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3D Printing Filament Manufactured by PET Material Recycling Part A: Literature Review in Plastic Recycling Field

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Abstract
The paper is part of a series of papers regarding the implementation of a simple plastics recycling method at a local environment, meaning a higher education institution at the Transilvania University of Brașov, the Faculty of Technological Engineering and Industrial Management. This first paper presents a brief current state of the art in the field of plastic recycling. It presents a brief introduction regarding the main methods used for recycling plastic materials and which are the most recycled plastic materials nearby the sources of those plastic wastes. Furthermore, the paper present some of the most well-known applications for these recycled plastic materials, applications from automotive field, constructions field or even for individual uses. Following the study presented in this paper, a decision was made regarding which recycling method is the most suitable to be used at the mentioned level, which are the easiest plastic materials to collect and recycle and for which application can be used further for those plastic recycled materials.

Keywords
plastics recycling, PET filament, filament extrusion, 3D printer

1. Introduction

Worldwide, one of the hottest issues that captures the attention of major researchers in the field of environmental protection is the pollution of the planet through the unsustainable usage of materials in products manufacturing for various industries fields. Often, in products manufacturing processes, different materials are used inefficiently with significant losses and low recycling rates, sometimes even completely ignoring recycling. Thus, sustainability is sometimes completely ignored, regardless of what kind of materials are used in production industry in general.

Thermoplastic polymeric materials are one of the most used materials because of their numerous technological and economic advantages. The main advantage of plastic parts is a low weight compared to other materials. A recent study shows that in the modern car structure, approximately 12-15% of the parts is manufactured from plastic and rubber materials, which considerably reduces the weight of new cars generation [1, 2]. Regarding the products design stage, plastics offer another great advantage due to its flexibility which allows complex parts design that can be manufactured relatively easily using injection moulds [2]. Once a mould has been obtained and prepared for manufacturing, the manufacturing cost per piece is low. So basically, plastics are suitable for large-scale or volume production. Most of the polymers do not corrode, thus from this point of view, those are superior to metal parts and therefore are suitable for applications which are exposed to moisture or chemicals factors. For instance, plastics reduce the need for corrosion protection (painting/anodizing), decreasing considerable the products maintenance costs [2]. Plastic parts still have many other advantages that can be easier identified in the literature.

Regarding the sustainability aspect, plastic materials can be recycled and reused much more easily than other types of materials, being one of the first chose in manufacturing parts from all kinds of products assembles. Recycling is necessary because of the plastics drawbacks that create environmental problems due to which legislative regulations have also emerged at different levels in countries, regions or even on an entire continent, as is the European directive 2000/53/EC, since 2015 [3, 4].

By recycling, a reduction in environmental pollution is achieved, making plastic parts more sustainable compared to others. The recycling of plastic materials can be done at an international or a national level, but also on a local or even institutional level. An important aspect is raising the population awareness about the recycling significance on environment quality. This can be done relatively easily where the people spend a significant part of their time, namely in the place/offices/buildings where they are employed. Therefore, recycling at the institutional level is considered useful, even at the level of a certain department of an employer or a company that operates in a restricted area such as an office, an entire building, a public institution or an educational institution.

The research aims to present a simple method of recycling plastic wastes found in a building at Transilvania University in Brasov for the Faculty of Technological Engineering and Industrial Management. More precisely, this research is split in at least 2 parts, this paper being the first part which content is regarding a short state of the art in plastic recycling field. The paper also proposes a method to reuse plastic materials collected as wastes within this institution.

Further, the paper content includes a description of the plastic recycling methods, the most common plastic materials that are usually recycled, several applications for recycled plastics.

2. Short Literature Review

2.1. Plastic recycling methods

The multitude of plastic materials and the variety of parts design for plastic materials processing led to the development of different methods for recycling them to reuse it. Literature research was followed to identify plastic recycling methods which are forward presented.

