



How circular are plastics in the EU?: MFA of plastics in the EU and pathways to circularity



Wan-Ting Hsu^{*}, Teresa Domenech, Will McDowall

Institute for Sustainable Resources, University College London, 14 Upper Woburn Place, WC1H 0NN, London, United Kingdom

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ABSTRACT

Plastic is valued for its versatility, but concerns have been raised over the environmental impacts of mismanaged plastic waste. A better understanding of plastic flows can help to identify areas of inefficiency and potential leakage to natural systems. This research provides an overview of plastic flows in the EU and discusses options to increase plastic circularity. The study conducted a comprehensive stationary material flow analysis covering over 400 categories of plastic-containing products with detailed analysis of the final destination of waste. The results show the relevance of the EU plastic sector with production of over 66 MT of plastic polymers/fibres and an estimated consumption for plastic products of 73 MT in 2016. Plastic waste arisings amounted to over 37 MT and, though increasing plastic recycling rates have been reported, the analysis shows that a significant amount of plastic waste was not returned to production in the EU. The uncertainty analysis highlights important data quality issues that need to be addressed, particularly: data on the plastic fraction in plastic-containing products, and data on the final destination of plastic waste. Building on the analysis, the paper discusses a number of strategies for re-directing the plastic system to more circular pathways.

1. Introduction

Plastic is an important and ubiquitous material in modern society due to its affordability, light weight and durable features. Plastic has contributed important benefits to society such as extending the shelf life of food through packaging (Andrady and Neal, 2009). Worldwide plastic production increased twentyfold between 1964 and 2014, reaching 311 million tonnes (MT) in 2014 (EMF, 2016) Geyer et al. (2017). estimate that overall 8300 MT of plastics have been produced to date. As the second largest producer following China, the EU plays an important role in the global plastic value chain, accounting for around 19% of world plastic material production and 12% of its consumption (Plastics Europe, 2017). A recent study predicted that plastics demand is likely to continue to grow until the year 2050 (Material Economics, 2018).

Increasing plastic production and consumption results in more plastic reaching end-of-life (EoL) and potentially increased risks of plastic leakage to the environment. EoL management of plastics is complex, because of several factors: (1) the large variety of polymers used and the increase in composite materials; (2) the different life spans of plastics depending on application; (3) cross-contamination issues; (4) the technical challenges and economic viability of recovering plastics embedded

in complex products (Allwood, 2014 Hahladakis and Iacovidou, 2018). These factors also create difficulties for tracking plastic flows, from product to waste management, across different applications and through time and space (Deloitte Sustainability, 2017). This has resulted in data gaps and limited understanding in the quantification of plastic waste reaching EoL, and uncertainty with regard to the sources and quantity of leakage to ecosystems.

Recent years have seen increased public awareness of the potential damage arising from mismanaged plastic waste, particularly marine litter (Jambeck et al., 2015; Lau et al., 2020; Lebreton and Andrady, 2019). EU policy developments in the area have been notable. In 2015, plastics were identified as a priority material in the EU circular economy action plan (European Commission, 2015), which was followed by a strategy for plastics in 2018 (European Commission, 2018). The EU has adopted several ambitious targets: 10 MT of recycled plastics are to be used in new products by 2025; 55% of plastic packaging waste is to be recycled by 2030 (European Parliament, 2018); and beverage bottles should contain a minimum of 30% recycled content in 2030 (European Parliament, 2019).

Packaging has also been the target of a number of voluntary initiatives, such as the New Plastics Global Commitment (EMF and UNEP,

^{*} Corresponding author.

E-mail addresses: wan-ting.hsu.16@ucl.ac.uk (W.-T. Hsu), t.domenech@ucl.ac.uk (T. Domenech), w.mcdowall@ucl.ac.uk (W. McDowall).

2019), the Circular Plastics Alliance's Voluntary Pledges (European Commission, 2019), Plastics 2030 —Plastics Europe's Voluntary Commitment (Plastics Europe, 2019b), The European Plastics Pact (European Plastics Pact, 2020) and The UK Plastics Pact (WRAP, 2018).

Global developments around trade in plastic waste are having a significant impact on European plastic waste trade flows. In 2017, China introduced a ban on low-quality mixed plastic waste imports, with strict contamination benchmarks (Brooks et al., 2018; Wang et al., 2019). Moreover, the Basel Convention has agreed a new amendment to control mixed and contaminated plastic waste trade (UNEP, 2019).

A better understanding of plastic flows is important for addressing the plastic waste challenge, by identifying areas of inefficiency, material losses and potential leakage to natural systems. This has been acknowledged by the European Commission (2018) and Plastics Europe (2018), who point to a lack of reliable data as a limiting factor for the introduction of effective policy and business measures to increase plastic circularity. This paper aims to fill this gap by presenting the results of an all-encompassing material flow analysis (MFA) for plastics in the EU across more than 400 product categories and detailed EoL routes.

2. Literature review

Recent years have seen publication of studies providing insights of plastic flows for specific geographic boundaries, in specific application sectors, or for some types of plastic polymers (e.g. Deshpande et al. (2020); Jiang et al. (2020); Nakatani et al. (2020)). Most of the early studies in European countries (Bogucka et al., 2008; Joosten et al., 2000; Patel et al., 1998; Salmons and Mocca, 2010) did not differentiate across plastic application categories in the consumption stage (Graedel, 2019; Van Eygen et al., 2017).

More recently, plastic MFAs with a variety of scopes have been conducted for different EU member states, including Spain (Sevigné-Itoiz et al., 2015), the UK (Cullen et al., 2020; McCaffery et al., 2014; Thomson and Sainsbury, 2016), Austria (Van Eygen et al., 2017, 2018), Finland (Sahimaa and Dahlbo, 2017) and Denmark (Faraca and Astrup, 2019; Pivnenko et al., 2019). These findings seem to confirm that the vast majority of plastic waste still ends up in landfill or incineration. However, the issue of plastic losses remains poorly understood, with only a few studies estimating leakage to the environment (Ryberg et al. (2019) estimated losses on a global scale, while Hann et al. (2018) estimated microplastics in Europe released to the aquatic environment. Kawecki and Nowack (2019) estimated flows and losses of seven polymers in Switzerland.

Some studies also exist at the EU level for specific categories of plastic polymers (Bishop et al., 2020; Ciacci et al., 2017; Deloitte Sustainability, 2017; Kawecki et al., 2018). Ciacci et al. (2017) conducted a comprehensive estimation of the European PVC cycle from 1960 to 2012. Based on probabilistic MFA, Kawecki et al. (2018) described the flows of seven commodity plastics in Europe by type of plastic polymer. Deloitte Sustainability (2017) extrapolated the data from five EU member states to analyse flows of plastic packaging waste in the EU in 2014. Finally, Bishop et al. (2020) analysed the fate of PE waste after recycling in the EU28, Norway and Switzerland, in 2017. However, a comprehensive, all-encompassing MFA of plastic flows in the EU is still missing.

A key methodological challenge relates to the need to account for plastic embedded in complex products. Previous studies have used rather broad product group categories (e.g. Kawecki et al. (2018); Van Eygen et al. (2017)). However, such aggregated product categories generate large uncertainties in the final material flows. This study relies on disaggregated data on more than 400 product groups, enabling a more detailed assessment of plastic flows embedded in products than in previous EU studies. Such a comprehensive analysis provides the basis for a better understanding of the implications of policies and targets for plastics currently being discussed. The proposed methodological framework also enables future updates both at EU level and at member state level.

3. Methods

3.1. Material flow analysis

This study uses Material Flow Analysis (MFA), a systematic approach to assess the flows and stocks of materials through a system within a defined spatial and temporal boundary (Brunner and Rechberger, 2016). Based on the principle of mass conservation, inputs from nature used by the socio-economic system are balanced by all the processed outputs (or residuals) generated by the system, plus the additions to the socio-economic stock.

