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Plastics Recycling as a Part of Circular Economy

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This article describes the plastics recycling assessment based on a practical selection of waste plastic samples from a municipality in the Czech Republic. The assessment included classification, analysis of the composition and experimental investigation of the recyclability of the samples. The recyclability investigation involved shredding, washing, drying, granulation, and extrusion – following the typical steps of a recycling process.As a result, a feasible recycling route has been identified and described for treating municipal plastic waste and processing based on the average composition of the plastics bins based on field research. A case example of secondary raw material processing for subsequent recycling and testing the recyclability of plastics in laboratory conditions are additional outputs.

1. Introduction

There has been a significant intensification of waste management efforts in the European Union (EU) with an emphasis on primary resource-saving and waste recycling. The Circular Economy Package was released in 2018 by European Commission in order to support the advancements in member states. This legislation should be incorporated into the national legislation of all EU member states. Directive (EU) 2018/851 (EU, 2018b) provides the framework for the collection, transport, recovery and disposal of waste and also sets a target for the minimum percentage of recycled or reused municipal solid waste at 55 % in 2025, 60 % in 2030 and 65 % in 2035. Landfill of municipal waste is set to 10 % in 2035 by Directive (EU) 2018/850 (EU, 2018a). Directive (EU) 2018/852 (EU, 2018c) then gives details about minimum recycling and reuse targets for the individual types of packaging waste. The main EU waste management goal, is to adhere to the Waste Hierarchy (Fan et al., 2021), where the priority is the prevention of waste generation. If waste is already produced, it should join the system of the circular economy. The main idea is to maximise the material use of waste and limit its disposal, especially landfilling – e.g. ban on landfilling of recyclables by 2030 in the Czech Republic (OECD, 2018). In the context of the hierarchy and the landfill ban, it is very important to identify materials that can play a significant role in the circular economy.
Efficient plastic waste recycling is necessary to counter the high rate of plastic waste landfilling. Klemeš et al. (2020b) have shown that during the COVID pandemic, plastic consumption (packaging and medical) has surged. A further analysis (Klemeš et al., 2020a) has stressed the need for a proper recyclability evaluation method to enable the discourse on legislation and regulations that implement waste management. A detailed analysis of HDPE recycling and mathematical models of HDPE processing is dealt with in the article by Zhao and You (2020). Based on the analysis, the main objective of the presented work has been to identify feasible waste plastics recycling routes for the mixed waste bin contents in Municipal Solid Waste. This is especially relevant considering that, since 2018, China has banned the import of plastic waste from abroad, so it is very important to focus on the potential for recycling and deal with plastics management in local conditions.

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2. Problem description

Given the surge of plastics use and the ever more stringent requirements for the share of recycled material in new products, it is important to deal with the recyclability of waste plastics. The issue is aggravated by the presence of plastics is in almost all products of daily use and its high share in the packaging (Sinha and Chaturvedi, 2020).Plastic municipal waste management starts with a separate collection. It is then transported to a sorting line, where it is sorted according to individual fractions. Typical tradable fractions are PET bottles (transparent, coloured), PP (typical are yoghurt cups), HDPE (hard plastics, especially drugstore products), LDPE (e.g. bags) and others (maybe a plastic mixture). The price of secondary plastics varies widely by place and time. Fractions of commercial value are traded. The remaining parts are used for energy recovery or landfilled. A new trend is the processing of plastic waste into Solid Recovered Fuel (Martignon and Edo, 2020) – complying with certain quality standards.Tradable fractions are used in recycling plants for the production of flakes or regranulate. In the case of flakes, only shredding is applied. For obtaining regranulate, it is necessary to shred, wash, dry and process the material on an extrusion unit. This pattern – extrusion and regranulation, has been analysed in the current laboratory tests. It should be noted that the cost of plastics treatment and processing (collection, sorting, recycling) is quite high (Gregor et al., 2016) and can reach up to 1,000 EUR/t (Gregor et al., 2018). Therefore, the design and operation of the treatment and processing of waste plastics have to be optimised so that the cost of secondary raw plastics does not exceed that of virgin material. At the same time, it is necessary to take into account the benefits of reuse over recycling – bottle-to-bottle reuse is more efficient than material-level recycling.

