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Predictive model for the Dutch post-consumer plastic packaging recycling system and implications for the circular economy

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ABSTRACT

The Dutch post-consumer plastic packaging recycling network has been described in detail (both on the level of packaging types and of materials) from the household potential to the polymeric composition of the recycled milled goods. The compositional analyses of 173 different samples of post-consumer plastic packaging from different locations in the network were combined to indicatively describe the complete network with material flow analysis, data reconciliation techniques and process technological parameters. The derived potential of post-consumer plastic packages in the Netherlands in 2014 amounted to 341 Gg net (or 20.2 kg net.cap^{-1}.a^{-1}). The complete recycling network produced 75.2 Gg milled goods, 28.1 Gg side products and 16.7 Gg process waste. Hence the net recycling chain yield for post-consumer plastic packages equalled 30%. The end-of-life fates for 35 different plastic packaging types were resolved. Additionally, the polymeric compositions of the milled goods and the recovered masses were derived with this model. These compositions were compared with experimentally determined polymeric compositions of recycled milled goods, which confirmed that the model predicts these compositions reasonably well. Also the modelled recovered masses corresponded reasonably well with those measured experimentally. The model clarified the origin of polymeric contaminants in recycled plastics, either sorting faults or packaging components, which gives directions for future improvement measures.

1. Introduction

One of the five priorities within the European Circular Economy package (European Commission, 2015) is the reduction of plastic waste-to-landfill, in particular achieved by recycling of post-consumer plastic packaging waste (PPW), which has already been a legislative focal point since 1994 (European Parliament, 1994). Although substantial amounts of PPW are now being collected in various member states, these recycling systems are still far from circular. Circularity is also a diffuse terminology. It is very much related to the cradle to cradle principle as defined by McDonough and Braungart (2002), more recently named closed loop recycling. Reality, however, is complex, and many technical and economic issues arise that result in deviations from this perfect circularity. The current state-of-the-art within recycling is therefore more related to open loop recycling, sometimes also called 'downcycling' or even 'upcycling'. For European households for example, the majority of plastic packages is still not collected (Plastics Europe, 2015) and roughly 60% of the plastic packages that are collected for recycling within the EU are exported (Furfari, 2016). Specifically for the Netherlands three PPW recycling systems are in place: separate collection from households, mechanical recovery from the mixed municipal solid refuse waste (MSW) and a deposit-refund system for large PET bottles for water and soda drinks. The latter is officially treated and registered as post-industrial packaging waste and excluded from this study. Polyethylene-terephthalate (PET) bottles are the only plastic packaging type that is being recycled in large volumes to produce rPET for new packaging applications (bottles and trays – which could be called closed loop recycling) as well as non-packaging applications (strapping, fleece fill textiles – which could be called open loop

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recycling) (Awaja and Pavel, 2005; Welle, 2011). The successful closed loop recycling of PET beverage bottles relies on three factors: a high polymeric purity, a low level of molecular contamination (i.e. absorbed single molecules causing odour and migration issues) and restoration of the polymeric chain lengths. The high level of polymeric purity for rPET can be achieved by mechanical recycling PET bottles of which the designs are optimal for recycling. The low level of molecular contamination and the restoration of the polymeric chain lengths can both be achieved for rPET with the solid state post-condensation (SSPC) treatment (Welle, 2011). The most common plastic packaging materials are, however, polyethylene (PE) and polypropylene (PP) (Plastics Europe, 2015). And although a few examples of post-industrial recycled PP in food packaging have been documented (EFSA, 2014), in general the molecular pollution of both recycled PE and PP is so substantial that the legal migration limits for food packages are exceeded (Palkopoulou et al., 2016; Dutra et al., 2014). Therefore, their application is usually limited to non-food packaging and non-packaging applications. These are typical examples of open loop recycling. Moreover, recycled PE and PP are susceptible to thermal and thermo-oxidative degradation processes. Recycled PP is susceptible to chain scission and recycled PE is susceptible to both chain scission as well as cross-linking (Yin et al., 2015). However, there are no straight-forward technologies to restore their chain lengths and undo oxidative damage (Vilaplana and Karlsson, 2008). Additionally, recycled PE and PP often contain polymeric contaminants which form immiscible blends and hence a profound particle contamination (Luijsterburg, 2015). Hence the application of recycled PE and PP is often limited to non-transparent, non-white articles of a lesser mechanical strength (Meran et al., 2008; Pivnenko et al., 2015; Borovanksa et al., 2012; Sjöqvist and Boldizar, 2011).