Following MFA methodological guidelines (Brunner and Rechberger, 2016; Eurostat, 2018), the system boundary in this study is the EU28, according to its definition in 2016. For the temporal boundary, 2016 is chosen as a reference year because it had the most up-to-date and comprehensive datasets when this analysis was conducted. The biennial datasets of waste streams are published with a few years' delay. Plastic MFA in 2016 is also suitable to be a baseline scenario for measuring the plastic circularity, as the circular economy action plan started in 2015, and the relevant policies and targets were set afterwards. Fig. 1 displays the system boundary. The resource flow has been analysed according to five main phases that cover the whole life cycle of plastics, including (1) production and consumption of plastic polymers/fibres; (2) manufacturing of plastic products; (3) plastic products consumption and in-use stock; (4) plastic waste generation and collection; and (5) plastic waste treatment and other destinations. Initial extraction of primary materials (e.g. fossil fuels) and manufacturing of monomers lie outside the defined system boundaries for this study.

Plastic flows include all fossil-based plastic polymers and synthetic fibres (see SI Page S-2). With regard to the plastic products, a total of 416 plastic-containing products have been identified from the PRODCOM (production of manufactured goods) database (Eurostat, 2016) and from Scudo et al. (2017) for the personal care and cosmetics products (PCCP) (see Table S8). For the calculation of plastic waste flows, product categories have been linked to waste categories in order to match the plastic-containing waste categories from the European Waste Catalogue (see Table S4).

Additives used in plastic production are embedded in plastic material flows. Geyer et al. (2017) estimate that approximately 7% plastic products may be additives. However, due to poor quality data and the relatively small share in the overall weight of plastic, additives are not considered in this study. Further discussion about additives in plastics can be found in Hahladakis et al. (2018).

The approach to the estimation of plastic losses is based on the method of Ryberg et al. (2019). The estimation includes the losses from manufacturing, washing of textiles, microbeads of PCCP, waste water treatment plants (WWTP), mismanaged plastic waste, and recycling processes. Using the balancing equations, estimations are calculated and then validated by other sources of data. Overall recycling losses are estimated based on a case study by Recycling Technologies (2016), and were subsequently validated through expert interviews. Four interviews were conducted: Two representatives of large integrated waste management companies, one recycler, and a recycling consultant – all of whom have experience across Europe.

To be consistent with the system boundary of this study, the losses relevant to rubber (e.g. tyre abrasion, city dust), weathering of marine coatings, fishing nets and maritime-related losses are excluded. Paints are coatings on other non-plastic products and thus follow other waste collection routes, so abrasion of paints (including road markings) are not considered further in the analysis. Further details for the estimation are explained in the supplementary information (Page S-2 – S-10).

3.2. Data collection

There are seven principal types of data used in this study: (1) Trade and production data on plastic polymers/fibres, intermediate goods and

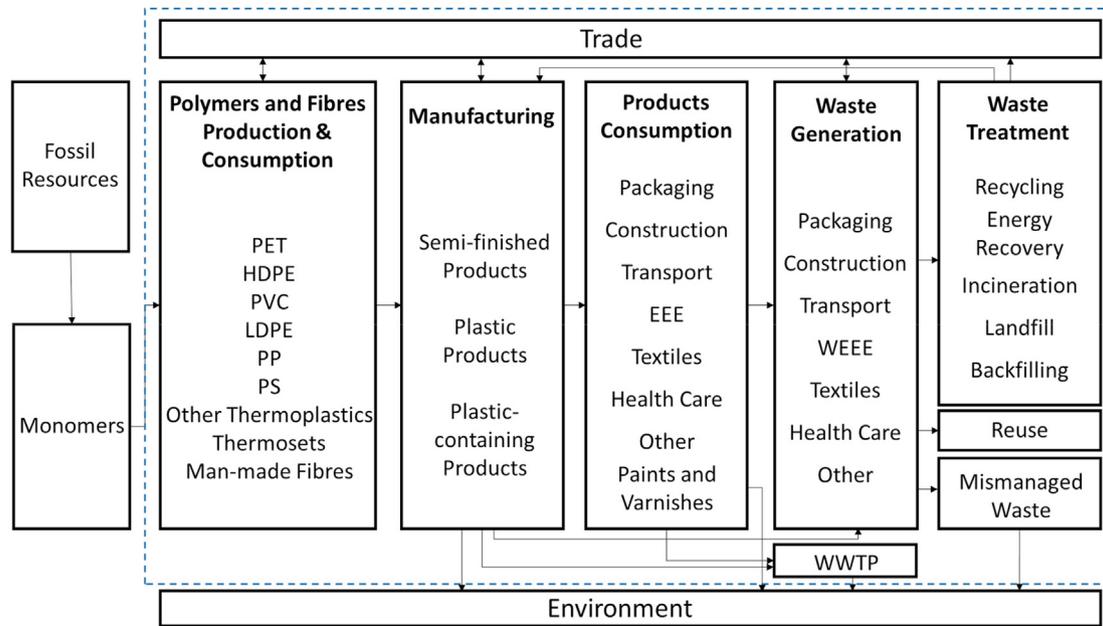


Fig. 1. System boundary.

manufactured products (Eurostat, 2016), and secondary plastic (Stadler et al., 2018); (2) Data on the plastics embodied in products (Swedish Chemicals Agency, 2015); (3) Data on weight per unit of item (Amazon, 2018); (4) Trade data on plastic waste (UN COMTRADE, 2018); (5) Data on generation and treatment of waste (Eurostat, 2013); (6) Data on the plastic fraction of different waste streams; (7) Transfer coefficient of losses along the life cycle stage (Ryberg et al., 2019). Estimation of recycling losses derived from the MFA analysis was subsequently validated through an expert interview process.

Further details regarding data sources and assumptions made are given in the supplementary information. Fig. S1 displays the framework of plastic data. Table S1 lists the sources of data and main assumptions for the plastic MFA, whilst Table S2 lists the sources of data for the plastic fraction in different waste categories. Table S3 lists the transfer coefficient of losses along the life cycle stages.

3.3. Uncertainty characterization

Uncertainty analysis was undertaken to estimate the level of intrinsic uncertainty of the model. This study follows the MFA uncertainty analysis framework developed by Laner et al. (2015). This approach estimates uncertainties derived from data gaps, and uses a qualitative assessment of uncertainty method to calculate quantitative probability distributions that are then used for the MFA data reconciliation process using STAN software (Cencic and Rechberger, 2008). The first step is to qualitatively assess each input based on a variety of data quality criteria. Details of the data quality indicators proposed by Laner et al. (2015) and adopted in this study are shown in Table S5. There are five main indicators. The 'source reliability' indicator focuses on the quality of documentation for data generation. The 'completeness' indicator refers to comprehensiveness of data sources and whether the data includes all the relevant flows or not. 'Temporal correlation' and 'geographical correlation' evaluate the congruence of the available data with respect to selected time and geographical boundary respectively. 'Other correlation' evaluates the congruence of the available data with respect to variety of products and technologies. Indicators are scored 1 to 4 ranging from 1 very good, to 4 very poor data quality. Secondary data derived from expert judgement is assessed differently with an assessment of source reliability.

