ISSN 1831-9424

European Commission

JRC TECHNICAL REPORT

Modelling plastic flows in the European Union value chain

Material flow analysis of plastic flows at sector and polymer level towards a circular plastic value chain

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2022

Joint Research Centre

EUR 31242 EN

EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC130613

EUR 31242 EN

PDF	ISBN 978-92-76-57510-8	ISSN 1831-9424	doi:10.2760/66163	KJ-NA-31-242-EN-N

Luxembourg: Publications Office of the European Union, 2022

How to cite this report: Amadei, A. and Ardente, F., *Modelling plastic flows in the European Union value chain*, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/66163, JRC130613.

Contents

Abstract

This study aimed at establishing a mass flow analysis model (MFA) for the whole value chain of plastics in the EU27 for the year 2019, from pellets production to end-of-life plastic management and secondary plastics (i.e., “recyclates”) production. The analysis is focused on deriving sector-specific MFAs for 9 sectors in total. Additionally, 5 sectors (out of the 9 considered in the sector-specific assessment) were also further examined for deriving polymer-specific MFAs by analyzing a selection of 10 plastic polymers within each sector through a top-down approach. These estimates were further assessed with scenarios for the year 2025 in the plastic context, by following expected trends in the value chain and leveraging on the current and future EU plastic policies’ ambitions. Overall, a total of 5.47Mt of recyclates were produced in EU27, with a total of 4.46Mt recyclates being consumed within the EU27 territory (considering that 18% are exported). On average, the EU27 end-of-life recycling rate (i.e., recyclates produced over total waste being generated) was equal to 19% (16.6% when export is considered). Total value-chain losses of plastics (microplastics and macroplastics) across all sectors amounted to 2.11Mt, which is 4% of the total production estimated in the present study. These estimated losses included 39% of losses during the use phase (e.g., microplastic emissions from tyre abrasion or washing of synthetic textiles), 21.5% of microplastic emissions from incineration and landfill, 20% of losses due to plastic waste littering, 17% of losses due to mismanaged waste not recollected, and 2.5% of pre-consumer microplastic emissions. Results of the assessment of the 2025 scenarios indicated that one single targeted action (such as a reduction in waste export or an improvement in the separate collection of plastic waste) would not be sufficient to ensure that the EU/Circular Plastic Alliance (CPA) target of 8.8Mt of post-consumer recyclates to be consumed in the EU27 is achieved by 2025 (the target was adjusted from the 10Mt for EU27+UK to enable a fair comparison with the results of the present study). Only when multiple actions are combined (i.e., combining all the 4 scenarios assessed in this study plus a +10%/-10% or 0% variation in total plastic production), the 8.8Mt target is reached and surpassed by the year 2025. The estimated total recyclates consumed with the combined scenarios ranged from 9.11Mt to 11.13Mt by 2025, resulting in a maximum recyclates consumption rate as high as 35.5% (i.e., the ratio between the recyclates consumed and the total waste being generated). Results of the present study underlined that, to support the achievement of the EU target endorsed by the CPA, significant efforts are needed to establish a complete overview of plastic materials flows, for multiple sectors and polymers, from plastic products manufacturing to plastics end-of-life management and recyclates fate. This should be coupled with data and estimates of both losses and mismanaged waste. Delivering on the key commitments for actions at EU level requires an improvement and rethinking of the plastic value chain, which should be driven by up-to-date knowledge of all its various hotspots.

Acknowledgements

This report is a deliverable of the project "Comparative Life Cycle Assessment (LCA) of alternative feedstocks for plastics production" between European Commission DG GROW and Joint Research Centre (Administrative Agreement N° DG GROW SI2.762599 / JRC 34854-2017).

The authors of the report would like to thank Serenella Sala for the conception of this research and the support and guidance provided during the whole project development. Authors would also like to thank Hans Saveyn, Davide Tonini and Esther Sanyé-Mengual for the help and the feedback provided during the work development; and Silvia Bobba and Fabrizio Biganzoli for suggestions related to the material flow model and its visualization. Authors would like to thank Laure Baillargeon for the precious reviews and the recommendations provided during the project. The author would like to also thank Metabolic for the continuous and fruitful exchanges of results and references.

Executive summary

This study aimed at establishing a mass flow analysis model (MFA) for the whole value chain of plastics in EU27 for the year 2019, from pellets production to end-of-life plastic management and secondary plastics (i.e., "recyclates") production. The analysis covers the plastic flows of the entire European Union (EU) and is especially focused in deriving sector-specific MFAs for a total of 9 sectors in total for deriving sector-specific MFAs. Additionally, 5 sectors (out of the 9 considered in the sector-specific assessment) were also further examined for deriving polymer-specific MFAs by analyzing a selection of 10 plastic polymers within each sector through a top-down approach. These estimates were further assessed with scenarios for the year 2025, by following expected trends in the plastic value chain and leveraging on the current and future EU plastic policies' ambitions. Scenarios' results were employed to provide analytical support on the achievement of the EU targets on improving the circularity of the plastic value chain (as described for instance in The European Green Deal and the European Strategy for plastics in a Circular Economy) and to also support strategies towards the achievement of the EU target of 10 million tonnes of recycled plastics annually used in the EU27+UK by 2025 (EC, 2018a), as endorsed by the Circular Plastics Alliance (CPA) (corrected[1] to 8.8 million tonnes of post-consumer recyclates for EU27 for a fair comparison with the results of the present study).

In the first step of the work, a literature review was performed to gather all the relevant data for building the mass flow models, and key literature sources were identified. Data adjustments were then performed to adapt the data to a common reference (EU27 2019). The sector-specific MFAs were established by defining their system boundaries and by the generation of a transfer coefficients (TCs) matrix at sector level, based on literature data. A series of scenarios for the year 2025 were also analyzed for the sector-specific MFAs, assuming improvements in the value chain regarding waste collection and waste management and recycling rates. All these effects were translated in variations in the TCs to represent a hypothetical future value chain. On the other hand, to establish polymer-specific MFAs, comprehensive end-of-life assessments of polymer flows, analysis of recyclates and destination in the EU economy were employed when available. Following a top-down approach, the above information was coupled with a breakdown of the most relevant polymers within each sector (i.e., the input to each polymer-specific MFA was modelled starting with the total sector-specific plastic demand).

Results of the sector-specific MFAs underlined the role of packaging as the most important sector among those assessed, contributing to 33% of the total plastic consumption[2], followed by the construction sector (23%). Waste generated from consumption amounted to 64% of the total consumed plastics, with 34% of the consumed plastic being kept in stock, and the remaining 2% lost during use. Of the total amount of post-consumer waste being generated in the year 2019 (28.8Mt) only 38% was separately collected, and a significant fraction (13%) was mismanaged (intended as inadequately disposed waste - e.g., disposed in open dumps, unspecified landfills, unaccounted, etc. - and/or treated/managed - e.g., by unauthorized third parties - in ways that could create routes for potential losses and releases into the environment). Waste being mismanaged was particularly significant for plastic waste originating from the transport and Electric and Electronic Equipment (EEE) sectors (44% and 22% of the total waste generated in these two sectors, respectively). Out of the total plastic waste sent to recycling, 70% derived from the packaging sector. Overall, a total of 5.47Mt of recyclates were produced in EU27, with a total of 4.46Mt recyclates being consumed in 2019 within the EU27 territory (considering that 18% are exported). On average, the EU27 end-of-life recycling rate (i.e., recyclates produced over total waste being generated; defined according to Antonopoulos et al., 2021 and UNEP, 2011) was equal to 19% (16.6% when trade effects are considered). Most of the total microplastics and macroplastics losses of all sectors in the whole value chain (2.11Mt) occurred during the use phase (39%), amounting to 4% of the total production estimated in the present study. Results of the polymer-specific assessment suggested that a subset of polymers drove the overall plastic consumption for the analyzed sectors, with a major role especially played by HDPE, LDPE, PP, PVC and PET (covering 70% of the total demand). On average, the highest end-of-life recycling rates for the five sectors analyzed in the polymer-specific assessment (namely: packaging,

[1] To enable a fair comparison with the results of the present study, the EU/CPA target of 10Mt for EU27+UK was corrected to EU27 considering: (i) the ratio between the plastic demand in UK and the plastic demand in EU27+UK (equal to 7% and calculated from PlasticsEurope, 2021), and that (ii) an amount of pre-consumer PVC recyclates (approximately equal to 0.5Mt, as estimated under the Vinylplus voluntary commitment (VinylPlus, 2022)) from and used in construction sector is to be included in the 10Mt target.

[2] Amount of plastics consumed by end-users in EU-27 (i.e. "apparent consumption" calculated as semi-finished or finished production minus exports plus imports).

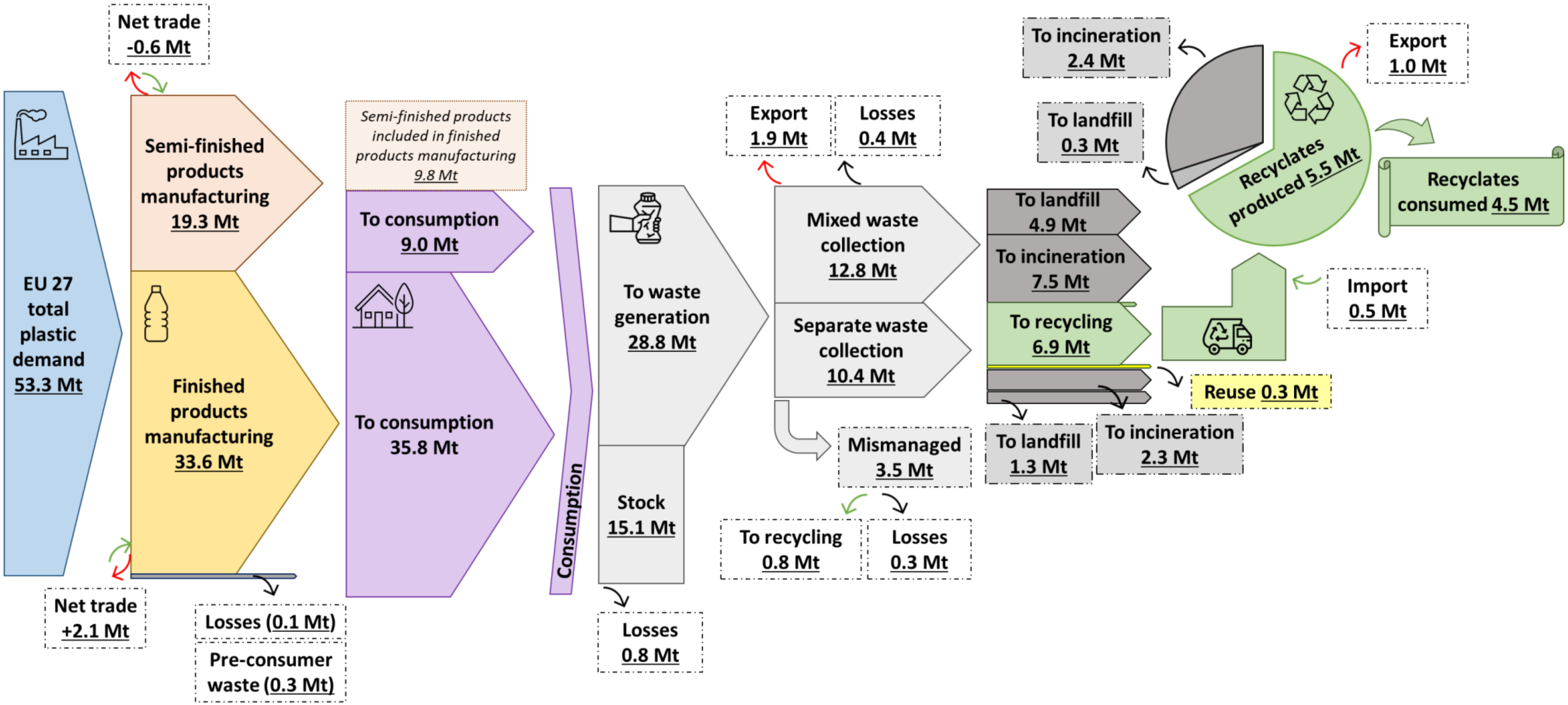
construction, transport, EEE and agriculture) were recorded for PET (23%), LDPE (18%) and PVC (17%).
Although packaging plays a pivotal role in the whole plastic value chain, the analysis of less-explored sectors should be refined and supported in the next years and should not be underestimated. This is particularly relevant in the case of sectors such as synthetic textiles, fishing and healthcare, which are mostly unexplored in current literature. In the case of the transport and EEE sectors, a proper handling of waste currently being mismanaged (total of 3.5Mt) could significantly boost the total plastic mass arriving to the authorized waste management system. An overview of the main flows and results of the full EU27 MFA is reported in Figure 1.

Based on the findings of the sensitivity assessment and leveraging on expected trends on plastic production and plastic waste management, a series of scenarios for the year 2025 were drafted. When considering the 4.46Mt of recyclates resulting from the 2019 model, the EU target of 8.8Mt of post-consumer recyclates to be used annually in the EU-27 by 2025 (adjusted from the 10Mt target defined in 2018 for the EU-28) seems challenging. Results from the assessment of the scenarios for the year 2025 indicated that one single targeted action (such as reduction in waste export or an increase in the separate collection of plastic waste) is not sufficient to ensure that the 8.8Mt target is achieved by 2025. Among the assessed scenarios for the year 2025, the highest impact is achieved with the improved waste collection scenario (i.e., 30% increase of separate waste collection for packaging and 10% for other sectors), leading to an estimated recyclates consumption of 6.47Mt by 2025 (45% increase compared to 2019). Nevertheless, when all actions are combined (i.e., considering all scenarios simultaneously[3] and a +10%/-10% or 0% variation in total plastic production) the 8.8Mt target is reached and surpassed by 2025. Results indicate that for the combined scenario assuming a +10% variation in production, a total of 11.13Mt recyclates consumed coupled with an overall recyclates consumption rate equal to 35.5% could be achieved by 2025. Current estimates in trends in plastic packaging production (as suggested for instance by the European Commission (EC, 2018a), and data from Plastics Europe reports) indicated a yearly increase in the total production (virgin plastics) of around 4-5% (based on data for the 2010-2018 timeframe). However, the recent COVID-19 outbreak and the Ukraine war, coupled with EU commitments on plastic production prevention (EC, 2019a) and brands and retailers' commitments on reducing plastic consumption, could signify an unprecedented reduction in plastic production in the near future (as suggested for instance by Systemiq, 2022). When a reduction of 10% in plastic production is assumed and combined with all other (positive) scenarios, a total recyclates consumption of 9.11Mt is achieved, which would still meet the EU/CPA target. The 8.8Mt target is also achieved and surpassed with the combined scenario when assuming a stagnating plastic production, as this would lead to 10.12Mt of recyclates being consumed by 2025 in EU27.

Results of the present study underline that to fulfil the EU ambitions and industry targets, such as the EU/CPA target, significant efforts are needed to further improve the granularity and details of overviews of plastic flows in the EU. Such enhancements could include better sector-specific and polymer-specific data for less explored sectors (such as textiles and clothing, fishing, or healthcare), coupled with in-depth knowledge of recyclates fate, and both losses and mismanaged waste flows. Considering these key commitments for actions at the EU level, an improvement and rethinking of the plastic value chain is mandatory and should be driven by up-to-date knowledge of all its various hotspots.

[3] The four improvements considered simultaneously in the combined scenarios [Scenarios F1, F2, F3] are: 1) 10% reduction in plastic waste export, and 20% for automotive and EEE waste [Scenario A]; 2) Improved waste collection i.e. 30% increase in separate collection for packaging and 10% for other sectors [Scenario B]; 3) Improved sorting yields i.e. 15% increase in sorted waste sent to recycling for packaging and 10% for other sectors [Scenario C]; and 4) improved recycling yields i.e. 20% lower rejects at recycling facilities for packaging, and 10% for other sectors [Scenario D]. The percentages represent variations applied to the transfer coefficients of the modelled MFAs.

Figure 1. Simplified diagram of the main flows [expressed in Mt] of the plastic value chain analyzed in the present study. Each arrow width is proportional to the total EU27 plastic demand for the year 2019 (53.3 Mt). The reader should consider that potential differences in totals reported elsewhere in this report compared to the totals of this figure are due to the rounding. Note that some additional flows are modelled in the context of the present study (e.g., incineration and landfill losses; losses fate; etc.) but are not presented in this Figure with the goal of providing a clear summary of the most relevant contributions to the whole value chain.



1 Introduction

1.1 Plastic flows in Europe: policy background and state of the art

Plastics represent a ubiquitous material in the worldwide economy and a fundamental component of our daily lives. Plastic products can fulfil a wide array of purposes and applications, due to their unique properties and features of high-performance. However, as understood by the EU Plastics Strategy (EC, 2018a), plastics are currently produced, used, and discarded in way that leads to severe environmental impacts and limits the space for establishing a “circular” plastic value chain. The effects of plastics pollution became highly visible in recent years because of the littering of single-use plastics (Charles et al., 2021) and due to the rising effects of microplastic pollution on the environment (Welden et al., 2020; Kawecki and Nowack, 2019; Ryberg et al., 2019) and on both humans and the whole food-chain (UNEP, 2016).

Understanding the effects of plastic pollution, especially due to plastic debris in the marine environment, is central for the achievement of the UN (United Nations) Sustainable Development Goal (SDG) 14, aimed at conserving and sustainably using oceans, seas, and marine resources (UNEP, 2022). In this context, several EU policies actions have been put forward to address the considerable challenge that plastic represents. Stemming from the EU Circular Economy Action Plan (EC, 2015), the European Strategy for plastics in a Circular Economy (EC, 2018a) represents a milestone for achieving circularity in the plastic value chains as it addresses different topics ranging from reuse and recycling of plastics to more sustainable production and more sustainable consumption and use of plastics, together with better collection and sorting of plastics. A reduction in resource consumption coupled with waste reduction measures for key products (in the field of packaging, construction materials and vehicles) is also promoted in the new Circular Economy Action Plan (EC, 2020), which strives to further develop a circular economy including in the plastic sector.

Currently most of the generated plastic waste is either incinerated, landfilled, or exported outside the EU, leading to losses of valuable resources and releases of emissions (mainly CO_2 from incineration) (Tonini et al., 2021). The prevention and reduction of impacts of certain plastic products (especially single-use-plastics) on the environment and on human health are also within the scope of the Single-Use Plastics (SUP) Directive (EC, 2019a). In the context of the Packaging and Packaging Waste Directive (EC, 2018b), ambitious targets have been set on the recycling of plastic packaging waste (i.e., 50%, 55%, and 60% of the amount generated to be achieved by 2025, 2030, and 2035, respectively). Additional targets have been also set by The European Green Deal (EC, 2019b), which not only aims at reducing intentionally added microplastics and unintentional releases of plastics, but also at ensuring that all packaging in the European market is reusable or recyclable in an economically viable manner by 2030.

To understand the most effective ways towards the abovementioned ambitious targets, it is of crucial importance to have a deep knowledge of plastic material flows in Europe. Albeit no standard methodology is currently recognized in the field of measuring plastics flows, Material Flow Analysis (MFA) is commonly employed in literature to model such flows (Chen et al., 2020). According to Brunner and Rechberger (2005), MFA is an approach to systematically assess the flows of materials of a system that is defined in space and time. While meeting the law of conservation of matter, MFA connects flows between processes for all inputs and outputs. An MFA can be controlled in terms of mass balance by Transfer Coefficients (TCs), which are defined for each input and output flows of a process. TCs add up to 100% and serve the purpose of detailing the total amount of a substance that is transferred from a process to another one.

Several literature studies performing MFAs of plastics have been published in recent years, analysing not only value chains of specific States (such as Switzerland (Kawecki and Nowack, 2019)) or Member States (MS) (such as Denmark (Pivnenko et al., 2019) or Austria (Van Eygen et al., 2017)), but also attempting at describing the whole EU value chain (e.g., in the case of Kawecki et al., 2018 and Hsu et al., 2021). The granularity of available information varies widely between studies. An analysis of aggregated flows (i.e., of general “total plastics” flows) is frequently preferred to a sectors-specific assessment. Differences in the level of details, with some sectors (e.g., packaging) more explored than others (e.g., healthcare and fishing) are also evident. In the case of polymers, a lack of common classification is also frequent, limiting aggregability and comparability of results reported by different studies.

Recent attempts (Amadei et al., 2022; Hsu et al., 2021) at calculating EU mass-flows based on annual statistics (such as the PRODCOM database, Eurostat, 2022a) suggests that MFAs could be built on annual product-based consumption data. This approach could limit methodological inconsistencies between different studies, although assumptions are necessary to derive mass-based flows from available statistics (e.g., units' conversion to mass; assumptions on the plastic content of products under a specific category; etc.). A key asset in enabling the EU foreseen targets in the plastic value chain, is the knowledge about recycled plastics production and recycled plastics (i.e., "recyclates") fate in the manufacturing process of new products. Few in-depth assessments of recyclates generation and fate (i.e., upcycling, downcycling, sectors of origin of recycled plastics and sectors of destination of recycled plastics) are available to date. Notably, in the study proposed by Watkins et al. (2020) a model aiming at mapping product flows from waste generation to the second life is set up, with the idea of investigating the potential fate of the plastic recyclates (i.e., sectors of origin and sectors of destination of plastics' recyclates).

To fulfil the EU ambitions in the context of the plastics value chain, further efforts are needed to further improve the granularity and details of overviews of plastic flows in the EU. Such enhancements could include better sector-specific and polymer-specific data for less explored sectors (such as textiles and clothing, fishing, or healthcare), coupled with in-depth knowledge of recyclates fate, and both losses and mismanaged waste flows. Considering these key commitments for actions at the EU level, an improvement and rethinking of the plastic value chain is needed and should be driven by an up-to-date knowledge of all its many hotspots.

1.2 Objectives and scope of the study

In this wide policy context and pursuing research objectives in the plastics field, this study aims at establishing a mass flow model for the whole value chain of plastics in the EU27 for the year 2019, from pellets production to end-of-life plastic management and recyclates production. The model includes details for a total of 9 sectors (i.e., packaging, construction, transport, Electrical and Electronic Equipment (EEE), agriculture, textiles and clothing, healthcare, fishing and other). Plastic flows for 10 polymers (i.e., low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), expanded polystyrene (EPS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), styrene-based polymers (acrylonitrile butadiene styrene (ABS), acrylonitrile styrene acrylate (ASA), styrene acrylonitrile resin (SAN)), polyamides (PA) such as nylon6 (PA6) or nylon66 (PA66), polyurethane (PUR)) were also modelled for the packaging, construction, transport, EEE and agriculture sectors.

Despite a growing interest in addressing plastic flows in recent years (Section 1.1) comprehensive studies enabling detailed assessments across multiple sectors and polymers along the whole value chain are lacking, especially including consideration on losses and recycled plastics fate. In this context, this paper aims to:

- Assess the plastic flows within the EU27 for the year 2019, not only detailing the demand of plastic manufacturing and consumed plastic, but also waste management and recyclates production and fate, as well as modelling the main plastic losses to the environment along the value chain. The assessment aims to shed light on the main data gaps and inconsistencies concerning available data and to provide estimates also for less explored sectors, such as the textiles and clothing, healthcare and fishing sectors.
- Detail the amount of recyclates produced from each sector and the sector of destination of such recyclates in the context of the manufacturing of new plastic products. This assessment aims at highlighting the current state of play in the EU in the context of the 10 million tonnes of recycled plastics consumed in EU27+UK target set by the Commission (EC, 2018a) and endorsed by the Circular Plastics Alliance (CPA, 2019) [corrected to 8.8 million tonnes of post-consumer recyclates for EU27 to enable a fair comparison with the results of the present study].
- Understand which future scenarios could ensure a sufficient feedstock for reaching the target of 8.8 million tonnes of post-consumer recyclates used annually in the EU27 by 2025 and provide recommendations on potential actions to be employed for enhancing the recyclability of plastics and the generation of sufficient amount of recycled plastics.

Among the collected literature information, when possible, data from two sources were prioritized to model specific steps in the value chain:

- To model plastic product manufacturing, consumption and trade, details from the consumption statistics-based approach described by Amadei et al. (2022) were prioritized in the present study. The analysis of Amadei et al. (2022) proposes two estimates of plastic consumption in the EU27 (for the year 2014): (a) an estimate which built on a literature-based approach and (ii) an estimate built on a consumption statistics-based approach (based on data retrieved from PRODCOM; Eurostat 2022a). In the case of the consumption statistics-based approach, each PRODCOM code relates to a plastic product or to products including other materials beside plastics. Each code was then mapped by economic sector (namely: packaging, construction, transport, Electrical and Electronic Equipment (EEE), agriculture, textiles, clothing, healthcare, fishing and other) and corrected to express its plastic content in terms of mass. In the supplementary material of the study, the full list of PRODCOM codes and the specific assumption for each code is provided, including data concerning the share by economic sector of PRODCOM codes attributable to different sectors.

- To model the end-of-life management of separately collected plastics, the recycling phase and the recycled plastics production and fate (i.e., rate of utilization within new plastic products across different sectors), the study from Watkins et al. (2020) was employed. This aimed at supporting the Circular Plastic Alliance (CPA, 2019) target of 10 million tonnes of recycled plastics to be used annually in the EU27+UK by 2025 (adapted to 8.8Mt of post-consumer recyclates for EU27 for a fair comparison with the results of the present study). Based on a list of "priority products and product groups" (for the agriculture, packaging, electrical and electronic equipment (EEE), construction and automotive sectors) the distance from the 8.8 million tonnes target is analyzed, by modelling plastic flows through data for the 2014-2018 years' range. The assessment of Watkins et al. (2020) is based on a bottom-up approach, where polymer-specific information for each of the identified priority products is considered. From these data, sector-specific insights are also provided. To understand if the EU recycling plants could have the necessary feedstock to meet the abovementioned target, a waste management perspective was considered for the plastic flows accounting. In the present study, the information from Watkins et al. (2020) represented a key starting point to mapping waste plastic flows, and especially for detailing the potential fate of the plastic recyclates (i.e., to be absorbed into the same sector from which they originated or into different sectors).

These two literature references were prioritized as their coverage in term of sectors as well as recyclates fate enabled to capture with a considerable level of detail the plastic flows in the EU context. In particular, the consumption-statistics approach proposed by Amadei et al. (2022) could represent a basis for establishing a dynamic procedure for calculating sector-specific consumptions in the EU, as PRODCOM data are updated yearly. The results of the study from Watkins et al. (2020) represented a prime example of a model detailing the fates of recycled plastic flows, being mostly based on primary data from industries.
To model the full plastic value chain in scope of the present study, data retrieved from several other literature references beside the study from Amadei et al. (2022) and Watkins et al. (2020) were collected and coupled with specific assumptions when data gaps were identified.

An estimation of plastic losses and mismanaged waste was also integrated, to detail the stage at which plastic losses may occur and lead to releases to the environment (i.e., to water and soil). In fact, microplastics (recognized as small sized plastic debris of less than 5 mm in diameter) are nowadays commonly found in the marine environment and knowledge on their impacts on both environment (e.g., Gregory, 2009) and on human health and the biota (e.g., Wagner & Lambert, 2018; Yang et al., 2015) is currently limited. To calculate the plastic emissions to the environment a bottom-up approach was employed, based on the 'Plastic Leak Project' (PLP) (Peano et al. 2020). Peano et al. (2020) propose a bottom-up approach for analyzing the plastic leakage of both macro- and microplastics along the supply-chain of products, as well as the amount and fate of mismanaged waste (defined as inadequately disposed waste, which could be inappropriately disposed (e.g., open dumps, unspecified landfills, unaccounted, etc.) and/or treated and that could create routes for potential losses and releases in the environment).

2 Methodology

The present study aims at developing a material flow assessment (MFA) model of plastic flows in the EU27 for the year 2019, at the level of sectors and polymers. The MFA models aims at detailing the mass of plastics flows (expressed as ktonnes or megatonnes) along the main steps of the value chain of plastics. A plastic flow is understood as single flow at sector level (e.g., in the case of the packaging sector, a "packaging plastic flow" represents a general plastic flow for the "packaging" sector). Plastic flows might be composed of several polymers. A polymer flow is instead understood as a flow expressed directly at the level of specific polymers (e.g., in the case of the packaging sector, a "LDPE packaging plastic flow" represents specifically a polymer flow for the "packaging" sector).

The model development followed a four-stepped procedure: (i) a literature review was performed to gather all the relevant data points for building the mass flow models and key literature sources were identified; (ii) data adjustment was performed to adapt the data to a common reference (EU27 2019); (iii) a MFA of EU plastic flows by different economic sectors was estimated; (iv) MFAs of polymers for a subset of the different economic sectors selected at point (iii) were derived following a top-down approach.

2.1 Literature review

Studies were collected through a search on the Scopus® database (Scopus, 2022) aimed at gathering documents related to material flow assessment at level of sectors and polymers in the EU. Several keywords were considered for screening the literature documents (titles and abstracts), such as: "mass flow model plastics"; "plastics Europe"; "plastic flows"; "material flow assessment Europe"; "plastic polymers Europe". Following a similar screening approach and leveraging on snowball sampling, other literature sources (such as reports) and additional references were collected. The temporal scope of the search was 2000-2022 and EU-based studies or studies providing sector-specific or polymer-specific information were prioritized.

As indicated in Section 1.2, the study from Amadei et al. (2022) and Watkins et al. (2020) were considered as key sources for modelling the consumption step and end-of-life step of the value chain respectively.

2.2 Data correction for the material flow analysis

A data adjustment step was necessary to align the data collected through the literature review to the same geography and temporal scope. The correction was based on the Gross Domestic Product (GDP) (The World Bank, 2022), was performed when needed to adapt the plastic flows to EU and to 2019. The adaptation followed a country- or region-specific approach, as explained by Equation 1.

$$Plastic\ flow_{EU27,2019} = Plastic\ flow_{Country\_i,year\_j} * \frac{GDP_{EU27,2019}}{GDP_{country\_i,year\_j}} \quad (1)$$

Where:

- Plastic $flow_{country\_i,year\_j}$: consumption of a specific plastic flow for a specific country and a specific year;
- $GDP_{EU27,2019}$: GDP in EU for the year 2019 (Eurostat, 2022b);
- $GDP_{country\_i,year\_j}$: GDP for a specific country and a specific year.

2.3 MFA of EU plastic flows at the level of sectors

The MFA model was established following a three-stepped procedure: (i) definition of the MFA system boundaries and assessed sectors; (ii) generation of a transfer coefficients (TCs) matrix at sectors' level based on literature data and dedicated assumptions; (iii) calculation of the plastic flows along the modelled value chain.

A key objective of this study is to estimate the overall plastic flows in the EU, including recyclates production. The model was therefore analysed through a hotspot analysis to identify the most relevant assumptions on the modelled flows and produced recyclates. The hotspot analysis enabled the identification of key TCs in the modelled system: their variations were tested by a sensitivity assessment. A series of scenarios for the year 2025 were then prepared in view of understanding potential room for improvement in the overall circularity of the plastic system, and under which conditions the 8.8 million tonnes recycled plastics target of the EU/CPA could be achievable.

2.3.1 System boundaries

In the MFA model the following sectors were considered: packaging, construction, transport, Electrical and Electronic Equipment (EEE), agriculture, textiles and clothing, healthcare, fishing and other (hence the MFA model is representative of the full EU market). Key sectors included in the study were based on the analysis performed by Amadei et al. (2022), and on other recent MFA of plastics (such as Kawecki et al. (2018), Kawecki et al. (2021) and Hsu et al. (2021)).