One of the most well-known and at the same time the most common method for plastics waste recycling is the mechanical method which usually consist of many possible processing phases including collection, sorting, washing and grinding, shredding, granulation, re-extrusion or injection of the material. Some of those phases can miss or can be followed in different order than is described above or even can be processed multiple times [5]. Basically, the mechanical recycling method is a physical method which convert plastic parts wastes into re-granulated flakers with size about 1-12mm. To obtain small size flakers, the plastic wastes are processed by cutting into small pieces using one or two shredders followed by a re-granulation process. This is one of the simplest and most mature recycling methods, being easy to be implemented for one or more recycling stages. It also has a well-known drawback meaning the possibility of material contamination as well as two types of degradations caused by reprocessing or degradation during its lifetime, both being described in the literature [5]. For this type of recycling can be mixed two or more materials which respects the same thermodynamic conditions during blending [6].

Even if it is an alternative on the mechanical method, the chemical recycling is a completely different technique to reuse the plastic wastes. This method is applied to that plastics which contain a chemical structure closely to the conventional petroleum fractions or have a high hydrocarbon content, being suitable for PET, PUR or Nylon [5]. Chemical plastics recycling is considered an additional solution to mechanical recycling but with different results, being used in order to convert polymers in simple monomer or other simple molecules. Usually, by chemical recycling on changing the chemical structure of plastics in order to produce basic chemicals as fuels, oils, gaseous or other feedstocks used to obtain new raw plastic materials [7, 8]. The literature describes many techniques for plastics chemical recycling as follow: pyrolysis and gasification, catalysis (chemical depolymerisation), biocatalytic (biological recycling) [7, 8, 9]. Chemical plastic recycling is a high-performance method which allows to reuse the plastic wastes but, even so, a great drawback prevents its use in a wide range of applications. The drawback consists in a low economic efficiency in addition with another complementary costs for the preliminary stages (for collecting, sorting and others). Those high costs make the chemical recycling to become uneconomical and a bit expensive than using directly new raw materials [7]. Additionally, another disadvantage on using chemical recycling is that, the plastics wastes require a carefully cleaning and sorting and also a high amount of energy necessary in order to break the polymers chains into simple molecules which have also a relatively low value in producing new raw materials [7].

2.2. Plastics waste recycled

Plastic materials found their utility in almost all production sectors and in any manufacturing field, whether are talking about the well-known automotive industry or other productive industries as the food industry, the chemical industry. Usually, plastics are used to manufacture components that are either design components on even as mechanical functional parts, or in most situations those are used for container-type parts as bottles, packaging parts, bags, houseware or other containers used to store various raw materials, liquids, gases or even powder materials. In addition, plastics are used in many other fields and for many other purposes. Table 1 presents a brief example of the usage of the most well-known plastic materials for certain categories of parts or applications [8].

Table 1. Plastics applications [7, 8]

Plastic name	Plastic abbreviation	Applications
Low-Density Polyethylene	LDPE	bags, plastic cutlery, packaging film, plastic toys
High-Density Polyethylene	HDPE	food containers, washing powder or shampoo bottles, domestic and industrial pipes water supply, domestic houseware and containers, plastic toys
Polypropylene	PP	food containers, bottles, plastic bags with high resistance than the PE ones
Polyethylene Terephthalate (Polyester)	PET	plastic bottles for beverages drinks, recipients for cleaner substances, textiles and various fabrics
Polyvinylchloride	PVC	construction pipes for drainage and sewerage system, wires and cable, medical usage due to its chemical resistance and germs impermeability applications
Polystyrene	PS	electrical products because it does not conduct electricity packaging containers for alimentary usage (milk, meat and fish packaging) construction usage as thermal insulations, electrical equipment or even hydro insulation
Polyamides and Nylon	PA	automotive and transportation industry (usually as functional parts) textiles, protective films
Polyurethane	PUR	foams, coatings, adhesives sponges, mattresses, footwear

In the last decades, the plastics materials popularity gained an accelerated growth usage in various fields and industries. This growth is achieved due to the necessity to meet the modern society demands and requirements, but also because plastic parts are usually cheap to be achieved especially for particular users. The literature presents through numerous references which are the most used plastic materials as percentages out of a total volume of materials used. The graph from Figure 1 presents a comparison on the most used plastic materials published by two references from 2012 and 2021 [5, 8]. It can be easily observed that in almost 10 years, the consumption of plastic materials gains considerable differences. For materials such as LDPE or PVC, the consumption has decreased, while for PET or the category "other" materials, consumption has increased considerably.