The second step is to use those qualitative scores to generate a

quantitative measure of data uncertainty, expressed as the coefficient of variation (CV). This involves combining the score for each attribute of data quality with a sensitivity parameter, used to reflect a judgement about the relative importance of each specific attribute of data quality. Parameters a and b for each sensitivity level are defined by Laner et al. (2015). The CVs are parameterized based on the equations (1) and (2), shown in Table S6. For the secondary data from expert judgement, the criteria of estimation is shown in Table S5 and Table S6.

$$CV_{source\ reliability} = a \times e^{b \times score} \quad (1)$$

$$CV_{completeness;temporal\ correlation;geographical\ correlation;other\ correlation} = a \times e^{b \times (score-1)} \quad (2)$$

Thirdly, the total coefficient of variation (CV) is assessed by aggregating the individual CV based on equation (3). The addition of individual flows (M_A , M_B) is estimated based on equation (4), while the multiplication of the amount of products, plastic contents and weight per unit is based on equation (5). Finally, this CV_{total} (or CV_c) can be applied to characterize the uncertainty of each flow.

The CV values for each parameter describe a probability distribution, which is assumed to be normal. The data reconciliation process in STAN then allows deviations from the central values of these distributions (assumed to be the mean of this distribution), by minimizing the sum of squared errors. Parameters with estimated lower 'data quality' have wider distributions, providing greater flexibility to identify a more likely accurate value given the other material flow data during the reconciliation process in STAN.

$$CV_{total} = \sqrt{CV_{reliability}^2 + CV_{completeness}^2 + CV_{temp.corr.}^2 + CV_{geo.corr.}^2 + CV_{other.corr.}^2} \quad (3)$$

$$\left(M_C \times \frac{CV_C}{100}\right)^2 = \left(M_A \times \frac{CV_A}{100}\right)^2 + \left(M_B \times \frac{CV_B}{100}\right)^2 \quad (4)$$

$$CV_C^2 = CV_A^2 + CV_B^2 \quad (5)$$

4. Results

The results from the MFA of plastic in the EU28 in 2016 are

EU28 Plastic Flows 2016

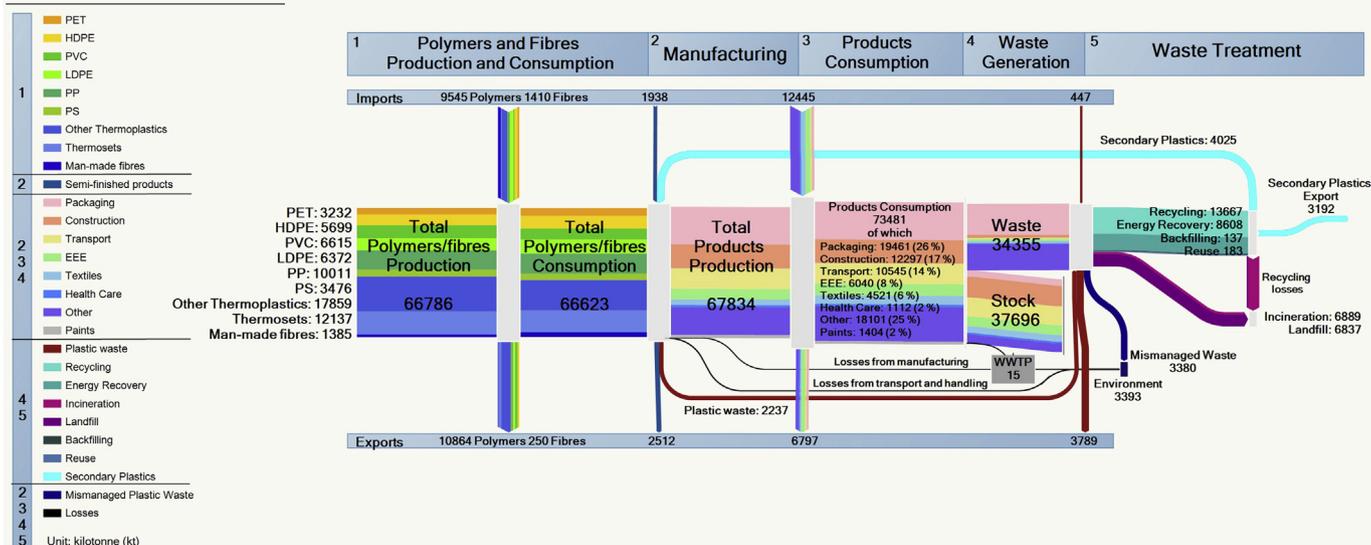


Fig. 2. Plastic flows in the EU28 in 2016.

summarised in Fig. 2. Details of uncertainty values and data are detailed in the supplementary information (Figs. S2 and S3).

4.1. Plastic flows

As shown in Fig. 2, total virgin plastic polymers and fibres production in the EU28 amounted to 66,786 kilotonnes (kt). This includes PET, HDPE, PVC, LDPE, PP, PS, other thermoplastics, thermosets, and man-made fibres. Consumption of plastic polymers and fibres accounted for 66,623 kt. The most consumed plastic polymer is PP, closely followed by LDPE, HDPE, PVC, PET and PS respectively. Consumption of man-made fibres, which are mainly polyamide, polyester and PP, was around 2,544 kt. While the major groupings (PP, PE, PVC) make up a substantial share of total plastics, there is a very large range of other plastic polymers. In fact, 'other thermoplastics' represented 15,823 kt, while 'other thermosets' represented 11,140 kt in 2016 (see Fig. S3 and Table S7). The array of different types of plastics is the result of different product specifications, and creates challenges for sorting and segregation at the EoL.

EU trade of plastic polymers and fibres is very significant, with a positive trade balance of virgin plastic polymers. In total, the EU exported 10,864 kt plastic polymers to other countries. However, plastic fibres showed a trade deficit (1,410 kt imported and 250 kt exported). As shown in Fig. 2, there was a positive trade balance in semi-finished products (1,938 kt imported and 2,512 kt exported), while final products showed a trade deficit, with net imports of around 5,648 kt plastic in final products.

Plastic polymers were compounded and moulded into different types of product. The mass of plastic in plastic-containing products assembled and distributed into different applications was 73,481 kt (Fig. 2). Fig. 2 displays the consumption of plastic and plastic-containing products by segment. Packaging accounts for 26%, followed closely by 'other' (25%), construction (17%), transport (14%), EEE (8%), textiles (6%), health care (2%), paints and varnishes (2%). These include virgin and secondary plastics. The product list of 'other' is shown in Table S9.

Additions to stock have been estimated at 37,696 kt as indicated in Fig. 2, representing plastic and plastic-containing products that remain in use in the socio-technological system. Packaging (+3,339 kt) and health care (+879 kt) had small additions to stock due to their short product lifetimes. Additions to stock were higher in the case of construction (+10,760 kt) and transport (+9,768 kt) products as plastics in these

applications have longer product lifetimes. Stocks accumulated in the system are important to account for as they will become future waste.

At the EoL stage, the MFA reports 2,237 kt of waste generated from plastic manufacturing processes and 34,355 kt of post-consumer plastic waste in 2016 (See Fig. 2). The plastic waste generated from manufacturing processes excludes the plastic waste recycled back into the production system.

As shown in Fig. 3, the two largest flows of post-consumer plastic waste are 'packaging' and 'other', which accounted for 47% and 40% respectively. This 40% of 'other plastic waste' is a heterogeneous mix of different waste streams, including the following categories: plastic waste; household and similar waste; mixed and undifferentiated materials. 'Plastic waste' refers only to plastic separately collected from the economic activities. 'Household and similar waste' is the combination of mixed municipal waste, waste from markets, bulky waste and street cleaning waste. 'Mixed and undifferentiated materials' contain undifferentiated plastic-containing waste from different economic activities. The heterogeneity of 'other plastic waste' creates difficulties to adequately trace and recover plastic waste in this category.

'Other plastic waste' is followed by construction plastic waste (4%), WEEE (3%), textiles (3%), transport (2%), and health care waste (1%). Paints and varnishes are coatings applied on other products, and they are embodied in other waste streams (e.g. wood waste, plasterboard, etc.). Paint and varnish also dissipate to the environment directly from in-use products. As a result, estimates of the final destinations of these products have not been included in the calculation of plastic waste.