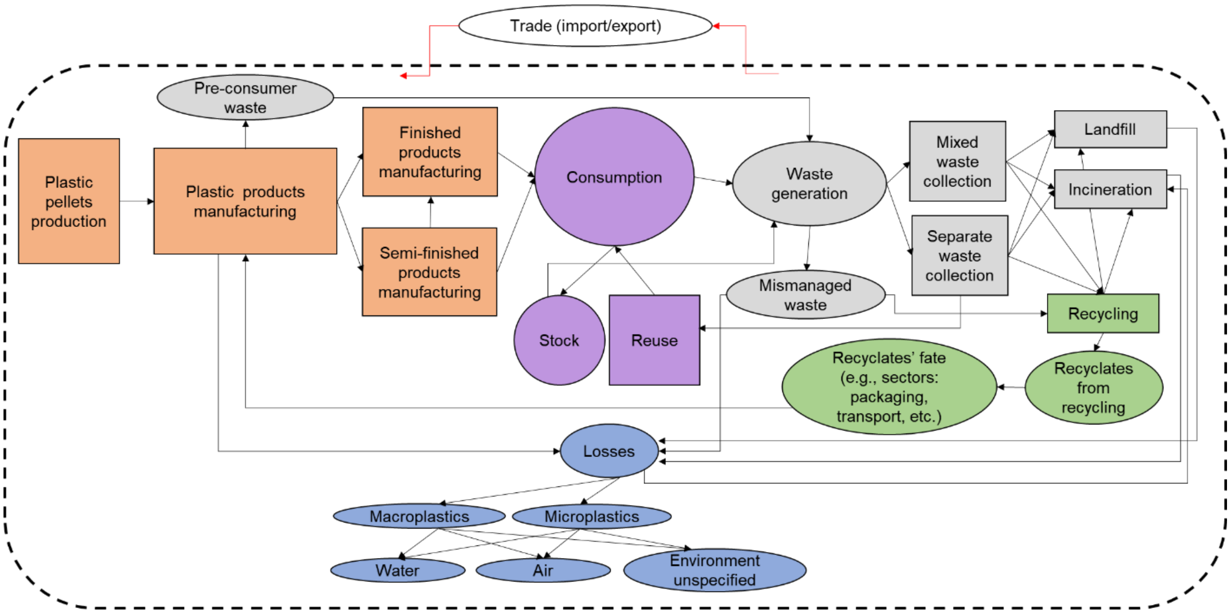
Table 1 provides a brief description of the sectors included in the present work.

Table 1. Details on the sectors included in the study (note: EEE = Electrical and Electronic Equipment).

Sector	Description and details
Packaging	This sector includes plastic products and the plastic components of products serving the purpose of protecting other products through a physical barrier (e.g., bottles, films and bags, etc.).
Building and construction	This sector includes plastic products and the plastic components of products employed in the field of buildings and constructions (e.g., mattresses, floor coverings, plastic doors, plastic lavatory seats and bidets, etc.).
Transport	This sector includes plastic products and the plastic components of vehicles and automotive, and other similar means of transport and other (e.g., tyres, vehicles' parts such as bumpers, etc.). Transport such as freight and other transport operators are not included.
EEE	This sector includes plastic products and the plastic components of Electrical and Electronic Equipment (e.g., household appliances, electrical tools, Information and Communications Technology (ICT), toys, electronic sport equipment, lighting, etc.).
Agriculture	This sector includes plastic products and the plastic components of products related to the agriculture field (e.g., agricultural twines, tubes and pipes, etc.).
Textiles and clothing	This sector includes plastic products and the plastic components of products related to the textiles and clothing/apparel sectors (e.g., knitted or crocheted products, yarn filaments, t-shirts, trousers, etc.).
Healthcare	This sector includes plastic products and the plastic components of products related to the medicine and medical field (e.g., syringes, disposable gloves, etc.).
Fishing	This sector includes plastic products and the plastic components of products being employed in the fisheries sector (e.g., nets, bobbins, other fishing tools, etc.).
Other	This sector includes the plastic products and plastic components of products not classified in any of the other sectors (e.g., personal care and cosmetic products, household plastics, etc.).

The system boundary (Figure 2) was drafted to include all the main steps involved in the life cycle of the plastics, from plastic pellets production to end-of-life (EOL) management operations and recycled plastics production.

Figure 2. Simplified diagram of the system boundaries included in the MFA model at sectors level.



Each box included in the MFA (Figure 2) is considered a "node" or "step" of the plastic value chain. In the context of the present study, each node could either represent:

- A simplification of an industrial process/collection of multiple industrial processes, represented in Figure 2 with a rectangular shape - e.g., the node "recycling" includes all the activities (i.e., dismantling phase, sorting phase, recycling phase) related to the recycling of plastics -.
- A "step/action" of the value chain of plastics, (e.g., the node "waste generation" represents the moment in which a plastic waste is generated from consumption) or a relevant output of a given process about the overall goals of the present study (e.g., "recyclates" are intended as the output of the recycling process), both being represented in Figure 2 with an oval shape.

In Figure 2, the same colour was used to visually differentiate between major steps in the plastic value chain (i.e., orange for plastic production and products manufacturing; violet for consumption; grey for waste management/mismanagement and green for recycling and blue for losses and releases). To ensure that the mass balance is preserved, plastic inflows equal plastic outflows from each node.

The system boundaries cover the value chain of plastics, starting from the plastic pellets production and excluding other previous phases (e.g., oil raw material extraction, crude oil distillation). Other raw materials or plastic additives were not included in the assessment. Plastic pellets production includes the total (i.e., primary plastic and secondary plastic from recycling) production of plastic pellets and represents the input mass to the overall model. Plastic pellets from plastic producers are handled by plastic product converters/manufacturers.

During the manufacturing/conversion step, pellets are assumed to be transformed into either "finished" or "semi-finished"/"intermediate" products. Semi-finished products are intended as products that could be either used as inputs for other finished goods, or products directly sold to consumers, as indicated by Amadei et al. (2022). Examples of semi-finished products include plastic plates, sheets, tubes, and profiles. A series of specific assumptions were employed to distinguish between: (i) semi-finished products exploited in the manufacturing of finished products from (ii) semi-finished products which are directly available for consumption (described in Annex 1). This approach aimed at reducing the potential effect of double counting that may occur if a semi-finished product plastic mass is already accounted in the total mass of the related finished products. Waste arising from plastic product manufacturing (i.e., "pre-consumer waste") was estimated only for the packaging sector, due to data gaps. Trade of both semi-finished and finished products was included in the model. Pellets may be emitted during the manufacturing phase: such pellet losses and the related releases/emissions to the environment were estimated based on the methodology detailed in the 'Plastic Leak Project' (PLP) (Peano et al., 2020). A detailed overview of the approach followed for estimating losses along various steps of the value chain is detailed in Annex 2. Overall, the model estimates macro- and microplastic releases to soil, to water, to environment unspecified (if no specific details are available) and recollections of lost plastics to incineration.

“Microplastics” are intended as small sized plastic debris of less than 5 mm in diameter (if higher than 5 mm, such debris are instead intended as “macroplastics”) which are nowadays ubiquitous in the marine environment and that could be linked to impacts not only in the biota but also on humans, due to their presence in seafood products (Yang et al., 2015).

The sector-specific apparent EU consumption was calculated as indicated by Equation 2, based on the mass flows of plastic products manufacturing (both finished and semi-finished products):

$$Apparent\_consumption_{sector_i,year_j} = Production_{sector_i,year_j} + Import_{sector_i,year_j} - Export_{sector_i,year_j} \quad (2)$$

Where:

- $Production_{product\_i,year\_j}$: represents the mass of plastic related to a specific sector produced in the EU territory for a specific year (i.e., plastic products manufacturing);
- $Import_{product\_i,year\_j}$: represents the mass of plastic related to a specific sector imported in the EU territory for a specific year;
- $Export_{product\_i,year\_j}$: represents the mass of plastic related to a specific sector exported in the EU territory for a specific year.

In case of semi-finished products, Equation 2 was applied only to the mass of semi-finished products destined for consumption. The remaining mass of semi-finished products was assumed to be already accounted in the consumption of finished products, and therefore removed from the model to avoid double counting. Consumed plastics could either be discarded as waste, lost (see Annex 2) or maintained in “stock”.

In the context of the present study, a “stock variation” was assumed and calculated as the difference between the plastic consumed and the plastic waste generated from consumption. A “positive stock variation” represents a situation in which the amount of waste generated is lower than the amount of plastic consumed. A situation in which waste generation is higher than the consumed amount was modelled as “negative stock variation”: in this case, plastics accumulated within a sector stock is partially or entirely discarded in the year 2019. As the present study aims at estimating the MFA for the year 2019, properly capturing the effect of stock variation linked to products’ lifetime was out-of-scope (Section 4.3).

The total amount of waste generated could be either (i) separately collected, (ii) collected as mixed waste, (iii) mismanaged (see Annex 2), (iv) lost (see Annex 2) or (v) exported. Import of waste was also considered at this stage and included in the total mass of plastic waste generated.
Plastic collected as a separate stream refers to the amount of plastics which is kept separate from other materials and managed as a specific stream of plastic. Plastics collected separately could either be recycled, incinerated, landfilled, or prepared for reuse and reused (both steps included under “reuse” in the present study). The amount of separately collected waste assumed to be reused was ultimately sent back the consumption step. All additional steps related to the management of plastic waste as a separate stream before recycling (e.g., sorting, cleaning, etc.) are intended as included within the separate collection step (node named “Separate waste collection” in Figure 2) and were not modelled individually.
Plastic collected as a mixed stream refers to the amount of plastics which is not kept separate from other materials and managed as a mixed stream of waste (i.e., a waste stream that includes plastics among other materials). Incineration and landfill were modelled as the two specific destinations for plastic collected as a mixed stream. Only in the case of the mixed plastic waste stream for the packaging sector, a certain amount of waste was assumed to be sorted from the other waste fractions and sent to recycling. All additional steps related to the management of plastic waste as a mixed stream (e.g., sorting, cleaning, etc.) are intended as included within the mixed collection step and were not modelled individually.

Recycling of plastic waste includes all the activities and processing steps aimed at converting waste plastic into suitable input material (i.e., recycled plastics or “recyclates”/”secondary plastics”) for the manufacturing of new plastic products. In the present study, mechanical recycling of plastic was not distinguished from chemical recycling of plastics.
The total amount of recyclates from a specific sector was allocated between the inflow of secondary plastic to

the plastic manufacturing step and an exported amount. The inflow of secondary plastic to the plastic manufacturing step was also detailed in term of final receiving sector (e.g., recyclates arising from the packaging sector could be employed in the manufacturing of products for the packaging sector, for the building and construction sector, for the transport sector, etc.).
Besides recyclates, other outputs from the recycling step (i.e., residues from the process) were either sent to incineration or landfill.

In the incineration step, waste is converted into energy, flue gas and heat.
The landfill step receives waste from several other steps of the value chain (Figure 2) and is considered as a step of final disposal of waste. From both the incineration and the landfill steps losses to the environment may occur, as described in Annex 2.

2.3.2 Generation of a transfer coefficient matrix at sectors level

Beside nodes, each MFAs is also described by TCs. Each TC (expressed in %) enables the allocation of the total plastic flows inputs in a node to the various output flows from that node. TCs are expressed as % and must add up to 100% to maintain the mass balance of each node.

The various steps of the value chain presented in Section 2.3.1 were analyzed and modelled for each of the selected sectors, by employing data-points gathered from various literature references. Data-gaps were recognized and assessed leveraging on (i) proxies from other sectors, (ii) non-sector-specific information (i.e., established on "total plastic flows", not detailed at the level of sectors) or (iii) assumptions based on expert judgment.

For each sector, the modelling steps is characterized by the estimation of the set of TCs of each node. A complete overview of each node, TCs and employed literature source/modelling approach is detailed in Annex 3.

2.3.3 Calculation of the plastic flows at sector level

The estimated TCs sets (Section 2.3.2) were employed to calculate the MFAs of each plastic sector included in the present study (Section 2.3.1).

The approach followed to calculate the full MFAs for each sector was the following:

- The plastic mass input of each sector was calculated as the sector-specific plastic demand. The total plastic demand was estimated for EU27 from Plastics Europe (PlasticsEurope, 2019). Following a top-down approach, the total demand in EU27 was allocated to the various sectors. From Plastics Europe (PlasticsEurope, 2020) it was possible to derive the share of raw material demand for the sectors packaging, building and construction, transport, EEE and agriculture. The remaining demand was allocated between the textiles and clothing, healthcare, fishing and other sectors leveraging on the sector-specific production of semi-finished and finished products, estimated from Eurostat (2022a) following the "consumption-statistics approach" described in Amadei et al. (2022).
- The full MFA of each sector was modelled separately starting with the abovementioned input mass and calculating each inflow and outflow from nodes based on the sector specific TCs sets. Each full MFA (i.e., each MFA of the 9 sectors under assessment) covered the entire system described in Figure 2.
- By calculating the sum of the flows of all sectors in a specific step of the value chain, a "total plastic" flow for that specific step was derived. Therefore, it was possible to estimate an additional full MFA, comprising plastics from each sector (named "total plastic" MFA).

Leveraging on the calculated mass flows, it was possible to calculate "ratios" or "rates" between flows and steps in the value chain. A "ratio" is intended as the mathematical quotient between two mass plastic flows in two different steps of the value chain (for instance, in the present study, "end-of-life recycling rate" refers to the ratio between the estimated recyclates produced and the total plastic waste generated).

2.3.4 Sensitivity assessment

To highlight the most relevant constraints in the modelled MFAs (called in the present report "Base Scenario"), a sensitivity assessment of the main assumptions/transfer coefficients was performed. The approach followed for the sensitivity assessment was structured as follows: (i) a hotspot analysis was performed in view of identifying the most relevant TCs employed in the MFA model. A TC was considered relevant if it could significantly affect the whole model, especially the estimated total recyclates production. The screening covered all steps of the value chain where a dedicated approach or assumption were necessary to model a certain plastic flow (e.g., the assumption related to the consumption of semi-finished products). In addition, the screening was also focused on all end-of-life management options, waste mismanagement assumptions and waste trade, to understand those mostly impacting the overall recycling rates and recyclates consumption rates of the Base Scenario; (ii) assessment of the effects on the overall model due to variations on the identified assumption and TCs (this analysis was based on a series of "sensitivity assessment alternative cases", see Table 2). The assumptions related to the end-of-life management of the healthcare and fishing sectors were specifically analyzed in a dedicated sensitivity alternative case, due to the data limitations for modelling these sectors; (iii) comparison of the results of the MFA models (Base Scenario vs sensitivity assessment cases). Within a sensitivity alternative case, a set of TCs is varied one by one while maintaining the remaining transfer coefficients at a constant value. The sensitivity assessment cases represent test cases aimed at understanding the most impactful assumptions on the overall model (i.e., a sensitivity assessment cases might be a non-realistic scenario in the real plastic value chain).

Table 2 summarizes the tested sensitivity assessment alternatives.

Table 2. Scenarios tested for the sensitivity assessment on the MFAs models.

Identifier	**Sensitivity assessment alternative cases' name**	**Base Scenario**	**Sensitivity assessment alternative cases**	**Varied TCs**
1	All manufactured products are consumed	In the Base Scenario, a distinction between the semi-finished and finished products was established, as described in Annex 1, to differentiate between the manufacturers' demand/consumers' consumption of plastics from semi-finished products and plastics from finished products, and the related consumption.	In the sensitivity assessment alternative case it was assumed that all plastic demand for the manufacturing of new products is ultimately consumed. In this case, all products (either semi-finished or finished) are directly consumed (i.e., the assumption that a certain amount of semi-finished products is employed in the manufacturing of finished products is removed).	For all sectors, TCs distinguishing between finished products and semi-finished products were set to 0, and it was assumed that all the plastic demand is consumed (the entirety of the manufacturers' plastic demand was assumed to be converted into products that are directly sold to consumers).
2	Only finished products are sold to end consumers	In the Base Scenario, a distinction between the semi-finished products sold to consumers and the semi-finished products employed in the manufacturing of finished products was established, as described in Annex 1.	In the sensitivity assessment alternative case it was assumed that all semi-finished products are employed for the manufacturing of finished products (i.e., no semi-finished products sold directly to consumers).	For all sectors, TCs from semi-finished product manufacturers to consumption were set to 0 (the entirety of the semi-finished products flows was assumed to be needed to manufacture finished products and modelled as described in Annex 1).

Identifier	Sensitivity assessment alternative cases' name	Base Scenario	Sensitivity assessment alternative cases	Varied TCs
3	Reduced stock variation	In the Base Scenario, the stock variation was modelled to identify the plastic currently in-use for each sector.	In the sensitivity assessment alternative case it was assumed that the assumed stock volumes are 50% lower, and that the corresponding waste generation is 50% higher.	For all sectors, TCs from consumption to stock were reduced by 50%, whilst all TCs from consumption to waste generation were increased by 50%.
4	Absence of waste trade	In the Base Scenario, the trade of waste generated was modelled according to Annex 3.	In the sensitivity assessment alternative case it was assumed that no waste trade occurs.	For all sectors, TCs related to the trade of waste generation were set to 0.
5	Absence of mixed waste collection	In the Base Scenario, the management of the waste generated was distinguished between flows following a separate plastic collection stream and flows following a mixed waste collection stream.	In the sensitivity assessment alternative case it was assumed that no mixed waste collection occurs.	For all sectors, TCs related to the management of waste flows as mixed waste were put to 0 (the entirety of waste generated was assumed to be managed as a separate stream).
6	Absence of mismanaged waste	In the Base Scenario, a fraction of the waste generated was assumed to be mismanaged.	In the sensitivity assessment alternative case it was assumed that no mismanagement of waste occurs and that all the equivalent plastic waste mass is managed as separately collected waste.	For all sectors, TCs related to the mismanagement of waste were put to 0 (all mismanaged waste was assumed to be managed as separately collected waste).
7	Absence of mismanaged waste being recollected and recycled	In the Base Scenario, a fraction of the mismanaged waste was assumed to be recollected and sent to recycling, as described in Annex 2.	In the sensitivity assessment alternative case it was assumed that no mismanaged waste is recollected and recycled.	For all sectors, TCs related to the recycling of mismanaged waste were put to 0 (all mismanaged waste could either be lost to the environment as litter or be managed through unknown channels).
8	Revised mismanaged waste assumptions	In the Base Scenario, a fraction of the amount of waste generated within each sector was assumed to be mismanaged, as described in Annex 2.	In the sensitivity assessment alternative case it was assumed that only a fraction of the waste generated for the EEE sector, and the	TCs related to the mismanagement of waste generated were put to 0, excluding for the EEE and transport sectors (all mismanaged

Identifier	Sensitivity assessment alternative cases' name	Base Scenario	Sensitivity assessment alternative cases	Varied TCs
			transport sector was mismanaged. It was assumed that no mismanaged waste was generated for the EEE and transport sectors. Additionally, it was assumed that no mismanaged waste was sent to recycling.	waste arising from the EEE, and transport sectors could either be lost to the environment as litter or be managed through unknown channels).
9	Improved recycling performance	In the Base Scenario, a fraction of the waste entering recycling facilities was assumed to be sent to incineration and landfill.	In the sensitivity assessment alternative case it was assumed that no waste is sent to landfill from recycling facilities.	For all sectors, TCs from recycling to landfill were put to 0 (this amount of waste was assumed to be recycled instead).
10	Locked recycling performance	In the Base Scenario, waste entering recycling facilities was assumed to be either recycled or sent to incineration and landfill based on sector-specific assumption (Annex 3).	In the sensitivity assessment alternative case it was assumed that 50% of all waste entering recycling facilities is turned into recyclates.	For all sectors, TCs from recycling to recyclates were fixed to 50% (the remaining waste was managed either through incineration of landfill. The TCs for incineration were recalculated to close the mass-balance, whilst the TCs for landfill were kept constant as the Base Scenario).
11	Improved management of separately collected waste	In the Base Scenario, a fraction of the waste separately collected was assumed to be sent to incineration and landfill.	In the sensitivity assessment alternative case it was assumed that all separately collected waste is sent to recycling facilities.	For all sectors, TCs from separate waste collection to landfill and to incineration were put to 0 (all waste was assumed to be sent to recycling facilities instead).
12	No recyclates are exported	In the Base Scenario, a fraction of the produced recyclates was assumed to be exported.	In the sensitivity assessment alternative case it was assumed that all recyclates produced are used to manufacture new products within the EU boundaries.	For all sectors, TCs from recyclates to export were put to 0 (the entirety of recyclates were assumed to be sent to plastic products manufacturing).

Identifier	Sensitivity assessment alternative cases' name	Base Scenario	Sensitivity assessment alternative cases	Varied TCs
13	Revised assumption for the waste management of the healthcare and fishing sectors	In the Base Scenario, the TCs for the waste management of the healthcare and fishing sectors were modelled based on the assumptions described in Annex 3.	In the sensitivity assessment alternative case, it was assumed that all waste generated for the healthcare and fishing sectors is managed as mixed waste.	For the healthcare sector, the TCs from waste generation to separate waste collection were put to 0 (the entirety of waste generated was assumed to be managed as mixed waste, i.e., no recycling is assumed on the entirety of the waste generated from the healthcare and fishing sectors).

2.3.5 Scenarios for the year 2025

Based on the findings of the sensitivity assessment and leveraging expected trends of plastic production and plastic waste management, a series of simplified "2025 scenarios" were drafted. Such potential trends, together with the respective actions for each scenario, were inspired by some key literature sources (e.g., Systemiq et al., 2022) and coupled with expert judgment based on the underpinning EU policy background. These scenarios serve the purpose of understanding the hypothetical features of the plastic value chain in the near future (i.e., year 2025), bearing in mind the overall goal of the EU/CPA (EC, 2018a; CPA, 2019) of meeting the target of 8.8 million tonnes of post-consumer recyclates used in products for the EU27 market. These scenarios represent hypothetical future variations in some key steps of the value chain and could be put in the context of specific goals for plastics, like the EU/CPA target. A scenario could either be based on the analysis of the effects of the variation of a single TC (i.e., a single TC was varied, keeping constant all other TCs) or on the combination of multiple variations.

Table 3 summarized the parameters that were included in the scenarios assessment.

Table 3. Parameters included in the assessment of the scenarios for the year 2025.

Scenario identifier	Scenario name	Affected parameters	Description
A	Reduced waste export	TCs related to export outside the EU of waste generated from consumption.	Background Following the example of international waste bans on the import of plastic waste, such as China's waste import ban (ECA, 2020), it was assumed that waste export could decrease soon. The decrease could be driven by an additional ban from countries or an increase in the need of waste management within the EU borders. Action In this scenario, an absolute reduction of 10% of the exports of waste was assumed for the sectors packaging, building and construction, transport, EEE, agriculture, healthcare,

Scenario identifier	Scenario name	Affected parameters	Description
			fishing, other. A reduction of 20% was assumed for the total export for EEE and textiles and clothing.
B	Improved waste collection	Increase of the TC related to separate waste collection from total waste generation. Reduction of the TC related to mixed waste collection from total waste generation. Reduction of the TC related to mismanaged waste from total waste generation.	Background In the modelled MFAs, it was assumed that the plastic waste collected within the mixed waste stream could either be incinerated or landfilled. Currently, the EU sets a target of a maximum 10% of the total solid municipal solid waste to landfill after 2035, according to the Landfill Directive (EC, 1999). Although the most likely destination of such waste could be incineration (Systemiq, 2022), it may also be assumed that the EU could continue its effort towards achieving circularity in the context of the resource-efficiency envisioned by the European Green Deal (EC, 2019b). Such plastic flows are assumed to be therefore deviated towards recycling in place of incineration. Plastics is also in scope of targeted actions set for 2030 by the European Strategy for plastics (EC, 2018a), which stems from the EU Circular Economy Action Plan (EC, 2015), aimed at establishing ambitious actions and measures covering the whole life cycle, from production and consumption to waste management and the market for secondary raw materials. The 2018 strategy proposes effective actions aimed at achieving a more circular plastics economy, including actions for better and more harmonised separate collection and sorting. Action For this reason, in this scenario it was assumed that the significant EU strive towards a plastic circular economy could lead to an increase of plastics being recycled instead of landfilled or incinerated. In this scenario, for packaging, an absolute reduction of 30% was assumed of the mixed waste collection, and a corresponding increase of 30% of separate waste collection. In the case of building and construction, agriculture, textiles and clothing, healthcare, fishing and other, a reduction of 10% was assumed of the mixed waste collection for packaging, and a corresponding increase of 10% of separate waste collection. In the case of transport and EEE, a reduction of 25% was assumed of the mismanaged waste, and a corresponding increase of 25% of separate waste collection (no variations in the estimated amount of

Scenario identifier	Scenario name	Affected parameters	Description
			mixed waste collection for these two sectors).
C	Improved management of separately collected plastic waste	Reduction of the TC related to incineration of plastic waste separately collected, and improvement in separately collected waste sent to recycling facilities.	Background Based on similar considerations as those illustrated for scenario B, it was assumed that a systematic improvement in the mixed waste stream management could also lead to an improved management of the separately collected plastic waste. Action In this scenario, for packaging, an absolute reduction of 15% was assumed of the separately collected plastic waste sent to incineration, and a corresponding increase of 15% in the separately collected plastic waste sent to recycling (starting from a TC for this sector equal to 75% related to sorting yields). In the case of building and construction, transport, EEE, agriculture, textiles and clothing, healthcare, fishing and other a reduction of 10% was assumed of the separately collected plastic waste sent to incineration and a corresponding increase of 10% in the separately collected plastic waste sent to recycling.
D	Improved recycling performance	Improvement in the recycling performance (reduction of waste residues sent to incineration from recycling and increased recyclates production).	Background Several EU policies affecting plastic waste (such as the Waste Framework Directive (EC, 2008) and the Packaging and Packaging Waste Directive (EC, 2018b)) have been introduced over the years. An increase in the total amount of recycled plastics could be listed not only among the goals of these legal acts, but also in the context of the European Strategy for Plastics (EC, 2018a). In the EU strategy, key plastic-related challenges are identified and an improved quality of recycled plastic together with a boosted demand for recycled plastic is envisioned. On top of these policy actions, similar efforts in the context of plastic recyclates production have been introduced by industries and industry associations (e.g., the EU/CPA (EC, 2018a; CPA, 2019) or the European Plastic Pact (EPP, 2022)). To achieve the ambitious targets set by policymakers and industries alike, a substantial growth in the entire recycling value chain would be necessary. Action For this reason, in this scenario, an absolute reduction of 20% was assumed of the amount of rejects that are sent to incineration from

Scenario identifier	Scenario name	Affected parameters	Description
			recycling facilities, and a corresponding increase of 20% in the recyclates production from recycling, in the case of the packaging sector (starting from a TC for this sector equal to 71% related to recycling yields). In the case of building and construction, transport, EEE, agriculture, textiles and clothing, healthcare, fishing and other a reduction of 10% was assumed of the amount of rejects that is sent to incineration from recycling facilities, and a corresponding increase of 10% in the recyclates production from recycling.
F: - F1 - F2 - F3	Combined scenarios and changes in plastic production	A combination of scenarios A, B, C, D and variations (+10% for F1; -10% for F2) or stagnation (0% variation for F3) in plastic production.	<u>Overview-(F1)</u> F1 refers to a combination of scenarios A, B, C, D. In this scenario, it was assumed that the overall plastic demand is increase by +10%. <u>Background-(F1)</u> A significant number of literature sources seem to indicate an increase of plastic production and demand should be expected soon. Projections by Plastics Europe and cited by the EEA (2021a) indicate a yearly-growth in the EU plastic demand of around 4.6% per-year, by employing estimated demand in the period 2010-2019. Such trends are also confirmed by the European Commission (EC, 2018a) as well as the Ellen MacArthur Foundation (EMAF, 2022). ------------------------- <u>Overview-(F2)</u> F1 refers to a combination of scenarios A, B, C, D. In this scenario, it was assumed that the overall plastic demand is reduced by -10%. <u>Background-(F2)</u> The Single-Use Plastic Directive (SUP Directive) (EC, 2019a) represents a crucial step in the prevention and reduction of potential releases and impacts of certain plastics products in the EU, and its effect could produce a reduction in plastic demand. Based on the potential effects of the SUP Directive and considering the recent economic effects on the EU of the COVID-19 outbreak and the war in Ukraine, a reduction of 10% in plastic production is assumed. ------------------------- <u>Overview-(F3)</u> F1 refers to a combination of scenarios A, B, C, D. In this scenario, it was assumed a stagnation in plastic production (i.e.: 0%

Scenario identifier	Scenario name	Affected parameters	Description
			variation in plastic demand). <u>Background-(F3)</u> Along the lines of scenario F2, considering the potential effects on the EU of the recent economic and social effects of the COVID-19 outbreak and the war in Ukraine, a stagnation on plastic production is envisaged in this scenario (0% variation in plastic demand).

2.4 MFA of EU plastic flows at the level of polymers

The MFA models at polymer level were established leveraging on the sector specific MFA presented in section 2.3, with the goal of estimating polymers flows in the EU from production to end-of-life. A three-stepped approach was followed: (i) analysis of available literature information for each polymer and each sector and selection of polymers and sectors to be analyzed; (ii) allocation of the total plastic production per sector to the most relevant polymers within a sector; (iii) generation of a polymer-specific transfer coefficient (TC) matrix and calculation of the various MFA models. The following sections describe in detail each methodological step for the polymer-specific MFAs.

2.4.1 Top-down approach for polymers MFA

Due to the differences in the granularity of information for polymers, the availability of data for each step of the value chain considered in the study (Figure 2) varied considerably among literature sources. To establish a polymer-specific MFA each literature source was screened for: (i) a comprehensive end-of-life assessment of polymer flows, detailing the management approach (i.e., collection performances, overall recycled, incinerated, and landfilled amount) and the recyclates production and sector-specific destination; (ii) the breakdown of the main polymers in the current value chain of a sector. In particular, the collected literature data exhibited a polymers-level granularity deemed sufficient for estimating MFAs for the following sectors: packaging, construction, transport, EEE and agriculture. For each of these sectors, information available enabled a detailed assessment of the following polymers: low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), expanded polystyrene (EPS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), styrene-based polymers (acrylonitrile butadiene styrene (ABS), acrylonitrile styrene acrylate (ASA), styrene acrylonitrile resin (SAN)), polyamides (PA) such as nylon6 (PA6) or nylon66 (PA66), polyurethane (PUR). A general “other polymers” category was also created, to include unspecified polymers and other plastics (i.e., polymers such as polycarbonates (PC), poly(methyl methacrylate) (PMMA) or other thermoplastics polymers were included within this category).

To model the polymer-specific MFAs of each of the selected sectors, a top-down approach was adopted. The input to each polymer-specific MFA was modelled starting from the sector-specific total amount of plastic demand. Polymer-specific shares were applied to sectors demands in EU27 to derive the corresponding polymers demands. A polymer-specific share indicates the amount (%) of the polymer plastic demand within a sector. The polymer-specific shares were calculated based on the information available from Plastics Europe (PlasticsEurope, 2021) for the packaging, building and construction, EEE and agriculture sectors. In the case of the transport sector, an average of the polymer-specific shares derivable from PlasticsEurope (2020) and Maury et al. (2022) was estimated.