PE and PP materials together still account for approximately 50-60% from the total plastics used worldwide. LDPE, HDPE and PP are cumulatively discussed because they can be recycled together and can be used both individually and in the form of mixes or blends of materials. The products made from these plastics are often for one-time usage, being the reason why the consumption is increasing considerably especially for products from the food industry [7].

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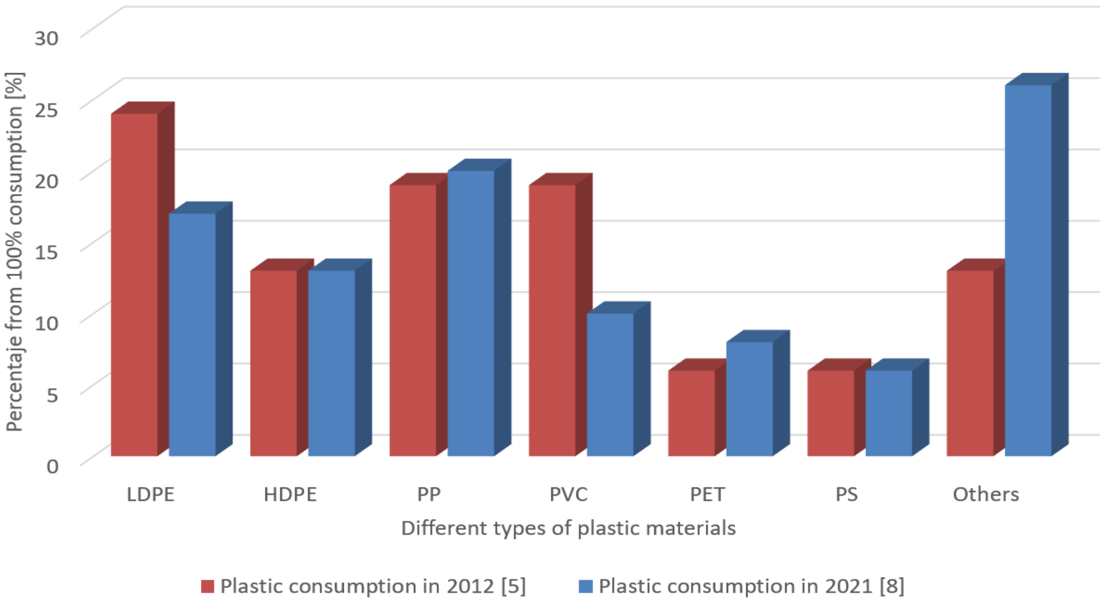

Fig. 1. Comparative approach on plastic consumption

PVC is another widely used plastic material accounting approximately 10% of the total plastic material consumed in the world as is presented in Figure 1 [5, 8]. Unlike PE and PP, parts made from PVC are mostly parts that are designed and manufactured for a longer term of use, thus for longer-term applications as the construction pipes for drainage and sewerage system or the profiles used in buildings windows manufacturing. For such an application, the PVC live time is from 20 up to 40 years, even exceeding this value [7]. PVC recycling suppose several problems due to a high chloride content. This means a polymer degradation during the recycling process. The main recycling method used for PVC materials the mechanical one as a suitable method considering that the PVC parts are often big parts or at least long parts. However, when PVC is melted for reuse at temperatures around 200°C or even more, its tendency is to release HCI, being unstable at certain temperatures and even considered environmentally harmful in different situations [7, 10, 11].

PET material is the most common postconsumer plastic being used widespread for parts as drinks bottles. Drinks are all sold at PET soft bottles with constant volume supply, thus, PET material is almost everywhere. This is why PET is perhaps the most recycled plastic material on the planet, being easy to be collected, sorted, dried, shredded, melted and re-granulated [7, 12]. This material has a high rate of recycling compared to other plastics and can be recycled both chemically and especially mechanically. Moreover, PET is one of the plastics that can be recycled many times, from zero-order up to the fourth-order recycling [12]. PET mechanical recycling consists on many recycling stages as collection, sorting, shredding, drying, melting, re-granulation and further injection or blow forming. A high level of recycling PET material is also due to the fact that in certain regions, countries or areas, laws have been implemented that force the consumers to recycle drinks bottles or other PET containers, thus greatly facilitating the recycling in terms of collecting and sorting stages [12].

