods in a PET container/bottle).

In the logistics supply chain, an information vector on the packaging has been introduced to easily and unambiguously identify the packaging materials; for illustration, packaging marked: UN/1A1/Y1.4/150/06/PL/COBRO/nnn – complies with UN requirements, drum-shaped packaging with a detachable lid, made of steel, Class Y, for Group II and III substances, gross weight 150 kg, manufactured in 2006 in Poland, certified by COBRO (http://www.cobro.org.pl/english/). It is enough to remember that material (P) stands for materials from group: A, ... P from paper (ISO 16106:2006) (Kočí 2019). Unfortunately, with PET bottles, all inscriptions and information are included on the label; the logistic label also contains information on the type of plastic and its recycling – Fig. 1.

Recycling is affected by many factors, e.g. what is stored in the packaging and what colour it has been dyed to – it is very difficult or even impossible to recycle black PET packaging. A transparent PET water bottle is most likely to be recycled. Still, the same bottle containing oil should already go into mixed waste or, in some cases, be set aside separately in a landfill because of contamination with hazardous substances.

Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste, applicable in EU countries, defines the term "separate collection" as a process whereby a waste stream comprising waste of one type and nature is separated to facilitate specific processing (Art. 3. pt. 11). In practice, this means carrying out the collection with a very general division (e.g. metals, plastics, paper, glass, etc.) that does not take into account the possibility of incompatible or even antagonistic materials within a single fraction (stream). In the case of the so-called separate collection of plastics, this means collecting items made of a range of plastics (HDPE, PP, PET, PVC, ABS, PS), which often cannot be co-processed, in one container. Community law places ever higher demands on Member States regarding the quality of products to be represented after the recycling process. Following the regulations under Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste, member states (including Poland) must increase the recycling rate to 50% by 2020. Concerning plastics, among others, a level of almost 24% is required. To meet the above requirements under Polish conditions, it is necessary to develop a dedicated technology adapted to raw material with varying degrees of purity, including highly contaminated raw material, cost-optimised to ensure that the recovered raw material is competitive concerning the price of virgin raw materials.

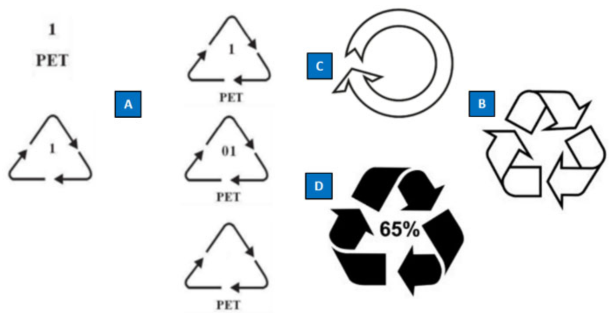

Fig. 1. Marks on plastic packaging: A – PET; B – Mobius loop; the mark is a graphic form of a manufacturer's declaration that the requirements for the recyclability of the material have been met; C – Compliant with the Regulation of the Minister of the Environment of 3 September 2014 on the manner of labelling of packaging with the recycling suitability marking; D – Symbol specifying the content of secondary raw material in the packaging. In the example, 65% of the materials used to manufacture the packaging in question are recycled

From 2020 onwards, EU countries, including Poland, will have an obligation to recover 40% of municipal waste and 70% of other waste. Following this, in Poland, efficient recovery processes will become increasingly important. All the more so as the solutions introduced do not exactly make the system more efficient. Other European countries already have a long history of implementing solutions to maximise the recovery of secondary raw materials. PET waste (fraction) can be selectively or non-selectively selected within the process lines. It should be added that the non-selected mode implies the selection of fractions from mixed waste carried out on sorting lines. The cost of separation in mode 2 is higher due to the operation of a longer sorting line. The collection type used significantly impacts the quality of the final recycled product, which is PET flake, granules or regranulate. In Poland, PET bottle waste collection is carried out using containers (bins) deposited at the waste site and transported to waste disposal sites.