2.4.2 Generation of a transfer coefficient matrix at polymers level

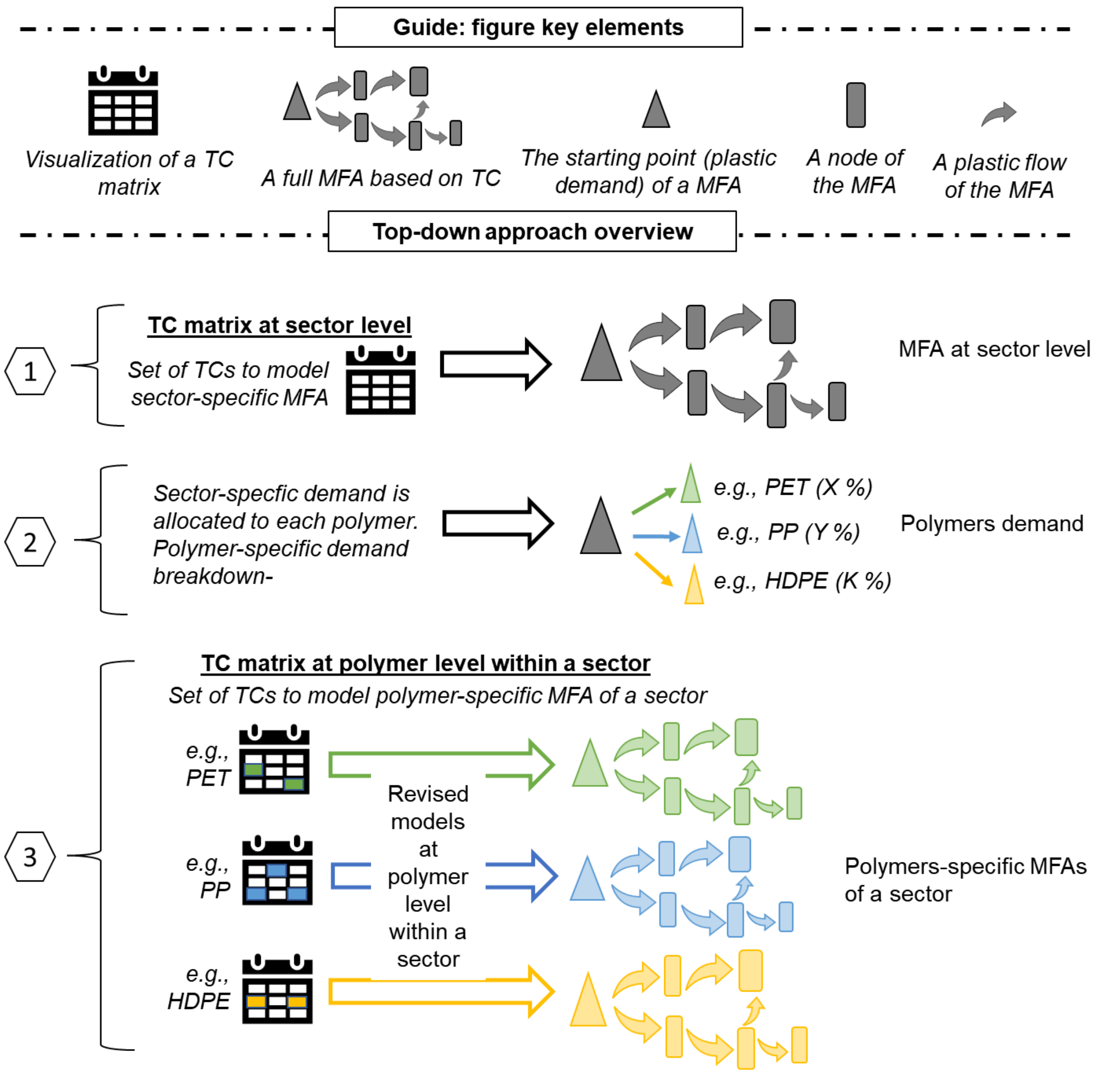
A series of dedicated TC matrixes were modelled to establish the polymer-specific MFAs for each of the selected sectors. To derive such matrixes, the following procedure was adopted (all assumptions are detailed in Annex 4):

- The polymer specific demand for each sector was derived as described in Section 2.4.1.
- For the pre-consumption phase (i.e., from manufacturers demand to consumption, Figure 2): the TC matrix for each polymer was based on the TCs modelled for the whole sector, as the focus of the polymer assessment is to detail the main differences in terms of polymer management at the end-of-life.
- For the collection of the waste generated (i.e., allocation between mixed waste management/separate waste management): the TCs for each polymer were derived from Watkins et al. (2020) in the case of building and construction, transport, EEE and agriculture, and as an average between the information retrieved from Watkins et al. (2020) and Antonopoulos et al. (2021) in the case of packaging.
- For the management of separately collected waste, the modelling of recycling step and recyclates production and sector-specific destination for each polymer stream: the TCs for each polymer were derived from Watkins et al. (2020) in the case of building and construction, transport, EEE and agriculture, and as an average between the information retrieved from Watkins et al. (2020) and Antonopoulos et al. (2021) in the case of packaging.

An overview of the described top-down approach to derive MFAs at polymers level is summarized in Figure 3:

- For a given sector, polymer-specific shares (in green, blue and orange) were applied to derive the total demand per polymer within a given sector [see step 2 of Figure 3].
- Polymer-specific Transfer Coefficients (TCs) were prepared to model the end-of-life management and recyclates fate of each polymer within a sector. When available, the polymer-specific TCs were included only for modelling the end-of-life phases (see Annex 4) and complemented with sector-specific TCs for all other steps [see step 3 of Figure 3].
- Polymer-specific MFAs were prepared having as input the polymer-specific demands of a given sector and the polymer specific TCs (when available) detailing the end-of-life steps of the value chain.

Figure 3. Overview of the top-down approach for building the polymers material flow analysis (MFAs) within a sector. (Note: TC = Transfer coefficient; MFA = Material Flow Analysis).



2.4.3 Calculation of the plastic flows at polymers level

The estimated TCs sets (Section 2.4.2) were employed to calculate the polymer-specific MFAs for each sector included in the present study (Section 2.4.1). Similarly to the approach described in Section 2.3.3, the polymers-specific MFAs for each sector were derived by calculating the polymer-specific total demand for each sector (as described in Section 2.4.1) and calculating each inflow and outflow from nodes based on the polymer-specific TCs set. Each full MFA covered the entire system described in Figure 2. By calculating the difference between the total sector-specific plastic flows and the sum of the calculated polymer-specific flows in a specific step of the value, a “other polymers” flow for that specific step was derived (Section 2.4.1).

3 Results

The literature review yielded a total of 89 studies, which served as the basis for the sector-specific assessment as well as for the polymer-specific assessment. A total of 26 studies referred to the EU (EU28, EU27 or unspecified), whilst most of the other collected studies were either studies related to the whole worldwide plastic economy or dealing with country-specific value chains (predominantly UK, Norway, China, Spain and other EU countries). Most of the collected data referred to recent years (such as 2017, 2016, 2018 and 2019), with few relevant recent studies providing data for the year 2000s. When needed, data were corrected as described in Section 2.2.

3.1 Material flow analysis and sector-specific results

The overall results of the MFA of EU plastic flows at the level of sectors are illustrated in Figure 4 and Figure 5. From Figure 4 and Figure 5, the leading role of some sectors is evident compared to others in terms of plastic flows along the key steps of the value chain, from plastic pellets production to end-of-life. Packaging was the most important sector in terms of plastics flows in the EU27, not only concerning consumed plastics (33% of total plastics), but also the amount of post-consumer plastic waste generated (70% of total post-consumer plastic waste generated). Besides packaging, the construction sectors manifested the highest contribution in terms of consumed plastics (23% of total consumed plastics), although most of the plastic from this sector remained in stock for the year 2019 instead of being discarded (63% of consumed plastics). The heterogeneous 'other' sector ranked third regarding plastic consumption (17% of total consumed plastics), followed by the transport (10% of total consumed plastic) and the EEE sector (8% of total consumed plastics). For both transport and EEE, results suggested that a high amount of generated plastic waste is being mismanaged (32% and 33% out of the total waste generated, respectively), which hindered the amount of plastic waste available for a proper end-of-life management.

To provide a global overview of the plastic flow assessed, the main findings at the level of all sectors are summarized in Table 4. The manufacturing of finished products contributed to 80% of the total plastic consumption (44.7Mt), with the remaining amount attributable to direct consumption of semi-finished products. Waste generated from consumption amounted to 64% of the total consumed plastics, with 34% kept in stock, and the remaining 2% lost during use. Considering that 1.94Mt of waste are being exported (Table 4), results indicate that 48% of waste being collected as mixed waste stream and 39% as a separate fraction, with mismanaged waste also having a relevant role in the overall figures of waste management (13% of waste generated being mismanaged). Overall, 65% of separately collected waste (equal to 6.51Mt, representing 23% of the total waste generated) are sent to recycling. An amount equal to 31% of the total plastics entering the recycling step (8.66Mt, including imports) are not being converted into secondary plastic, as they are either sent to incineration or landfill. Packaging plays the main role in the total recyclates being produced (5.47Mt; Table 4), with a contribution as high as 70% (Table 6). Construction and transport are the second and third most relevant sectors, regarding the total recyclates produced, with 10% and 7% respectively. Exported recyclates represent 18% of the total recyclates output from EU27 facilities.

To enable a sector-specific breakdown of the various plastic flows presented in Figure 4 and Figure 5, and summarized in Table 4, a series of specific sub-sections were prepared to provide an in-depth description of key steps of the value chain. Each section is also accompanied by a dedicated table in Annex (number of the Annex clarified in each of the bullet step below) to provide further details on the specific flows from the MFA assessment. In particular, the following sections are structured as follows:

- Plastic manufacturing, consumption and waste generation (Section 3.1.1 and Annex 5, Table 33): sector-specific details on the plastic flows related to semi-finished and finished products manufacturing (production and trade), consumption and post-consumer waste generation.
- Management of plastic waste (Section 3.1.2 and Annex 5, Table 34): sector-specific details on waste plastic flows exported, the separate collection and mixed collection of plastic waste and the related fate (i.e., sent to recycling, incineration or landfill).
- Recycling of plastic waste (Section 3.1.3): sector-specific details on the amount of recycled plastics and fate of recyclates produced.
- Mismanaged plastic, losses and environmental releases (Section 3.1.3): sector-specific details on the amount of plastic being mismanaged together with plastic losses and releases along the value chain.

The results section is also accompanied by an overview of the main findings for the packaging sector (Section 3.1.5) due to its main role in the whole plastic value chain.

Figure 4. General overview of the material flow assessment of the EU-27 plastic flows at the level of sectors. The width of the arrow lines is proportional to annual plastic flow volume in 2019 (for reference, the input flow to plastic manufacturers equals 5.33E+04 ktonne). All data are expressed in [ktonne] and are referred to the year 2019. "Plastic manufacturing" is used to indicate plastic conversion in the case of finished products and semi-finished products.

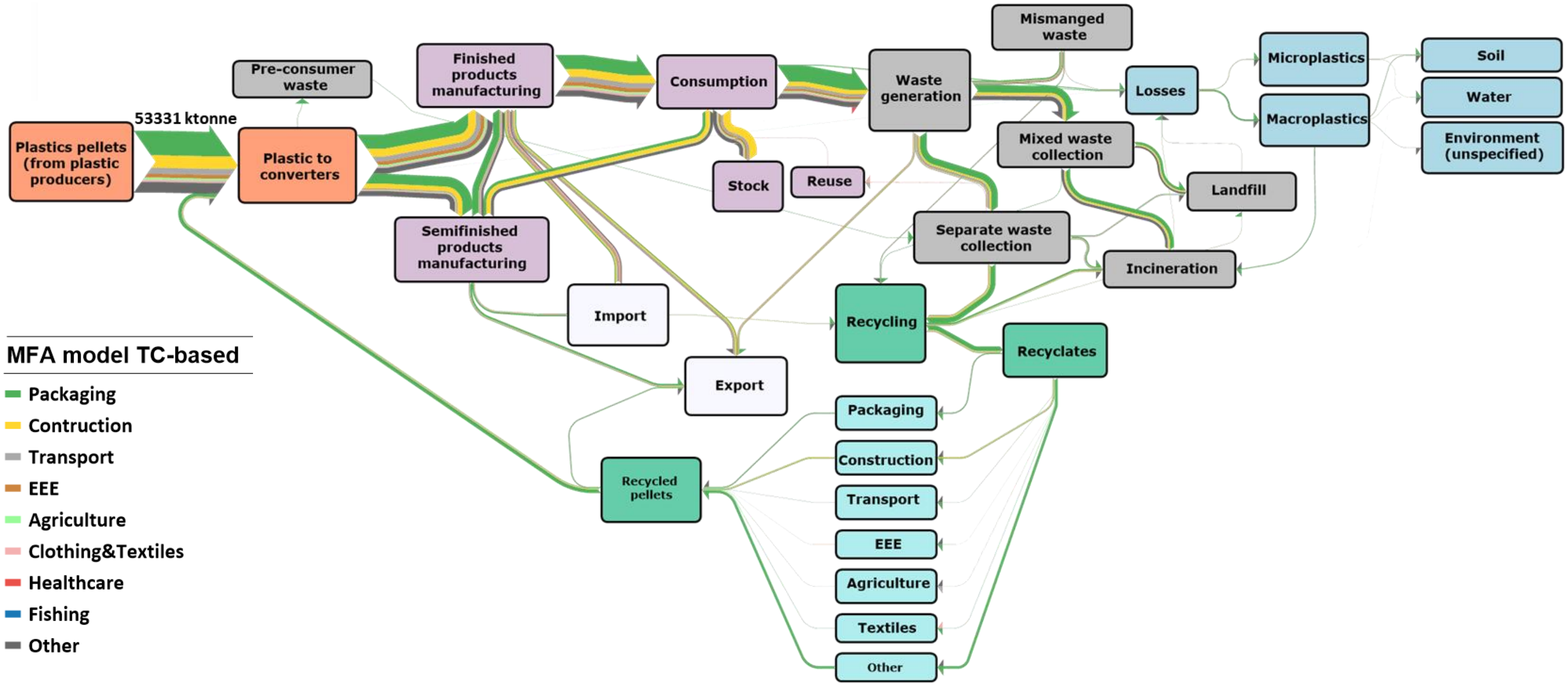


Figure 5. General overview of the material flow assessment of EU plastic flows at the level of sectors. All data are expressed in [ktonne]. (Note: “Consum.” = Consumption; “Pre-cons. Waste” = Pre-consumer waste; “Fin. Prod.” = Finished products manufacturing; “Semi-fin. Prod.” = Semi-finished products manufacturing; “Waste gen.” = Waste generation; “Mism. Waste” = Mismanaged waste; “Pl. to manuf.” = Plastic to manufacturing processes. “Plastic manufacturing” is used to indicate plastic conversion in the case of finished products and semi-finished products; “Environ. (unsp.)” = Environment (unspecified); “Mix. Waste. Coll.” = Mixed waste collection; “Sep. waste. Coll.” = Separate waste collection; “Recollected (recy.)” = Recollected to recycling; “Recollected (incin.)” = Recollected to incineration; EEE = Electrical and Electronic Equipment; Numerical values on nodes represent the total input mass).

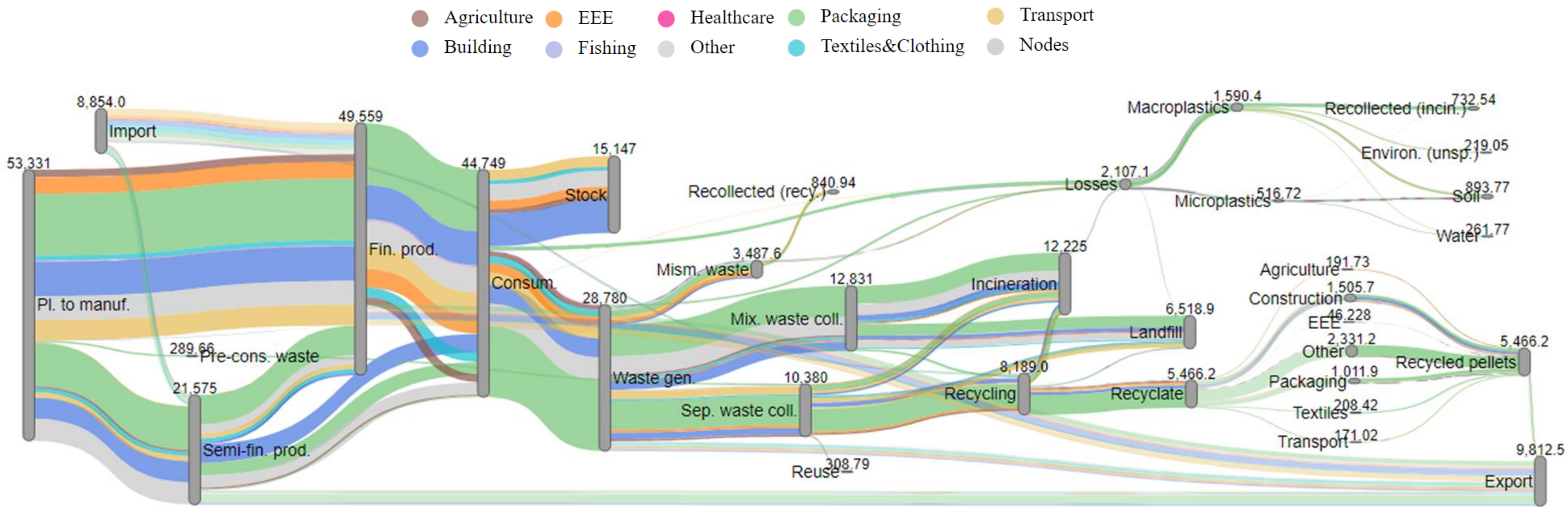


Table 4. Overview of the main steps of the plastics flows modelled in the sector-specific material flow assessment (expressed in [ktonne]). The column "Amount – all sectors" indicate the plastic flow as a sum of all the assessed sectors, namely Packaging, Construction, Transport, Electrical and Electronic Equipment, Agriculture, Clothing and textiles, Healthcare, Fishing, Other.

MFA step	Amount – All sectors [ktonne]
Semifinished products manufacturing	19,341
Semifinished products net trade (import-exports)	-584
Consumed semifinished products	8,998
Finished products manufacturing	33,647
Finished products net trade	2,103
Consumed finished products	35,750
Consumption	44,748
Waste generated	28,780
Waste generated exported	1,942
Waste collected (mixed)	12,831
Waste collected (separate)	10,380
Mismanaged waste	3,488
Mixed waste to recycling	372
Mixed waste to incineration	7,513
Mixed waste to landfill	4,947
Separate waste to reuse	309
Separate waste to recycling	6,508
Separate waste to incineration	2,276
Separate waste to landfill	1,286
Recycling losses (to incineration)	2,437
Recycling losses (to landfill)	286
Recyclates produced from recycling	5,466
Imported waste to recycling	468
Recyclates employed in the packaging sector	1,012

MFA step	Amount – All sectors [ktonne]
Recyclates employed in the construction sector	1,506
Recyclates employed in the transport sector	171
Recyclates employed in the EEE sector	46
Recyclates employed in the agriculture sector	192
Recyclates employed in the textiles sector	208
Recyclates employed in the 'other' sector	2,331
Exported recyclates	1,004
Total recyclates (consumed in the EU27, after exports)	4,462

3.1.1 Plastic manufacturing, consumption and waste generation

In the first steps of the value chain, the manufacturing of semi-finished and finished products together with the flows of products consumed were calculated based on the study from Amadei et al. (2022), as described in Section 2.3.1. Results presented in Table 33 (Annex 5) underline the leading role of packaging and construction sectors: packaging amounted to 34% of all the finished products consumed (35.8Mt) and 28% of all semi-finished products consumed (9.00Mt), whilst construction contributed to 23% of the finished and 40% of semi-finished products consumed. The assumptions needed to distinguish between semi-finished and finished products limited the granularity of sector-specific details resulting in high contributions of the heterogeneous 'other' sector (contributing to 27% of all semi-finished products consumed and 14% of all finished products consumed). The exports of semi-finished products were higher than the corresponding imports for all sectors beside textiles and clothing, whilst for healthcare and fishing no trade was estimated due to data gaps. By contrast, exports of finished products manifested higher values compared to imports only for construction, agriculture, and fishing. The delta between the mass of consumed products and the semi-finished products manufacturing demand was assumed as being already captured in the estimates of finished products consumption and therefore is contributing to the total amount of consumed plastics (Section 2.3.1; Annex 1). A total of 66% of all plastics consumed in EU27 was related to packaging (33%), construction (23%) and transport (10%). This resulted especially in a major contribution of packaging (49%) to the total amount of waste generated (28.8Mt). In fact, whilst the entirety of plastic packaging was assumed to be immediately discarded, a relevant amount of plastic for all the other sectors was assumed to be accounted as a stock variation. The amount of consumed plastics modelled as stock ranged from 63% for the construction sector to 35% in the clothing and textiles sector, with values ranging from 41-51% in all other sectors. In the case of healthcare, results suggested a negative stock variation (waste generated being higher than consumed) in the order of additional 2% of waste being discarded from stock compared to the modelled amount from consumption. Losses from consumption were also estimated as indicated in Annex 2. A detailed overview of the resulting plastic flows for the steps described in this section is provided in Annex 5 (Table 33).

3.1.2 Management of plastic waste

Waste export represented a considerable share of the total waste generated of EEE and textiles (24% and 31% of waste exported out of 1.82Mt and 1.35Mt of waste generated, respectively). For all other sectors, waste exported ranged from 3% (for packaging and agriculture) to 8% (construction). In the case of packaging, results indicate that a comparable amount of plastic is either collected separately (42%) or as mixed stream (46%), whilst the remaining fraction is either lost or mismanaged. In the case of construction, only 37% of plastics is separately collected, similarly to clothing and textiles (30%) and EEE (38%). However, EEE represented the sector with the highest share of mismanaged waste (44% of the total waste generated, equal to 1.39Mt after trade), followed by transport (with 33% of the total waste generated, equal to 2.35Mt after trade). As for packaging, results suggest that comparable amounts of plastic waste arising in the agriculture, farming, and gardening (total of 0.85Mt), healthcare (total of 0.08Mt) and fishing (total of 0.07Mt) sectors are either collected separately (47%, 44% and 44% respectively) or as mixed waste stream (44%, 47% and 47% respectively), complemented by 9% of waste being mismanaged for all the three sectors. Only 6% of the mixed plastic packaging waste (equal to 6.19Mt) was assumed to be sent to recycling, because of sorting operations of valuable fractions in sorting plants. For all other sectors, no mixed plastic waste was collected for recycling, and a 60-40% split was assumed as plastic destined to incineration and landfill. By contrast, most of the separately collected plastic waste resulted as being sent to recycling, especially for packaging (75% of the total separately collected waste), agriculture (81%), EEE (65%) and construction (64%). In the case of clothing and textiles, as much as 60% of all the separately collected waste is sent to preparation for reuse and reuse. For the other sectors, results suggest a reuse rate of only 8% of plastic waste separately collected for transport and 2% for EEE. Overall, 10.1Mt of plastic waste were separately collected in the EU27, 12.8Mt were collected as mixed fraction. An overview of the main plastic flows related to plastic waste generation and management are listed in Annex 5 (Table 34).

3.1.3 Recycling of plastic waste

Results of the model suggested that plastic waste from packaging plays the main role in terms of recycling, being 70% of all plastic waste sent to recycling derived from this sector. The performance of the recycling step ranged from 50% (for EEE) to 71% (for packaging), whilst un-recycled residues were mostly sent to incineration (35% on average across sectors) or landfill (5% on average across sectors). A large level of uncertainty and lack of data granularity was evident concerning the fate of recyclates, resulting in a noticeable relevance of the heterogeneous ‘other’ sector among all the sectors considered as potential destination for the consumption of secondary plastics. Nonetheless, results indicated that the construction sector is the main target sector for the consumption of secondary plastics, followed by the packaging sector. It must be considered that only 82% of plastic recyclates are being used within the EU27 boundaries, whilst the remaining 18% are exported. Overall, a total of 4.46Mt of plastic recyclates were modelled as being produced and consumed in the EU27 territory (5.47Mt including exports). An overview of plastic recycling and the fate or recycled plastics is reported in Figure 6 and Table 5.

Figure 6. Plastic flows [ktonne] of each economic sector related to recycling and recycled plastics fate. (Note: EEE = Electrical and Electronic Equipment).

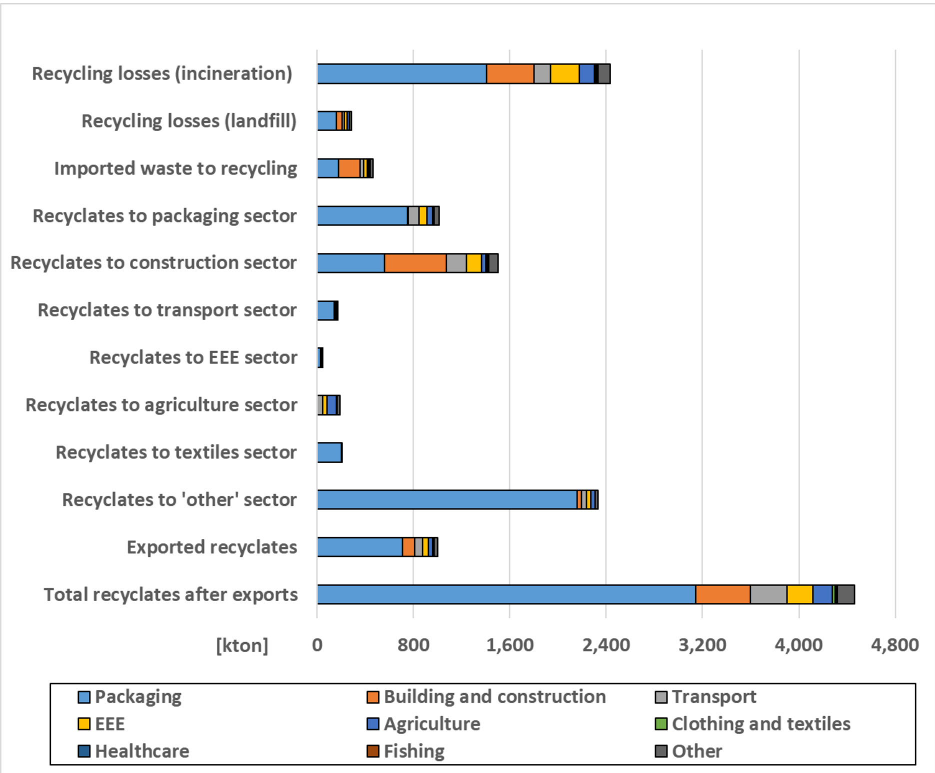


Table 5. Plastic flows [ktonne] of each economic sector related to recycling and recyclates origin and destination. (Note: P = Packaging; C = Construction, T = Transport, E = Electrical and Electronic Equipment (EEE), A = Agriculture, C&T = Clothing and textiles, H = Healthcare, F = Fishing, O = Other; values reported in coloured cells are calculated before trade).

MFA step	P	C	T	E	A	C&T	H	F	O	TOT
Recycling losses (incineration)	1,405.9	392.9	141.5	239.5	124.1	13.6	8.1	6.6	104.6	2,436.9
Recycling losses (landfill)	163.2	45.6	16.4	27.8	14.4	1.9	1.1	0.9	14.5	285.9
Imported waste to recycling	180.2	175.6	33.5	26.1	14.5	10.4	0.0	0.0	27.8	468.0
Recyclates to packaging sector	750.5	10.4	88.4	64.1	44.9	5.5	3.3	2.7	42.2	1,011.9
Recyclates to construction sector	560.7	513.3	169.5	122.9	36.6	10.5	6.3	5.1	80.8	1,505.7
Recyclates to transport sector	145.2	0.0	11.1	8.0	0.0	0.7	0.4	0.3	5.3	171.0
Recyclates to EEE sector	29.0	0.0	7.4	5.3	0.0	0.5	0.3	0.2	3.5	46.2
Recyclates to agriculture sector	0.0	0.0	47.9	34.7	80.1	3.0	1.8	1.4	22.8	191.7
Recyclates to textiles sector	205.7	0.0	0.0	0.0	0.0	2.7	0.0	0.0	0.0	208.4
Recyclates to 'other' sector	2,159.9	34.9	44.2	32.1	36.1	0.0	1.6	1.3	21.1	2,331.2
Exported recyclates	707.3	102.6	67.7	49.1	36.3	4.2	2.5	2.0	32.3	1,004.0

MFA step	P	C	T	E	A	C&T	H	F	O	TOT
Total recyclates after exports	3,143.7	456.0	300.8	218.0	161.4	18.7	11.2	9.0	143.5	4,462.2

Each coloured row in Table 5 represents the sectors to which each plastic recyclate is destined. By contrast, the columns of these coloured cells represent the sector from which a plastic recyclate was generated. For instance, the 560.7 ktonne of plastics recyclates indicated in Table 5 for the row "Recyclates to construction sector" were "generated" from the packaging sector and "destined" to the construction sector. The same distinction between recyclates origin and destination is also applicable to the rows "Exported recyclates" and "Total recyclates after exports" of Table 5. To better distinguish between recyclates origin and destination, the total secondary plastic destined to a given sector (named: "Recy_destin") is therefore defined as the sum of the recycled plastics arising from one or more sectors and destined to a single specific sector (e.g., recyclates derived from the packaging, construction, agriculture, etc. sectors that are all flowing to the packaging sector) with respect to the total recyclates produced. On the other hand, the sum of all recycled plastics arising from a sector and destined to multiple sectors (named: "Recy_origin") returns the total amount of recycled plastics generated from a specific sector (e.g., recyclates derived from packaging that are flowing to packaging, construction, agriculture, etc.). By calculating the ratio of the "Recy_origin" (after trade) and the total plastic demand for each sector (i.e., the starting point of the MFA described in Section 2.3 and in Annex 3) the share of recycled plastics out of the total plastic demand in a given sector (named: "Recy_content") is derived. The results for these parameters are summarized in Table 6. As introduced in Figure 6 and in Table 5, the main role of construction and packaging as the main target sectors for the entirety of recycled plastics generated across all sectors is evident from Table 6. However, large uncertainties limited the possibility to further detail the specific destination of most of the recycled plastics generated, resulting in 43% of all recyclates modelled as being used in the heterogeneous 'other' sector. Table 6 underlines the leading role of packaging as the main sector contributing to recyclates production, accounting for more than two thirds of the total production throughput. When compared to the total demand of a given sector, clothing and textiles, construction and agriculture represented the main sectors in which recycled plastics contribute to the manufacturing of new products (in the order of 10% of the total demand). In the case of packaging, result highlighted how only recycled plastics covers only 4% of the total demand.

Table 6. Relative shares [%] of the total recycled produced concerning the final sector of destination ("Recy_destin") and the sector of origin ("Recy_origin"), and content of recycled plastic in a given sector ("Recy_content"). For the calculation of "Recy_destin [%]" and "Recy_origin [%]" the total plastic recyclates production (after trade) was considered (4.46E+03 ktonne). For the calculation of "Recy_content [%]" the total plastic demand for each sector was considered. (Note: EEE = Electrical and Electronic Equipment).

MFA sector	Recy_destin [%]	Total recyclates destined to sector [ktonne] [1]	Recy_origin [%]	Total recyclates originated from sector [ktonne]	Recy_conten t [% calculated as [1] over [2]]	Sector-specific plastic demand [ktonne] [2]
Packaging	18.5	826.1	70.5	3,143.7	3.9	21,119.1
Building and construction	27.5	1,229.1	10.2	456.0	11.3	10;879.5

MFA sector	Recy_destin [%]	Total recyclates destined to sector [ktonne] [1]	Recy_origin [%]	Total recyclates originated from sector [ktonne]	Recy_content [% calculated as [1] over [2]]	Sector-specific plastic demand [ktonne] [2]
Transport	3.1	139.6	6.7	300.8	2.7	5,119.8
EEE	0.8	37.7	4.9	218.0	1.1	3,306.5
Agriculture	3.5	156.5	3.6	161.4	8.6	1,813.3
Clothing and textiles	3.8	170.1	0.4	18.7	10.7	1,806.1
Healthcare	0.0	0.0	0.3	11.2	0.0	86.0
Fishing	0.0	0.0	0.2	9.0	0.0	153.3
Other	42.6	1,903.0	3.2	143.5	21.0	9,047.6

A summary overview of the management of plastic waste is presented in Figure 7 and in Table 7. Results highlighted how no more than 37% (in the case of packaging; whilst 24% on average) of the total waste generated is recycled (with respect to the total post-consumer waste being generated, including trade), with the highest end-of-life recycling rates being associated to the packaging and agriculture sectors. On average, the EU27 end-of-life recycling rate were equal to 19% (16.6% when export is considered).

Incineration and landfill still manifested a leading role as the most adopted waste management options of the waste generated (having a 36% and 23% among the waste management options of all plastics in EU27, respectively). Although results indicate that around 9% of all waste generated is being mismanaged or lost for most sectors, the amount of mismanaged waste, as previously mentioned in the case of the transport and EEE sectors was much higher: a total of 31% of all waste is mismanaged in the case of EEE, and a total of 24% in the case of transport.