Fig. 4 displays the waste arisings by source, distributed across households (50.5%), services (21.6%), construction (5.8%), manufacturing sectors (20.2%), agriculture, forestry and fishing (1.9%).

A total of 37,068 kt of plastic waste were generated in 2016. Fig. 5 details main destinations of all plastic waste and estimated losses along the life cycle. Although 13,667 kt plastic waste were sent to recycling, the model estimates losses of 6,450 kt (47%) associated with initial sorting, pre-processing, changes in moisture content and efficiency losses from recycling processes. The MFA estimate of losses from recycling processes is based on the literature (Recycling Technologies, 2016) (Fig. 2). In order to verify this result, and investigate the details on different stages of the recycling process, we sought to validate this with experts. Their estimates for recycling losses are in the range 20–50%, representing the state of play across Europe. However, the estimates at the low end of that range focused on losses associated with relatively pure waste streams

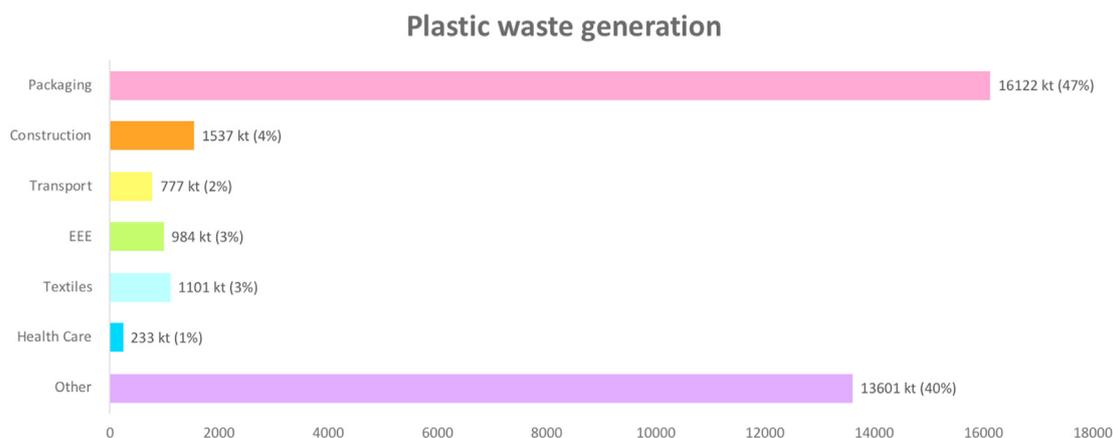


Fig. 3. Plastic waste generation.

(e.g. HDPE milk bottles) following some separation. Estimates at the higher end of the range took account of segregation losses. Of these experts, the most detailed breakdown was provided by Freegard (2019), who broke the losses down as follows: a) 10–20% losses occur at primary sorting at a material recycling facility (relating to commingled waste resulting from poor sorting technology and inaccurate hand-sorting); b) a further 10–20% loss occurs at a plastics recycling facility when separating the polymer grades and making bales of different polymer types, coloured and clear natural; c) further losses in a specialist plastic recycling plant, given contamination from labels, bottle caps, and inaccurate polymer sorting (Freegard, 2019).

Given the variety of plastic polymers in the market and different organisation and technology levels across collection, processing and recycling systems in the EU, recycling losses have inherent uncertainty (variation occurs for different plastic products and across segregation systems, sorting technologies and recycling systems). The model estimates that only 53% plastic waste sent to recycling is transformed into secondary plastics. From that, only around 4,025 kt was transformed into secondary materials in EU plants and sold as recycled polymers for transformation within the EU, while 3,192 kt plastic was treated in EU plants and sold as secondary plastics to other countries. This means that despite improved recycling rates, only 11% of all the plastic waste generated along the value chain was reprocessed and used as secondary plastics in the EU. Overall, 8,608 kt plastic waste went to energy recovery, 6,889 kt to incineration and around 6,837 kt were sent to landfill. These overall non-circular treatments include the treatment of losses

from recycling. Backfilling accounted for only 137 kt (see Fig. 5).

Reusing plastic products and components and increasing the quality of recycling, such that secondary plastic can substitute primary materials are important strategies towards circular plastics. However, data around reuse is highly fragmented and limited. Approximately 183 kt plastic waste were recorded as re-used in the EU, but this is likely to be underestimated as a large share of peer-to-peer reuse is not recorded and escapes official statistics.

With regard to the trade of plastic waste, Fig. 2 shows that while plastic waste imports (447 kt) were minimal, 3,789 kt of plastic polymer-based, fibre and plastic-containing (WEEE and textiles) waste were exported for recycling outside of the EU. Generally, exports of plastic waste to other countries are dominated by lower quality plastic waste with higher cross-contamination (Crippa et al., 2019). Some studies have pointed to the lack of traceability of exported plastic waste as an issue that may lead to ocean plastic waste pollution (Bishop et al., 2020). Fig. 6 shows the destination of overall plastic polymer-related waste, including PE, PVC, PS, other plastic waste, and excludes other plastic waste in plastic-containing products. This shows the lack of traceability of trade of plastic waste embedded in plastic-containing products. The main destination of plastic waste in 2016 was still China, before the introduction of its ban on the import of plastic waste (Fig. 6). In the ranking, China (1,636 kt) was followed by Hong Kong (765 kt), Malaysia (154 kt), Vietnam (134 kt), India (128 kt), with the all other destinations summing to 302 kt (see Fig. 6). Plastic waste exports are associated with insufficient recycling capacity in the EU and the economics of plastic recycling, with more competitive prices offered outside of the EU

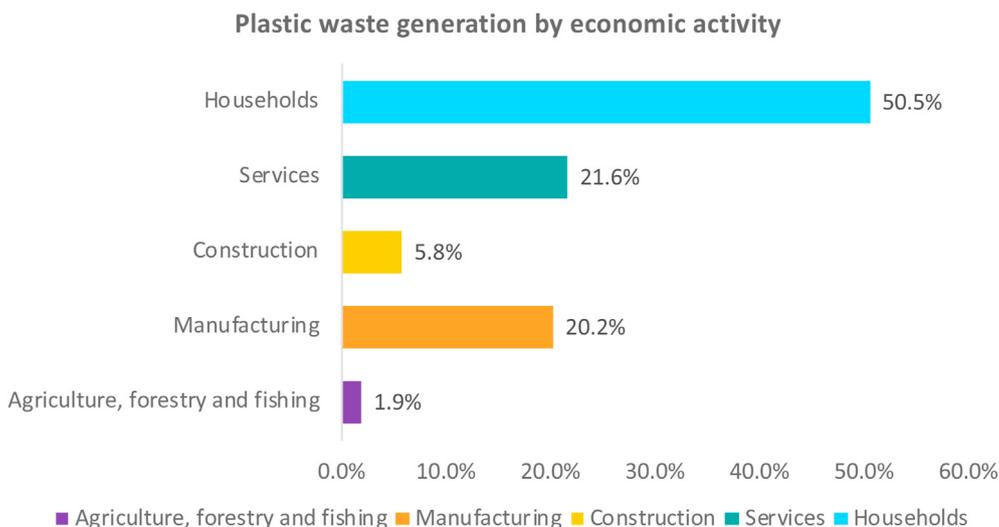


Fig. 4. Plastic waste generation by economic activity.