Empty packaging available on the market, collected at waste sites and destined for processing, is characterised by a high degree of contamination. Experimental investigations for the article identified the presence of sand, oils, food substances (residues), and solvents on the surface of the bottles. In addition, inclusion-type contamination of plastics other than PET was identified. Including metals (ferrous and non-ferrous), PVC plastics, G-PET, polyolefins, multilayer plastics, paper, wood and rubber – Fig. 2A. The contamination intensity was determined by DSC, FTIR, and TGA methods.

The "plastics and metals" fraction, discussed in more detail in section 4 of the paper, includes items made of steel, copper, and aluminium; plastics: polyethylene, polypropylene and others. Mixing multiple plastics within a single fraction at the input of the material recovery system (Fig. 2B) complicates the implementation of recycling by automated sorting technology, as discussed later in this article. When PET bottles end up in one container with metals, they are often permanently contaminated with them, and in this form, they end up in recyclers. The same is true for rubber, ash and other plastics, which, as mentioned earlier, often cannot be processed together.

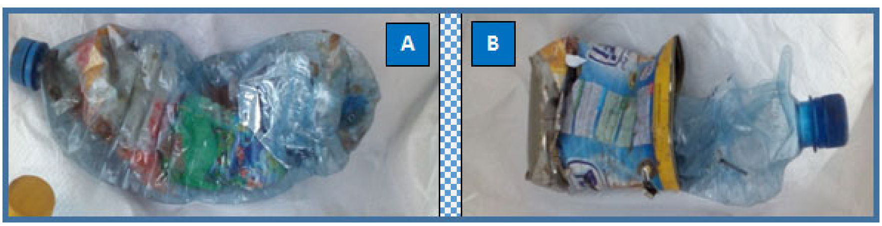

Fig. 2. PET bottle contamination

Separation of the individual waste fractions occurs at sorting plants, where they are sold as secondary raw materials to other businesses that use them for processing, treatment or disposal. Sorting the bottles is done manually or mechanically, depending on the size and throughput capacity of the processing plant. The bottles are sorted by colour and divided into four groups: green, blue, clear and mixed colours. Subsequently, the bottles are compacted (baled) into bales and, after being strapped together, permanently form the compressed waste into cubes suitable (equally sized) for transport to the following actors in the supply or storage chain (Fig. 3 and Fig. 4).

Fig. 3. Prepared bottles for transport, the cube-bale weights 60-120 kg

Fig. 4. Prepared bottles for transport. Photo by CS Recycling

Analysing PET collection and recycling systematically over the last 5 years, PET is the most recycled plastic, and the volume calculated year-on-year has increased by 6.8%. At the same time, the estimated market demand for bottles/containers made of PET was 57%, based on data from companies that make up the beverage packaging logistics chain. This state of affairs proves that there is a shortage of PET packaging on the market.

At the same time, it is worth emphasising that companies interested in packaging food products (and beverages are among these) in PET bottles are obliged to comply with the applicable rules. Therefore, implementing the guidelines (Hazard Analysis and Critical Control Points) in the typical recycling line presented in diagram 4 and Fig. 5 to X, is not feasible. Currently, PET bottle producers in Poland use the so-called virgin PET as raw material for producing PET bottles.

The bottles are transported from the waste collection site (level 1) to local (level 2) and regional (level 3) waste collection stations. The lower level stations in the recovery system sort plastic waste by separating the PET bottle fraction. Pre-selection facilitates work at level 3. They are made manually or automatically, yielding material of 90-99% purity, most commonly 95-98%.

The study shows that recyclers are not interested in completely segregating PET waste because the decision parameter, at this level of recycling, is to obtain a waste density that ensures the profitability of transferring PET waste in the recycling system to a higher level 3. At level 3, PET waste is separated more thoroughly than at level 2.

The waste is prepared for transport (Fig. 3 and Fig. 4) by crushing and baling in special crushers to reduce the volume. Then, as shown in Fig. 2, the waste is compacted, as described by the parameters: 600-800 kg/m^3 – which makes transport cost-effective at max. 50-80 km, accordingly. Crushing may precede the separation of bottles by colour. Some processing plants accept compressed PET packages, including paper and plastic closures and labels.