Reuse exhibited a relevant role not only for the clothing and textiles sectors (18% of all waste generated) but also for the transport sector (6% of all waste generated), whilst its contribution remained negligible for all other sectors (1% maximum). All values reported in Figure 7 and in Table 7 were calculated considering the export of post-consumer plastic waste. The import of plastic waste sent to recycling was considered for calculating the total recycled produced out of waste generated, although the amount of imported waste has a minimal effect on the resulting shares (less than 1% variation).

Figure 7. Rates [%] of total plastic recycled, incinerated, landfilled, reused or lost/mismanaged for each sector. (Note: the rates are calculated considering waste being generated and trade of waste; EEE = Electrical and Electronic Equipment).

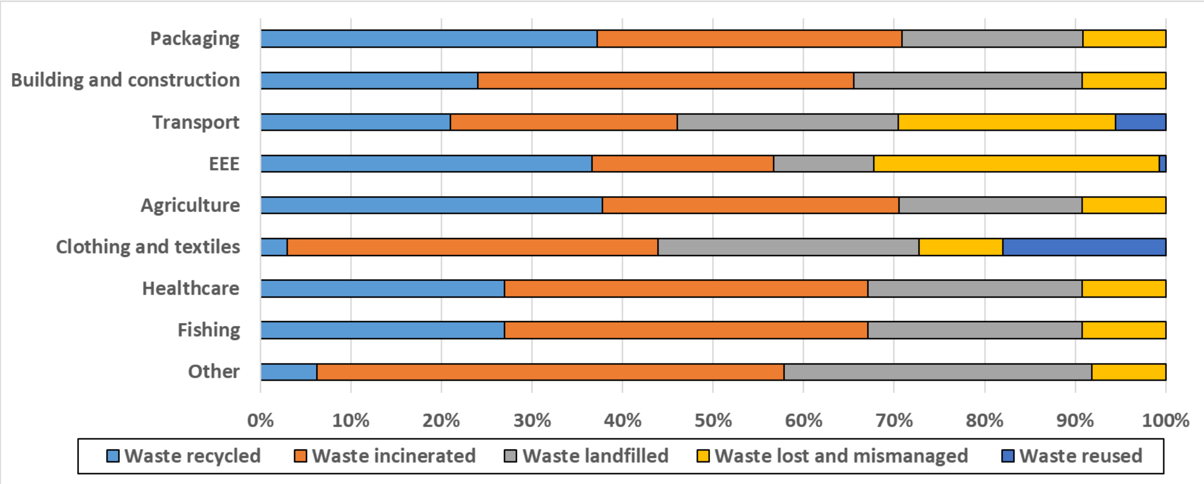


Table 7. Sector-specific rates [%] of the total plastic recycled, incinerated, landfilled, reused or lost/mismanaged and total amount of recycled produced out of the sector-specific total post-consumer waste generated. (Note: P = Packaging; C = Construction, T = Transport, E = Electrical and Electronic Equipment (EEE), A = Agriculture, C&T = Clothing and textiles, H = Healthcare, F = Fishing, O = Other; [1] = this ratio was calculated without considering trade of waste generated and trade of recyclates produced; potential differences in the totals are due to rounding).

MFA step	**P [%]**	**C [%]**	**T [%]**	**E [%]**	**A [%]**	**C&T [%]**	**H [%]**	**F [%]**	**O [%]**	**TOT [Mt]**
Waste recycled	37.2%	24.0%	21.0%	36.6%	37.8%	3.0%	27.0%	27.0%	6.3%	7.5
Waste incinerated	33.6%	41.5%	25.1%	20.1%	32.8%	41.0%	40.1%	40.1%	51.6%	9.7
Waste landfilled	20.0%	25.2%	24.4%	11.1%	20.2%	28.8%	23.7%	23.7%	34.0%	6.2
Waste lost and mismanaged	9.1%	9.3%	24.0%	31.5%	9.3%	9.3%	9.3%	9.3%	8.2%	3.1
Waste reused	0.0%	0.0%	5.6%	0.8%	0.0%	18.0%	0.0%	0.0%	0.0%	0.3
TOT [Mt]	13.5	3.4	2.3	1.4	0.9	0.9	0.1	0.1	4.3	26.8

MFA step	P [%]	C [%]	T [%]	E [%]	A [%]	C&T [%]	H [%]	F [%]	O [%]	TOT [Mt]
Total recycled produced out of total waste generated [1]	28.2%	15.5%	15.5%	18.9%	22.8%	2.4%	16.1%	16.1%	4.1%	5.5
TOT [Mt]	3.9	0.6	0.4	0.3	0.2	0.02	0.01	0.01	0.18	

3.1.4 Mismanaged plastic, losses and environmental releases

A total of 2.11Mt of plastics was lost in the year 2019, of which: 39% being lost during the use phase (e.g. emissions due to tyre abrasion or washing of synthetic textiles), 37% being macroplastic losses from generated waste (including 20% due to plastic waste littered and 17% due to mismanaged waste that is not recollected), 2.5% being losses of pre-consumer plastics, and 21.5% being microplastic emissions from incineration and landfill (11.6 and 9.90% respectively).

Four types of plastic losses to the environment were considered, for which the key assumptions are detailed hereafter to provide context to the presented results:

- Microplastic emissions during plastics manufacturing (pre-consumer plastics). In this case, for each sector, the losses were estimated as 0.10% of converted amounts, out of which 14% were assumed to be recollected (and sent to incineration). The estimations were based on Peano et al. (2020) following the suggested "loss rate or plastic pellets" (Annex 2).
- Microplastics and macroplastics losses during the use phase. In this case, microplastics emissions from tyre abrasion during transport or from synthetic textiles during washing were estimated as suggested by Peano et al. (2020). Microplastic emissions from tyre abrasion were calculated based on a distinction at the level of vehicle types, losses rates and average travelled distances. Microplastic emissions from textiles washing were calculated considering both the losses rates of microfibers per wash and the average number of washes. According to Peano et al. (2020), both loss types could be partially recollected to incineration. To model the microplastic and macroplastic releases (together with the amounts being recollected to incineration), the data from Kawecki and Nowack (2019) were employed as proxies for the estimations in the case of the packaging, construction, EEE, agriculture, healthcare, and 'other' sectors. In the case of the fishing sector, the total amount of fishing gear lost to sea was derived from Deshpande et al. (2020) (Annex 2). Typical macroplastics lost during the use phase could originate from durable plastics, from parts of packaging products or parts of fishing nets. Although macroplastic could be further fragmented into "secondary" microplastic by time and erosion, this process was not explored in the present study.
- Macroplastic losses from waste generated. In this case, littering of plastic waste for the packaging sector (2.67% of waste generated for packaging) and for the 'other' sector (1.67% of waste generated for the 'other' sector) were estimated based on Peano et al. (2020). The method proposed in Peano et al. (2020) details littering rates for different plastic items (differentiated by size and use). On top of the losses from the waste generated, the method by Peano et al. (2020) allows the calculation of the fraction of mismanaged waste, based on the share of mismanaged waste out of the total waste generated for the packaging and 'other' sectors. Mismanaged waste is intended as an inadequately disposed waste, which could be either not appropriately disposed and/or treated and that could create routes for potential losses and releases in the environment. In the case of the EEE sector, a 44%

share of waste mismanaged was calculated from Huisman et al. (2015), including the waste managed with non-compliant collection systems and the unknown management (excluding exports and scavenged practices outside the EU). On the other hand, the share of mismanaged waste arising from the total waste generated in the transport sector (33%) was derived from Maury et al. (2022) and that indicates how from 1.5 Mt of waste generated from vehicles, 0.5 Mt ends up in unknown whereabouts. A certain amount of mismanaged waste could be either recollected and sent to recycling or lost. The amount of mismanaged waste recollected (equal to 28% of the mismanaged waste for the packaging, transport, EEEE and 'other' sectors) was calculated based on Peano et al. (2020) and represents waste not released to the environment that could be collected by waste pickers and ultimately recycled or reused. The amount of mismanaged waste lost (equal to 10% of the mismanaged waste for the packaging, transport, EEEE and 'other' sectors) was based on Ryberg et al., (2019).

- Microplastic emissions from landfilling and incineration. In this case, shares derived from the European Chemical Agency (ECHA, 2019) were employed for each sector (2% of the amounts landfilled or incinerated, excluding any recollection).

For the packaging[4], construction[5], agriculture, healthcare[6] and fishing sectors, the losses of microplastics and macroplastics during the use phase (e.g., release of microplastics from the abrasion of synthetic textiles during laundering or from tyre abrasion during transport) manifested the highest relevance (ranging from 35% of the total losses in case of construction to 74% in case of fishing, out of the total plastic losses along the value chain). Losses from waste littered (e.g. cups, shopping bags, or wrappers/lids) resulted in high contribution in the case of the packaging sector (25% of the total losses) and the 'other' sector (33% of the total losses). Results indicated that the losses from the incineration and landfill steps represented a significant proportion of the total lost plastics for the textiles and clothing sector (28% and 27% losses from the incineration step and the landfill step respectively, out of the total losses in this sector). Lastly, losses derived from the total amount of mismanaged waste were significantly higher especially in the transport and EEE sectors (69% and 74% of the total losses, respectively), compared to the remaining sectors. This could be explained by the significant amount of mismanaged waste modelled for these two sectors (Figure 7).

In the case of microplastics releases, the modelled flows indicated that the highest contribution to the total releases to soil derived from landfill losses (56%), incineration losses (33%) and losses from manufacturing step (10%). The microplastics emissions from incineration and landfill were modelled as suggested by ECHA, i.e., estimated at 2% of the total amount of plastics incinerated or landfilled (European Chemical Agency) (ECHA, 2019). In the ECHA report, microplastic general release shares (i.e., not sector specific) from incineration and landfill are suggested, for both water and soil (50-50 for emissions from incineration, while 99.99% of emissions from landfills go to soil). By contrast, the assumptions related to plastic losses and their releases/recollection and the assumptions on plastic mismanagement/losses from mismanaged waste and mismanaged waste being recollected were based on sector-specific assumptions derived from Peano et al. (2020) and Kawecki and Nowack (2019) (for more details, see Annex 2). The suggested values of microplastic releases from incineration and landfill were therefore adopted for all sectors under assessment in the present study: this could explain the high contribution of microplastic losses from landfill and incineration compared to the manufacturing step (that is instead based on sector-specific data from Peano et al. 2020). Altogether, roughly one third of all microplastic losses happened to be released to water, with the remaining part being released to soil. Findings indicate that a minor amount (2%) was recollected and sent to incineration. On the other hand, macroplastic releases were mostly due to losses from the generated waste, with 84% of the total macroplastic losses for soil being due to losses from waste generated and 94% for water being due to losses from waste generated. Overall, almost half of the macroplastic losses were collected and sent to incineration, with the remaining amount mostly released to soil (33%), to an unknown environmental compartment (i.e., "Environment (unspecified)", see Annex 2; 14%) or water (8%). An overview of the total losses per sector and per

[4] These losses are mostly related to consumer packaging products (e.g., films, bags, and bottles), as suggested by Kawecki and Nowack (2019).

[5] These losses are mostly related to construction pipes, insulation materials, covering materials, as suggested by Kawecki and Nowack (2019).

[6] These losses are mostly related to hygiene articles that are flushed in place of being appropriately discarded (e.g., tampons, wet wipes, cotton swabs, sanitary pads, etc.), as suggested by Kawecki and Nowack (2019).

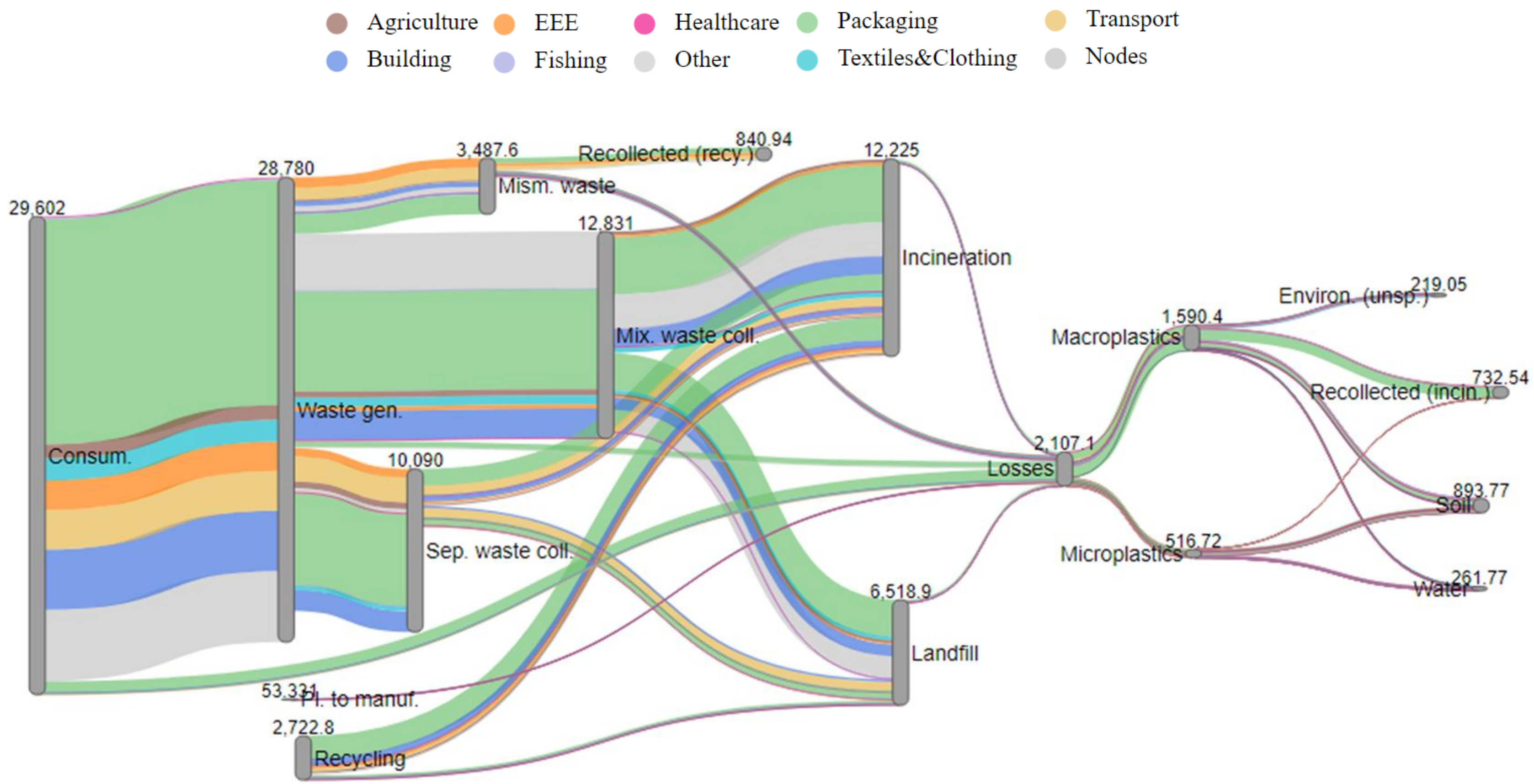
environmental compartment of the final release (including any potential recollection) is reported in Table 8.

Table 8. Sector-specific releases [ktonne] of plastics (sum of all releases along the value chain) per sector and per environmental compartment or potential recollection routes. Of the total amount of recyclates produced out of the total post-consumer waste generated. (Note: P = Packaging; C = Construction, T = Transport, E = Electrical and Electronic Equipment (EEE), A = Agriculture, C&T = Clothing and textiles, H = Healthcare, F = Fishing, O = Other; Micro = microplastics; Macro = macroplastics).

Losses	**P**	**C**	**T**	**E**	**A**	**C&T**	**H**	**F**	**O**	**TOT**
Micro to water	63.5	20.0	8.2	5.7	4.3	5.2	0.4	0.4	24.6	132.3
Micro to soil	171.8	60.7	26.5	14.8	12.5	13.1	1.2	1.0	72.3	373.8
Micro to incineration (recollected)	3.0	1.7	0.7	0.5	1.5	1.0	0.0	0.0	2.2	10.6
Macro to water	77.3	5.2	12.3	9.5	1.2	1.4	0.2	5.3	17.2	129.4
Macro to soil	329.5	28.7	44.0	34.2	13.7	4.9	2.1	0.9	61.9	520.0
Macro to incineration (recollected)	663.2	41.2	0.0	0.0	8.6	0.0	4.8	0.0	4.1	721.9
Macro to environment (unspecified)	135.2	8.9	22.0	17.1	2.2	2.4	0.2	0.2	30.8	219.0

Overall, plastic losses from the packaging sector contributed to 69% of the total microplastics and macroplastics losses, with minor contributions due to the construction and transport sectors (8% and 5% respectively). An overview of the main flows related to plastic losses and mismanaged waste is reported in Figure 8.

Figure 8. General overview of the material flow assessment of EU plastic flows at the level of sectors: focus on all flows related to plastic losses and mismanaged waste. Mass balances to each node might not be ensured as the figure focuses on losses and mismanaged waste flows (i.e., some flows from the complete model were excluded). All data are expressed in [ktonne]. (Note: "Consum." = Consumption; "Waste gen." = Waste generation; "Mism. Waste" = Mismanaged waste; "Pl. to manuf." = Plastic to manufacturing processes (i.e., losses in the manufacturing step); "Environ. (unsp.)" = Environment (unspecified); the dark red flow linking incineration and losses is intended from incineration to losses; "Recollected (recy.)" = Recollected to recycling; "Recollected (incin.)" = Recollected to incineration; EEE = Electrical and Electronic Equipment (EEE), A = Agriculture, C&T = Clothing and textiles, H = Healthcare, F = Fishing, O = Other; Numerical values on nodes represent the total input mass).

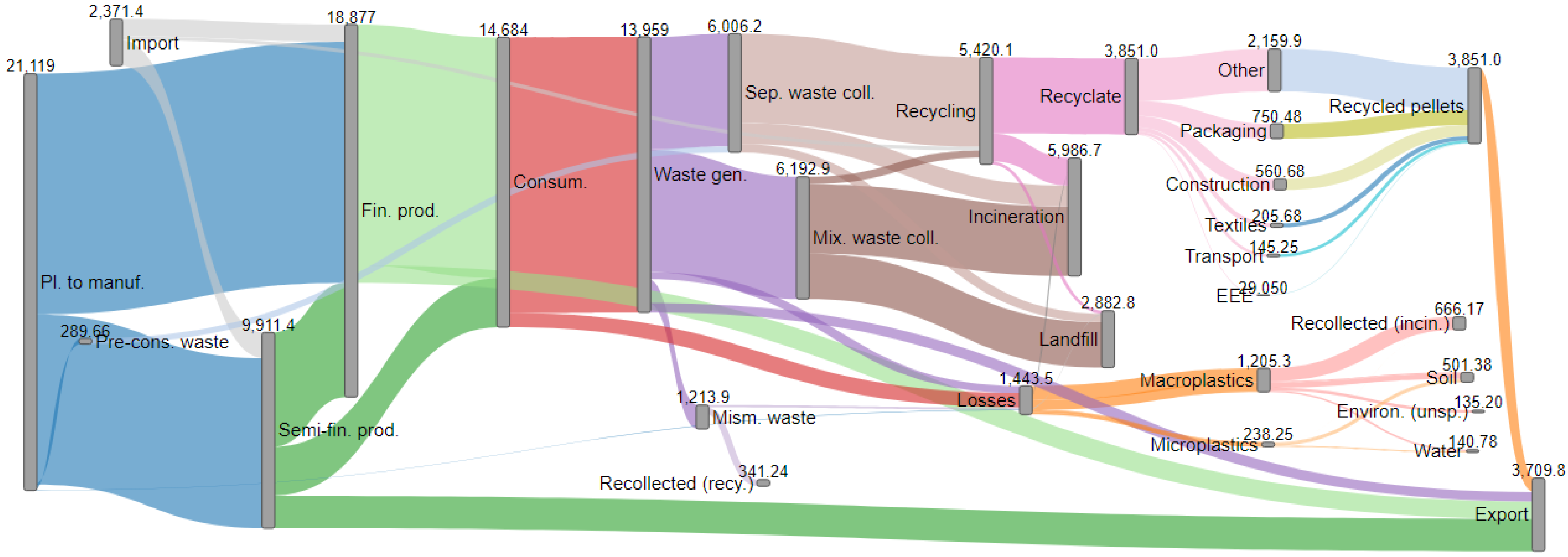


3.1.5 Details of the material flows for the packaging sector

As described in the previous section, the packaging sector resulted in the most relevant sector regarding the total mass flows in the EU27 economy.

Plastic packaging products have been the main target of several EU policies from recent years (EC, 2018a; EC, 2018b; EC, 2019a). The specific purpose and nature of packaging (inherently shorter lifespan) required targeted policy actions aimed at both preventing excessive packaging use but also improving its end-of-life management. Results for the present study indicate that packaging plastics not only represented a total of 33% of the consumed plastics compared to other sectors, but also constituted the most important sector regarding the total post-consumer plastic waste generated (14.0Mt, 49% of the total post-consumer plastic waste generated) due in fact to its disposable nature. Although 46% of the total post-consumer waste generated (after trade) is currently collected as a mixed plastic waste stream (with only 5% being recollected as valuable pre-consumer waste), 75% of the total packaging waste separately collected is currently sent to recycling, resulting in 3.85Mt of plastics recyclates being produced (3.14Mt after trade). This was equal to 70% of the total recyclates produced from all sectors, and therefore represented the most relevant recyclates stream being consumed as secondary material by EU manufacturing facilities. This stream was mainly destined to the manufacturing of other packaging products, to the construction sector, or to 'other' sectors. Despite being the most dominant sector concerning mass flows being recycled at the end-of-life, results suggested that a total of 34% and 20% of the total post-consumer waste generated are still being incinerated or landfilled, respectively. Concerning losses (1.44Mt in total along the whole value chain), a total of 35% of them ended up as releases to soil (66% of which due to microplastic releases).
An overview of the material flow analysis for the packaging sector is reported in Figure 9.

Figure 9. General overview of the material flow assessment of EU plastic flows for the packaging sector. All data are expressed in [ktonne]. The colours of the flows are employed only for an easier visualization of their origin and destination. (Note: “Consum.” = Consumption; “Pre-cons. Waste” = Pre-consumer waste; “Fin. Prod.” = Finished products manufacturing; “Semi-fin. Prod.” = Semi-finished products manufacturing; “Waste gen.” = Waste generation; “Mism. Waste” = Mismanaged waste; “Pl. to manuf.” = Plastic to manufacturing processes. “Plastic manufacturing” is used to indicate plastic conversion in the case of finished products and semi-finished products; “Environ. (unsp.)” = Environment (unspecified); “Mix. Waste. Coll.” = Mixed waste collection; “Sep. waste. Coll.” = Separate waste collection; “Recollected (recy.)” = Recollected to recycling; “Recollected (incin.)” = Recollected to incineration; EEE = Electrical and Electronic Equipment; Numerical values on nodes represent the total input mass).



3.2 Sensitivity and scenario analysis

In this section the results of the hotspot and sensitivity assessment are reported, together with the results of the analysis of the scenarios for the year 2025. The sensitivity analysis is a methodological study of the model aiming to identify the most impactful assumptions on the overall model[7]. By contrast, the scenarios' assessment (presented after the sensitivity analysis in this section) serve the purpose of understanding the hypothetical features of the plastic value chain in the near future (i.e., year 2025), bearing in mind the overall goal of the EU/CPA (EC, 2018a; CPA, 2019).

In the hotspot and sensitivity assessment, the underpinning assumptions of key TCs affecting crucial steps of the modelled value chain were analyzed. Each modelling assumption related to the sector-specific MFA is described in Annex 3. The hotspot analysis was aimed at recognizing those assumptions that could potentially lead to significant variations in the modelled MFA, especially about the total amount of recyclates produced and employed in the manufacturing of new products in the EU. From the hotspot analysis, a total of 17 assumptions were identified and selected for the sensitivity assessment (i.e., the "Sensitivity alternative case"). These sensitivity alternative cases covered several steps of the value chain, from finished/semi-finished products manufacturing to end-of-life waste management and covered all sectors or only a subset of selected sectors (e.g., healthcare and fishing sectors). For each of the sensitivity alternative cases, TCs were varied (e.g., put to 0% or put to 100%) and the resulting total recyclates production was analyzed to provide insight on the effects of such variations compared to the MFA "Base Scenario" (i.e., the results of the sector-specific MFA presented in this study and described in Annex 2). The main results of the hotspot and sensitivity assessment are reported in Table 9.

Table 9. Total recyclates production for the sector-specific material flow analysis [expressed as megatonnes] resulting from the sensitivity alternative cases, compared to the results of the 'Base Scenario' sector-specific material flow analysis (calculated as a percentage variation). A description of the rationale for each sensitivity scenario is described in Section 2.3.4. (Note: E = Electrical and Electronic Equipment (EEE)).

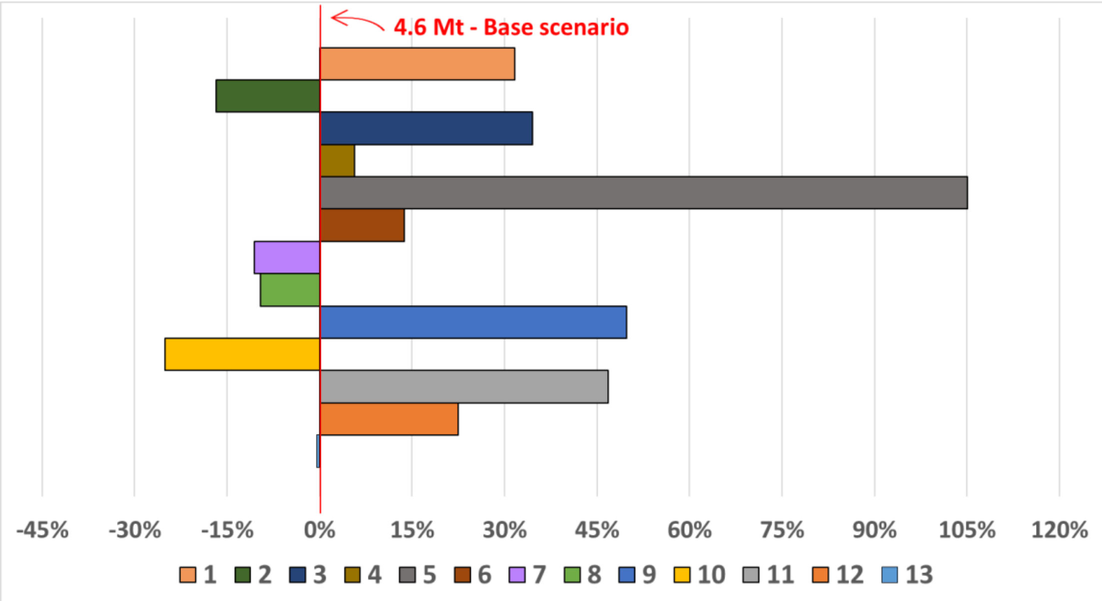
Identifier	Sensitivity alternative case name	Recyclates produced (and consumed in EU27) [Mt]	Percentage variation with respect to the base MFA [%]
1	All manufactured products are consumed	5.88	+32%
2	Only finished products are sold to end-consumers	3.72	-17%
3	Reduced stock variation	6.00	+35%
4	Absence of waste trade	4.71	+6%
5	Absence of mixed waste collection	9.15	+105%
6	Absence of mismanaged waste	5.08	+14%
7	Absence of mismanaged waste being recollected and recycled	3.99	-11%
8	Revised mismanaged waste assumptions (mismanaged waste only occurs for the transport and EEE sectors and it's not recollected for recycling)	4.04	-10%
9	Improved recycling performance	6.68	+50%

[7] Notice that assumption for the sensitivity analysis might not be a representative scenario for the real plastic value chain.

Identifier	Sensitivity alternative case name	Recyclates produced (and consumed in EU27) [Mt]	Percentage variation with respect to the base MFA [%]
10	Locked recycling performance	3.34	-25%
11	Improved management of separately collected waste	6.55	+47%
12	No recyclates are exported	5.47	+23%
13	Revised assumption for the waste management of the healthcare and fishing sectors	4.44	-0.45%

Results from Table 9 and Figure 10 highlighted the sensitivity of the whole material flow analysis model to variations of some key modelled parameters, resulting in a total amount of plastics recyclates in the order of 4.46 Mt ± 38% (including the standard deviation calculated based on the 13 cases of Table 9). The modelling assumption at the base of waste management practices in the context of the EU value chain resulted in the highest overall variation of recyclates produced (+105% if all waste is separately collected). Although this sensitivity alternative case might not be feasible in practice, the sensitivity assessment results underlined how the amount of waste collected separately could improve significantly the total recyclates output for the EU economy. This could be especially relevant in the context of recent studies which hinted at a major underestimation of plastic waste flows in available statistics (e.g., Material Economics, 2022; Systemiq, 2022). On the other hand, the model is also influenced by the assumption on finished/semi-finished products consumption, as the employed approach for distinguishing between the two types of products could lead to an overestimation/underestimation of the consumed plastics and therefore also of the recyclates produced (e.g., total recyclates produced would be 17% lower by removing all semi-finished products directly sold to consumers). Looking at the recycling step, the analysis also suggested that the obtainable recyclates production is strongly dependent on the assumed recycling performance. Higher amounts of recyclates being produced are also strongly linked to an improved management of the separately collected waste.

Figure 10. Percentage variation of the total recyclates production for the sector-specific material flow analysis for the sensitivity alternative cases, compared to the results of the "base" sector-specific material flow analysis (expressed as megatonnes). Description of the rationale for each sensitivity alternative cases: number 1 = "All manufactured products are consumed"; number 2 = "Only finished products are sold to end-consumers"; number 3 = "Reduced stock variation"; number 4 = "Absence of waste trade"; number 5 = "Absence of mixed waste collection"; number 6 = "Absence of mismanaged waste"; number 7 = "Absence of mismanaged waste being recollected and recycled"; number 8 = "Revised mismanaged waste assumptions (mismanaged waste only occurs for the transport and EEE sectors and it's not recollected for recycling)"; number 9 = "Improved recycling performance"; number 10 = "Locked recycling performance"; number 11 = "Improved management of separately collected waste"; number 12 = "No recyclates are exported"; number 13 = "Revised assumption for the waste management of the healthcare and fishing sectors"; for more details see Section 2.3.4.



As described in Section 2.3.5, the findings of the assessment of the sensitivity alternative cases were further elaborated and modified leveraging on expected trends of plastic production and plastic waste management, to derive a series of scenarios for the year 2025. The main results of the scenarios assessment for the year 2025 are reported in Table 10.