PS common use is as expanded polystyrene (EPS) which is basically foam-type PS obtained by adding blowing additives or expanding agents during polymerization. The result is a soft plastic material with different densities, usually utilised as insolation material in automotive bodies or in refrigerant appliances, building heat or sound insulation, in the food industry or even as an aggregate for lightweight concrete in constructions [7, 13]. Mechanical recycling of the PS involves similar steps as for other plastic: collecting, grinding into flakes, sorting the impurities, drying, extrusion, degassing end re-granulation. This is a stable process, but the implementation costs are unreasonably high due to the transport fee. Polystyrene is a material with a large volume and low weight and requires a big transport fleet in order to ensure the waste volume for recycling. Another shortcoming can become the material degradation during reheating, obtaining a material discoloration [7]. An alternative to mechanical recycling of PS is the solvent recycling which consist of spraying PS with a solvent (can be a hydrocarbon) which leads to polymer degradation as a quasi-liquid substance that can be easily transported [7, 13].

The rest of the plastic materials are all centralized in Figure 1 in the category called “other” materials. The most well-known polymers that are used in various industries but was not discussed above are: acrylonitrile-butadiene-styrene (ABS), polyacrylic acid (PAA), polycarbonate (PC), polylactic acid (PLA), polyurethane (PUR), polymethyl methacrylate (PMMA) or various polyamide (PA) [14].

2.3. Applications for recycled plastics

Recycled plastics are used in almost the same ways as virgin plastic materials possible with various restriction. Therefore, for recycled plastics parts manufacturing can be implemented the same processing methods that are already well-known as follows: injection moulding, compression moulding, rotational moulding, extrusion, blow-forming, extrusion blow-moulding, thermoforming / vacuum forming, plastic welding or plastics machining and so on [15, 16].

Further are presented several applications or several types of parts for which recycled plastics have been used. The automotive industry is probably the sector where plastic recycling is most widely implemented, especially in Europe, where a European directive [4] requires manufacturers to reuse a certain percentage of the average weight of their vehicles. Thus, many car manufacturers have increased the recycling rate and reuse it for new parts for new generation vehicles. Several examples are presented:

- Ford manufacturer was using recycled PET in their carpet fibres in order to create upholstery for passenger seat cushions in numerous models [3, 17];
- Opel is trying to use recycled plastics to manufacture visible design components on their cars [3];
- Honda is also recycling damaged bumpers from their cars and using as recycled materials in order to manufacture splash and mud guards [3, 17];
- General Motors use recycled plastics to manufacture air car deflectors or radiator protections [17];
- Nissan is using recycled plastic fibres for sound insulation of dashboards or is recycling old bumpers to manufacture new bumpers or other automotive parts [17];
- Toyota assume that 20% of their auto plastic parts are manufactured using recycled materials [17];
- Volvo also affirm that at least 25% of the number of plastics parts they use in their cars will be recycled [17];
- Renault produces bumpers and wheel arch liners for Clio 4 model from recycled materials [3, 17]. In the same time Renault claims that their vehicle is designed to be 85% recyclable [18].

In the field of building construction, composite materials are being intensively research. Various mixtures between concrete, mortars or different adhesives and recycled plastics [7, 13, 19-22]. The goal is to obtain lightweight concrete with keeping the material properties or to obtain powder adhesives with superior properties as increased strength or temperature resistance or with increased adhesion to the contact surface for many construction materials (tiles, granite, marble, travertine, tiles).

Recently, numerous experimental research has been identified regarding the possibility of using recycled thermoplastic to manufacture filaments for additive manufacturing technologies as 3D printing [23, 24]. This kind of usage is more accessible for any user, thus also for individual researchers, because 3D printing technology is not expensive and can be implemented personally by the researcher without to involve a private company or different research institutions. For this reason, research into recyclable materials used for 3D printing has gained popularity, so that research has been identified for different materials such as PET, ABS, PLA or HDPE [25]. This topic will be covered more detailed in the introduction to the second part of this research, in a specific paper.