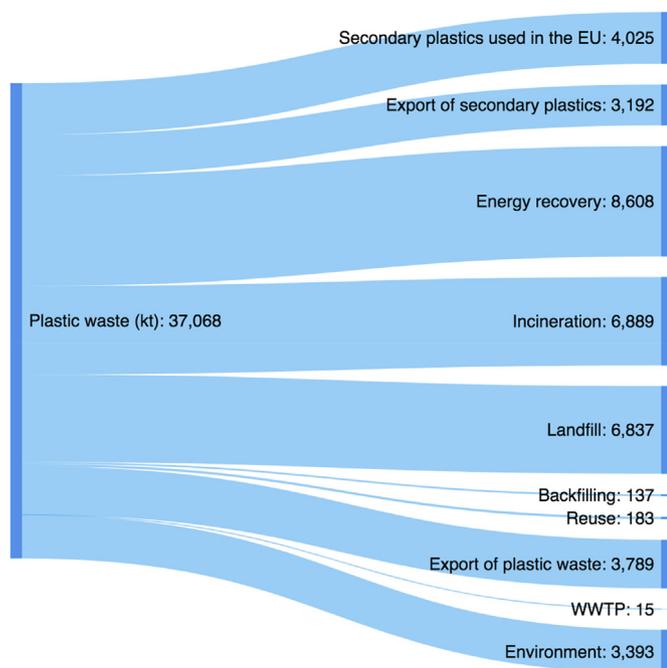


Fig. 5. Destinations of plastic waste.

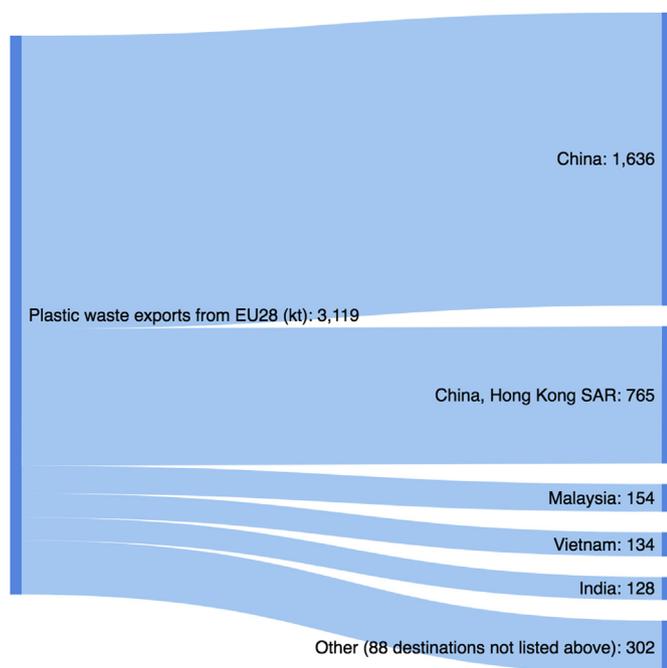


Fig. 6. Export destinations of plastic polymer-related waste.

(OECD, 2018).

Fig. 2 and Fig. S3 show the losses along the life cycle. At the manufacturing stage, it is estimated that around 1 kt spill of pellets from the production line may be eventually released to drains and captured in wastewater treatment plants (WWTP). Around 2 kt of pellets are lost during transport and handling and potentially released to the environment through urban runoff and other forms of dispersion. At the consumption stage, 24 kt of microfibres are lost during washing clothes from households and industrial laundries, whereas 1 kt of microbeads in PCCP are lost from households, sport facilities and hotels. Most microfibres and microbeads are channelled from sewage systems to the WWTP, and about

15 kt plastic waste were captured at WWTP stage. However, the model estimates that 11 kt total losses from WWTP, including 2 kt of microfibres from textiles that potentially entered into the ocean from the EU in 2016 and 9 kt were leaked into soils by the application of wastewater sludge on agricultural fields. Microbeads lost to the environment (~1 kt) constitute a relatively small amount, which is not considered further in the analysis.

It is worth noting that 1,404 kt of paints and varnishes were consumed, coated on non-plastic products, and are lost in the EoL management routes of these coated products (e.g. walls and plasterboard in demolition waste). The EoL destination of paints and varnishes is a mix of dissipative losses and disposal with the other products. Dissipative losses account for 23%–43% (up to 100%) of road markings (Toben, 2017) and approximately 1%–6.5% of losses during the use of other coated products (e.g. building paints, transport equipment painting, furniture coatings) (OECD, 2009). The remainder of plastic in paints and varnishes at EoL is treated embedded in the products (e.g. wood, plasterboard, etc.) through other waste routes (e.g. incineration, landfill) (OECD, 2009).

The majority of losses occur at the waste generation stage, with an estimated total of about 3,380 kt mismanaged plastic waste. This includes cross-contamination and illegal dumps (Murgese, 2020; Pittiglio et al., 2017), deposits in non-compliant landfills which failed to comply with the Landfill Directive, and the littering of single-use plastic packaging on the street or in natural surroundings. Littering is problematic in some EU member states such as Greece, Slovakia, Italy, and Bulgaria (Eurobarometer, 2014). Major illegal exports of plastic waste have been reported to be shipped from the UK, Germany, Italy to Malaysia (Greenpeace Malaysia, 2018; Murgese, 2020; Pittiglio et al., 2017); however, traceability and magnitude of this are difficult to establish. Overall, the model estimates that around 3,393 kt mismanaged plastic waste and losses accumulated in the environment.

4.2. Uncertainty analysis

4.2.1. Assumptions on the level of sensitivity and data gaps

Quantitative uncertainties attributed to each flow are shown in Fig. S3. Each uncertainty is described as a CV, expressed as a percentage. This CV describes a distribution, assumed to be normal, within which the true value of each flow is believed to lie. Data reconciliation helped to reduce the uncertainties of the flow estimates.

The current model relies heavily on data from Eurostat product and waste databases. Following Laner et al. (2015)'s approach to characterize uncertainty, Eurostat data are rated highly in terms of source reliability, because they are derived from an official statistical body, with associated methodological rigour. However, there are widespread concerns that Eurostat data in this area are relatively weak. We, therefore, assign a high level of sensitivity to the source reliability scores for parameters derived from Eurostat. The secondary data from references is derived initially from expert estimation. For this data, the qualitative evaluation criteria follow the expert estimate criteria.

The model makes assumptions where data gaps exist. In particular, it was necessary to make allocations of intermediate plastic products to final consumption groups, as data available to convert intermediary flows into final goods for specific product categories (e.g. construction, transport and general 'other') is limited. While this allocation introduces uncertainty of the flows of intermediary products into final product categories, this is not fully reflected in the Laner et al. (2015)'s uncertainty method, suggesting that for this flow the true uncertainty range may be higher than that suggested by the CV derived.

4.2.2. Uncertainty of upstream and downstream flows

Upstream flows of plastic polymers and fibres are based on data from the PRODCOM database, which is relatively high quality, so the uncertainty range is moderately small (up to $\pm 6.4\%$). Among plastic polymers, PVC has higher uncertainty due to the estimation of PVC's fraction within the categories of 'PVC mixed with any other substances'. There is higher uncertainty for the manufacturing and consumption stages of plastic-

containing products, for which uncertainty ranges from $\pm 5.1\%$ (for the consumption of paints) to $\pm 21.2\%$ (for EEE consumption), and the highest uncertainty occurs within import of EEE ($\pm 22.3\%$).

The waste generation flows have uncertainty ranges from $\pm 8.2\%$ (for WEEE) to $\pm 21\%$ (for transport waste). Transport waste only includes discarded vehicles, data for which lack completeness (e.g. other transport equipment). Uncertainty associated with waste generation is propagated from the uncertainty associated with the estimation of plastic fraction for product categories. Larger relative uncertainties come from the temporal mismatch between data sources for estimating plastic content of packaging, construction and health care waste, and from the heterogeneity of products within household waste and mixed waste. The model uncertainty decreases for the trade of plastic waste as these flows mainly rely on official data. The uncertainty lies in the waste generated from 'other applications' as this spreads across different waste categories. We assumed a 10% plastic fraction in the 'mixed and undifferentiated materials' waste category so that the overall amount of waste generated from 'households' and 'services' in this study is aligned with 'municipal waste data' from Eurostat and 'post-consumer waste' data from [Plastics Europe \(2017\)](#). Although the uncertainty of this mixed waste flow is very high ($\pm 43.7\%$), the aggregation of all different plastic waste flows uncertainty compensates leading to a lower overall uncertainty.