3. Experimental procedure

The experiment consisted in obtaining samples of municipal plastic waste from producers, sorting into main fractions, followed by shredding and extrusion under laboratory conditions. The main motivation of the experiment was to test the possibility of recycling in laboratory conditions (Aziz et al., 2020). The following groups were used:

- **PET** (polyethylenterephthalat) – glass transition approx. at 75 °C, melting point approx. at 250 °C, decomposition point approx. at 430 °C. This group includes mainly PET bottles, they are thermoplastics from the group of polyesters. This material is relatively well recycled currently.
- **HDPE** (high density polyethylen) – glass transition approx. at -100 °C, melting point approx. at 130 °C, decomposition point approx.at 490 °C. The abbreviation refers to polyethylene, a high-density plastic that is also classified as a thermoplastic. Typical HDPE representatives include e.g. baby bottles, PET bottle caps, cooking bags, hollow hard packaging, etc.
- **PVC** (polyvinylchloride) – glass transition approx. from -20 °C to -80 °C, melting point approx. at 210 °C, decomposition point approx. from 290 °C to 460 °C according to additives.
- **LDPE** (low-density polyethylene) – glass transition approx. from - 100 °C to -10 °C, melting point approx. at 105 °C, decomposition point approx. at 405 °C. A type of plastic that, due to its low density, is usually the basis of plastic bags, plastic baskets and food crates.
- **PP** (Polypropylene) – glass transition at ≈ 10 °C, melting point approx. at 160 °C, decomposition point approx. at 447 °C. It is a plastic that is typical, especially in the food industry (e.g. yoghurt cups) or in the textile industry.
- **PS** (polystyrene) – glass transition ≈ 100 °C, melting point ≈ 245 °C, decomposition point ≈ 440 °C. Polystyrene is a firm but brittle material. Typical applications include insulation boards or disposable plastic cups and cutlery.
- **Other plastics** – for example, polycarbonates, polyurethane, epoxides or polyamides. It is a mixture of plastic materials that cannot be effectively separated or identified.

So far, the authors have dealt with very detailed analysis, especially of the first group (PET) and marginally the second group (HDPE) because of their favourable marketable potential of PET. HDPE is part of PET bottles in the form of caps. PET bottles were further divided into three groups - transparent, green and blue; in the case of HDPE material, it was a colour mix. Plastics were obtained during the field survey of the TIRSMZP719 (TA ČR Starfos, 2019) project by sorting analysis of the contents of a municipal waste plastic container. The waste sorting was focused on the overall composition of municipal waste. The analysis was based on the method in (Kropáč et al., 2020). The benefit of this procedure in terms of PET analysis was the simulation of waste treatment on sorting lines and the simulation of the production of tradable secondary raw materials. The obtained PET materials were divided according to colour. Easily separable plastic additives such as labels, lids, rings and more were removed. If a paper label was affixed to the PET bottle or HDPE, it was not removed. The composition of plastics from the TIRSMZP719 project samples and the sorting result is shown in Figure 1 and Figure 2.

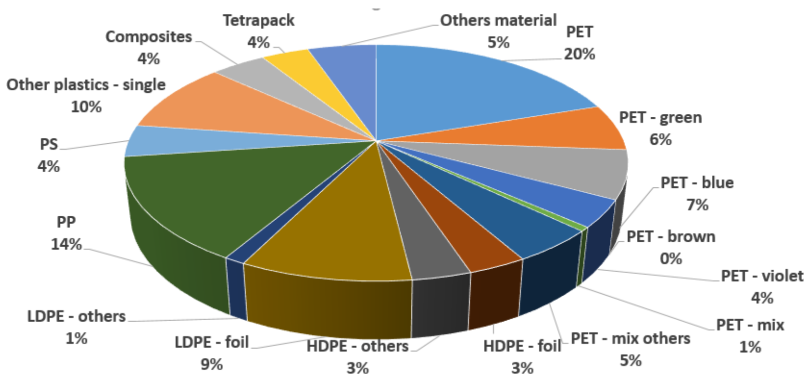

Figure 1: Composition of the municipal waste plastics separated in summer season (example of the TIRSMZP719 project data) (TA ČR Starfos, 2019)

Figure 2: Illustration of PET processing from bottles (municipal waste) to shredded flakes (extrusion input)

The sorting was followed by shredding the material. Shredding took place on a hammer shredder. Several different screens with meshes of 20 mm, 10 mm, 4 mm and 2 mm were used for shredding tests; an illustration of the shredder including a cyclone and an example of screens is shown in Figure 3.
First, shredding tests were performed for specific types of packaging (PET bottle as a whole, HDPE packaging as a whole and others), so a mixture of several different plastic materials with a predominant representation of, e.g. PET or HDPE was created. This proved to be completely unsuitable for subsequent extrusion, and further shredding was always performed in individual material fractions (PET, HDPE).
Three laboratory extrusion tests corresponding to the shredder setup have been performed so far:

- **The first experiment** – coarse shredded PET and HDPE flakes on 20 mm screen.
- **The second experiment** – fine shredded PET and HDPE flakes on 10 mm screen.
- **The third experiment** – fine shredded PET and HDPE flakes on 4 and 2 mm screen and water washing.