To summarise: to level 3, PET waste is (mostly) transported by truck, as in Figure 3, in the form of compressed cubes Fig. 2. The cost component of the recycling company's budget is the Tkm cost of the waste (Woźniak et al. 2016). Level 3 of PET bottle separating is described and illustrated with photos from an actual recycling line.

3. Identification of an Automatic PET Bottle Recycling Line

Pre-separation, when bottles made of other plastics are rejected using X-ray, infrared and visible methods, washing (soluble contaminants are removed), fine separation, i.e. labels, caps, glass and metal impurities are separated.

The amount, form and level of contamination (dirtiness of the regranulate) are the main factors (besides price) to consider when considering PET reprocessing. Chemical recovery processes such as methanolysis and glycolysis were used in parallel with mechanical processes. Improvements in methods and efficiencies meant that the amount of production waste declined significantly, and simultaneously, the price of virgin PET fell sharply. It has resulted in a reduced interest in more expensive PET recovery technologies. Instead, several companies (called **Recyclers**) have emerged to deal with mechanical recovery methods. They started to supply secondary PET granules or flakes with improved purity and lower impurity content, which earned them some trust with PET converters in Europe.

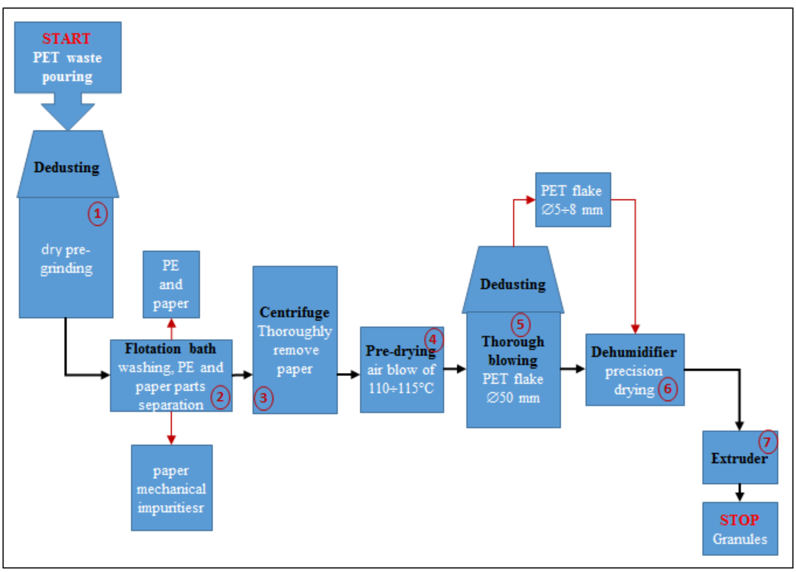

Fig. 5. Structural diagram of the PET bottle recycling system

PET can be recovered by a wide variety of methods, which we can divide into three main categories:

- mechanical technologies (cleaning, cutting, grinding, melting and regranulation),
- chemical technologies (methanolysis, glycolysis and hydrolysis),
- energy technologies (combustion).

This article describes the mechanical recycling process for PET (Fig. 5). The recycling line produces PET flake/regranulate (based on the regranulation process at Polipak Ltd.). This type of recycling line is used for PET fractions with low contamination. Mechanical recovery methods are technologically the simplest and, simultaneously, the most efficient methods of recovering PET. The purified material is either entirely used on its own or mixed with virgin PET to obtain the desired properties and then processed in the same way as the original material. In some cases – depending on the degree of contamination, the regranulate will not meet the criteria (Hazard Analysis and Critical Control Points), which may be applicable to PET packaging outside of food packaging. The quality of the input secondary raw material determines the final application and the need for percentage mixing with the primary PET. The essential requirements are molecular weight, colour and level of physical impurities. The plastic resulting from the PET recycling process can be used in the production of the following:

- fibres – in the form of staple fibres for stuffing, e.g. mattresses, cushions, furniture padding, and rain jackets, in the production of technical fibres for webbing, belts, abrasive fabrics, cleaning cloths and filters, in the production of carpets, upholstery, workwear, fleece;
- thermoforming films;
- injection moulded products (automotive parts, furniture, packaging, sports equipment);
- non-food bottles (for packaging of detergents);
- production of strapping tapes for packaging;
- polyester resin loads (COBRO http://www.cobro.org.pl/english).