Data on the quantities of both products and waste come from official databases with the same temporal and geographical system boundary, enhancing consistency of the analysis. The main sources of uncertainty relate to the estimation of plastic content and weight per unit in product and waste categories, given variations in plastic content over time due to technological progress and market changes. This is particularly true for vehicles and EEE, which have shown progressive replacement of metal components by plastic.

The destination of plastic waste faces a number of areas of high uncertainty. Uncertainties associated with the estimation of landfill and incineration are higher than those associated with recycling and energy recovery. This is because a larger share of household waste and mixed waste (which are associated with higher uncertainties) ends up in landfill and incineration compared to other waste categories. The reuse data is probably underestimated, given robust second-hand markets for clothes, vehicles, toys and other product categories, which in most cases escape official records. Data on recycling losses as estimated by the model have been validated by the literature and expert interviews; however, great uncertainty remains ($\pm 44.3\%$). The export of secondary plastics is also highly speculative, which is reflected in uncertainty scores of $\pm 30.9\%$, due to data gaps. As one would expect, areas of highest uncertainty also relate to the losses and leakage to the environment (up to $\pm 42\%$) due to lack of available data.

5. Discussion

5.1. Comparison with other studies

This study provides a comprehensive overview of plastic flows within the EU in 2016. Building on previous studies, this study provides a more exhaustive examination of plastic flows with detail for over 400 product categories and a comprehensive analysis of waste treatment and EoL flows. The findings of the study are largely aligned with those of previous work (e.g. [Kawecki et al. \(2018\)](#)). However, the estimation of total production is higher than that reported by [Plastics Europe \(2017\)](#), which may be explained by the different inclusion of some plastic polymers and fibres.

For the potential leakage, this study estimates 3,380 kt of mismanaged plastic waste, which is consistent with the estimation by [Lebreton and Andrady \(2019\)](#). [Lebreton and Andrady \(2019\)](#) suggest 3.3 (1.3–9.1) MT mismanaged municipal plastic waste in Europe, defined as unsound disposal, which includes urban litter and open dumps, based on population density, GDP distributions, per capita municipal solid waste generation and an estimate of the mismanaged fraction. Our estimates of

losses of microfibres from washing clothes are aligned with that of [Hann et al. \(2018\)](#). However, losses from manufacturing are lower than [Hann et al. \(2018\)](#). This may be because the transfer coefficient applied in this study originally came from a survey of firms operating in the best practices ([Lassen et al., 2015](#)) – and, in consequence, our estimate may be more optimistic. Despite the inherent uncertainty of losses estimates, this and other studies point to this being a significant area of concern with associated environmental implications.

5.2. Directing plastic waste destinations to circular pathways

This study highlights that the EU still has a long way to go to achieve a more circular plastics system. Based on the findings from the study, we propose six key complementary strategies for circular pathways of plastics and improved traceability of plastic flows along different life cycle stages, which are discussed below.

- (1) Eco-design of plastic products at the production and manufacturing stages

Our results show approximately 30 MT of other thermoplastics and thermosets are manufactured in the EU, creating challenges for circularity. For these types of plastics, waste destinations are largely non-circular. Therefore, a fundamental element leading to circular pathways would be eco-design of plastic products to ensure easy recycling. This is especially relevant for complex products containing different types of plastic polymers. This requires collaboration between product designers and recyclers to gain knowledge of current and forthcoming sorting and recycling technologies, and to redesign plastic products that can be effectively recycled. This also requires the development of design guidelines for better recycling, and improved knowledge of the relationship between product material choices and different EoL pathways.

- (2) Reuse and repair plastic products at the consumption and in-use stock stage

The large scale of the in-use stock (37,696 kt) highlights the potential importance of extending product lifespans through reuse and repair. Innovative circular business models and networks across the EU, such as RREUSE, facilitate the reuse and repair of plastic-containing products. As our findings of reuse mainly include textiles, WEEE and discarded vehicles, the findings show very poor data on current reuse of plastic, and further research is necessary to examine both physical and online markets for second-hand goods.

- (3) Manage non-circular treatment and trade at the waste generation and treatment stage

This study found that 17,515 kt plastic waste went through non-circular treatment and exports. With regard to the 3,789 kt export of plastic waste, the EU not only needs to work on increasing recycling capacity locally, but also needs to better monitor the trade of plastic waste and collaborate with countries that receive EU plastic waste, to improve recycling quality and to share the responsibility for plastic pollution at the global scale.

The Waste Shipment Regulation of the UN Basel Convention and China waste import ban have reportedly reduced the amount of plastic waste export, but have increased the waste to landfill in the short term ([EEA, 2019](#)). There is a need to assess options to further reduce the amount of plastic waste entering landfill (from the 6,837 kt identified here), including a possible landfill ban for plastic waste. There are still some illegal exports of plastic-containing waste resulting in a lack of traceability. Data on waste flows are likely to improve as a result of increased policy focus on the waste trade. China's ban and the resulting scrutiny of waste exports show the need for better traceability of plastic waste in order to avoid illegal trade and dumping.

(4) Strengthen the role of chemical recycling at waste treatment stage

The findings show a significant mass of plastic waste (13,667 kt) is sent for mechanical recycling. However, recycling losses significantly compromise secondary plastic production. The main problems arise from flaws in processes of collection and segregation, and because of cross-contamination. There is still a high proportion of plastics going to land-fill or incineration, highlighting the need to develop better segregation and collection systems.

The high share of plastic that is not recycled also suggests a need to further develop options for chemical recycling, which would enable recovery of energy or monomers for re-polymerisation for plastics unsuited to mechanical recycling. Currently, chemical recycling is not accounted for in the recycling fraction from the official databases at the EU level. There is some ambiguity about this in the relevant waste legislation, which has been under discussion and needs to be clarified. There is an ongoing discussion about using chemical mass-balance approaches to measure the performance of chemical recycling in the plastics industry (EMF, 2020), and further research and standards are needed to assess recycled materials from chemical recycling.

(5) Increase the quantity and quality of secondary plastics at the waste treatment stage

According to the results, around 4 MT of secondary plastics were used in the EU, 6 MT below the target of 10 MT in 2025. Secondary plastics used in packaging have been prominent in recent public debate. The EU policy target of 30% recycled content in PET bottles in 2030 could create a 123 kt demand for secondary plastics in the EU. Applying this commitment to all packaging would increase secondary plastic demand to approximately 5,638 kt, according to our model calculations. Clearly not all applications can accommodate secondary plastics given current technology or quality specifications. The promotion of secondary markets needs to be accompanied by efforts in infrastructure and technology development and stringent quality standards to further develop the secondary plastics market. The key to increasing the quantity and quality of secondary plastics would be policy interventions, such as extended producer responsibility schemes and tax incentives for the use of secondary plastics.

Moreover, data on secondary plastic flows need to be improved. Official databases record trade of plastic waste but not secondary plastics. Since the future target is to increase to 10 MT of secondary plastics demand, it is important to track destinations of secondary plastics and include further specification of plastic waste by type of polymer. *Plastics Europe (2019a)* shows most secondary plastics are used in the construction sector, and some of them could be considered downcycling applications. It is also important to develop platforms on trade of secondary plastics to improve traceability and transparency for closing loops, and to facilitate monitoring and analysis of secondary plastic flows at the European level.