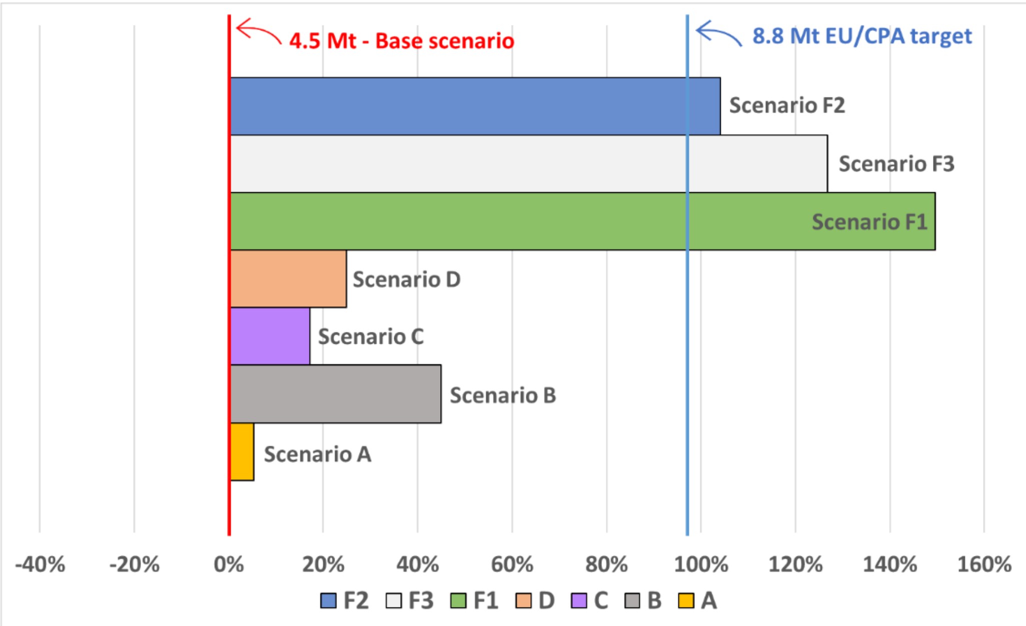
Table 10. Total recyclates production for the sector-specific material flow analysis [expressed as megatonnes] resulting from the scenarios at the year 2025, compared to the results of the "base" sector-specific material flow analysis (calculated as a percentage variation). For more details see Section 2.3.5. Percentage variations are intended as variations applied directly at the level of the Transfer Coefficients of the flow models.

Scenario identifier	**Scenario name (short description)**	**Recyclates produced (and consumed in EU27) [Mt]**	**Percentage variation with respect to the base MFA [%]**
A	<u>Reduced waste export</u> (assumption of a 20% decrease of plastic waste export for the EEE and textiles and clothing sectors and 10% for other sectors - following the example of international waste bans on the import of plastic waste, such as China's waste import ban)	4.70	+5%
B	<u>Improved waste collection</u> (it was assumed that the significant EU strive towards a plastic circular economy [e.g., Landfill Directive (EC, 1999), the European Green Deal (EC, 2019b), the European	6.47	+45%

Scenario identifier	Scenario name (short description)	Recyclates produced (and consumed in EU27) [Mt]	Percentage variation with respect to the base MFA [%]
	Strategy for plastics (EC, 2018a), the EU Circular Economy Action Plan (EC, 2015; EC, 2020)] could lead to a 30% increase in the separate collection of plastic packaging waste and 10% for plastic waste from other sectors. In the case of transport and EEE, a reduction of 25% was assumed of the mismanaged waste, and a corresponding increase of 25% of separate waste collection).		
C	<u>Improved management of separately collected plastic waste</u> (it was assumed that a systematic improvement in waste management and efforts towards recyclability and investments in state-of-the-art sorting equipment could lead to 15% more plastic packaging waste sent to recyclers from sorting centres, and 10% for other sectors than packaging. This entails an improved sorting-for-recycling yield, on average, at 78% for packaging waste and 71% for other sectors.)	5.23	+17%
D	<u>Improved recycling performance</u> (it was assumed that to achieve the ambitious targets set by policymakers [e.g., the Waste Framework Directive (EC, 2008), the Packaging and Packaging Waste Directive (EC, 2018b), the European Strategy for Plastics (EC, 2018a)] and industries alike [e.g., the EU/CPA target on recyclates consumption, the European Plastic Pact], investments and efforts towards improved recyclability and recycling would lead to 20% lower rejects from recycling sent to incineration for packaging waste and 10% for waste from other sectors. This entails an improved recycling yield, on average, at 72% for packaging waste and 69% for waste from other sectors.)	5.57	+25%
F1	<u>Combined scenario (A+B+C+D+increasing plastic production [+10%])</u> (this scenario is a combination of previously described scenarios)	11.13	+150%
F2	<u>Combined scenario (A+B+C+D+decreasing plastic production [-10%])</u> (this scenario is a combination of previously described scenarios)	9.11	+104%
F3	<u>Combined scenario (A+B+C+D+stagnating plastic production [0% variation])</u> (this scenario is a combination of previously described scenarios)	10.12	+127%

Results from Table 10 and Figure 11 served the purpose of providing potentially realistic scenarios for the year 2025, following expected trends in the plastic value chain and leveraging on the current and future policy landscape of this material for the EU27 (as described in 2.3.5). This exercise could be particularly helpful in the context of the EU/CPA target of 8.8 million tonnes of recycled plastics to be used annually in the EU27 by 2025 (adapted from the EU target of 10 million tonnes set for EU28 in the European Strategy for plastics,; EC, 2018a), for understanding how close the modelled plastic value chain would be to such an ambitious target. Overall, results indicated that one single targeted action (i.e., scenarios from A to D) is not sufficient to ensure that the 8.8Mt target is achieved. But by adopting combined efforts (scenario F1, scenario F2 and scenario F3) the 8.8Mt target is reached and surpassed by the year 2025, under all considered assumptions related to plastic production (decrease, increase or stagnation). To date, trends in plastic packaging production (as suggested for instance by the EEA, 2021a leveraging on Plastics Europe data) suggested a steady yearly increase (for the period 2010-2019) in the total production (as described by scenarios E1 and F1), but due to the COVID-19 outbreak and the recent Ukraine war, a decreasing trend could be also reasonable (as suggested for instance by Systemiq, 2022). In all cases (also when assuming a stagnating plastic production i.e., 0% variation, scenario F3), the EU/CPA target remains reachable.

Figure 11. Percentage variation of the total recyclates production for the sector-specific material flow analysis for the scenarios for the year 2025, compared to the results of the “base” sector-specific material flow analysis (expressed as megatonnes). Description of the rationale for each sensitivity scenario: scenario A = “Reduced waste export”, scenario B = “Improved waste collection”, scenario C = “Improved management of separately collected plastic waste”, scenario D = “Improved recycling performance”, , scenario F1 = “Combined scenario (A+B+C+D & +10% plastic production)”, scenario F2 = “Combined scenario (A+B+C+D & -10% plastic production)”, scenario F3 = “Combined scenario (A+B+C+D & stagnating plastic production [0% variation])”; for more details see Section 2.3.4.



3.3 Material flow analysis and polymer-specific results

In the present study, the top-down approach presented in Section 2.4 was employed to derive polymer-specific MFAs for 10 polymers (namely: LDPE, HDPE, PP, EPS, PVC, PET, PUR, ABS and PA) in the case of the packaging, construction, agriculture, transport and EEE sectors. Although the top-down approach was only applied to the packaging, construction, transport, agriculture and EEE sectors, these sectors contributed to around 80% of the overall EU27 demand according to the sector-specific results.

Results presented in Table 11 summarize the relevance of each polymer for each sector regarding some key steps of the value chain. For instance, in the case of consumption, the ratios of Table 11 were derived by comparing the consumed amount of a polymer for all the investigated sectors (i.e., packaging, construction, agriculture, transport and EEE) with the total consumption of the investigated sectors.

Table 11. Relevance of each polymer regarding the total plastic for the packaging, construction, transport, agriculture and Electric and Electronic Equipment (EEE) sectors. Data are expressed as [%]. (Note: [1] = this refers to the amount of recyclates produced after trade).

MFA step	LDPE [%]	HDPE [%]	PP [%]	PS [%]	EPS [%]	PVC [%]	PET [%]	PUR [%]	ABS [%]	PA [%]	Other [%]
Consumption	17	13	19	3	5	12	9	6	2	2	12
Waste generated	21	14	21	3	3	8	13	4	2	2	9
Recyclates	21	18	16	2	2	7	22	3	1	1	7

Results suggests that a subset of polymers drive the overall plastic consumption for the analyzed sectors, with a major role especially played by HDPE, LDPE, PP, PVC, PET covering 70% of the total demand. Furthermore, the same polymers contributed to a total of 84% recyclates out of the total waste generated.

Given that the packaging sector represents the most relevant sector with regard not only to the total plastic demand but also the overall recyclates produced (Section 3.1), a specific focus was given to the packaging sectors for the assessment of polymer-specific results.

To allocate the total plastic demand mass to the most relevant polymers in the packaging sector, data from PlasticsEurope (2021) were considered, resulting in the demand described in Table 12. Following a similar approach as for the sector-specific MFA illustrated in Figure 4 and Figure 5, a MFA for all polymers in the packaging sector was derived in Figure 13. By adopting the same approach, MFAs could be also derived for the construction, agriculture, transport and EEE sectors (for more details, see Annex 4).

Results indicate LDPE, HDPE, PET and PP amounted to a total 92% of the total polymer demand needs for the packaging sector, as is also noticeable from Figure 13.

Table 12. Polymer-specific plastic demand for the packaging sector, calculated based on the data from Plastics Europe (2021). Data are expressed as the polymer-specific share [%] regarding the total plastic demand in the packaging sector. Additional information is reported in Annex 4.

	LDPE [%]	HDPE [%]	PP [%]	PS [%]	EPS [%]	PVC [%]	PET [%]	PUR [%]	ABS [%]	PA [%]	Other [%]
Polymer-specific plastic demand for the packaging sector	29.78	17.96	23.44	2.92	1.41	2.01	20.62	0.25	0.10	0.30	1.21

When considering both Figure 13 and Table 12 it is evident how the most common polymers in the packaging sector represent not only the most frequently consumed polymers in the whole EU27 economy, but also the most relevant polymers regarding recyclates being produced and ultimately consumed in the EU. A further confirmation of this relevance is evident from Figure 12 and Table 13, which compares how each sector contributes to the total amount of recyclates produced by polymer type.

Figure 12. Polymer-specific contribution of each sector regarding the total recyclates produced (reported in Table 13). Polymer-specific shares for each sector are expressed as [%]. (Note: EEE = Electrical and Electronic Equipment).

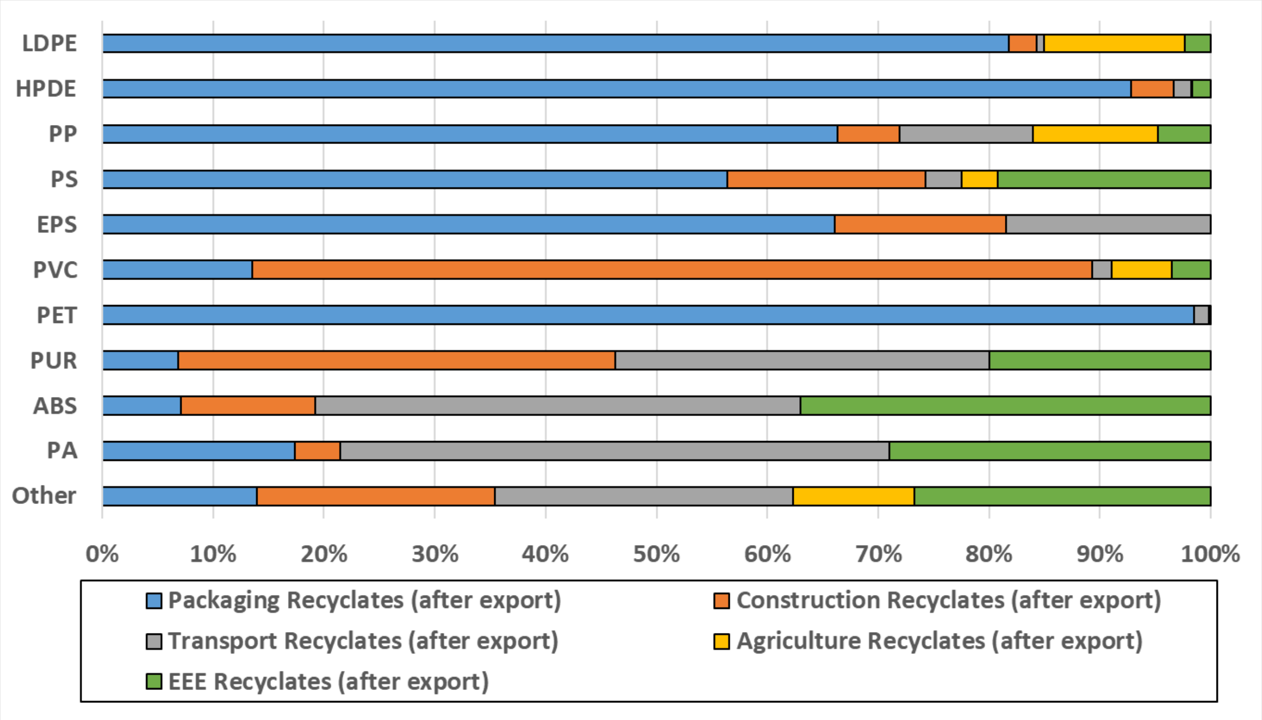


Table 13. Polymer-specific contribution on the total recyclates produced (i.e., 4Mt). The total recyclates produced (after exports) are expressed in [ktonne]. (Note: TOT recy. = Total recyclates for each polymer, after export, for the Packaging, Construction, Transport, Agriculture and Electrical and Electronic Equipment sectors).

	LDPE	HDPE	PP	PS	EPS	PVC	PET	PUR	ABS	PA	Other
TOT recy. [kilotonne]	846	728	652	64	67	266	894	115	45	55	272

Beside LDPE, HDPE, PP, PS, EPS, and PET for which the dominant role of packaging is evident (Figure 12 and Table 13) regarding recyclates production, other insights could be collected on the other investigated sectors. PVC and PUR were mostly linked to the construction sector and the construction and transport sectors, respectively. On the other hand, recyclates production of polymer such as ABS and PA was mostly related to the EEE and transport sectors.

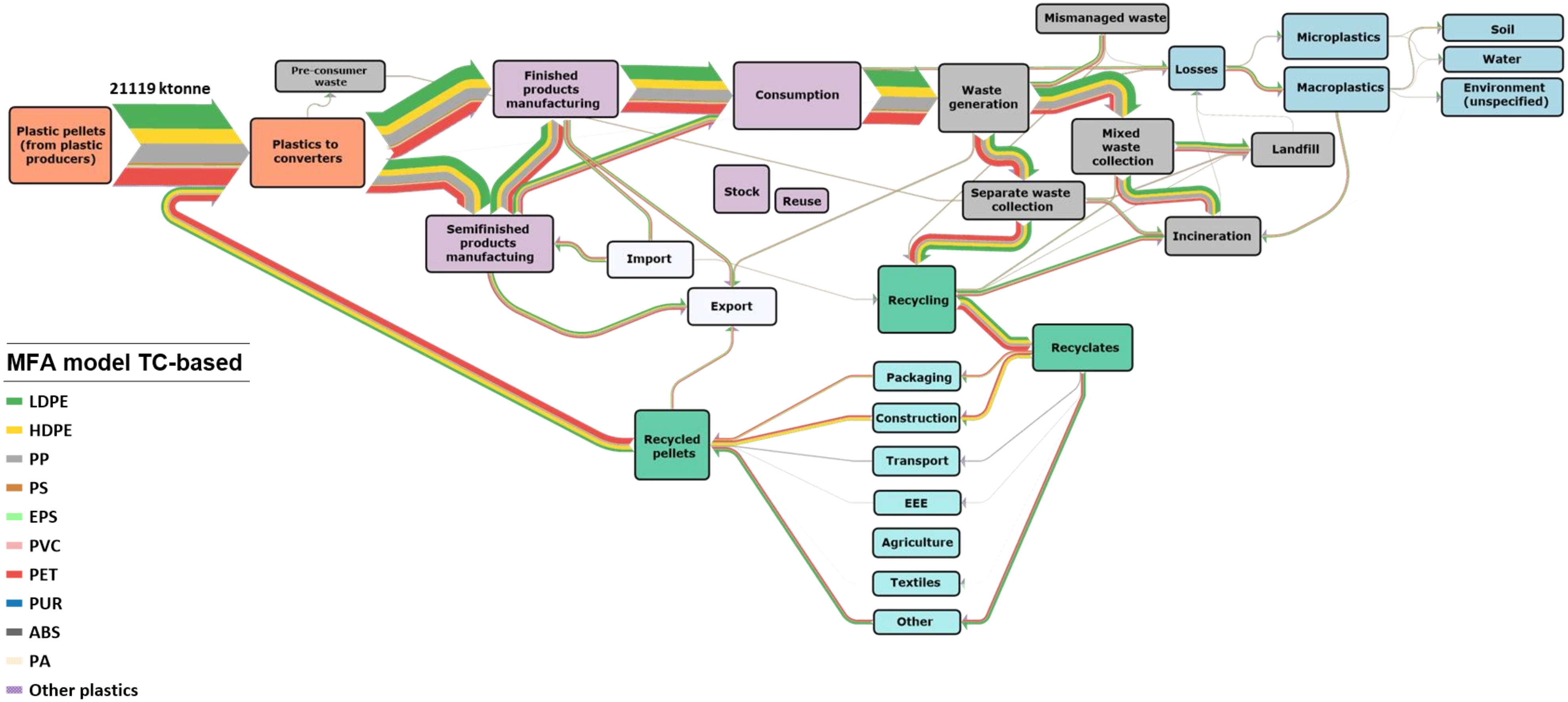
Lastly, recyclates end-of-life recycling rates for each polymer and sector are summarized in Table 14.

Table 14. Polymer-specific end-of-life recycling rates for each of the investigated sectors. Results are expressed as [%]. (Note: P = Packaging; C = Construction, T = Transport, E = Electrical and Electronic Equipment (EEE), A = Agriculture).

	LDPE [%]	**HDPE [%]**	**PP [%]**	**PS [%]**	**EPS [%]**	**PVC [%]**	**PET [%]**	**PUR [%]**	**ABS [%]**	**PA [%]**	**Other [%]**
P	21	34	17	11	29	16	39	29	29	29	29
C	15	7	15	15	3	19	-	15	15	15	15
T	15	15	13	15	15	13	15	13	15	15	15
A	44	2	30	22	-	22	22	-	-	-	22
E	15	15	13	15	-	15	15	15	15	15	15

On average, the highest end-of-life recycling rates were observed for PET (23%), LDPE (18%) and PVC (17%), along the lines of what was observed in Table 13.

Figure 13. General overview of the material flow assessment of EU plastic flows at the polymer level of the packaging sector. The width of the arrow lines is proportional to annual plastic flow volume in 2019 (for reference, the input flow to plastic manufacturers equals 2.11E+04 ktonne, of which: 29.78% LDPE, 17.96% HDPE, 23.44% PP, 2.92% PS, 1.41% EPS, 2.01% PVC, 20.62% PET, 0.25% PUR, 0.10% ABS, 0.30% PA, 1.21% Other plastics; for reference, the total EU plastic manufacturers demand is equal to 5.33E+04 ktonne, according to the results of the present study). All data are expressed in [ktonne] and are referred to the year 2019/year]. "Plastic manufacturing" is used to indicate plastic conversion in the case of finished products and semi-finished products.



4 Discussion

This section is aimed at discussing the results and the methodological challenges of the present study.

4.1 Comparison with other studies and main novelties of this study

This study provided a comprehensive overview of plastic flows in the EU27 for a total of 9 sectors and detailed the main polymer flows (10 polymers in total) for 5 out of 9 of the sectors under examination. To establish the MFAs for each sector and polymer, several literature studies were screened and analyzed. In the following sections, the main similarities and differences with other literature references are highlighted, together with the most relevant novelties of the performed study.

4.1.1 Main novelties of the present study

Building on previous studies and methodological approaches, the present assessment aims at providing the most detailed overview of plastic flows in the EU economy to date. It aims at bridging the gap between the scattered knowledge on plastic flows and sectors by modelling comprehensive MFAs. The analysis of literature information suggested several main issues related to the information currently available in the context of sector-specific MFAs:

- At the level of plastic sectors, the degree of details is inconsistent between the value chain phases, with most sector-specific literature data available only for the consumption/waste collection steps of the value chain. Sector-specific information related to end-of-life management of plastic flows and pre-consumer phases of the plastic value chain is either missing (e.g., for some sectors, such as healthcare and fishing) or detailed only at the level of country-specific studies. This study provides results for a total of 9 sectors, ensuring that the same level of details is available for each sector-specific MFA and providing specific flows for the end-of-life management and pre-consumption steps. This was achieved by combining data from EU-based statistics with data retrieved from report and literature in the field of plastic MFAs to derive specific transfer coefficients able to model the whole plastic value chain in scope. Additionally, most MFAs available to date do not include less explored sectors such as the clothing and textiles, healthcare and fishing sectors that are instead analyzed in the present study on an equal footing compared to other sectors.
- At the level of the steps in the value chain, the literature review highlighted that some key flows are currently not included in most of the comprehensive plastic MFAs. In particular, the assessment of both mismanaged waste flows and plastic losses (together with the final environmental compartment in which they are released) is frequently not integrated in the context of the wider plastic value chain. This could lead to an underestimation of some flows potentially relevant, especially for some sectors (e.g., mismanaged waste for the transport and EEE sectors). This study aims at detailing the flows of sector-specific losses and mismanaged waste by employing the most up-to-date methodological approaches and data knowledge.
- At the polymer level, the polymers included in the gathered literature references were frequently aggregated in different groups, varied widely across studies. The absence of a clear and consistent classification among literature studies, limited the comparability and increased the complexity of establishing sector-polymer links. The top-down approach proposed in this study represents a potential way forward to derive full MFAs for all polymers within each sector, ensuring that all flows along the full value chain are detailed for each polymer. This approach represents a potential tool for deriving in a consistent way polymer-specific MFAs from sector-specific ones. The proposed approach could also be used for those sectors that are greatly influenced by data-gaps if information on the most common polymers in use would be available.

By employing an approach based on transfer coefficients (TCs), the calculated MFA could be adapted according to recent developments and findings and could be employed for calculating scenarios to understand the behavior of the whole value chain and compare it against targets. Furthermore, by following the consumption statistics-based approach introduced by Amadei et al. (2022) and based on PRODCOM data, to model the TCs for consumption and products manufacturing, it would be possible to update the data with a yearly frequency and to evaluate time trends in a systematic manner.

4.1.2 Comparison with key literature references

The quantification of the TCs for consumption and pre-consumption flows in the present study leveraged extensively the consumption statistics-based approach introduced by Amadei et al. (2022). As described in Annex 1, the present study aimed at improving the estimates related to semi-finished products being directly sold to consumption. These flows were excluded from the study by Amadei et al. (2022) to limit the potential effect of double counting of consumed plastics, as a certain amount of semi-finished products is being employed for the manufacturing of finished products. In Table 15 a comparison between the estimated consumption of plastics from the two studies is reported.

Table 15. Total consumed plastics as reported by Amadei et al. (2022) (consumption statistics-based approach) compared with the results of the present study. Results are presented as [kg/person] (EU27 population) and as share of total consumption for each sector [%] (Note: P = Packaging; C = Construction, T = Transport, E = Electrical and Electronic Equipment (EEE), A = Agriculture, C&T = Clothing and textiles, H = Healthcare, F = Fishing, O = Other).

Consumption	**P**	**C**	**T**	**E**	**A**	**C&T**	**H**	**F**	**O**
Amadei et al. (2022) [kg/pers.]	30.52	37.65	8.08	14.43	0.15	8.25	0.47	0.43	29.36
Amadei et al. (2022) [%]	24%	29%	6%	11%	0.12%	6%	0.36%	0.33%	23%
Present study [kg/pers.]	32.84	23.02	10.21	8.01	3.94	4.65	0.20	0.34	16.86
Present study [%]	33%	23%	10%	8%	4%	5%	0.2%	0.3%	17%

To enable a direct comparison, the results from Amadei et al. (2022) for the two categories ‘Clothing’ and ‘Textiles’ were aggregated (by calculating the sum of the two).

As described in Section 2.3.3 and Annex 3, the input mass of the present study (i.e., the total amount of plastic assumed to be demanded by product manufacturers, equalling 53.3Mt for the EU27 in 2019) was allocated to the various sectors, mostly based on PlasticsEurope (2020) following a top-down approach. This approach could explain the differences in term of the overall shares of the most relevant sectors (Table 15) between the two studies. In fact, Amadei et al. (2022) leveraged a categorization of PRODCOM codes to derive the total consumed mass of a given sector, following a bottom-up rationale. This approach is strongly dependent on the categorization choices of each PRODCOM codes, that could directly affect the plastic mass associated to a given sector. Moreover, it should be also considered that the results from Amadei et al. (2022) focused on the EU27 for the year 2014. In the present study, the amount of plastics labelled under the heterogeneous ‘other’ sector manifested a difference of 6 percentage points compared to the results by Amadei et al. (2022), followed by the EEE sector (3 percentage points). Results indicate a relevance of the agriculture sector higher in this study compared to the results from Amadei et al. (2022). Similarly, the packaging sector resulted in the most relevant sector in the present assessment, compared to the construction sector in the Amadei et al. (2022) study. In particular, the study from Amadei et al. (2022) highlighted a significant variability in the share of plastic consumption between sectors from year to year, according to information gathered from PRODCOM codes. This was especially evident in the case of the construction sector for the year 2014, compared to the other years (with a minimum contribution equal to 8% in the year 2010 and a maximum equal to 29% for the year 2014). Overall, both studies agreed that (beside the ‘other’ sector) most of the plastic consumption in the EU is related to the packaging, construction, transport and EEE sectors. The total plastic consumption in the EU27 was estimated as 100.6 kg/person by the present study and 129.3 kg/person by Amadei et al., (2022). This difference could suggest that estimating consumption directly from PRODCOM data might lead to overestimations due to the several data corrections needed (Section 1.2). The assumptions on semi-finished products consumption should be also considered when flagging a potential overestimation, as these were not considered in the study by Amadei et al. (2022). Lastly, it should be noted that the performed revision concerning the categorization of PRODCOM codes (i.e., association of each PRODCOM code to each sector under examination) performed in the present study (compared to those selected by Amadei and colleagues) could also have a role in explaining the resulting differences (this revision is described in Annex 2).

As previously mentioned, the report from Watkins et al. (2020) served as a key basis for the modelling of the recycling step and recyclates fate. Watkins et al. (2020) indicated a total amount of recyclates produced equal to 3.8 Mt by considering data for the year range 2014-2018. By contrast, the total recyclates produced in the present study amounted to 4.5Mt for the year 2019 (after exports). Notably, the clothing and textiles, healthcare, fishing, and 'other' sectors included in the present study were not analyzed by Watkins et al (2020). By excluding these sectors from the results of the present report, the total recyclates production would be equal to 4.3Mt in 2019. The difference in scope and in the time-period (rapid growth in the recyclates production and consumption) considered in the two studies could explain this gap: Watkins et al. (2020) based their estimate on a bottom-up approach (focusing on the priority products selected by the Circular Plastics Alliance[8], which only account for a share of the market) for the period 2014-2018, whilst the present study leveraged the direct assumptions on the whole plastics for each sector (as explained in Annex 3) for the year 2019. A comparison of the relevance of each comparable sector to the total recyclates calculated by the two studies is reported in Table 16.

Table 16. Share of the total recyclates produced for comparable sectors for the study by Watkins et al. (2020) and the present study (recyclates produced after export). Results are expressed as [%]. (Note: P = Packaging; C = Construction, T = Transport, E = Electrical and Electronic Equipment (EEE), A = Agriculture).

Reference	P	C	T	E	A
Watkins et al. (2022) [%]	72%	9%	9%	2%	8%
Amadei et al. (2022) [%]	73%	11%	7%	5%	4%

A certain agreement about the most relevant sectors is evident from Table 16, especially regarding the role of the packaging sector. It is important however to notice that Watkins et al. (2020) did not consider that a certain amount of recyclates is currently being exported and therefore not available for the consumption within the EU territory (i.e., are not contributing to the EU/CPA goal). Considering that 18% of recyclates are exported (as suggested by PlasticsEurope, 2019), the value estimated from Watkins et al. (2020) would lead to 3.1 Mt recyclates consumed in the EU.

As previously mentioned, the TCs related to the fate of plastic recyclates (i.e., the sectors in which the recycled plastics are ultimately being used) were modelled based on data from Watkins et al. (2020) study, being one of the most detailed analyses concerning such fates. For this reason, results related to recyclate fates are aligned in the two studies, especially for the packaging, construction, and agriculture sectors. For the transport and EEE sectors, assumptions based on PlasticsEurope (2019) were employed in the present study, to overcome data gaps in the modelling of TCs for these sectors.

Data reported yearly by the Plastics Europe reports (e.g., PlasticsEurope, 2020; PlasticsEurope, 2021) represented a key data source to estimate several TCs along the plastic value chain (for more details, see Annex

[8] CPA work plan on design-for-recycling: https://ec.europa.eu/docsroom/documents/47334.

3). A comparison of the main figures reported within recent PlasticsEurope reports and the results of the present assessment are reported in Table 17.

Table 17. Comparison of the results from Plastics Europe references with the present study. Results are expressed as [ktonne] and for all plastics on the EU-27 market. (Note: reported data from Plastics Europe have been corrected for EU27 2019 as described in Section 2.2).

All plastics	**PlasticsEurope (2019) [ktonne]**	**PlasticsEurope (2020) [ktonne]**	**PlasticsEurope (2021) [ktonne]**	**Present study [ktonne]**
Plastic demand	53,331	42,924	47,135	53,331
Waste collected	25,442	24,637	28,320	22,921
Waste incinerated	10,838	10,495	11,894	9,738
Waste landfilled	6,238	6,135	6,627	6,212
Waste recycled	8,365	8,007	9,799	6,212

Although Plastics Europe reports do not allow for an in-depth comparison at sector-specific level, the comparison on the total EU27 plastics amount suggested a good alignment. As Plastics Europe reports do not provide any specific information related to "plastic consumption", the reported "plastic converter demands" were compared to the estimated consumption in the present study (Table 17). In the present study, the data suggested by PlasticsEurope (2019) were prioritized, when possible, in comparison with other studies from Plastics Europe (e.g., PlasticsEurope, 2020; PlasticsEurope, 2021. In fact, the 2019 report (PlasticsEurope, 2019) offers one of the most insightful and complete analysis concerning the plastics flows in the EU; not only regarding sector-specific details for the end-of-life plastic value chain stages, but also providing flows' details for the plastic demand, conversion and use phases. The difference in the plastic demand suggested by the 2019 report (PlasticsEurope, 2019), compared to the other Plastics Europe reports illustrated in Table 17, could be explained by the explicit inclusion of virgin and non-virgin plastics as an input to plastic converters. Concerning "waste collected", a certain alignment with Plastics Europe data is also evident, although it should be considered that from the amount of waste generated estimated in this study (28.8Mt), a certain amount could also be mismanaged or exported. For comparison, the total "waste generated" after trade calculated in the present study would amount to 26.8Mt. When looking at the fate of plastics waste, it must be considered that the present study considers further options compared to Plastics Europe (i.e., it also includes waste mismanagement and lost). For this reason, the total amount of the "waste incinerated", "waste landfilled", and "waste recycled" in Table 17 do not add up to the total "waste generated". However, by looking at the relative relevance of the three waste management options, results of the Plastics Europe studies and the present report suggested that 42-44% of the total waste is being incinerated, with 23-28% being landfilled and 28-35% recycled.

4.1.2.1 Comparison with the study performed by Metabolic et al. (2022)

A recent study performed by Metabolic (2022) aimed at improving the results reported by Watkins et al. (2020) in the context of providing support to the EU/CPA target on plastic recyclates. The study from Metabolic aimed at (i) improving the quality of data and modelling on plastic flows in Europe and (ii) exploiting the insights gained on the plastic value chain to identify the most impactful strategies available for improving the circularity of plastics in the EU. A comparison of the main assumptions, approaches, and overall goals of the two studies are illustrated in Table 18.

Table 18. Comparison of the main assumptions and approaches at the base of the model of the Metabolic study (Metabolic, 2022) compared with those of the present study. (Note: EEE = Electrical and Electronic Equipment; MFA = Material Flow Analysis).