The bottles, after delivery to the recycling line (Fig. 4) from mostly proven recyclers, are stored in the yard (usually under a shed, on a concrete slab – although bales have been found stored on the ground, in the mud), the storage areas are separate for each colour of the bottle. In the first stage, the bales go to a conveyor, where the bottles are unpacked, and the straps fastened in the baling process are cut.

Fig. 6. Bale opening station for waste PET bottles

Fig. 7. Bale opening station for waste PET bottles

The waste is then transported by conveyor belt to a rotary sifter, ensuring that the bottles are pre-cleaned of any loose solids such as (Fig. 6 and Fig. 7): sand, caps, foil, etc. Fig. 8 and Fig. 9.

Fig. 8. Bale opening station for waste PET bottles

Fig. 9. Conveyor belt, rotary sifter. Preliminary separation of loose solids

The bottles arrive on a horizontal conveyor belt (Fig. 10) that allows manual separation of the PET bottles, during which any impurities and undesired elements are separated and selected. After manual separation, the first metal detector is placed on the line (Fig. 11).

Fig. 10. Manual separation, metal separator

Fig. 11. Manual separation, metal separator

The material in the next stage goes by conveyor to the mill, where the bottle is cut, and the first rinsing takes place, during which sand, grit and minor impurities are removed, and labels are separated from the bottles. The water-filtered material then enters a label separator (Fig. 12) called a zig-zag, which pre-dries the shredded flakes and removes most of the paper and plastic labels through an air jet cyclone. Magnets are placed at the end of the separator to separate ferromagnetic metals (Fig. 13).

Fig. 12. Label separation station

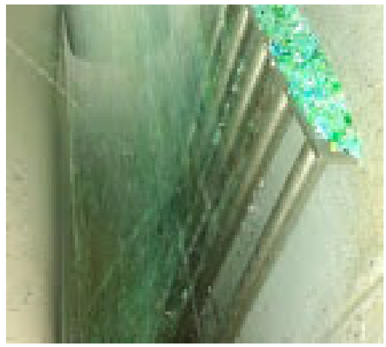

Fig. 13. Ferromagnetic metal separation station

From the separator (Fig. 13), the material in the production line goes to a buffer silo and then to a rotary washer (Fig. 14), where the hot flake washing process takes place. The flake is washed with sodium lye with added surfactants. During this process, mainly the glue is removed.

Fig. 14. Rotary washer

The material is then transferred to a system of baths (Fig. 15) connected in series. In the first bath, the polyolefin fraction (Fig. 15A) is separated from the PET fraction, and the material is washed from detergents. Separation is based on differences in the specific weight of the different plastic fractions (polyolefins float, PET sinks). In the second bath, the final rinsing and separation of the fraction (Fig. 15B) take place.

Fig. 15. System of baths: A – separated polyolefins from PET flake, B – the final rinsing and separation of the fraction

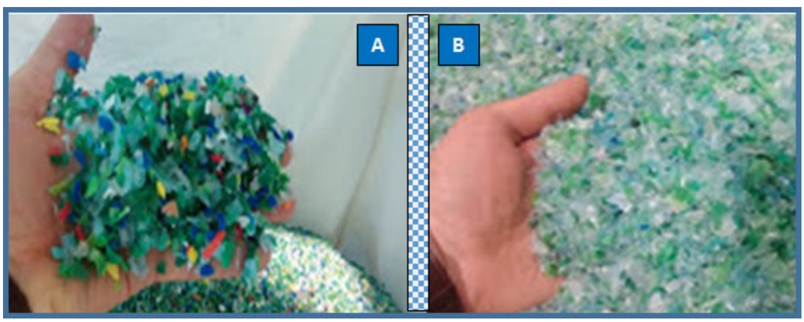

Fig. 16. System of baths, separated polyolefins from PET flake. Loading stations, flake prepared in the process: A – pre-flakes PET, B – final PET flakes (on the basis of the regranulation process at Polipak Ltd.)