(6) Reduce losses along all stages of the plastic life cycle

Losses pose a critical challenge for increasing plastic circularity, requiring a variety of policy measures, behavioural changes and technological interventions across the life cycle of plastic. The MFA demonstrated considerable mismanaged plastic waste in the EU, causing 3,393 kt of plastic waste lost to the environment. Our results show the main areas of losses are: (1) manufacturing; (2) microfibre losses during the use stage; (3) littering and (4) losses from recycling processes. Strategies on tackling plastic losses of manufacturing, pellet transport and prevention of losses to wastewater systems have been put forward in policy strategies like Operation Clean Sweep programme (*Plastics Europe, 2019c*), but current measures face obstacles such as high costs relative to the low economic value of losses, and an absence of stringent environmental monitoring systems that account for leakage and its

socio-economic and environmental impacts. The majority of losses during product use stems from microfibres lost during clothes washing. Proposals for developing standards to restrict the maximum losses threshold of fibres have been suggested (*Hann et al., 2018*), combining behavioural interventions, such as consumer education campaigns focused on washing habits, and technological interventions (e.g. fitting washing machine filters). However, further restrictions to limit the amount of microplastics through the Sewage Sludge Directive to minimise plastics entering the environment are still needed (*Stubenrauch and Ekardt, 2020*). For littering, education-based campaigns and adequate waste collection infrastructure are key.

Data in this area are weak, and there is a need for further investigation of the volume and impacts of losses caused by littering, illegal dumps and illegal export. Approximately 47% of losses from recycling processes are associated with poor segregation and collection practices. Positive and cost effective impacts could be achieved in this area through behavioural, technological and policy interventions, to drive improved recycling efficiency and collection infrastructures, combined with novel sorting technologies.

6. Conclusions

This study provides a comprehensive plastic MFA for the EU showing more than 66 million tonnes (MT) of plastic polymers and fibres were produced, 73 MT plastic-containing products were consumed, and more than 37 MT plastic waste were generated. However, only around 4 MT of secondary plastics were returned to the EU market. The detailed examination of plastic waste destinations in this study shows that plastics in the EU are still far from being circular.

The analysis has also highlighted profound data gaps, especially for plastic fraction estimation of complex products. Such data are not routinely collected, and the available data are outdated. Further research is needed to update data on the plastic fraction of products. The movements of the market towards block-chain and big data applications with details of product composition have the potential to improve the traceability of plastics throughout the whole system. The requirements of improving data quality and availability allow for reliable monitoring of plastic management, and for more accurate assessment of opportunities and infrastructural gaps.

Based on the findings, six strategies, combining a range of policy instruments, behavioural and technological interventions, are suggested to move towards more circular pathways. This study can help to monitor the progress of ongoing plastic circular economy policy strategies and point to areas of future development.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cesys.2020.100004>.