Comparison field	Metabolic study	Present study
Overall goal	This study is framed in the context of the 10Mt recyclates target for the year 2025 of the EU/CPA for EU27+UK, and an option is provided to update the existing model with new data sources and assumptions. The study aims at modelling plastic flows for improving data quality of mass flows in the EU (and in the EU MS), in view of identifying high-impact strategies for improving the circularity of plastics.	This study aims at bridging the gap between available literature information in the context of MFA for plastics. It aims at providing an eagle-eyed view of sector-specific plastic flows and polymer-specific plastic flows, not only for the most explored sectors and flows, but also exploring less-known sectors and flows (e.g., sectors such as clothing and textiles, fishing and healthcare; and flows such as plastic losses and mismanaged waste).
Models – Rationale and boundaries	MFA models are based on priority products for the packaging, construction, transport, EEE and agriculture sectors. An MFA model was built for the EU27 (2019) and a series of country-specific models were calculated for 5 products (one for each sector).	MFA models are based on sector-specific information gathered from literature and statistics for the packaging, construction, transport, EEE, agriculture, clothing and textiles, healthcare, fishing and 'other' sectors. An MFA model was built for the EU27 (2019) and a series of polymer-specific models were calculated for 5 sectors (namely: packaging, construction, transport, EEE, agriculture), detailing for all the plastic flows of 10 polymers (namely: LDPE, HDPE, PP, PS, EPS, PVC, PET, ABS/SAN, PA, PUR).
Models - Differences	It includes literature/statistics data with primary information collected through interactions with stakeholders of the CPA. The MFA models provide details at the level of products and are mostly focused on separately collected waste (no details on the fate and management options of waste not destined to recycling). It distinguishes between mechanical recycling and chemical recycling.	Based on information available in literature/statistics. MFA models were calculated also for sectors that are less commonly explored in literature: clothing and textiles, healthcare, fishing. It also includes details on the waste management options for the waste not being recycled; the amount and fate of mismanaged waste being generated for each sector; the amount and fate of plastic losses and environmental releases (to soil and water) along the plastic value chain.
Models – Approach	Bottom-up approach: for each priority product in the selected sectors, polymer-specific data were compiled and added up to obtain total sector-specific values. For each product, specific transfer coefficients (TCs) were employed to derive the MFA models.	Sector-specific MFA model: this model was based on TCs derived from literature sources and statistics providing data for sectors. The approach aimed at merging sector-specific MFA models available in literature related to end-of-life plastic management and MFA models related to the plastic consumption step. It is based on TCs.

Comparison field	Metabolic study	Present study
		Polymer-specific MFA model: a top-down approach was established to derive from the sector-specific MFA models, polymer-specific models within each sector based on: (i) when available, specific TCs calculated from literature, especially for the waste management steps of the value chain; (ii) in all other cases, TCs were based on those calculated for the sector-specific models.
Models – Data	Plastic production and consumption: based on PRODCOM data to estimate production, imports and exports, following a revision of the approach developed by Amadei et al. (2022). The revision covered multiple PRODCOM codes and the related sectors, as well as the categorization of plastic products (i.e., semi-finished or finished). Assumptions on semi-finished products and finished products production are considered but not reported explicitly in the MFA model results (i.e., no distinction between the consumed mass of finished and semi-finished products). Waste generation and treatment: mostly based on information from Eurostat that were adapted for the considered priority products. Such approach required extrapolations to 2019 as Eurostat waste data is unavailable for this year. Includes assumption on pre-consumer waste for all sectors under examination, mostly based on country-specific assumptions (i.e., data for Germany) and packaging-specific data. Most details are related to waste streams destined to recycling. Waste recycling, recyclates generation and fate: based on estimates gathered from stakeholders and expert judgements, together with data from Plastics Europe and sector-specific information when available (e.g., Maury et al., 2022 for the transport sector). It includes estimates on the flows destined to mechanical recycling and chemical recycling. Recyclate fates are mostly based on Watkins et al. (2020). The sector-specific models are built on polymer specific data for the priority products. Exports and imports are considered in several steps of the value chain.	The overall EU plastic demand was derived from PlasticsEurope (2019) and was allocated to each sector based on data from PlasticsEurope (2020) and on calculations from the data from Amadei et al. (2022) (see Annex 3). Plastic manufacturing and plastic consumption: based on PRODCOM data to estimate production, imports and exports, following a revision of approach developed by Amadei et al. (2022). The revision focused on few PRODCOM codes and the related sectors. Assumptions on semi-finished products and finished products production are considered explicitly in the MFA model results (i.e., distinction between the consumed mass of finished and semi-finished products). Waste generation and treatment: mostly based on information from Watkins et al. (2020) combined with data from PlasticsEurope (2019) and PlasticsEurope (2020). Assumptions for pre-consumer waste generation and fate are employed for the packaging sector only. Details are related not only to the waste streams destined to recycling, but also to the other waste management options. Waste recycling, recyclates generation and fate: it based on sector-specific data (e.g., Maury et al., 2022 for the transport sector and Huisman et al., 2015 for the EEE sector). Recyclate fates are based on Watkins et al. (2020). Plastic losses and mismanaged waste: several literature sources were employed for estimating these flows (see Annex 2). Mostly, the assumptions were based on data from Peano et al. (2020) to obtain losses of microplastics and microplastics and to estimate the final environmental releases to soil and water.

Comparison field	Metabolic study	Present study
		The polymer-specific models are built following a top-down approach based on the sector-specific models. Exports and imports are considered in several steps of the value chain.
Projections to 2025	A shortlist of interventions is derived by means of a survey submitted to CPA stakeholders. Based on the collected feedbacks, interventions on the MFA model are estimated to establish projections to the year 2025. In the report, projections are categorized as “individual” and as “combined” (where potential synergistic or antagonistic effects between single actions are considered). The “individual” actions include: (i) effects on collection (e.g., banning the landfill of recyclable plastics; making incineration more costly than recycling through incentives;, etc.); (ii) effects on sorting efficiency (e.g., invest in proven sorting technology capacity; standards to characterise sorted plastic waste adopted in the whole EU market, etc.); (iii) effects on recyclates production, improving recycling efficiencies and capacity (e.g., invest in proven recycling technology capacities; invest in post-shredding technology for automotive waste recycling; etc.) and (iv) effects aimed at increasing the demand for recyclates in different applications excluding any possible effect of supply shortages or cost/price issues (e.g., embedding recycled plastics between virgin plastics in application with high quality demand). The “combined” actions include a combination of individual interventions and how these could interact having synergistic/antagonistic effects (e.g., if landfilling of recyclable plastic would be banned, this would lead to higher amounts of plastic previously landfilled being instead either incinerated or recycled. If such a measure is put in practice, making incineration more expensive than recycling would have a higher impact on the total recycles production). Further details are provided in Section 4.2.	Projections for the year 2025 are based on variations on the parameters (i.e., TCs) of the sector-specific models. These variations are assumed based on considerations related to the current EU policies (e.g., the Single Use Plastics Directive; the European Strategy for plastics in a Circular Economy) and to actions such as the EU/CPA goal for 2025 to represent expected trends in the near future. The scenarios include: (i) reduced waste export (i.e., assumption of a 20% decrease of plastic waste export for the transport and EEE sectors and 10% for the other remaining sectors, following the example of international waste bans on the import of plastic waste, such as China’s waste import ban), (ii) improved waste collection (i.e., assumption on the effects of the EU policy efforts towards a plastic circular economy. Such efforts could lead to a 30% increase in the separate collection of plastic packaging waste and 10% for plastic waste arising from the remaining sectors. In parallel, a 25% reduction of the mismanaged waste for the transport and EEE sectors is considered); (iii) improved management of separately collected plastic waste (i.e., assumption on how a systematic improvement in the mixed waste stream management and efforts towards recyclability could lead to 15% more plastic packaging waste sent to recyclers from sorting centres, and 10% for the remaining sectors); (iv) improved recycling performance (i.e., assumption on how to achieve the ambitious targets set by policymakers and industries alike, a substantial growth in the entire recycling value chain would be necessary, leading to 20% lower rejects from recycling sent to incineration for packaging waste and 10% for waste from the remaining sectors) and (v) combined scenarios with increasing/decreasing/stagnating plastic production (i.e., a combination of the previous scenarios with a +10%/-10%/+0% assumption on plastic production). Further

Comparison field	Metabolic study	Present study
		details are provided in Section 4.2.

As described in Table 18, to model the MFA of plastics flows in the EU27 for the year 2019, Metabolic (2022) followed a bottom-up approach. The total sector-specific plastic flows were built based on a subset of selected "priority products", following an approach like the one employed by Watkins et al. (2020). Overall, the report focused on the packaging, construction, transport, agriculture and EEE sectors. The focus of the Metabolic study was related to the analysis of the plastic waste flows being separately collected, including their fate after being recycled into secondary plastics in view of providing feedback to the feasibility of the EU/CPA target of 8.8Mt of recyclates for the year 2025 (EC, 2018a; CPA, 2019). By contrast, the present study leveraged literature and statistics information to establish sector-specific MFA models that were then analyzed in detail at the polymer level through a top-down approach. A graphical comparison of the approach performed by Metabolic (2022) and the approach followed in the present study is provided in Figure 14. Compared to the Metabolic report, the results of the present study also included estimates for less explored sectors (such as clothing and textiles, healthcare and fishing) and details for all waste management options (including for instance the fate of waste streams not being recycled, the amount of losses and mismanaged waste). A comparison of the total results of the two studies for the comparable sectors and the most relevant steps in the value chain is reported in Table 19.

Figure 14. Comparison of the approach followed by Metabolic (2022) and the approach followed in the present study or deriving MFAs of plastic flows in the EU27 for the year 2019.

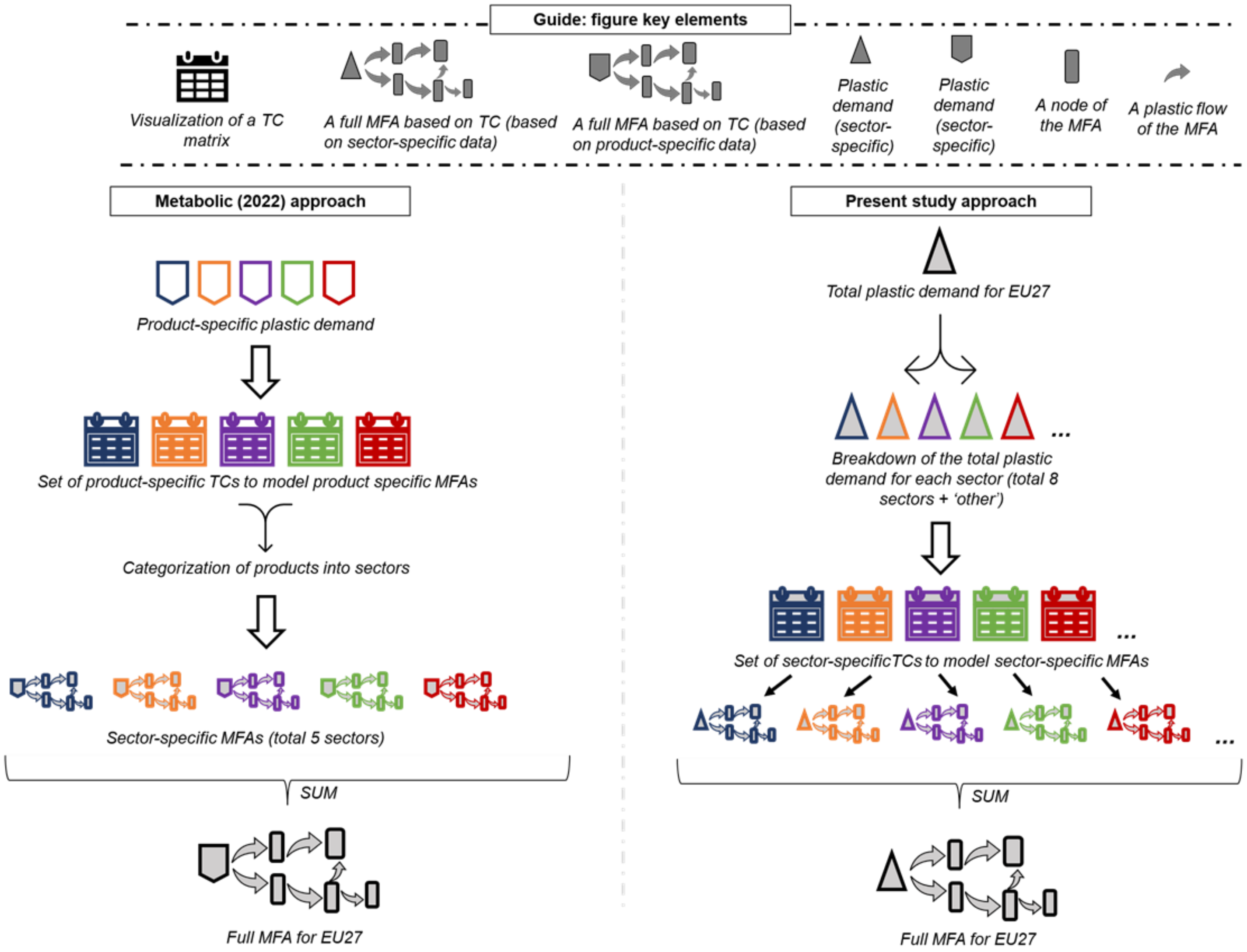


Table 19. Comparison of the results from the Metabolic study (Metabolic, 2022) and the present study for key comparable steps in the value chain. Results are expressed as Megatonnes [Mt] and for the EU27 market. The percentage variation is calculated with respect to the Metabolic study and expressed as [%]. (Note: the total plastic is intended to cover the packaging, construction, transport, agriculture, and Electrical and Electronic Equipment sectors; recyclates destined to the textile sector (0.2Mt) calculated in the present study are considered under 'Recyclates to Other' for comparative purposes).

MFA step	Metabolic study	Present study	Percentage variation
Total primary material used in production	39.80	41.91	5%
Total pre-consumer waste generation	1.56	0.29	-81%
Total post-consumer waste generation	18.69	22.85	22%
Total pre- and post-consumer waste to recycling	7.18	7.60	6%
Total pre- and post-consumer waste not recycled	11.44	15.54	36%
Total waste exported outside of EU	1.63	1.36	-17%
Total Non-EU recyclables import to recycling	0.82	0.47	-43%
Total recyclates (before trade)	5.26	5.24	-0.4%
Total recyclates (after trade, i.e., consumed in the EU)	4.26	4.28	0.4%
Recyclate to Packaging (before trade)	0.63	0.96	51%
Recyclate to Construction (before trade)	1.14	1.40	23%
Recyclate to Automotive (before trade)	0.24	0.16	-31%
Recyclate to EEE (before trade)	0.07	0.04	-41%
Recyclate to Agriculture (before trade)	0.04	0.16	294%
Recyclate to Other (before trade)	2.14	2.51	18%
Recyclate to Export (before trade)	1.00	0.96	-4%

The difference in the input of plastic raw material to the EU27 economy could be explained by the different approaches employed for estimating this plastic flow. In the present study, it was estimated leveraging on data from PlasticsEurope (2019) and allocated to the various sectors adopting data from PlasticsEurope (2020) following a top-down approach. In the study performed by Metabolic, the total material used in production was based on a bottom-up approach leveraging on the selected priority products and data from PRODCOM. The total amount of primary material used in production in EU27 was estimated as the sum of the product-specific productions from PRODCOM, associated to each of the priority products in each sector. About the total pre- and post-consumer waste to recycling, both results agreed that around 7.1Mt-7.6Mt of plastics are made available for EU recyclers in 2019 for the sectors assessed in Table 19. The percentage variation (36%) in the total pre- and post-consumer waste not recycled could be explained considering that Metabolic (2022) employed in the MFA model TCs based on waste generation and waste collection estimates from Eurostat; whilst in the present study TCs were calculated leveraging on Watkins et al. (2020) and PlasticsEurope (2019) as described in Annex 3. In both studies waste trade was estimated based on Eurostat data but considering different starting data points and leveraging on different assumptions. In the present study, Eurostat data were collected for several waste scraps of different polymer types that were allocated to the sectors under study by considering PlasticsEurope (2021) shares (a more detailed description of the employed calculations is detailed in Annex 3). On the other hand, in the case of Metabolic (2022), Eurostat data related to the total EU27 imports and exports of plastic waste were allocated to each priority product for each sector by employing product-specific assumptions.

Results from Table 19 indicate that the estimated secondary plastics consumed in the EU (for packaging, construction, transport, EEE and agriculture) is comparable (0.4% percentage variation) with the one indicated by Metabolic (2022). According to the estimates of the present study, the sectors included in the Metabolic study cover around 78% of the total plastic consumption and around 96% of the EU27 total recyclates output. In fact, the clothing and textiles, healthcare and fishing cumulatively contributed to only 0.9% of the total recyclates consumed in the EU27 according to the present study, with an additional 3.2% due to the heterogeneous 'other' sector. Results from statistics in the field of plastics (Table 17) seems to suggest a value of total EU recyclates consumption of around 4.0Mt, in line with the findings of both studies.

One of the most relevant differences for the two models is represented by the total amount of pre-consumer plastic waste generated. In both studies, an estimated amount of pre-consumer waste for the packaging sector was derived from Cimpan et al. (2021). However, in the Metabolic study, an estimated amount of pre-consumer plastic waste being generated for the other sectors (around 5% of the production amount) was estimated from Cimpan et al. (2021) and a country-specific study of Germany (Conversio, 2020). Assumptions were also employed regarding the fate of such pre-consumer waste, as it was assumed that 55% (for packaging) and 82% (for the EEE, construction, agriculture, and automotive sectors) of the total waste was recycled. When similar assumptions are applied to the sector-specific MFA for the present model[9], variations in the total recyclates produced would be in the order of +18%. For the MFA presented in the present study (and the sectors in common with Metabolic), this would result in a total throughput of recyclates equal to 6.5Mt (before exports) and 5.3Mt (after exports). This seems to indicate a potential role of the pre-consumer plastic waste generation and its management assumptions on the total recyclates' production and consumption. Even if a relatively small percentage of the total production of each sector is assumed to be discarded as pre-consumer waste, differences in the total plastic recyclates output might be observed. Regarding recyclates' fate, the present study suggests that 15% of the total recyclates produced are ultimately employed in the packaging sector, and 23% in the construction sector; whilst Metabolic (2022) indicates 15% and 27% respectively. If recyclates' fates of the present study were estimated based on Watkins et al. (2020), by contrast in the Metabolic study a combination of data from Watkins et al. (2020) and values shared by CPA signatories (targeted to the identified priority products) was employed.

4.1.2.2 Comparison with recent MFA studies in the plastic field

MFAs of plastics flows focused on the EU represented a key source of information for the present study. In particular, the study by Kawecki et al. (2018) was carefully analysed. In their analysis, Kawecki et al. (2018) propose a probabilistic material flow analysis for plastic flows in sectors following a bottom-up approach by firstly building polymer specific MFAs (for seven polymers, namely: LDPE, HDPE, PP, PS, EPS, PVC, and PET). Results from the analysis of Kawecki et al. (2018) are reported for 8 sectors (namely: packaging, construction, transport, EEE, agriculture, clothing, textiles, 'other'). Sector-specific MFA details are provided only concerning the consumption and waste collection step, whilst all other phases are modelled for a 'total' plastic waste stream. By comparison, the present study also includes the healthcare and fishing sectors and details sector-specific information as well for the pre-consumption steps and the end-of-life steps (after waste collection) of the value chain. A more recent study performed by Hsu et al. (2021) detailed a comprehensive EU28 plastic MFA for 2016. Similarly, to the consumption statistics-based approach proposed by Amadei et al. (2022), Hsu et al. (2021) leveraged the PRODCOM database for establishing sector-specific MFAs, by categorizing plastic-containing products to each sector (namely: packaging, construction, transport, EEE, textiles, varnishes, healthcare and 'other'). Information related to sectors such as textiles and healthcare are reported by Hsu et al. (2021) and represented key starting points for deriving the MFAs of the present study. As described for Kawecki et al. (2018) precise sector-specific details for the end-of-life steps are not available in the study of Hsu et al. (2021), therefore limiting the comparability with the present study, especially regarding recyclates fates. A comparative summary of the main differences between the present study and the ones from Kawecki et al. (2018) and Hsu et al. (2021) are reported in Table 20.

[9] i.e., 5% of the total production for finished/semi-finished products of all sectors being discarded as pre-consumer waste, and managed as a separately collected waste stream, which is mostly sent to recycling.

Table 20. Comparison of the results from the study by Kawecki et al. (2018), the study by Hsu et al. (2021) and the present study. Results are expressed as [ktonne] and for the total plastics (adapted for EU27 2019). (note: [1]: no information on the type of collection).

MFA step	Kawecki et al. (2018)	Hsu et al. (2021)	Present study
Consumption	38,985.5	61,946.7	44,747.8
Waste generation	39,355.6	34,422.5	28,780.2
Mixed waste collection	25,248.0	34,422.5 [1]	12,830.8
Separate waste collection	17,002.3		10,089.8
Recycling	6,557.0	12,480.8	8,189.0
Recyclates (after trade)	5,350.4	3,675.7	4,462.2

As described by Amadei et al. (2022), results from Table 20 suggest that an approach based solely on PRODCOM categories (such as the one adopted from Hsu et al., 2021) might lead to higher results when compared with other studies. Overall, the present study manifests a good alignment with the compared references. Differences could be explained by the different approach employed in the development of the MFAs in the three cases and the data adjustment needed to adapt the data for EU27 2019 in view of a fair comparison (performed as described in Section 2.2).

4.1.2.3 Polymer-specific comparisons

Regarding the polymer-specific assessment, literature information related to polymer consumption in the EU are aligned with the findings of the present study. Data reported especially by Kawecki et al. (2018) and further elaborated by Amadei et al. (2022) suggest that seven polymers (namely: LDPE, HDPE, PP, PS, EPS, PVC, PET) are responsible for a total of around 70% of the overall EU consumption, compared to the 78% calculated in the present study. Worldwide mapping exercises of the plastic value chain (e.g., Ryberg et al., 2018) also confirm that one third of the total plastic production could be related to the abovementioned seven polymers alone.
Additionally, findings from the present study indicate that PUR plastics consumption is comparable to the combined EPS-PS consumption (6% of the total consumption). PUR polymer was not considered in the study performed by Kawecki et al. (2018) and the study from Amadei et al. (2022), although its relevance is confirmed by Ryberg et al. (2019). The consumption of PUR was found to be mostly linked to the construction and transport sectors, with 49% and 32% respectively of all the PUR plastics consumed in the EU. A recent study performed by Charles et al. (2021), details the global plastic consumption of industries accountable for 90% of the total single-use plastic production. By analyzing such facilities, Charles et al. (2021) recognized PP and LDPE as the most used polymers worldwide, which confirms the findings of the present study for the highest consumed polymers in the EU (Table 11).

In the study by Eriksen et al. (2020), a dynamic MFA was performed for analyzing EU flows of PET, PE and PP to provide insights on future scenarios aimed at enhancing the circularity of the value chain, compared to a 2016 baseline. When considering baseline results by Eriksen et al. (2020), resulting end-of-life recycling rates are lower than those in Table 14 regarding PET (around 16-17% in the Eriksen et al. (2020) study; 23% in the present study) and PP (around 13-14% in the Eriksen et al. (2020) study; 18% in the present study); whilst PE results are aligned (around 18-19% in the Eriksen et al. (2020) study; 18% in the present study, calculated as the average of the end-of-life recycling rates for HDPE and LDPE). Eriksen et al. (2020) employed a bottom-up approach for building polymer-specific MFAs, leveraging on product types (e.g., rigid, soft, bottles, furniture, etc.) that were categorized into sectors (namely: packaging, electronics, agriculture, automotive, building and construction, fibers, others). As this study follows instead a top-down approach for polymer flows in the packaging, construction, transport, agriculture and EEE sectors, the effect on end-of-life recycling rates of certain PET, PE or PP products in the non-investigated categories might be overlooked (such as those included by Eriksen et al. (2020) under the 'other' and fibers categories).

The Kawecki et al. (2021) work represents a recent follow-up of the Kawecki et al. (2018) study, focusing as well on LDPE, HDPE, PP, PS, EPS, PVC and PET flows in EU, but proposing instead a dynamic probabilistic MFA. Recycling rates are reported by Kawecki et al. (2021) to vary from 11% in the case of EPS and 33% for PET, manifesting a broader range of compared to what was observed in the MFAs calculated in the present study (15% for EPS and 23% PET). Notably, results from Kawecki et al. (2021) also included the textiles and 'other' sectors and represented a 2016 scenario for EU28. A potential explanation of the differences in the estimates could be due to the lack of a clear definition of how "recycling rates" were calculated in the study of Kawecki et al. (2021).

Literature studies related to the assessment of plastic polymer flows are also available in literature (e.g., Pivnenko et al. (2019) in the case of Denmark; Picuno et al. (2021) in the case of Germany). Data about plastic recycling in Denmark were recognized to be lacking by Pivnenko et al. (2019), which nonetheless calculated Denmark-specific recycling rates in the range of 22-26% (calculated either as the ratio of waste plastic recovered from recycling compared to waste plastic generated or waste plastic recovered for recycling and imported for recycling compared to waste plastic generated and waste plastic imported). This would suggest a higher recycling rate for Denmark compared to the overall EU27 figures as calculated in the present study (recycling rates in the range 16-19%). A similar result was found in the case of Germany by Picuno et al. (2021), with recycling rates in the order of 26% and 38% (calculated analogously to the end-of-life recycling rates calculated in the present study), when the potential recycling of mixed polyolefins is considered (mostly HDPE, PP and films originating from mixed packaging, representing a plastic flow stream which is sorted as a mixed plastic fraction). Out of the polymers analyzed by Picuno et al. (2021), HDPE, PET, and films (such as LDPE) manifested the highest recyclability potential being more properly collected and sorted compared to other polymers, along the lines of the findings of the present report.

When looking especially at the packaging sector, another recent study from Antonopoulos et al. (2021) describes results of material flow analysis based on primary data collected from sorting and recycling facilities managing plastic packaging waste. The analysis of the data collected from recycling plants suggests that on average the highest efficiencies related to secondary plastic outputs (i.e., "reprocessing rates"; according to the definition provided by Antonopoulos et al., 2021) are achieved when managing HDPE (84%), PET (80%) and PVC (80%) plastics. In the present report reprocessing rates are aligned with those suggested by Antonopoulos et al. (2021) for PVC (82%) and HDPE (84%), whilst are lower in the case of PET (76%). This could be explained considering that TCs for PET packaging (Annex 4) leveraged the estimated recycling performance from Watkins et al. (2020) (71%). Regarding the end-of-life recycling rates (i.e., the secondary material in output of a recycling plant compared to the post-consumer waste generated) from the study of Antonopoulos et al. (2021), a total end-of-life recycling rate of 14% was suggested (25% if the potential recycling of exported waste is considered). As for Eriksen et al. (2021) these results are lower than those by the present study in the case of packaging (26%) and might suggest that real-case recycling rates are less encouraging than what could be estimated based on available statistics.

4.1.2.4 Other comparisons

Other examples of MFAs applied at the country level are also available from literature (e.g., Austria (Van Eygen et al., 2017), Switzerland (Kawecki and Nowack, 2019), and Denmark (Pivnenko et al., 2019)). Among these studies, the MFA from Van Eygen et al. (2017) represented an interesting MFA at sector level, providing insights also for the healthcare and textiles sectors. For instance, consumed volumes of textiles plastics reported by Van Eygen et al. (2017) (corrected for EU27 2019) amounted to 3.23Mt and waste generated amounted to 1.7Mt, compared to 2.1Mt and to 1.4Mt for the present study, respectively. However, several data-gaps are noticeable for these two sectors, especially regarding the pre-consumer steps of the plastic value chain and the fate of the generated waste, which are instead captured by the present study. As already noticed in the case of Kawecki et al. (2018), the MFA proposed by Van Eygen et al. (2017) covers as well sector-specific information only for consumption-related steps of the plastic value chain, whilst sector-specific details especially related to the recycling and recyclates fate are lacking.

Another study related to the textiles sector was performed by Köhler et al. (2021), exploring circular economy approaches in the EU textile sector based on Eurostat data. Köhler et al. (2021) indicated (after correction for EU27 2019) a total of 1.95Mt waste being generated. By comparison, in the present study the total of 1.35Mt waste generated is estimated.

Regarding the healthcare sector, few literature sources are available with detailed data lacking especially regarding the consumption step. According to the present study plastic consumed for this sector amounted to

9.0E+01 ktonne. This amount is strongly linked with the base assumptions on the distribution of the plastic manufacturers demand between sectors (described in Annex 3). Compared with the consumption suggested by Hsu et al. (2021) (1.0E+03 ktonne) and by Van Eygen et al. (2017) (7.5E+02 ktonne), a certain variability is evident even when data are adapted to EU27 2019.

The study by Maury et al. (2022) provides an interesting insight on the share of the end-of-life treatment options for several plastic sectors, based on Plastics Europe data. When comparing the results for the transport sector with the results of this study (Figure 7 and Table 7), Maury et al. (2022) indicates that 21% of plastics for this sector is currently recycled, compared to the 19% estimated in this study. Additionally, results of the study from Maury et al. (2022) seems to indicate an overall reprocessing rate lower (less than 50%) compared to the one estimated in the present study for this sector (around 70%). It should be considered that Maury et al. (2022) focused especially on the automotive sector, whilst the present study aims at covering the whole transport sector.

Another sector which was affected by several data gaps and missing information is the fishing sector. For this reason, several assumptions were needed to model the MFA for this sector in the present study. The study from Deshpande et al. (2020) focuses on the fishing gears value chain in Norway and suggests a total of 7.5E+02 ktonne of consumed plastics and 1.7E+02 ktonne of waste being generated (results adapted to EU27 and 2019). In the present study results indicate lower values (1.5E+02 ktonne and 6.9E+01 ktonne for consumed plastics and waste generated, respectively) that could hint at the effect of the different scope and regionalization of the studies, influencing results even after data collection.

Concerning plastic emissions to the environment, in the study by Kawecki and Nowack (2019), material flows of micro and macroplastics for Switzerland are reported, detailing losses for water and soil. The model prepared by the two authors covers losses from the pre-consumer step of the value chain, as well as from the consumption and waste management steps (especially losses from waste collection). In the present study, the approach proposed by Peano et al. (2020) was employed to model all losses and related fate at the pre-consumption step and the waste generation phase. On the other hand, all losses and related fate from the consumption step were modelled after Peano et al. (2020) only for the transport and textiles and clothing sectors, whilst data from Kawecki and Nowack (2019) were applied elsewhere. A summary of the main findings in comparison with the results of the present study are reported in Table 21.

Table 21. Comparison of the results from the study by Kawecki and Nowack (2019) and the present study. Results are expressed as [ktonne] and for the total plastics (adapted for EU27 2019). (Note: [1]: referred to losses happening at the 'waste collection' step, whilst losses in the present study were calculated on the total waste generated, losses from incineration and landfill estimated in this study are excluded in this row).

MFA step – Results for Kawecki and Nowack (2019)	**Total losses [ktonne]**	**Microplastics [ktonne]**	**Macroplastics [ktonne]**
Pre-consumer steps	1.7	1.5	0
Consumption	1,000	21	1,000
Waste management steps [1]	43	3	40
MFA step – Results for the present study	**Total losses [ktonne]**	**Microplastics [ktonne]**	**Macroplastics [ktonne]**
Pre-consumer steps	53	53	0
Consumption	820	11	810
Waste management steps [1]	780	0	780

Overall, a certain agreement is evident from Table 21, especially regarding the total losses estimated (1.0Mt in the case of Kawecki and Nowack (2019) and 1.7Mt in the present study). The differences in the results could be explained by considering the methodological differences in the two studies, as the approach followed by Kawecki and Nowack (2019) leveraged the results of the study by Kawecki et al. (2018) that employed data directly collected from several literature sources and reports. According to Peano et al. (2020) (based on Boucher et al. (2019)) 3% of the yearly produced plastics are lost worldwide. By comparison the amount of lost plastics relative to the production output estimated in the present study (according to the data indicated in Table 21, amounting to 1.7Mt) reached 3.1%.