Polyolefins are taken from the process and resold. The flake from the bath re-enters the centrifugation system and then enters a system of two air separators, where the final separation of the labels takes place. The final step in the process is to pass the material through a system of three metal detectors, ferrous and non-ferrous. The material then goes (Fig. 16) to the loading stations, where it is filled into big bags and prepared for transport (Fig. 17).

Fig. 17. Flake loading stations for transport from the recycling line, e.g. for storage, production, etc. (based on the regranulation process at Polipak Ltd.)

The production process results in flakes, green, blue, transparent and a mix of colours. CS Recycling is the main supplier of raw materials to the Oława plant. Here, the flake is used to produce strapping tapes, which are used to secure loads during transport. As a result of the production processes involved in processing the flake, it can be seen how the bottle's purity significantly impacts the quality of the secondary raw material. Currently, the biggest problem with contamination is the amount of metal entering. Despite a tight separator system on the production line, metal is currently a fraction, occurring in large numbers in the flake, which harms the conduct of the production process. The metal in the bottles comes from waste contamination with cans, wires, and metallised packaging. Mixing waste at the input to the whole process increases flake contamination at the end of the process. Knowledge of packaging and what happens to it after the product has been used – also known as monitoring – is increasingly important for recyclers and packaging manufacturers. Pro-environmental behaviour – defined as careful separation at every level is becoming fashionable and necessary. During research work in the PET packaging sorting process, it was observed that packaging manufacturers optimise the amount of PET so that a sufficient and necessary amount of regranulate is used for production while still meeting the qualification requirement.

PET flakes contain contaminants from paper or other plastic labels, acrylic label glue, caps, seals and random contamination. Separating collected packaging and other waste into different types of plastics is very important for PET recycling due to the significant difference in processing parameters between this polymer and most other thermoplastics. The separation of polyolefins and PVC is significant. Polyolefins reduce the strength of PET and its crush resistance, while PVC decomposes at elevated temperatures with the release of HCl, which causes hydrolysis of the ester bonds, as well as other undesirable chemical reactions, resulting in the colouring of the plastic.

The construction of hybrid packaging does not consider the recycling implemented according to the diagram shown in Fig. 5. Barrier packaging for some juices, dairy products, beer, and even some carbonated beverages requires increased barrier properties associated with, for example, UV-stopping barriers. There is no legal restriction on the guidelines related to the overall packaging that is bottle. It applies to caps, labels, and substances connecting the labels to the bottles. Another interesting example is the PET bottle, which contains a heat-shrinkable PVC label that fits tightly over the entire height of the bottle and makes the preparation and industrial recycling of PET bottles virtually impossible (according to the diagram in Fig. 5). Currently, this type of packaging is undesirable and rather sent for further processing to China. Still, companies already have the tooling to remove such labels mechanically. In most cases, such labels were removed by hand, making the removal method time-consuming and expensive. Companies using this type of packaging have introduced promotional campaigns to encourage users to remove the labels once the product has been used. Still, reality shows that this type of packaging ends up in the waste bin along with the labels. Metal or metallised caps impede automatic PET processing on the recycling line.

Fig. 18. Contaminants in collected PET waste

Fig. 19. Contaminants in collected PET waste

As documented in the snapshot studies (Fig. 18 and Fig. 19) of the waste performed by the authors, contamination of the main plastic PET with admixtures of other materials (fractions) is a serious problem. If, in addition, the inclusions are in PET containers/bottles, they are then very difficult to identify and remove automatically on the recycling line. The final product may contain substances not approved for direct food contact, such as printing inks, adhesives, varnishes, and coatings. PCR plastics may contain substances commonly considered harmful and undesirable, such as bisphenols, phthalates, heavy metals, SVHCs, etc. Hence, production batches can differ significantly from each other. For this reason, the scope and frequency of tests (DSC, FTIR, MFI) on regranulate in the recycling process and the pneumatic feeding of regranulate to production machines must be significantly increased.