References

- Allwood, J.M., 2014. Chapter 30 - Squaring the Circular Economy: the Role of Recycling within a Hierarchy of Material Management Strategies, *Handbook of Recycling*. Elsevier, Boston, pp. 445–477.
- Amazon, 2018. [Amazon.co.uk](https://www.amazon.co.uk/). (Accessed 8 June 2018).
- Andrady, A.L., Neal, M.A., 2009. Applications and societal benefits of plastics. *Philosophical Transactions of the Royal Society B: Biological Sciences* 364 (1526), 1977–1984.
- Bishop, G., Styles, D., Lens, P.N., 2020. Recycling of European plastic is a pathway for plastic debris in the ocean. *Environ. Int.* 142, 105893.
- Bogucka, R., Kosińska, I., Brunner, P.H., 2008. Setting priorities in plastic waste management—lessons learned from material flow analysis in Austria and Poland. *Polimery* 53 (1).
- Brooks, A.L., Wang, S., Jambeck, J.R., 2018. The Chinese import ban and its impact on global plastic waste trade. *Science advances* 4 (6), eaat0131.
- Brunner, P.H., Rechberger, H., 2016. *Handbook of Material Flow Analysis: for Environmental, Resource, and Waste Engineers*. CRC Press.
- Cencic, O., Rechberger, H., 2008. Material flow analysis with software STAN. *Journal of Environmental Engineering and Management* 18 (1), 3.
- Ciacci, L., Passarini, F., Vassura, I., 2017. The European PVC cycle: in-use stock and flows. *Resour. Conserv. Recycl.* 123, 108–116.
- Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Muncke, J., Ritschkoff, A., Van Doorselaer, K., Velis, C., Wagner, M., 2019. A Circular Economy for Plastics: Insights from Research and Innovation to Inform Policy and Funding Decisions.
- Cullen, J.M., Drowniok, M.P., Serrenho, A.C., 2020. The 'P' Word – Plastics in the UK: Practical and Pervasive ... But Problematic.
- Deloitte Sustainability, 2017. *Blueprint for Plastics Packaging Waste: Quality Sorting & Recycling*.
- Deshpande, P.C., Philis, G., Brattebø, H., Fet, A.M., 2020. Using Material Flow Analysis (MFA) to generate the evidence on plastic waste management from commercial fishing gears in Norway. *Resour. Conserv. Recycl.* X 5, 100024.
- Ellen MacArthur Foundation, 2016. *The New Plastics Economy: Rethinking the Future of Plastics*.
- Ellen MacArthur Foundation, 2020. *Enabling a circular economy for chemicals with the mass balance approach*.
- Ellen MacArthur Foundation and UN Environment Programme, 2019. *The New Plastics Economy Global Commitment - 2019 Progress Report*.
- Eurobarometer, 2014. *Attitudes of Europeans towards waste management and resource efficiency. Flash Eurobarometer 388 Report*.
- European Commission, 2015. *Closing the Loop - an EU Action Plan for the Circular Economy*.
- European Commission, 2018. *A European Strategy for Plastics in a Circular Economy*.
- European Commission, 2019. *Assessment Report of the Voluntary Pledges under Annex III of the European Strategy for Plastics in a Circular Economy*.
- European Environmental Agency, 2019. *The Plastic Waste Trade in the Circular Economy*. <https://www.eea.europa.eu/themes/waste/resource-efficiency/the-plastic-waste-trade-in>. (Accessed 2 August 2020).
- European Parliament, 2018. *DIRECTIVE (EU) 2018/852 of the EUROPEAN PARLIAMENT and of the COUNCIL of 30 May 2018 Amending Directive 94/62/EC on Packaging and Packaging Waste*.
- European Parliament, 2019. *DIRECTIVE (EU) 2019/904 of the EUROPEAN PARLIAMENT and of the COUNCIL of 5 June 2019 on the Reduction of the Impact of Certain Plastic Products on the Environment*.
- European Plastics Pact, 2020. *The European plastics Pact*. <https://europeanplasticspact.org/>. (Accessed 1 August 2020).
- Eurostat, 2013. *Manual on Waste Statistics - A Handbook for Data Collection on Waste Generation and Treatment*.
- Eurostat, 2016. *PRODCOM List 2016*.
- Eurostat, 2018. *Economy-wide material flow accounts handbook*.
- Faraca, G., Astrup, T., 2019. Plastic waste from recycling centres: characterisation and evaluation of plastic recyclability. *Waste Manag.* 95, 388–398.
- Freegard, K., 2019. *Personal Communication with Keith Freegard. Keith Freegard Consulting Ltd, 25 November 2019*.
- Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. *Science advances* 3 (7), e1700782.
- Graedel, T.E., 2019. Material flow analysis from origin to evolution. *Environ. Sci. Technol.* 53 (21), 12188–12196.
- Greenpeace Malaysia, 2018. *The Recycling Myth, Malaysia and the Broken Global Recycling System*.
- Hahladakis, J.N., Iacovidou, E., 2018. Closing the loop on plastic packaging materials: what is quality and how does it affect their circularity? *Sci. Total Environ.* 630, 1394–1400.
- Hahladakis, J.N., Velis, C.A., Weber, R., Iacovidou, E., Purnell, P., 2018. An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. *J. Hazard Mater.* 344, 179–199.
- Hann, S., Sherrington, C., Jamieson, O., Hickman, M., Kershaw, P., Bapasola, A., Cole, G., 2018. Investigating options for reducing releases in the aquatic environment of microplastics emitted by (but not intentionally added in) products. *Report for DG ENV EC*.
- Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. *Science* 347 (6223), 768–771.
- Jiang, X., Wang, T., Jiang, M., Xu, M., Yu, Y., Guo, B., Chen, D., Hu, S., Jiang, J., Zhang, Y., 2020. Assessment of plastic stocks and flows in China: 1978–2017. *Resour. Conserv. Recycl.* 161, 104969.
- Joosten, L.A.J., Hekkert, M.P., Worrell, E., 2000. Assessment of the plastic flows in The Netherlands using STREAMS. *Resour. Conserv. Recycl.* 30 (2), 135–161.
- Kawecki, D., Nowack, B., 2019. Polymer-specific modeling of the environmental emissions of seven commodity plastics as macro-and microplastics. *Environ. Sci. Technol.* 53 (16), 9664–9676.
- Kawecki, D., Scheeder, P.R., Nowack, B., 2018. Probabilistic material flow analysis of seven commodity plastics in Europe. *Environ. Sci. Technol.* 52 (17), 9874–9888.
- Laner, D., Fekettitsch, J., Rechberger, H., Fellner, J., 2015. A novel approach to characterize data uncertainty in material flow analysis and its application to plastics flows in Austria. *J. Ind. Ecol.* 20 (5), 1050–1063.
- Lassen, C., Hansen, S.F., Magnusson, K., Hartmann, N.B., Jensen, P.R., Nielsen, T.G., Brinch, A., 2015. *Microplastics: Occurrence, Effects and Sources of Releases to the Environment in Denmark*.
- Lau, W.W.Y., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., Koskella, J., Velis, C.A., Godfrey, L., Boucher, J., Murphy, M.B., Thompson, R.C., Jankowska, E., Castillo Castillo, A., Pilditch, T.D., Dixon, F., Koerselman, L., Kosior, E., Favoino, E., Gutberlet, J., Baulch, S., Atreya, M.E., Fischer, D., He, K.K., Petit, M.M., Sumaila, U.R., Neil, E., Bernhofen, M.V., Lawrence, K., Palardy, J.E., 2020. Evaluating scenarios toward zero plastic pollution. *Science* 1455–1461.
- Lebreton, L., Andrady, A., 2019. *Future scenarios of global plastic waste generation and disposal*. Palgrave Communications 5 (1), 1–11.
- Material Economics, 2018. *The Circular Economy - A Powerful Force for Climate Mitigation*.
- McCaffery, A., White, C., Fox, C., Sainsbury, P., 2014. *Plastic Packaging Market Study (Plastic Flow) 2014*. WRAP.
- Murgese, E., 2020. *Illegal Trafficking of Plastic Waste: the Italy–Malaysia Connection*. Istituto Affari Internazionali.
- Nakatani, J., Maruyama, T., Moriguchi, Y., 2020. *Revealing the Intersectoral Material Flow of Plastic Containers and Packaging in Japan*. Proceedings of the National Academy of Sciences.
- OECD, 2009. *Emission Scenario Document on Coating Industry (Paints, Laquers and Varnishes)*.
- OECD, 2018. *Improving Markets for Recycled Plastics*.
- Patel, M.K., Jochem, E., Radgen, P., Worrell, E., 1998. Plastics streams in Germany—an analysis of production, consumption and waste generation. *Resour. Conserv. Recycl.* 24 (3–4), 191–215.
- Pittiglio, R., Reganati, F., Toschi, L., 2017. How to detect illegal waste shipments? The case of the international trade in polyethylene waste. *Econ. Bull.* 37 (4), 2625–2640.
- Pivnenko, K., Damgaard, A., Astrup, T.F., 2019. *Preliminary assessment of plastic material flows in Denmark*. Technical Report.
- Plastics Europe, 2017. *Plastics - the Facts 2017*.
- Plastics Europe, 2018. *Plastics 2030 - PlasticsEurope's Voluntary Commitment to Increasing Circularity and Resource Efficiency*.
- Plastics Europe, 2019a. *The Circular Economy for Plastics - A European Overview*.
- Plastics Europe, 2019b. *Plastics 2030 PlasticsEurope's Voluntary Commitment to Increasing Circularity and Resource Efficiency*.
- Plastics Europe, 2019c. *PlasticsEurope Operation Clean Sweep® Report 2018*.
- Recycling Technologies, 2016. *Lodestar: a Case Study for Plastics Recycling*.
- Ryberg, M.W., Hauschild, M.Z., Wang, F., Averous-Monnery, S., Laurent, A., 2019. *Global environmental losses of plastics across their value chains*. *Resour. Conserv. Recycl.* 151, 104459.
- Sahmaa, O., Dahlbo, H., 2017. *Material flow analysis of plastic for Finland*.
- Salmons, R., Mocca, E., 2010. *Material Flow Analysis and Value Chain Analysis for the UK Plastics Sector*.
- Scudo, A., Liebmann, B., Corden, C., Tyrer, D., Kreissig, J., Warwick, O., 2017. *Intentionally Added Microplastics in Products*.
- Sevigñe-Itoiz, E., Gasol, C.M., Rieradevall, J., Gabarrell, X., 2015. Contribution of plastic waste recovery to greenhouse gas (GHG) savings in Spain. *Waste Manag.* 46, 557–567.
- Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., 2018. *EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input-output tables*. *J. Ind. Ecol.* 22 (3), 502–515.
- Stubenrauch, J., Ekardt, F., 2020. Plastic pollution in soils: governance approaches to foster soil health and closed nutrient cycles. *Environments* 7 (5), 38.
- Swedish Chemicals Agency, 2015. *Commodity guide*. <http://webapps.kemi.se/varuguide/n/varugruppermaterial.aspx>. (Accessed 22 March 2018).
- Thomson, H., Sansbury, P., 2016. *Plastics Spatial Flow - An assessment of the quantity of un-recycled plastic in the UK*. WRAP.
- Toben, M., 2017. *Microplastic Pollution Originating from Textiles and Paints: Environmental Impacts and Solutions*.
- UN COMTRADE, 2018. *United Nations Commodity Trade Statistics Database*. <https://comtrade.un.org/>. (Accessed 10 April 2018).
- UNEP, 2019. *BC-14/12: Amendments to Annexes II, VIII and IX to the Basel Convention*.
- Van Eygen, E., Fekettitsch, J., Laner, D., Rechberger, H., Fellner, J., 2017. *Comprehensive analysis and quantification of national plastic flows: the case of Austria*. *Resour. Conserv. Recycl.* 117, 183–194.
- Van Eygen, E., Laner, D., Fellner, J., 2018. *Circular economy of plastic packaging: current practice and perspectives in Austria*. *Waste Manag.* 72, 55–64.
- Wang, W., Themelis, N.J., Sun, K., Bourtsalas, A.C., Huang, Q., Zhang, Y., Wu, Z., 2019. *Current influence of China's ban on plastic waste imports*. *Waste Disposal & Sustainable Energy* 1 (1), 67–78.
- WRAP, 2018. *The UK Plastics Pact*. <http://www.wrap.org.uk/content/the-uk-plastics-pact>. (Accessed 27 March 2019).