One of the few examples of comprehensive MFAs detailing information on plastic losses is the study by Hsu et al. (2021) which includes an estimated 3.1Mt total plastic losses (corrected for EU27 2019). The value reported by Hsu et al. (2021) also includes mismanaged waste following the method proposed by Ryberg et al. (2019), whilst mismanaged plastics amounts were described separately in the present study. Another potential approach for estimating plastic losses was suggested by Amadei et al. (2022) by employing littered plastics observed on EU shores and combining them with PRODCOM consumption estimates. Currently, Amadei et al. (2022) indicated the total losses in terms of likelihood of certain items to be lost, even if, by considering the average unitary weights and the related consumption flows, estimates for total losses could be calculated.

4.2 Main outlook from the scenario assessment

Based on the main results of the model a certain level of resource inefficiency is evident. In particular, the European plastic system faces several challenges to improve the overall performance along the plastic value chain. Among these challenges, the effects of plastic waste mismanagement play a pivotal role in achieving a circular system. Results from Table 22 (presented for the both the packaging sector and the modelled total EU27 plastic) suggest that around 84% of the European plastics system it is still linear as this share of plastic waste ends up as either incinerated, landfilled, or mismanaged.

Bearing in mind the overall EU target, as endorsed by the CPA (CPA, 2019), of 8.8 million tonnes of post-consumer recyclates used in EU27 by 2025 (adjusted from the 10 million tonnes target for EU27+UK to enable a fair comparison with the results of the present study), the scenarios assessment suggests that the target can be achieved and surpassed through combined actions as presented in Section 3.2. Although a reduction of waste exports (Scenario A) can ensure a 5% increase (Table 10) in the total recyclates produced in 2019 (4.46Mt as estimated by this study), the effect of this action is negligible in terms of improving the overall circularity of the system (Table 22). It is worth noticing that no information is available regarding the specific fate of exported waste that could be in principle recycled in the receiving country.

One of the most relevant actions to ensure higher recyclates production and higher recyclates consumption rates is improved waste management (Scenario B and Scenario C). The main effect of improved separate collection of plastic waste (Scenario B i.e., +30% plastic packaging waste separately collected and +10% for plastic waste from other sectors) would be a reduction in the amount of plastic waste being landfilled, incinerated or mismanaged (especially for the transport and EEE sectors, for which a 25% reduction was assumed in the amounts of mismanaged waste). According to Scenario B, a total of 6.47Mt (Table 10) would be consumed in EU27 achieving a recyclates consumption rate of 24.1% (Table 22). Compared with other scenarios assessed, Scenario B alone contributed to achieving the highest improvement in the circularity of the modelled plastic system. This scenario was drafted considering the ambitious future goals the European Green Deal (EC, 2019b), European Strategy for plastics (EC, 2018a). It should be considered that substantial changes will be needed to achieve such improvements. Some key barriers for implementing these changes would be linked to: (i) the limits for implementing some collection procedures (e.g., door-to-door) in practice due to the intrinsic differences in MS territories; (ii) the economic feasibility of new collection practices and (iii) the necessary shift in consumers behavior especially for the less exemplary EU MS. Moreover, in Scenario B a 25% reduction was assumed in the TCs related to waste mismanagement for the transport and EEE sectors. It should be noticed that very few information regarding the fate and the precise amount of mismanaged plastic waste is available to date. Even if a certain amount of this waste could be exported and recycled in foreign countries, it can be assumed that most of these plastic waste flows are currently being scavenged or improperly managed (as suggested for instance by in the case of WEEE). Tracing and deviating flows of plastics currently being mismanaged towards separate collection system would require a significant effort for the EU but could also dispatch a significant amount of plastics to EU recyclers.

With Scenario C that assumes improved management of separately collected waste (i.e., 15% more plastic packaging waste separately collected is sent to recycling facilities compared to the Base Scenario, and 10% more plastic waste from other sectors than packaging), results indicate 5.23Mt (Table 10) recyclates being consumed in the EU27 and 19.5% of overall recyclates consumption rate (Table 22). Scenario C would in principle adhere to the expected outcomes of the Landfill Directive (EC, 1999) in terms of reduced landfilling.

However, a competitive effect might be related to an increase amount of incinerated waste in place of recycling (as suggested for instance by Systemiq, 2022). This effect could further reduce the recyclates consumption rates and total recyclates' production estimated in this study for this scenario. Overall, when comparing scenario B and C in terms of total recyclates production and overall recyclates consumption rates, it is evident that improved management of separately collected waste (i.e., increased sorting yields) has a lower impact than improved separate collection, the latter leading to higher amounts of plastic waste being separately collected.

Following the goal of many EU policies (e.g., EC, 2008; EC, 2018b; EC, 2018a) about an improvement in the amount of plastic being recycled, Scenario D (improved recycling performance: i.e., 20% lower rejects of plastic packaging waste from recycling facilities and 10% lower rejects of plastic waste from other sectors) was analyzed. The effects of Scenario D in the overall plastic value chain would be in the order of 5.57Mt recyclates (Table 10) being consumed in the EU and a recyclates consumption rate around 20.8% (Table 22). When analyzing potential improvements regarding plastic waste recycling, this Scenario entails a positive variation of 20% concerning the recycling performance for the packaging sectors and a 10% variation regarding all other sectors. Furthermore, alternative processes that could potentially lead to higher overall recyclates consumption rates in the EU, such as chemical recycling, are currently not commonly operating at full/commercial scale and could also compete with mechanical recycling for some plastic feedstocks. As an additional point, even small improvements in the recycling of plastics for some sectors (e.g., clothing and textiles, transport) might require significant efforts and a systematic reshape of the whole value chain of these sectors, considering the low end-of-life recycling rates currently observed.

When all actions are combined in Scenario F1 (together with an assumed 10% increase in plastic production), a total of 11.13Mt recyclates consumed (Table 10) and a recyclates consumption rates of 35.5% are achieved (Table 22). This would represent a pivotal result regarding the EU/CPA target of 8.8Mt of plastics recyclates by the year 2025 as the target would be covered and surpassed by an additional 2.33Mt. However, as described in Section 2.3.5, available information from statistics (such as Plastics Europe reports) and other sources (e.g., EC, 2018a), indicate a future growing trend in plastic production and demand in the EU27 based on observed data for the period from 2010 to 2019. Other external factors (such as the COVID-19 pandemic or the Ukraine war), coupled with EU commitments on plastic preventions (EC, 2019a) and brands and retailers' commitments in reducing plastic consumption (EMAF, 2022), could instead result in an unprecedented reduction in plastic production in the future. This is also suggested by Systemiq (2022) that indicates a 5% reduction in plastic demand by 2030. Moreover, as indicated by Table 6 in Section 3.1.3, most of the produced recyclates are destined to products in the construction sector. This would underline the presence of an additional barrier on circularity related to recyclates quality (compared to virgin materials) and closed loop recycling, which was not explicitly described in each of the Scenarios. However, when a reduction of 10% in plastic production is assumed in the present study (for the combined Scenario F2, Table 10), the resulting total recyclates consumption (9.11Mt) is still sufficient, although much lower, to achieve the 8.8Mt target. When a stagnation of plastic production is assumed (0% demand variation, as described in the combined Scenario F3, Table 10) the resulting recyclates being consumed (equal to 10.12Mt) are sufficient to achieve and surpass the EU/CPA target.

Overall, considering both the possible variations in plastic demand and the underpinning assumptions in each Scenario, the modelling results clearly suggest that the EU/CPA target can be achieved through a series of actions to be taken simultaneously in the next few years.

Table 22. Recyclates consumption rates [%] for the packaging sector and the total EU-27 plastic market under examination from the sector-based MFA for the scenario assessed for 2025. Each recyclates consumption rate was calculated as the ratio between the total waste generated (after trade) and the total recyclates produced and consumed (i.e., after exports of recyclates; it refers to the amount demanded by converters) in the EU27. (Note: [1] = calculated considering trade of waste generated and trade of recyclates produced).

Scenarios	**Scenario description**	**Packaging recyclates consumption rates [%]**	**Total plastic recyclates consumption rates [%] [1]**
Base model	Results of the sector-specific MFA model for EU27 2019 as presented in the report	23.3%	16.6%

Scenarios	Scenario description	Packaging recyclates consumption rates [%]	Total plastic recyclates consumption rates [%] [1]
A	Reduced waste export	23.3%	16.5%
B	Improved waste collection	35.8%	24.1%
C	Improved management of separately collected plastic waste	27.3%	19.5%
D	Improved recycling performance	29.9%	20.8%
F,	Combined scenario (same results for assumption on +10% [F1] , -10% [F2] and +0% [F3] variations in production)	54.4%	35.5%

A report published by the CPA ('Untapped Potential Report'; CPA, 2021) presented an overview scenario how the EU27+UK market could get to the 10Mt target by 2025, analyzing the untapped potential (i.e., additional quantities of plastic waste to be collected, sorted, and recycled in 2025 compared to the 2020 baseline) and the related investment needs in sorting and recycling capacities. This report covered the packaging, automotive, construction, EEE and agriculture sectors. It analysed the sector-specific untapped potentials concerning waste to collect and sort for recycling by 2025 compared to the 2020 baseline (additional 4.2Mt in total for all 5 sectors), for sorted plastic waste to reach recyclers and for recyclates that should go from recyclers to converters (additional 3.4Mt by 2025 compared to the 2020 baseline, in total for the 5 sectors). As a result, the analysis of the CPA (CPA, 2021) report underlined how a total of approximately 10.2Mt of recyclates could be achieved in Europe by 2025 (including an amount of pre-consumer PVC recyclates of approximately 0.5Mt, reported under the Vinylplus voluntary commitment (VinylPlus, 2022) - from and used in construction sector and included in the original EU 10Mt target). The result of the CPA untapped potential report concerning waste collected and sorted for recycling could be compared with the results of Scenario A (Table 10; reduced waste export; considering that both exports of waste and exports of recyclates are assumed to be significantly reduced in the assumption of the Untapped Potential Report), Scenario B (Table 10; improved waste collection) and Scenario C (Table 10; improved management of separately collected plastic waste), and considering the additional mass of plastic waste sent to recyclers when all three scenarios are combined. In this latter case, results of the present assessment indicate that 5.1Mt of plastics could be made available to plastic recyclers (compared to 3.4Mt estimated by the CPA). Despite the scope of the present report being EU27 (compared to EU27+UK for the CPA untapped potential report), in the present study additional sectors are included in the analysis that are currently excluded from the CPA scope (i.e., the clothing and textiles, healthcare and fishing sectors). This could be particularly relevant in the case of the clothing and textiles sector as results of this study suggest that more than half of the textiles waste is exported (an effect which is diminished in Scenario A). Additionally, in Scenario B, this study assumes a strong reduction (i.e., 25%) in mismanaged waste not only for the EEE sector (as also acknowledged by the CPA report), but also for the transport sector, where waste mismanagement is estimated at 33% of all waste generated in this sector. Because of the application of these scenarios, a total of 3.6Mt additional plastic waste (on top of the 4.5Mt of the base scenario) could be expected as an output from recycling, along the lines of the estimates of the CPA (CPA, 2021). Overall, when all scenarios of the present study are combined a total of 10.1Mt recyclates consumed was estimated for the EU27 (assuming a 0% variation in plastic production; 11.1Mt for a 10% increase and 9.1Mt for a 10% decrease). This result should be compared with the EU/CPA target of 8.8Mt (adapted to EU27). By contrast the result of the CPA untapped potential report are equal to 10.2Mt for EU27+UK (to be compared with the 10Mt target). The more optimistic results of the present study can be explained by its broader sectorial coverage. In addition, the CPA untapped potential report focuses on in-depth sector-specific assumptions to calculate the future recyclates consumption potentials; whilst in the present study the scenarios' assumptions are mostly inspired by some key literature sources (e.g., Systemiq et al., 2022) and coupled with expert judgment based on the underpinning EU policy background and social/economic background. However, the importance of targeting additional sectors is also recognized in the CPA untapped potential report, which considers the estimated

10.2Mt as a conservative scenario where no actions are included for less explored sectors (such as for instance the clothing and textiles sector). These sectors (clothing and textiles, healthcare, fishing) are instead modelled in the present study that is attempting at providing a full overview of their plastic value chain. Moreover, as previously mentioned, this report aims at collecting detailed data for less-explored flows (e.g., plastic losses and waste mismanaged) that, if properly managed could lead to an even higher amount of recycled made available for the EU consumption in the near future.

In a recent study by Metabolic (2022), a specific section is devoted to the assessment of solutions toward the EU/CPA 2025 target. In the study performed by Metabolic (2022) a list of potential actions was generated and evaluated by means of expert judgment from stakeholders through a survey. The survey was aimed at understanding the most feasible and impactful actions in terms of their potential effects by 2025. Four main categories were identified, namely: (i) actions influencing collection; (ii) actions influencing sorting efficiencies; (iii) actions influencing recyclates production and (iv) actions influencing demand. Additionally, an insight on the presence of antagonist and synergistic effects ("combination of actions") between actions was included. These effects were assessed by employing dynamic feedstocks for each sector (i.e., packaging, construction, transport, agriculture and EEE) in the MFA model. Results from the Metabolic study suggested that if all the shortlisted actions are adopted individually (albeit not considering a variation in plastic production), a cumulative total of 16.7 ± 6.4Mt recyclates could be produced by 2025 in the EU27 (compared to the range 9.1-11.1Mt estimated in the present study); and 23.8 ± 8.6Mt if combined actions were considered. Compared to the expected outcomes from the present study and other literature references (e.g., Systemiq et al., (2022); Material Economics (2022)), the results from Metabolic (2022) seemed to suggest a significant degree of feasibility of the EU/CPA target, especially if the presence of antagonistic and synergistic effects were considered. However, as indicated by Metabolic (2022) certain assumptions strongly influenced the total recyclates output estimated in the context of the "combination of actions" approach, and for this reason should be reviewed in the future and explored by employing more advanced modelling options (such as system dynamics modelling).

Results reported by Metabolic (2022) (for actions adopted individually) indicated that some of the highest impacts on the recyclates being produced could be achieved if waste destined to incineration and landfill is instead deviated to recycling. Similar conclusions have been drawn in the case of Scenario B discussed in the present study. In this case, the potential increase in term of recyclates consumed is aligned between the two studies (for Metabolic (2022): an additional 2.5 ± 0.6Mt of recyclates are consumed if landfill of recyclable plastics is banned and cost of incineration are increased; for the present study: 2.7Mt additional recyclates being consumed when considering Scenario B and C combined). Metabolic (2022) assumed that 63% of all landfilled waste would go to recycling if landfills were banned and that 57% of all plastic waste would go to recycling in place of incineration when the latter is made more costly. In the present study, it was assumed a 30% increase in separate collection of plastic packaging waste coupled with a 10% increase for the remaining sectors and a 25% decrease in the amount of waste being mismanaged for the transport and EEE sectors (Scenario B); and a 15% increase in plastic packaging waste sent to recyclers from sorting centres coupled with a 10% increase for the remaining sectors (Scenario C). Along the lines of Scenario C and D of the present study, results from Metabolic also indicated that scaling up of existing sorting technologies (i.e., proven technologies that already exist to be applied for all sorting plastic waste) could lead to an additional 2.4 ± 0.3Mt, compared to 1.9Mt of the present study, for Scenarios C and D. The differences in the assumptions on improvements due to these actions are significantly contributing to the differences in the total projections to 2025 of the two studies. The assumption of the Metabolic study on the scaling up of existing sorting technologies was based on the assumption of the CPA 'Untapped Potential Report' (CPA, 2021), leading to an overall 84% additional recyclates capacity expected from investing in proven recycling technologies. Overall, it would however require specific on-field pilot testing to indicate if real-case scenarios could result in recyclates production like the lower or to the upper bound of the two estimates. The remaining 11.9 ± 5.4Mt increase estimated from Metabolic (2022) was linked to several other actions. Among those, relevant contributions were acknowledged in the case of the promotion of sector procurement policies on recycled content (5.8 ± 2.8Mt, being the most impactful action overall), the establishment of standards to characterize sorted plastic waste adopted in the whole EU market (1.7 ± 1.1Mt) and the increase in investments in the chemical recycling capacities for plastic waste that cannot be mechanically recycled (1.1 ± 0.3Mt).

The effects of other potential factors (e.g., the effect of the establishment of extended producer responsibility schemes; the effect of investments in the field of private and public procurement policies, etc.) were also considered by Metabolic (2022) although being less effective than other previously mentioned actions with regards to an improvement in total recyclates being produced. The differences in potential impacts calculated by Metabolic (2022) could also be due to the different scope of each intervention, as for instance actions related to extended producer responsibility schemes EPR policies were sector-specifics, whilst interventions such as the banning of landfill would apply to all sectors.

Lastly, results of the present study (see especially Section 3.1.4 and Section 4.1.1) indicate that the amount of environmental losses represent only a small percentage compared to the total amount of produced plastics. As more knowledge on this topic is obtained, more light is shed on the relevance of microplastics (e.g., from tyre abrasion as described by Sieber et al., 2020) and macroplastic releases (e.g., from fishing gears as described by Richardson et al., 2019) as well as the potential interaction and transport of different plastic fractions (as described in El Hadri et al., 2021). In fact, the leakage of plastics into the environment remains a primary concern for the EU as recent studies highlighted the potentially dangerous effects on both animals and the biota and humans (Wagner & Lambert, 2018).

4.3 Main limitations and assumptions

Previous sections highlighted the main differences between the present study and other studies in literature as concerning system boundaries, scope, and specific methodological assumptions. On top of these differences, the variability in the considered sectors and the related data granularity, further limited the potential comparability of different sources. Furthermore, most literature sources typically report information only for 'total' plastic flows, without any detail at the level of sector. Considering the goal of providing a detailed MFA of plastics flows in the EU, literature references have been prioritized for their use in the present study for the calculations of the MFAs (Section 1.2, Annex 3). A potential alternative approach could be based on the calculations of TCs for each literature source and by employing an average TC in the model for each step of the value chain and each sector. However, inconsistencies in the system boundaries of literature sources and sensible differences in data granularity among sectors limited the application of this approach in a consistent way across sectors. For instance, in the case of waste management options (e.g., recycling, incineration and landfill), TCs calculated with respect to the total waste generated would be different for a study providing information solely on recycling and landfill compared to those derived for a study that considers recycling, incineration and landfill. Furthermore, the calculation of an average TC wouldn't be possible in case of sector-specific value chain for which no data points are available, and therefore the introduction of additional assumptions would anyway be needed.

The approach based on prioritization of reference sources introduces a series of drawbacks as the choice of the prioritized references could be an important driver on the results obtained. This aspect should be therefore considered when analysing the results of the present study. Additional statistical calculations (e.g., by considering different data assumptions, by including data uncertainties analysis, by including error propagation assessment, etc.) could benefit the projected mass flow results.

Overall, several factors contributed to the identification of a priority literature reference. In particular: (i) availability of sector-specific information on the flows for the 9 sectors under exam; (ii) availability of data for the EU rather than country-specific information; (iii) recent publications (i.e., 2016 onwards); (iv) if possible, availability of detailed background information related to the approach followed, the main references employed for estimating the flows and described rationale of assumptions and (v) the absence of alternative literature references for modelling a given plastic flow. The prioritized literature references include: Amadei et al. (2022) for the pre-consumption and consumption steps; Watkins et al. (2020) for the end-of-life management and recycling step as well as the fate of recyclates; data from Plastics Europe (PlasticsEurope, 2019; PlasticsEurope 2020; PlasticsEurope 2021) for modelling the total EU plastic demand; data from recent and detailed MFAs such as Kawecki et al. (2018) and Hsu et al. (2021) employed for modelling several flow of the value chain; and Kawecki and Nowack (2019) together with Peano et al. (2020) for the mismanaged waste and plastic losses. Other relevant literature sources included: Van Eygen et al. (2017) as a source of information for multiple steps of the value chain, and as a base for modelling the flows related to the healthcare sector; Köhler et al. (2021) and EEA (2021b) especially for the clothing and textiles sectors; Deshpande et al. (2021) especially for the fishing sector; Maury et al. (2022) for the transport sector; Huisman et al. (2017) for the EEE sector; Thomson and Sainsbury (2021) as a source of information for the end-of-life steps of the value chain; Sahimaa & Dahlbo (2017) as a source of information for the end-of-life steps of the value chain; Antonopoulos et al. (2021) and Lombardi et al. (2021) for modelling the packaging sector also at the polymers level.

The overall model is strongly dependent on the assumption on the total amount of plastic demand in EU (5.33E+04 [ktonne/year], derived from PlasticsEurope; 2019) as this represents the input to the various MFAs presented in the report. Although in the report from PlasticsEurope (2019) it is stated that the Plastics Europe's

Market Research Group has provided input related to plastics production and demand, it is not evident which are the underpinning assumptions and data employed to derive the total demand estimate. The Plastics Europe report for the year 2019 was employed as the starting point of the analysis due (i) to the higher level of details provided, not only about plastic demand and waste generation, but also regarding recyclates' production and fate and to (ii) enable a consistent data source for modelling several steps of the value chain (e.g., TCs related to recyclates' fate).

As the scope of the calculated MFAs also included a distinction between finished products and semi-finished products sold to consumers, a dedicated approach was established to detail the amount of semi-finished and finished plastic flows that is consumed. As described in Annex 1, this approach builds on the results of the consumption statistics-based approach by Amadei et al. (2022) and introduces a series of assumptions to calculate the total mass of semi-finished products sent to consumption. As no literature information was found differentiating between the fate of semi-finished products from that of finished products, this approach followed in the present study relies on expert judgment and assumptions to derive the mass of semi-finished products (within each sector) that is ultimately directly consumed. Additionally, to date there are no accepted definitions of "finished products" and "semi-finished products" in the context of plastics. For these reasons, assumptions must be introduced to distinguish between the two types of products, introducing potential effects of under/over-estimations of mass flows.

For all sectors included in the present study, the stock accumulation was calculated as the amount of plastics that closes the balance between the total consumption and the total waste generated within a sector. By employing this assumption, the resulting total waste generated is aligned with the amount commonly reported by statistics (e.g., Plastics Europe, see Table 17). In fact, results of the present study indicate that this assumption covers a gap of about 15Mt between the total consumed plastics and the total waste generated in 2019. Results of the present study also aimed at shedding light on less explored issues such as plastic waste mismanagement. The assumption on stock variation is linked to the amount of waste being generated from consumption and therefore could also be affected by an underestimation/overestimation of the flows of mismanaged waste, which are by nature not described in detail in official statistics. By comparison, in the case of 2019 Plastics Europe report (PlasticsEurope, 2019) the difference between the total plastic demand and the reported managed plastic waste amounted to 18Mt (after correction for the EU27 2019). This gap was recently acknowledged by a report from Material Economics and Agora Industry (Material Economics, 2022), which instead suggest an underestimation (as high as 45%) of the waste generated as a potential explanation of this gap, rather than a stock effect. By considering an increase of 40% of the total waste available in the construction, transport, EEE and agriculture sectors and keeping all other assumptions constants, the total plastic recyclates generated (after export) would be around 5.5Mt in place of the 4.5Mt of the current Base Scenario of the model. Building on the analysis performed by Material Economics (2022), the report from Systemiq (2022) suggests that beside an underestimation of plastic waste (especially plastic waste disposed as mixed plastic), other explanations of the "gap" between demand and waste plastic data could be found in an underestimation of products lifetime (i.e., net growth of plastic stock in the economy, as also assumed in the present study) and in higher levels of exports of plastic goods (i.e., illegal exports of plastic waste or greater levels of mismanagement). On the other hand, the current approach followed for deriving the stock accumulation could lead to underestimation of stock for some sectors (e.g., the transport and construction sectors in particular). In fact, an MFA of a single year might not properly capture the lifetime of certain products (e.g.: the plastic in stock for the transport sector of a given year might not be directly linked to the amount of plastic reaching end-of-life for that year). This could especially influence the sectors for which few data are currently available (e.g., healthcare and fishing) to model the flows along the whole value chain and that could include both durable and non-durable items having different lifetimes. An improvement of the estimates for the stock variation for these sectors would be possible thanks to: (i) more complete and up-to-date data and (ii) the inclusion of a dynamic assessment of the stock by looking at multiple years.

Regarding the pre-consumer waste, the present model only includes a certain amount of plastic from the packaging sector (around 1%, estimated based on Cimpan et al., 2021) assumed to be managed as a separately collected waste (i.e., it contributes to the total flows of plastics entering the "Separate waste collection" node as in Figure 5). If the amount of pre-consumer plastic waste for the packaging sector would be assumed to be managed as a mixed plastic waste stream (i.e., incinerated and landfilled) the MFA model of the present study would result in a total amount of 4.3Mt of plastic recyclates consumed in EU27. This would not affect the outcomes of analysis on the feasibility of the EU/CPA target of 8.8Mt of post-consumer recyclates by the year 2025 (Section 2.3.5; Section 3.2 and Section 4.2).

Regarding the plastic recyclates' fate, in the present study a perspective of "full recycling" of the plastic masses was accounted, not considering potential downcycling due to the quality of the recycled being produced. This could be captured by other types of analysis, for instance dealing with the quality of recyclates or their environmental impacts. This aspect is of relevance to better link the modelled MFA with the real world where industrial trade is also looking at plastic quality together with total amounts.

As described in Annex 2, the 'Plastic Leak Project' (Peano et al., 2020) was mostly used for estimating losses and mismanaged waste flows along the value chain. Regarding the mismanaged waste, a proxy TC based on the packaging sector (calculated based on the 'Plastic Leak Project') was also adopted for the construction, agriculture, clothing and textiles, healthcare, fishing, and 'other' sectors. The potential effect of this assumption on the total recyclates produced was discussed in Section 2.3.4 and Section 4.2, when the effects on the overall model of the amount of mismanaged waste recollected and sent to recycling were analyzed The amount of mismanaged waste was instead modelled for the transport and EEE sectors by employing different data sources. By following the 'Plastic Leak Project' method, results indicate that 45% of macroplastic lost (for all sectors) are being recollected and sent to incineration instead of being ultimately released in the environment. These favourable assumptions might lead to an underestimation of the total waste lost into the environment. Furthermore, the effect of fragmentation of macroplastics into microplastics is not considered in the current study, as the focus of the present assessment is a single year. However even within a one-year period, certain macroplastic fractions could already break down into microplastics according to the specific environmental conditions. By employing instead an approach focused on a longer time frame, it is possible that significant amount of macroplastics could be crumbled by environmental mechanism into microplastics. It is also worth noticing that the compartment 'environment (unspecified)' was created to ensure a closed mass balance in the context of the micro/macroplastic losses from consumption. Overall, it must be considered the results of the present study are influenced by data limitations and lack of established approaches, and where necessarily coupled with own assumptions to estimate all the sector-specific losses of along the value chain when needed.

The amount of plastic being sent to landfill from incineration was estimated for all sectors having as proxy the share for the packaging sector, as suggested by Van Eygen et al. (2017). This approach might lead to an overestimation of the amount of plastics not being eliminated through the incineration process.

As previously mentioned, data availability varied significantly across sectors, with some (e.g., packaging, construction) more investigated than others (e.g., healthcare, fishing) in the context of plastic flows. To overcome these data-gaps a series of assumptions, proxies from other sectors, combination of data from different sources were needed to establish complete MFAs.

The most relevant assumptions for each sector are listed hereafter:

- In the case of the packaging sector, the MFA was mostly based on data directly collected from literature (and employed as described in Annex 3). By considering the short lifespan of packaging products and that most packaging products are disposed of right after use, no stock was assumed for this sector. Adopting the method reported in the 'Plastic Leak Project' (Peano et al., 2020), which described losses for waste packaging products and other products, the amount of waste generated being lost was estimated for this sector. As suggested by Cimpan et al. (2021), the textiles sector was included in the present study's model among the potential destination for packaging recyclates, on top of the sectors indicated by Watkins et al. (2020).
- In the case of the construction sector, the data from Plastics Europe (2020) were employed to estimate the TC related to the amount of waste generated being managed as a mixed waste stream, since no specific assumptions were provided for this flow by Watkins et al. (2020). The amount of plastic waste being collected separately and as a mixed stream were derived from Plastics Europe (2020) by assuming a percentage equal to 48% and 52% respectively, as indicated for the management of all plastic waste in the EU. The mass of mixed waste was then allocated between incineration and landfill by employing shares derived from Hsu et al. (2021).
- In the case of the transport sector, information related to the automotive sector (from Maury et al. 2022) was used as proxy for deriving the TCs related to the amount of plastics being separately collected (67%) and mismanaged (33%). It was assumed that no mixed collection occurs in this sector. The management of waste separately collected for this sector was modelled according to the shares reported in Maury et al. (2022), which leveraged Plastics Europe data. A certain amount (8%) of

separately collected waste was assumed to be reused according to the information available from Maury et al. (2022). No specific information was available from Watkins et al. (2020) to derive the fate of recyclates produced (i.e., the target sectors of destination of secondary plastics), and therefore the data related to the fate of whole plastics in the EU economy were used as proxy for this sector (as described in PlasticsEurope, 2019).

- In the case of the EEE sector, no specific data points enabled an estimate of the losses from consumption. Based on Seyring et al. (2015), a TC was modelled to determine the mass of waste EEE (WEEE) being reused (2%). The data from Huisman et al. (2015) were employed to model the TCs of exported plastic waste (24% of the total waste generated), the amount of waste being collected as separate/mixed (38% and 19% respectively) as well as the amount of mismanaged waste (44%) related to this sector. No specific information was available from Watkins et al. (2020) to derive the fate of recyclates produced (i.e., the target sectors of destination of secondary plastics), and therefore the data related to the fate of whole plastics in the EU economy were used as proxy for this sector (as described in PlasticsEurope, 2019).

- In the case of the agriculture sector, the assumptions on plastic products demand in this sector are based on the share on the total demand suggested by PlasticsEurope (2020). Within this demand are included plastic products related to agriculture, farming and gardening that have a broader scope (e.g., also including packaging products) compared to recent estimates by the CPA for this sector (CPA, 2020; CPA, 2021) that are by contrast focused solely on non-packaging plastic products used directly by farmers in their production activities, with agronomic effect. This aspect should be considered when analysing the estimates for the agriculture sector. Estimates on plastic waste in agriculture by the CPA (CPA, 2020; CPA 2021) include the effect of soilage that has an effect of reducing the plastic content of the estimated waste stream. Although in the present study the soilage by organic and mineral matters or by water was not considered, a certain amount (around 9%) of plastic waste for agriculture was assumed to be mismanaged. If such waste would be instead considered to be collected waste, the total estimate (0.78Mt) would be aligned with the value suggested by the CPA (0.76Mt; CPA 2020, CPA 2021). Furthermore, it should be considered that in the present study the flows of certain plastic products (e.g., tubes) in the agriculture sector are also influenced by the assumptions on semi-finished/finished products that consider only a fraction as being sent to consumption (described in Annex 1). Additional research would be needed to improve the granularity detail of the estimates of plastic flows in this sector, and potentially to include effects such as soilage which could represent an important factor for determining recyclability of products, as well as cost and quality of recyclates.

- In the case of the clothing and textiles sector, based on data from the European Environment Agency (EEA, 2021b) and as also confirmed by Köhler et al. (2021), a TC equal to 30% was assumed for the waste generated being separately collected. From EEA (2021b), the TCs of waste being collected in the mixed stream (61%) as well as the amount of separately collected waste being reused (60%) were estimated. For this sector, it was necessary to model the fate of collected waste by combining a series of different data sources. For the mixed waste stream, the TC related to the flow to incineration and landfill (60% and 40% respectively) were estimated based on the shares reported for the whole EU plastics by Plastics Europe (2019). On the other hand, the report from Köhler et al. (2021) suggests that 20% of separately collected plastics are sent to recycling, whilst the Ellen MacArthur Foundation (EMAF) (EMAF, 2017) indicates that 73% of separately collected textiles are incinerated. A value of 25% was selected for the TC of separately collected waste being sent to recycling, whilst a TC of 38% for both incineration and landfill flows was adopted. For modelling the TCs related to the recycling step (recyclates produced, amount sent to incineration and landfill), the values were calculated as those estimated by Watkins et al. (2020) for the total plastics (aggregated total flows). No specific information was available from Watkins et al. (2020) to derive the fate of recyclates produced (i.e., the target sectors of destination of secondary plastics), and therefore the data related to the fate of whole plastics in the EU economy were used as proxy for this sector (as described in PlasticsEurope, 2019).