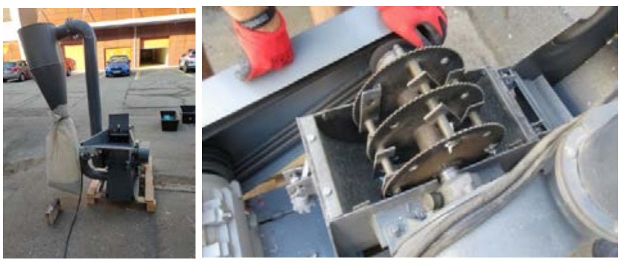

Figure 3: Hammer shredder with cyclone (left), detailed view of the shredder with 2 mm mesh (right)

Due to the comprehensiveness of measurements and tests, the processing will be demonstrated only for PET, and the main problem parts will be identified.Extrusion was performed on a HAAKE laboratory single screw extruder, screw diameter 19 mm, L / D = 25, screw compression 1: 4.
The extruder barrel temperatures can be variably set; on PET, it was from 270 °C to 265 °C and 50 rpm. Because the input was a mixture of PET and impurities, it was necessary to choose the processing

temperature with respect to the highest melting point (specifically PET melting point at ~260 °C), i.e. temperature 270 °C at extruder cylinder and 265 °C at the nozzle. The melted polymer was cooled in a water bath.

The first experiment was performed on the fraction processed on a 20 mm sieve (the resulting flasks were shredded twice more on the same sieve after primary shredding, which caused some refinement of the fraction). The result of the experiment was a disjointed string, and this was caused mainly by insufficient dosing into the screw system of the extruder (the flakes tended to make arches and bridges in the hopper). The actual extrusion of the material within the extruder screw has been feasible.

The second experiment was based on the fraction size below 10 mm; arches and bridges in the hopper were mostly eliminated. The main obstacle was the tearing of the string, which was caused by impurities and admixtures in the PET material. The need for waste plastic washing was identified as necessary for effective extrusion.

The third experiment was based on a very small fraction (below 4 mm, sometimes even powdery grit). During shredding of waste plastics, there was a great limitation, especially in the case of the hammer shredder, when it was not possible to shred all the examined material through a fine sieve (2 mm). Therefore, two fractions were formed, one so-called subscreen and one above the screen (Figure 4). It should be noted that the "above the screen" fraction was also reduced to about 5 - 7 mm. This mixture was relatively suitable for self-dosing.

Figure 4: Example of under 4 mm fraction (left) and a reduced waste fraction (right), illustration of shredding on 4 mm mesh - HDPE material

4. Results

Although the samples of tested material were relatively small (~ 100 g supplied for extrusion), it was possible to perform at least an informative processing test, i.e. to determine if the offered physical form is usable for laboratory extrusion. The tests showed that the sample plastic pulp fits relatively well into the extruder hopper, and the screw feeds it without significant problems. In some places, however, so-called bridges were formed, and it was necessary to intervene manually. This occurrence is due to the diversity of particle sizes. It can be expected that laboratory equipment may experience this problem more often than larger (industrial) equipment with larger screw inlets.

A more serious problem may be the inhomogeneity of the mixture (predominant PET with some unsortable impurities), which did not allow the extruder to provide a continuous string. The string tore mainly in places of unmelted impurities and in places of too much melted (volatile) impurities, e.g. PE impurities for which the processing temperature of 270 °C is too high. PET and polyolefins are polymers with significantly different structures, so it is not possible to mix them successfully for extrusion processing. Another difficulty in the addition of impurities is additional moisture content that can get into the material by imperfect drying. However, this fact is not the subject of the test performed, and the effect of the water content of the mixture should then be addressed separately.