3. Discussions

The previous chapter presents a brief literature review regarding the main the paper main topic, the plastic materials recycling. The purpose was to analyse the main aspects related to the recycling of plastic materials through the three chapters that target the methods used for recycling, the plastic materials that are most used, the most recycled and the reasons why they are recycled and also several applications with practical examples in which recycled plastic materials are used.

As already mentioned, the present research is presented through at least two papers, of which the first paper aims to ascertain several aspects for the current research:

- which is the recycling method that will be used;
- what are the plastic materials that can be collected a recycled most easier;
- what is the application for which the recycled plastic will be used.

In order to take a decision on the three aspects presented above, the area or place where recycling is desired to be implemented must be known. Given that it is considered that awareness of the recycling necessity must begin from each person individually, or from groups of people and collectives, it was chosen to begin this process within a building of the Faculty of Technological Engineering and Industrial Management from Transilvania University of Brasov. Therefore, in this context, the next step was to identify the main types of plastic materials that can be found around the identified community. Considering that it is about the university education unit, it is obvious that within the targeted area the main “suppliers” or responsible of plastic waste are the students, the professors or the administrative staff of the building. Each individual can produce a series of plastic waste such as plastic bottles, food containers, bags, and so on. Considering that each plastic waste can be made from various materials, it was found the main materials that can be recycled in this context: LDPE, HDPE, PP, PET, PS. Taking into account that a series of plastic waste can be manufactured from more than one of the materials mentioned above, this fact will complicate their collection and will require a sorting stage. In the case of plastic bottles, they are certainly made from PET material. Thus, the selection of this PET material to be recycled is made based on this reasoning, as an obvious choice. This material is easy to be collected and do not need an effective sorting before recycling. Also, the method of collecting PET can be relatively easy to implement by introducing containers on each floor, with the inscription of the material of the waste that is to be selectively recycled.

Therefore, following the selection of the material to be recycled, it is considered that the most appropriate recycling method, considering those presented in the previous chapter, is the mechanical recycling by shredding the wastes up to a fine granulation and then either re-granulated or used as flakes in a device that will be presented in a future paper. For shredding, a mechanical shredder will be purchased or will be designed and manufactured.

It was chosen that the recycled plastic material to be used also within the Faculty of Technological Engineering and Industrial Management, as didactic material. Considering that the main preoccupations of the faculty is in the field of manufacturing engineering, in addition to many manufacturing processes presented for students, additive manufacturing or rapid prototyping is also covered. One of the most well-known and the simplest to be implemented additive technology is the fused filament 3D printers. Therefore, it was decided to try using recycled PET in the form of filament which will further be used as a raw material for 3D printing. In order to obtain filaments for 3D printers using recycled PET, a proposal regarding a device for melting and extrusion of filaments will be presented in a future paper, meaning a second part of the research begun in the current work.

4. Conclusions

The present work aims to present research regarding plastic recycling field. A simple recycling method want to be locally implemented within a higher education institution of the Transilvania University of Brasov, Faculty of Technological Engineering and Industrial Management. The research is presented through several scientific papers, the current one being the first of this series. This paper (part A) represents brief research of the current state of the art in the field of plastic recycling. From this research, as a result of which it is desired to make a decision regarding some aspects presented in the previous chapter.

During the research, a decision was made that the recycled plastic material would be PET. Recycling it will be carried out selectively in imprinted containers for collecting of PET bottles used by peoples that are transiting the targeted building within the faculty.

Further, the recycling method was chosen. The mechanical method is considered to be the easiest to be implemented. The method supposed the bottles shredding to a fine granulation, possibly re-granulation or used as flakes in a device that will be presented in a future paper.

The recycled plastic material will be reused within the faculty in whose building it is desired to implement the recycling. Considering the specific disciplines of the industrial field of the faculty regarding manufacturing or prototyping, it was chosen that the recycled plastic material to be used as filament for 3D printers. For this purpose, a future research direction is proposed to design a device that converts recycled material into filament for 3D printing.

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