4. Research Experiment

Using the principle that any packaging, including a PET bottle containing a food product (according to (Hazard Analysis and Critical Control Points – HACCP)]) must be labelled with the barcode GS-1 13, Fig. 20.

4 5 1 2 3 4 5 6 7 8 9 0 6 >

Fig. 20. Typical GS1-13 code placed on the label of packaging, including PET bottle

The GS1-13 code symbology encodes an information vector according to the generally accepted reference vector – Table 1. The code contains three pieces of information (Table 2): 1 – country prefix, a symbol of the country of the producer or packer of the goods (Poland in this system is assigned the prefix 590); 2 – number/unique manufacturer code; 3 – number of individual goods – as an assortment of a particular manufacturer. In addition, there is a check digit K at the end of the code, which allows the code reader to check that the code has been read correctly.

Table 1. Structure of the information contained in the GS-113 code

Place of the digit	13	12	11	10	9	8	7	6	5	4	3	2	1
Number structure	Prefix/ Country number			Coding unit, manufacturer number					Individual goods number				Control digit
EAN 13	0	0	0	J_1	J_2	J_3	J_4	J_5	T_1	T_2	T_3	T_4	K

As part of the research experiment, an additional tagging of PET packaging was carried out with an RFID-enabled information vector. For this purpose, a hybrid label with a chip was used, made in the EPC standard (Table 2), which the GS-1 recommends. The information vector has been encoded in the EPC structure – on the obverse of the label; and on the reverse (Fig. 21A, B), there is an inscription with the GS-1 13 bar code designed by the manufacturer.

Before forming the plastic waste fraction into a cube, the PET bottles in place were labelled by making a unique, individual information vector based on the GS-1 13 code, encoded for each bottle on a hybrid logistics label. The PET bottles labelled in this way and other waste were mixed and subjected to compaction (baling, on a press) and strapping. Labelling was carried out for 5 randomly selected cubes of waste. Once the baled waste cubes have been transported to the recycler, workers equipped with RFID scanners (at stations: Fig. 10 and Fig. 11) passed it through the recycling sorting line as standard.

Table 2. Structure of the EPC information vector

EPC code format			
02	0000A68	00010D	00111DED
Version number 8 – bit	Closing identifier 26-bit code	Class of goods 24-bit	Serial number 36-bit

a) b)

Fig. 21. View of the hybrid label. A – printing on the outer surface of the label; B – view of the glued-on transponder

Studies of the efficiency of sorting from the plastic fraction of PET bottles on a standard recycling line show increase of 70% compared to typical recycling lines. Transponders were used during the study with no protocol for avoiding readout collisions. Hence the result is not 100%.

The hybrid part of the logistics label containing the RFID antenna and the chip at the label recycling station was separated and could be reused after programming in the course of sorting.

In the course of further planned experimental research, it is planned to introduce a Machine Learning (ML) technique (Szajna et al. 2021) that will learn the characteristic parameters of the packaging based on the unique logistics data available after the information vector has been read from the GEPIR GS-1 database (GS-1). The use of ML will allow the structure of a packaging and material base to be built for each coding unit of the GS-1 system to integrate RFID technology with optical readout. It can also be considered a digital twin of the above-described structure and facilities to increase the sorting efficiency or at least simulation modelling to arrange alternatives (Kosacka-Olejnik et al. 2021, Kostrzewski 2020).

5. Conclusions

The state of PET packaging recycling in Poland refers in business and scientific discussions to deposit solutions used in many EU countries, e.g., Germany, Denmark, Estonia, the Netherlands and Sweden, where up to 95% of PET bottles are recovered annually in these countries. The system enforces ecological behaviour on supply chain participants. The deposit and simultaneous return organisation available to each resident ensures that the system is almost 100% tight. Due to the deposit method of collecting bottles, Germany has a high-quality secondary raw material for further processing that is respected in the recycling community.

Using automatic identification systems such as GS-1 13 code and RFID in automated sorting technology improves the recycling rate of PET packaging. Further development work will consider the use of ML tools.

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