In the case of the unwashed sample extrusion, the output of the extruder was unusable for any further processing into a marketable form (*Figure 5)*. A significant proportion of impurities devalued the course of the whole process, after which the extruder and other laboratory accessories had to be cleaned.

In the case of washing, the output already looks usable (Figure 6), the string is continuous, and it is possible to produce granules, which are relatively high quality in both purity and structure (without foaming and bubbles).

Figure 5: On the left, there is an unwashed transparent PET (extrusion input); on the right, unusable extrusion output degraded by impurities

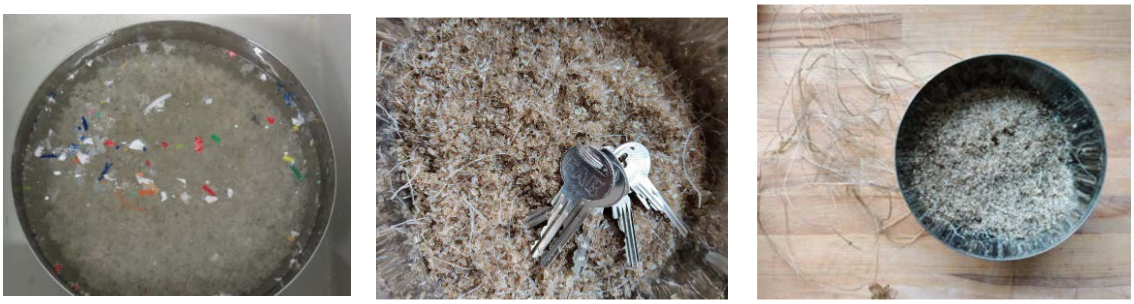

Figure 6: On the left experiment output in the case of washing, on the middle, the polymer strings and the produced granulate, on the right the detail of the granulate

5. Conclusions

Motivation, context and initial phase of experiments were introduced in the paper. Known parameters for experiments were demonstrated (e.g. melting temperatures and laboratory equipment); however, laboratory conditions are completely different from industrial plants.

Through experiments, it was found that there is potential for effective material recycling and thus compliance with the conditions of the circular economy. Further, very detailed research is needed to specify at what cost and how difficult it is to deal with the production of plastic secondary materials from municipal waste. In further research, extrusion will be tested at least for all fractions listed at the beginning of part 3. The subject of the planned tests will be primarily the requirements for the size of the fraction and the purity of the flakes. Figure 7 shows the ongoing preparation for further tests, i.e. the illustration of leaching, which will be followed by drying of the shredded samples.

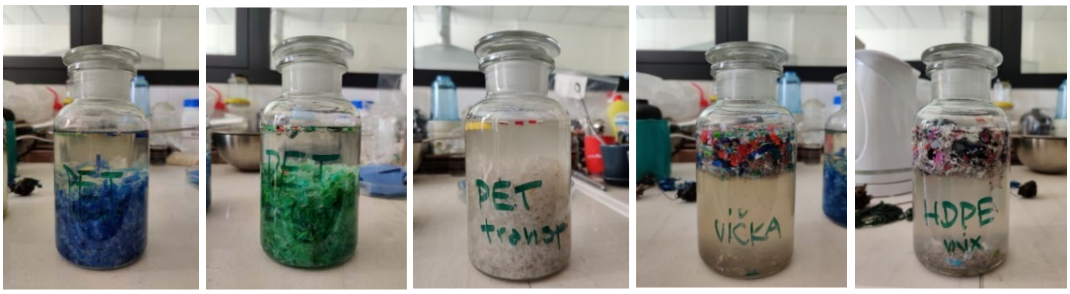

Figure 7: Demonstration of leaching of different types of plastics (PET blue, PET green, PET, HDPE bottle cups, HDPE mix) – a preparation for the subsequent experiments

Based on the tests performed, it is evident that the PET material can be recycled, but it is necessary to prepare the input material according to the parameters of the laboratory extruder.

The key areas are:

- Cleaning of input material - separation of pure plastic materials such as PET, HDPE, PP and others.
- Cleaning of extruded material from dust, grease and other potential sources of contamination.
- Drying and ensuring minimum moisture in the extruded material, avoiding porosity and bubble formation.
- Setting the correct extruder temperature and speed.
  At the same time, it should be noted that the preparation of laboratory samples for the necessary tests can be more complicated than in industrial operations, especially in terms of smaller processing capacities of the laboratory extruder and its hopper and thus the sensitivity impact on flake size.

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