In their much acclaimed report 'The New Plastics Economy', the Ellen MacArthur Foundation proposes to completely redesign the global plastic economy, in order to achieve the simultaneous creation of an effective after-use market for plastics and improved qualities of the recycled plastics (Ellen MacArthur Foundation, 2016). However commendable, such strategic efforts at the policy level would at the very least require, in order to succeed, detailed predictive knowledge of the polymeric composition of (potentially recycled) waste plastics. This knowledge is currently lacking, which severely hinders the progress towards a more circular plastic recycling system. Hitherto, the composition of sorted plastic packaging products is described with broad specifications, of which the so-called DKR list of specifications is most commonly applied in Europe (Duales System Deutschland, 2016). Compliance to specifications is determined by object-wise sorting of samples. For example, one of the nine quality aspects in the specification for PET product 328-1 demands that less than 0.1% (w/w) are PVC objects. Packaging objects are in almost all cases multi-material objects, though, yet being categorised on their main material. Thus, a PET bottle with a PP label and a PE cap is registered as a 100% PET object. This implies that compliance to a trading specification only renders a crude indication of the polymeric composition of the sorted product, as it only considers the sorting faults and not the packaging components made from different polymers. Moreover, polymeric contaminants are partially removed during the mechanical recycling process, yielding washed milled goods with unknown polymeric compositions. Since the processing options for and applicability of recycled plastics depends on their polymeric composition, there is a great need for methods to determine and describe the polymeric composition of recycled plastics.

Previous researchers have studied the polymeric composition of recycled plastics (Vilaplana and Karlsson, 2008; Brachet et al., 2008; Borovanksa et al., 2012; Hubo et al., 2014). Analyses have been performed on the level of washed milled goods, extruded granulates and injection moulded test specimen. Milled goods can be sorted automatically by near-infrared (NIR) based flake sorting machines. However, in our own experience with these machines, this yields 2–10% unknown materials, largely due to undesired light reflections of the irregular plastic particles. FT-IR (Fourier transform infrared) spectroscopy in ATR (attenuated total reflection) mode can be used to identify individual flakes and by repeating these measurements on hundreds of flakes the polymer composition can be obtained (Hubo et al., 2014). This is, however, tedious and laborious. FT IR–ATR spectroscopy can also be used to analyse the surface of test specimen made from recycled plastics. The concentration of polymeric contaminants in the test specimen can be determined if the concentration is roughly above 2%, but the concentration of these contaminants can be elevated at the surface as compared to the bulk (Luijsterburg, 2015). DSC (differential scanning calorimetry) can be used to estimate polymeric contaminants from 1% on, as long as the polymers have clearly distinguishable phase transitions (Vilaplana and Karlsson, 2008; Luijsterburg, 2015; Borovanksa et al., 2012). Again, multiple repetitions of the measurements can improve the level of accuracy. In any case, it has been proven difficult to determine the polymeric composition in the entire relevant range of 0.1–50% of polymeric contaminants in recycled plastics.

The current study has three objectives. First of all, this study aims to model the Dutch post-consumer plastic packaging network with material flow analysis (MFA) and data reconciliation techniques, from the household potentials to the produced amounts of washed milled goods. Secondly, the model is used to assess the end-of-life (EOL) fates of the 35 different plastic packaging types. Thirdly, the model derives the polymeric compositions of the produced milled goods. In order to estimate the polymeric composition of the milled goods this model needs to describe the network in an unprecedented level of detail, including a list of 35 different plastic packaging types and average material compositions per packaging type. In order to verify the model, milled goods made from Dutch sorting products will be analysed with manual NIR assisted sorting. Although NIR assisted sorting of milled goods is laborious and hence only single sample measurements have been performed, they have an indicative value and can be used to crudely verify the modelled composition of the milled goods. This MFA model explains the complex flow of plastic packages from the Dutch households to the produced milled goods. It clarifies the origin of polymeric contaminants in the recycled milled goods. This MFA model is dedicated for PPW and hence differs from more generic models that describe the flow of all plastics objects through specific countries, for instance Austria (Van Eygen et al., 2017). This dedicated MFA for Dutch PPW will be used in the near future to estimate the efficiency of industrial policy options –such as design-for-recycling measures and sorting policies-made by individual stakeholders on the amounts of washed milled goods and their polymeric composition. Since the latter parameter is indicative for the applicability of recycled plastics, this model can guide the redesign of the plastic recycling network towards a more circular economy.

2. Materials and methods

2.1. Origin of the data

A dedicated sorting team has determined the composition of 173 PPW samples taken at various locations in the recycling network in previous projects which were executed between 2010 and 2015. These compositions are described in data sheets, which categorise the material in terms of 35 different plastic packaging types, non-packaging plastics and 5 types of residual wastes. The data sheets have been combined to obtain averages and standard