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Mechanical and chemical recycling of solid plastic waste

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A B S T R A C T

This review presents a comprehensive description of the current pathways for recycling of polymers, via both mechanical and chemical recycling. The principles of these recycling pathways are framed against current-day industrial reality, by discussing predominant industrial technologies, design strategies and recycling examples of specific waste streams. Starting with an overview on types of solid plastic waste (SPW) and their origins, the manuscript continues with a discussion on the different valorisation options for SPW. The section on mechanical recycling contains an overview of current sorting technologies, specific challenges for mechanical recycling such as thermo-mechanical or lifetime degradation and the immiscibility of polymer blends. It also includes some industrial examples such as polyethylene terephthalate (PET) recycling, and SPW from post-consumer packaging, end-of-life vehicles or electr(on)ic devices. A separate section is dedicated to the relationship between design and recycling, emphasizing the role of concepts such as Design from Recycling. The section on chemical recycling collects a state-of-the-art on techniques such as chemolysis, pyrolysis, fluid catalytic cracking, hydrogen techniques and gasification. Additionally, this review discusses the main challenges (and some potential remedies) to these recycling strategies and ground them in the relevant polymer science, thus providing an academic angle as well as an applied one.

Contents

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1. Introduction

1.1. The lifecycle of polymers

The lifecycle of polymer materials can be described by the scheme in Fig. 1: raw materials – be they virgin or recycled – are transformed into products via the various converting techniques (injection moulding, extrusion, etc.). This is the start-of-life phase for the (consumer) product. During the manufacturing process, a first type of solid plastic waste (SPW) is generated: post-industrial (PI) waste, which never makes it to the consumer. This could include runners from injection moulding, waste from production changeovers, fall-out products, cuttings and trimmings. Typically PI waste has the distinct advantages that it is clean and the composition of the polymer is known (Ignatyev et al., 2014). Quite often, these waste streams are also mono-streams, meaning they are uncontaminated by other polymers or non-polymers. In terms of recycling, these are often the higher-quality grades of polymer waste.

At end-of-life, the product is disposed and becomes post-consumer (PC) waste. Depending on the country, PC plastic waste is collected separately or not. If it is, the different regional collection schemes vary from very strict (such as the PMD[1] scheme in Belgium) to very open (such as the orange bags allowing all packaging waste in the Netherlands). Typically, PC plastic waste consists of mixed plastics of unknown composition and is potentially contaminated by organic fractions (such as food remains) or non-polymer inorganic fractions (such as paper) (Hubo et al., 2014), which makes it a more complex stream to recycle than PI waste.

From an environmental point of view, it remains preferable to avoid the creation of SPW altogether, by avoiding production in the first place (smarter packaging, alternative materials) or promoting re-use of plastics products, both of which are strongly related to raising the awareness of the consumer (European Commission, 2013). Such efforts run parallel to those on effective and efficient valorisation of the large amounts of SPW that inevitably continue to come into existence.

Once it does, the further processing options are similar for both PI and PC waste. The preferred option, which in fact closes the loop back to the – now secondary – raw materials, is recycling. In recycling, new raw materials are obtained via a mechanical (typically leading to regranulate) or chemical (typically leading to monomer building blocks) pathway. If polymer waste cannot be recycled, energy recovery is the preferred option. Landfill, the least-preferred option, should be avoided at all cost.

1.2. Material/Product-to-waste: polymer waste in the EU

Even within the two broad categories of PI and PC plastic waste, large differences can occur, based on the source of the waste, or (for PC waste) the locally implemented collection schemes. Fig. 2 presents an (non-restrictive) overview of the different possible origins of plastic waste, with examples and their typical further use. Some important properties will strongly affect the degree to which this waste can be effectively recycled. These include:

- Is the waste a mono-plastic (only one component) or a mixed plastic? As discussed further in this review, reprocessing of mixed polymer waste poses quite a few challenges. Therefore, mono-streams are always preferred.
- Is the plastic clean or contaminated with inorganic components, (small fractions of) other polymers or organic waste? In other words: are washing and purifying steps required?
- Are the composing polymers and their respective ratios in the mix known? This is always the case for mono-streams, but can also occur for mixed streams. It is an advantage to know the (pro rata) composition of a mixed plastic waste. Sadly, for mixed PC waste, this is seldom the case and 'average bulk compositions' are used as a rule-of-thumb instead.

Quantitative information about PI plastic waste is not publicly available, as this often remains in-company or is handled business-to-business. PC waste, on the other hand, is handled by municipalities and well tracked throughout Europe.

On average, 25 million tonnes of PC plastic waste (PlasticsEurope et al., 2015) is generated in Europe per year. In 2014, 29.7% of this was effectively recycled, 39.5% was sent to energy recovery and the remaining amount of 30.8% was landfilled.

[1] PMD = Plastics (bottles and fluid containers), Metals (cans) and 'Drinkkarton' (TetraPak).

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