- In the case of the healthcare sector, the mass balance adopted for deriving the stock value resulted in a negative stock variation, which suggested that limited amount of plastic was discarded in 2019 from stock (1.4E+00 ktonne) on top of those being generated from consumption (8.5E+01 ktonne). No data for estimating the export of waste generated for this sector were available. Due to lack of data the TCs related to the amount of waste being managed as separate and mixed were derived from

PlasticsEurope (2019) considering the values for the total plastic as proxy (44% and 47% respectively). For the mixed waste stream, the TC related to the flow to incineration and landfill (60% and 40% respectively) were estimated based on the shares reported for the whole EU plastics by Plastics Europe (2019). The same approach was followed to derive the TCs distributing the mass of separately collected waste between recycling (62%), incineration (27%) and landfill (11%). For modelling the TCs related to the recycling step (recyclates produced, amount sent to incineration and landfill), the values were calculated as those estimated by Watkins et al. (2020) for the total plastics (aggregated total flows). No specific information was available from Watkins et al. (2020) to derive the fate of recyclates produced (i.e., the target sectors of destination of secondary plastics), and therefore the data related to the fate of whole plastics in the EU economy were used as proxy for this sector (as described in PlasticsEurope, 2019).

- In the case of the fishing sector, the TCs to model the recycling step (recyclates produced, amount sent to incineration and landfill) were calculated in line with the estimations by Watkins et al. (2020) for the total plastics (aggregated total flows). For the mixed waste stream, the TC related to the flow to incineration and landfill (60% and 40% respectively) were estimated based on the shares reported for the whole EU plastics by Plastics Europe (2019). The same approach was followed to derive the TCs distributing the mass of separately collected waste between recycling (62%), incineration (27%) and landfill (11%). For modelling the TCs related to the recycling step (recyclates produced, amount sent to incineration and landfill), the values were calculated as those estimated by Watkins et al. (2020) for the total plastics (aggregated total flows). No specific information was available from Watkins et al. (2020) to derive the fate of recyclates produced (i.e., the target sectors of destination of secondary plastics), and therefore the data related to the fate of whole plastics in the EU economy were used as proxy for this sector (as described in PlasticsEurope, 2019).
- In the case of the heterogeneous 'other' sector, the TC of waste generated from consumption (59%) was derived from the consumption value of Amadei et al. (2022) by considering the shares from PlasticsEurope (2019). The TC of separately collected waste was estimated as 6% following Maury et al. (2022), whilst the TC of mixed waste was equal to the remaining 83%. For the separate waste stream, the TCs related to the flow to incineration and landfill (27% and 11% respectively) and recycling (62%) were estimated based on the shares reported for the whole EU plastics by Plastics Europe (2019). No specific information was available from Watkins et al. (2020) to derive the fate of recyclates produced (i.e., the target sectors of destination of secondary plastics), and therefore the data related to the fate of whole plastics in the EU economy were used as proxy for this sector (as described in PlasticsEurope, 2019). As described for packaging, losses from the amount of waste generated were calculated adopting the method reported in the 'Plastic Leak Project' (Peano et al., 2020).

The top-down approach employed to assess the polymer-specific MFAs represented a potential tool for improving the granularity of sector-specific assessments. As polymer-specific information is less common for most sectors compared to the "total" sector information, a top-down approach is suited for understanding the most relevant underpinning polymer flows of a given sector. The approach (described in 2.4 and in Annex 4) for each sector leveraged polymer-specific demand values (i.e., the manufacturing industry demand of a given sector, expressed at the level of polymers) and a subset of TCs for the modelling of polymer-specific end-of-life management operations (see Figure 3); whilst all other TCs were based on the overall estimated TC of a given sector. When TCs values for a polymer in a sector were not available, the general TCs of the sector were used. This approach has three main shortcomings:

- To detail the polymer-specific flows of a given sector, the polymer-specific demand of a given sector is needed to allocate the total demand of a sector between its polymers. This data is fundamental as a starting point for building the MFAs according to the top-down approach.
- When sector-specific TCs are needed to model the value chain of polymers in each sector due to data constraints (e.g., polymer-specific TCs are absent), an effect of overestimation or underestimation of the actual polymer-specific flows might be present. This is of particular relevance in the case of the end-of-life management operation (especially collection rates and end-of-life recycling rates or recyclates consumption rates) where results could not be aligned with the actual rates of a given polymer in a given sector (for instance, in the agriculture sector, due to data limitations, it was

assumed that 59% of the PET plastics entering the recycling node is converted into recyclates following the assumption employed for the sector as a whole).

- On the other hand, when polymer-specific TCs are employed to model the MFA of a given polymer within a sector, a slight mismatch with the total sector-specific flows could be introduced. For instance, polymer-specific TCs related to waste management operations could be higher/lower compared to those employed in the overall sector-specific models. This could result in a difference in the separately collected waste estimated according to polymer flows (calculated as the sum of all polymer-specific separately collected waste flows), compared to the sector-based estimates. As an example, the total recyclates (after export) being calculated for the sector-specific MFA for packaging (Section 2.3) were equal to 4.3Mt. By contrast, the total recyclates (after export) calculated as the sum of all the polymer-specific recyclates in the packaging sector, following the top-down approach (Section 2.4) amounted to 4.0Mt (-6.5% percentage variation). This effect underlines: (i) the valuable added value of granular information throughout the value chain for polymer flows and (ii) suggests that calculating the total MFA of plastic flows of a sector based on polymer-specific data might lead to slightly different results compared MFAs built directly on sector-specific estimates (i.e., using a bottom-up approach to sum all polymer-specific contributions to a sector).

5 Conclusion and recommendations

Despite a growing interest in addressing plastic flows in recent years, comprehensive studies enabling detailed assessments across multiple sectors and polymers along the whole value plastic chain are currently lacking, especially including consideration on losses, mismanaged waste and recycled plastics fate. Understanding the effects of plastic pollution, especially due to plastic debris in the marine environment, is central for the achievement of the UN (United Nations) Sustainable Development Goal (SDG) 14, aimed at conserving and sustainably using oceans, seas, and marine resources (UNEP, 2022). In this context, several EU policies actions have also been put forward to address the considerable challenge that plastics represents (such as the EU Circular Economy Action Plan (EC, 2015), the European Strategy for plastics in a Circular Economy (EC, 2018a), The European Green Deal (EC, 2019b) and the new Circular Economy Action Plan (EC, 2020)).

This study aimed at establishing a mass flow analysis model (MFA) for the whole value chain of plastics in EU27 in 2019, from pellets production to end-of-life plastic management and recyclates production. The analysis focused on sector-specific MFAs for a total of 9 sectors. Additionally, 5 sectors (out of the 9 analyzed in the sector-specific assessment) were also further examined for deriving polymer-specific MFAs by analyzing a selection of 10 plastic polymers within each sector through a top-down approach. Estimates for the 2019 "Base Scenario" and future scenarios for the year 2025 were analysed in the context of the EU target of 10 million tonnes of recycled plastics used annually in the EU by 2025, set in 2018 for the EU28 and endorsed by the Circular Plastic Alliance (CPA, 2019). This target was corrected to 8.8 million tonnes of post-consumer recyclates for the EU27, to enable a fair comparison with the results of the present study.

Results of the sector-specific MFAs underlined the role of packaging as the most important sector among those assessed, contributing to 33% of the total plastic consumption. The construction sector was the second largest sector in terms of consumed plastics (23%), followed by the heterogeneous 'other' sector (17%), the transport and EEE sectors (10% and 8% respectively). Waste generated from consumption amounted to 64% of the total consumed plastics, with 34% of the consumed plastic being kept in stock and the remaining 2% lost during use. Of the total amount of post-consumer waste being generated in the year 2019 (28.8Mt) only 38% was separately collected, with a significant fraction (13%) being mismanaged. Waste being mismanaged played a crucial role in the end-of-life management of plastic waste originated from the transport and EEE sectors.

Out of the total plastic waste sent to recycling, 70% derived from the packaging sector. Overall, a total of 5.47Mt of recyclates were produced in EU27, with a total of 4.46Mt recyclates being consumed in 2019 within the EU27 territory (considering that 18% are exported). Despite a large level of uncertainty and lack of data granularity was evident when modelling the fate/destination of recyclates, result indicated the construction sector as the main destination for secondary plastics, followed by the packaging sector. The total plastic demand being covered by secondary plastics was around 10% (for the clothing and textiles, construction, and agriculture sectors) and as low as 4% in the case of packaging. Reuse exhibited a relevant role only for clothing and textiles (covering 18% of the waste generated management options) and the transport sectors (6%). On average, the EU27 end-of-life recycling rate (i.e., recyclates produced over total waste being generated) was equal to 19% (16.6% when trade effects are considered). Most of the total microplastics and macroplastics losses of all sectors in the whole value chain (2.11Mt) occurred during the use phase (39%), amounting to 4% of the total production estimated in the present study. Results indicate that losses of plastics that could be ultimately released to the environment are common in several step of the plastic value chain, although a certain amount could be recollected (and sent to incineration).

Results of the polymer-specific assessment suggested that a subset of polymers drove the overall plastic consumption for the analyzed sectors, with a major role especially played by HDPE, LDPE, PP, PVC, and PET covering 70% of the total demand. Furthermore, the same polymers contributed to a total of 84% of all recyclates out of the total waste generated. Also in this case, the packaging sector represented the most relevant sector with regard not only to the total plastic demand but also the overall recyclates produced. Results indicate that films (e.g., LDPE, HDPE), PET and PP amounted to a total 92% of the total polymer needs for the packaging sector. On average, the highest end-of-life recycling rates for the five sectors analyzed in the polymer-specific assessment were recognized for PET (23%), LDPE (18%) and PVC (17%).

Overall, the 4.46Mt of estimated recyclates used in the EU27 in 2019 seems to be far from the EU corrected target of 8.8Mt of post-consumer recyclates to be used annually in the EU27 by 2025 (adjusted from the 10Mt target for EU27+UK set in 2018 in the European Strategy for Plastics (EC, 2018a) and endorsed by the CPA). For this reason, a series of scenarios were also built to assess the sector-specific MFAs for the year 2025. Such scenarios were created following the expected trends in the plastic value chain and leveraging on the current and future ambitions of EU plastic policies.

Overall, results from the scenarios assessment indicated that one single targeted action (such as reduction in waste export or improved separate collection of plastic waste) would not be sufficient to ensure that the 8.8Mt target is achieved by 2025. Among the scenarios assessed, the highest benefits were achieved in the case of the improved separate waste collection scenario (+30% separate collection for packaging, and +10% for other sectors, to the detriment of mixed waste collection), leading to an estimated recyclates consumption of 6.47Mt by 2025 (increase of 45% compared to 2019). In this scenario, an increase in separate collection of plastic waste is assumed for the transport and EEE sectors, based on a 25% reduction in the waste flows currently mismanaged. When all actions are combined (i.e., considering all scenarios simultaneously and a +10%/-10% or 0% variation in total plastic production) the EU/CPA target could be reached by 2025. Results indicate that for the combined scenario (coupled with a +10% variation in production), a total of 11.13Mt recyclates consumed could be achieved by 2025 (against the corrected target of 8.8Mt), with an overall recyclates consumption rate equal to 35.5%. When a reduction of 10% in plastic production is instead assumed, a total recyclates consumption of 9.11Mt is achieved. When the combined scenario is coupled with a stagnating plastic production, results indicate how 10.12Mt of recyclates could be consumed by 2025 in EU27. Under the combined scenario, notwithstanding potential trends of plastic production in the near future, the EU/CPA could be achieved and surpassed by 2025 if (i) plastic waste export is reduced by 20% for the EEE and textiles and clothing sectors, and by 10% for the remaining sectors under assessment; (ii) separate waste collection is increased by 30% for plastic packaging waste and 10% for the remaining sectors, and waste being mismanaged is reduced by 25% for the transport and EEE sectors; (iii) an additional 15% of the plastic packaging waste that is separately collected is sent to recycling facilities, and 10% for the remaining sectors under assessment and (iv) rejects from recycling plants (i.e., incinerated/landfilled) are reduced by 20% in the case of plastic packaging waste and by 10% for the remaining sectors.

Regarding the results of the 2025 scenarios, it should be considered that, for achieving higher recyclates consumption rates, alternative processes (compared to the traditional mechanical recycling) for the recycling of plastic waste should be investigated. These technologies, such as chemical recycling, are currently less explored compared to mechanical recycling as globally few large-scale plants exist to date (Quicker et al., 2022). Moreover, chemical recycling might compete with mechanical recycling regarding plastic feedstock, as few information are available concerning the potential of treating (via chemical recycling) low-quality and mixed plastic waste fractions that are unsuitable for conventional recycling (Voss et al., 2022).

Furthermore, even reaching small improvements in the overall recycling of plastics from some sectors (e.g., the clothing and textiles and transport sectors) might require significant efforts considering the low end-of-life recycling rates currently acknowledged. In general, even if some of the assumptions at the base of the scenarios assessment might lead to an overestimation of their beneficial effects on the total recyclates production, the EU/CPA target could be achieved if multiple actions are put in practice simultaneously, as previously described.

Based on the findings of the present report, it is evident how the expected trend on plastic production could have an important role on the overall plastic recyclates figures in the near future. Current estimates in trends in plastic packaging production (as suggested for instance by the European Commission (EC, 2018a), and data from Plastics Europe reports) indicated a yearly increase in the total production of around 4-5% (based on data for the 2010-2018 timeframe). However, the recent the COVID-19 outbreak and the Ukraine war, coupled with EU commitments on plastic preventions (EC, 2019a) and brands and retailers' commitments in reducing plastic consumption, could signify an unprecedented reduction in plastic production in the near future (as suggested for instance by Systemiq, 2022). Even if a reduction of 10% in plastic production is assumed, with the combined scenario, a total recyclates consumption of 9.11Mt is achieved, which would still meet the corrected EU/CPA target of 8.8Mt. In the case of the combined scenario coupled with a stagnating plastic production, results indicate 10.12Mt of post-consumer recyclates being consumed by 2025 in EU27.

Despite the hypothesis on the future trend on plastic production could have a crucial role in the future development of the recyclates output in the EU27 context, results suggest that the EU/CPA target is achievable even under conservative assumption on such trends.

The literature analysis carried out in the present report revealed that most data are commonly presented in an aggregated way, rather than quantifying plastic flows by economic sectors or polymers, and some key aspects of the plastic value chain are neglected (e.g., a distinction between "semi-finished" and "finished" products). This aspect hinders the identification of hotspots (e.g., points in the value chain where valuable plastic flows are lost or not properly managed) and strengths (e.g., good plastic management practices currently in place) in the whole EU plastic economy, as several data-gaps must be filled by assumptions. A harmonization of plastic data collection could enhance the creation of monitoring frameworks to assess the implementation of current policy efforts in the EU value chain and more realistically assess future plastic flows. This could have a strategical role to assess the untapped potential for additional and better recycling in the plastic value chain. Results of the present assessment indicate that efforts should be devoted to the implementation of multiple actions along the plastic value chain, with careful attention to improvements especially regarding proper plastic waste collection. This is further supported by the potential underestimation of the total plastic waste currently being generated in the EU, as suggested for instance by Material Economics (2022). Additionally, the lack of sector-specific information related to pre-consumer waste generation and management, limits a precise assessment on the amounts that potentially turn into recyclates to be used within the EU economy. To overcome some of these issues, certain actions are currently being put forward, such as the establishment of transparent and reliable monitoring system for collecting data on the production and use of recycled plastics as well as the quantities of waste collected (e.g., the monitoring system established by the CPA).

Although packaging plays a pivotal role in the whole plastic value chain flows, the analysis of less-explored sectors should be refined and supported in the next years and should not be underestimated. This is particularly relevant in the case of sectors such as fishing and healthcare, which are mostly unexplored in current literature. In the case of the transport and EEE sectors, a proper handling of waste currently being mismanaged could significantly boost the total plastic mass in the authorized waste management system. When polymers are analyzed, the added value of the less common fractions should be exploited as well as the potential downcycling fate of recycled plastics. As also recommended by Antonopoulos et al. (2021), additional markets for lower value fractions could be created to ensure that these plastic flows (e.g., polypropylene) are collected with the aim of increasing total end-of-life recycling rates.

To fulfil the EU ambitions and industry action targets such as the EU/CPA target, significant efforts are needed to further improve granularity and details of complete overviews of plastic flows in the EU. Such enhancements could include better sector-specific and polymer-specific data for less-explored sectors (such as textiles and clothing, fishing, or healthcare) coupled with in-depth knowledge of and recyclates fate, and both losses and mismanaged waste flows. Considering these key commitments for actions at the EU level, an improvement and rethinking of the plastic value chain is mandatory and should be driven by an up-to-date knowledge of all its many hotspots.

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List of abbreviations

ABS	Acrylonitrile butadiene styrene
ASA	Acrylonitrile styrene acrylate
CPA	Circular Plastic Alliance
EC	European Commission
EEE	Electrical and Electronic Equipment
EMAF	Ellen MacArthur Foundation
EPS	Expanded polystyrene
EU	European Union
GDP	Gross Domestic Product
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
MS	Member States
MFA	Material Flow Analysis
PA	Polyamides
PA6	Nylon6
PA66	Nylon66
PC	Polycarbonates
PET	Polyethylene terephthalate
PLP	Plastic Leak Project
PMMA	Poly(methyl methacrylate)
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethane
PVC	Polyvinyl chloride
SAN	Styrene acrylonitrile resin
SDG	Sustainable Development Goal
SUP	Single-Use Plastics
TC	Transfer Coefficient
UNEP	United Nations Environment Programme
WEEE	Waste Electrical and Electronic Equipment

List of definitions

Downcycling Conversion (through recycling) of a plastic product into a recycled product that has lower quality and functionality compared to the native quality and functionality

Mismanaged waste Inadequately disposed waste, which could be inappropriately disposed (e.g., disposed in open dumps, in unspecified landfills, unaccounted, etc.) and/or inappropriately treated/managed (e.g., by unauthorized third parties) and that could create routes for potential losses and releases in the environment

Plastic loss The amount of macroplastic or microplastics that is lost from plastic management processes or by consumers

Plastic release The amount of macroplastic or microplastics that is lost from e.g., the production phase, use phase, etc.,, and is ultimately released to the environment (i.e., the fraction of lost plastic which is not recollected)

Plastic consumption The amount of plastics that is consumed by end-users (i.e., “apparent consumption”, calculated as semi-finished or finished production minus exports plus imports)

Plastic demand The total amount of plastics demanded by plastic converters to manufacture plastic products

Recyclates Secondary plastic (i.e., recycled plastic) being an output of a recycling process

Recyclates consumption The amount of recyclates needed/employed by plastic converters (i.e., consumed by converters) for the manufacturing of plastic products

Recyclates consumption rates The calculated ratio between the recyclates consumed (i.e., the amount of plastic recyclates after exports that employed by converters to manufacture new plastic products) and the total waste being generated (after exports/imports)

Recyclates production The amount of recyclates plastic being produced from recycling facilities

End-of-life recycling rate The calculated ratio between the recyclates produced and total waste being generated (after exports/imports).

Reprocessing rate The calculated ratio between the recyclates produced and total waste being

Upcycling Conversion (through recycling) of a plastic product into a recycled product that has higher quality and has functionality comparable to those of the native product

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Annexes

Annex 1. Estimation of the consumed mass of semi-finished products

In the present study, the manufacturing phase was modelled by distinguishing between "semi-finished products" and "finished products" manufacturing. Semi-finished products are intended as products that are normally employed as inputs for the manufacturing of other finished products (Amadei et al., 2022).

To model the consumption step of the MFA, the data of the consumption-statistics based approach presented by Amadei et al. (2022) were retrieved. In this study, Amadei et al. (2022) built the consumption-statistics based by mapping PRODCOM (Eurostat, 2022a) codes related to plastics products or products containing plastics and by allocating each code to a specific category (namely: packaging, construction, transport, Electrical and Electronic Equipment (EEE), agriculture, textiles, clothing, healthcare, fishing and other). Each PRODCOM code was categorized between finished and semi-finished products. Semi-finished products were excluded by the consumption-statistics estimate to avoid possible double counting, as the information available from PRODCOM didn't allow to establish direct links between semi-finished products and finished products manufacturing. The data reported in Amadei et al. (2022) for the two separated categories "textiles" and "clothing" were aggregated under the category "clothing and textiles" adopted in the present study.

A dedicated approach was employed in this study to better differentiate between the mass of semi-finished products directly sold to end-consumers from the mass employed in the manufacturing of finished products.

The approach was based on the following steps:

- Firstly, the full list of PRODCOM codes included in the analysis of Amadei et al. (2022) was retrieved (supplementary materials, "Table SM8"). Data of production, export and import of each PRODCOM code (distinguishing between semi-finished and finished products) were retrieved from PRODCOM (for EU27, 2019), and converted based on the conversion factors, plastic shares and sectors shares suggested by Amadei et al. (2022).
- Secondly, each PRODCOM flow of each category (distinguishing between production, export and import) was allocated between a series of categories, selected to represent groups of all the PRODCOM codes related to semi-finished products (namely: "automotive parts"; "fibers, yarns and fabrics"; "fitting and profiles"; "nets"; "plates and sheets"; "tubes and pipes"; "other"). The full list of each category, and its association to the PRODCOM code and the related sector was retrieved from Amadei et al. (2022) ("Table SM8" in the supplementary information spreadsheet). In some cases, the association of each PRODCOM code to a specific sector was revised in the present study, compared to the one employed by Amadei et al. (2022), as described in Table 23.
- Lastly, a series of assumptions were prepared to derive the mass of each semi-finished products category employed in the manufacturing of other finished products within the same sector (Table 24). The mass of plastics employed in the manufacturing of finished products was excluded from the MFA (to remove the potential double-counting effect acknowledged by Amadei et al., 2022). On the other hand, the remaining part (adding to 100%) was understood as semi-finished products ending up to consumption and was therefore included in the MFA. As it is noticeable from Table 24, in the case of packaging plates and sheets, it was assumed that most of the plastic mass associated to these products (70%) is included in the manufacturing of finished products. For construction tubes and pipes and agriculture tubes and pipes, together with construction fittings and profiles and plates and sheets, it was assumed that only 10% can be considered as an input to finished products manufacturing, whilst the majority (90%) was directly put on the market and made available to consumption. As much as 90% of semi-finished products for transport (tubes and pipes, plates and sheet, and automotive parts) and EEE (fitting and profiles) were modelled as being inputs to the manufacturing of finished products. Similarly, in the case of textiles, a 90% assumption was considered to derive the mass of fibres, yarns and fabric employed in the manufacturing of finished products. By contrast, all nets (referring to the PRODCOM category refers to "13941259 - Knotted netting of textile materials (excluding made-up fishing nets of man-made textiles, other made-up nets of nylon or other polyamides)") were modelled as sold to consumption. Lastly, in the case of the "other" sector, an average of the estimated shares from all other sectors was considered to allocate the mass of semi-finished products categories tubes and pipes, fittings and profiles, plates and sheets and other.

Table 23. Revised associations of sectors for each PRODCOM code compared to the associations adopted in Amadei et al. (2022).

PRODCOM CODE - Definition	Categorization in Amadei et al. (2022)	Categorization in the present study	Comment
13931200 - Woven carpets and other woven textile coverings (excluding tufted or flocked)	Textiles	Construction	Carpets were assumed to be included under the construction sector.
13931300 - Tufted carpets and other tufted textile floor coverings	Textiles	Construction	Carpets were assumed to be included under the construction sector.
13931990 - Carpets and other textile floor coverings (excluding knotted, woven, tufted, needle felt)	Textiles	Construction	Carpets were assumed to be included under the construction sector.

Table 24. Assumptions on the mass of semi-finished products employed in the manufacturing of finished products. The remaining part to 100% was assumed to be directly sold to end-consumers.

Semi-finished products category	Packaging	Construction	Agriculture	EEE	Clothing and textiles	Other
Tubes and pipes	-	10%	10%	90%	-	37%
Fittings and profiles	-	10%	-	-	-	50%
Other	70%	10%	-	90%	-	57%
Fibers, yarns and fabrics	-	-	-	-	-	100%
Nets	-	-	-	-	90%	-
Automotive parts	-	-	-	-	0%	-

Annex 2. Estimation approach for plastic losses and mismanaged waste

In the present study losses were estimated from the following steps of the value chain:

- Microplastic losses from manufacturing;
- Microplastics and macroplastics losses from consumption;
- Macroplastics losses from the generated waste. Additionally, the amount of mismanaged waste arising from the waste generated at the level of each of the sectors included in the present study was also estimated;
- Microplastics losses from incineration and landfill.

One of the most comprehensive approaches available to date that could be employed for the quantification of environmental releases of macro and microplastics is the one developed within the Plastic Leak Project (PLP) (Peano et al., 2020) (from now on named the "PLP method"). In the context of the PLP method guidelines, a series of specific calculation approaches have been proposed to model the losses and the releases of plastics to the environment at different life cycle steps and by considering different sources. In the PLP method, different environmental compartments (namely: terrestrial, freshwater, and marine environment) are also considered, as well as any potential redistribution among initial compartments of release (i.e., a distinction is made between "initial release" and "final release").

In the present study the PLP method was employed to estimate the losses from manufacturing, consumption, and waste generation. When a sector-specific approach was not provided by Peano and colleagues, a series of dedicated assumptions and data from other sources were employed, as described in the below sections. Only final releases were considered, estimating losses to water (ocean and freshwater) and soil. If no specific information was provided for the environmental compartment affected by the losses, a general "environment (unspecified)" category was created. Potential effects of recollection (e.g., lost plastics that is recollected and sent to incineration) were included and modelled as suggested by the PLP method.

Plastic losses from plastic manufacturing

In the case of microplastic losses from manufacturing, all loss estimates were based on the PLP method. The same assumptions were maintained for each of the sectors included in the present study. The mass of pellets lost was estimated as 0.10% following the suggested "loss rate of plastic pellets" as described by the PLP method. The total amount of lost pellets that are released to water were modelled by summing the contribution due to the final release rate to ocean (12%) and the final release rate to freshwater sediments (5%). The share of pellets released to soil were instead modelled considering the release rate to terrestrial environment (69%). A certain amount of lost plastic (14%) was properly managed and incinerated. All shares and assumption employed in the present study to model losses from manufacturing are summarized in Table 25.

Table 25. Main parameters and assumption employed to estimate the fate of lost plastics from manufacturing. (Note: P = Packaging; C = Construction, T = Transport, E = Electrical and Electronic Equipment (EEE), A = Agriculture, C&T = Clothing and textiles, H = Healthcare, F = Fishing, O = Other).

Flow details	P	C	T	E	A	C&T	H	F	O	Source
Total losses (out of all plastic demand)	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	Peano et al. (2020)
Losses to water (out of all plastic lost)	17%	17%	17%	17%	17%	17%	17%	17%	17%	Calculated from Peano et al. (2020)

Flow details	P	C	T	E	A	C&T	H	F	O	Source
Losses to soil (out of all plastic lost)	69%	69%	69%	69%	69%	69%	69%	69%	69%	Calculated from Peano et al. (2020)
Recollected to incineration (out of all plastic lost)	14%	14%	14%	14%	14%	14%	14%	14%	14%	Calculated from Peano et al. (2020)

Plastic losses from plastic consumption

In the case of plastic losses from consumption, the PLP method enables a detailed calculation of microplastic losses for the transport sector and the textiles and clothing sector.

In the case of transport, the estimated losses are calculated from the microplastics releases due to tyre abrasion. The PLP method suggests losses based on a distinction at the level of vehicle types that include heavy trucks, light trucks, cars, and motorcycles. For each vehicle type a share of Synthetic Rubber (SR [%]) in tyres is provided (heavy trucks, SR: 60%; light trucks; SR: 36%, cars, SR: 35%; and motorcycles, SR: 40%) together with the loss rate of microplastics (LR_tire [mg/km]) from tyres (heavy trucks, LR_tire: 517 mg/km; light trucks; LR_tire: 142 mg/km, cars, LR_tire: 102 mg/km; and motorcycles, LR_tire: 45 mg/km). In the present study, the average of the abovementioned parameters was considered and employed to calculate the total loss for the transport sector as indicated by Equation A1.

$$\begin{aligned} Consumption\_losses_{transport}\ [kton] &= Consumption_{transport}[kton] * (Tire_{ratio}[\%] \ * \ SR_{\ average}\ [\%] \\ &* LR_{\ tire,average}\ \left[\frac{mg}{km}\right] * average\_travelled\_distance\ [km] \\ &* 10^{-12}\ [\frac{kton}{mg}]) \end{aligned} \tag{A1}$$

Where:

- $Consumption\_losses_{transport}$ [ktonne]: represents the total mass of lost microplastics estimated for the transport sector in the MFA (Section 2.3) during the use phase (i.e., consumption);
- $Consumption_{transport}$ [ktonne]: represents the total mass consumed plastics microplastics estimated for the transport sector in the MFA (Section 2.3);
- $Tyre_{ratio}$ [%]: represent the ratio in terms of mass between the tyres of a vehicle (9 kg per tyre; estimated from Oponeo, 2019) and the overall weight of a passenger car vehicle (1300 kg; derived from Maury et al., 2022). Passenger cars were selected in this case as a proxy of the whole transport sector;
- SR_{ratio} [%]: represents the average content (42.75 %) in terms Synthethic rubber in tyres, calculated based on the values derived from Peano et al. (2020) for heavy trucks, light trucks, cars and motorcycles;
- $LR_{tire,average}$ [mg/km]: represents the average loss rate of micro-plastics from tyres (201.5 mg/km), calculated based on the values derived from Peano et al. (2020) for heavy trucks, light trucks, cars and motorcycles;

- Averge_travelled_distance [km]: represents the per-person average distance travelled by car in EU (13.607,5 km; derived from ACEA, 2019).

The calculated losses were then allocated to the environmental compartments (water and soil) and to the amount recollected to incineration, following the shares reported in Table 25.

In the case of textiles, the estimated losses are derived from the PLP method by considering the loss rate of microfibers per wash (LR_wash: 46 [mg/kg_textile/wash]; derived from Peano et al., 2020) and the average number of washes of the textile per life cycle (N_wash: 20 [wash]; derived from Peano et al., 2020). The calculations step to estimate the mass of plastic losses from textiles are summarized in Equation A2.

$$\begin{aligned} Consumption\_losses_{textiles}\ [kton] &= Consumption_{textiles}[kton] \\ &* (LR_{wash}[mg/kg\_textile/wash]\ *\ N_{wash}\ [wash] * 10^{+6}\ [\frac{kg}{kton}] \\ &* 10^{-12}\ [\frac{kton}{mg}]) \end{aligned} \tag{A2}$$

Where:

- Consumption_losses$_{textiles}$ [ktonne]: represents the total mass of lost microplastics estimated for the textiles and clothing sector in the MFA (Section 2.3) during the use phase (i.e., consumption);
- Consumption$_{textiles}$ [ktonne]: represents the total mass consumed plastics microplastics estimated for the textiles and clothing sector in the MFA (Section 2.3);
- LR$_{wash}$ [mg/kg_textile/wash]: represent the loss rate of microfibers per wash, estimated from the PLP method;
- N$_{wash}$ [wash]: represents the average number of washes of the textile per life cycle, estimated from the PLP method.

The calculated losses were then allocated to the environmental compartments (water and soil) according to the approach suggested by the PLP method. Final release rates to water were derived as follows, by multiplying corresponding release rates and redistribution rates:

- Final_release_ocean_1 [%] =
  release_rate_to_ocean (50 %) * redistribution_rate_to_ocean_from_ocean (100 %)
- Final_release_ocean_2 [%] =
  release_rate_to_freshwater (14 %) * redistribution_rate_to_ocean_from_freshwater (70 %)
- Final_release_ocean_3 [%] =
  release_rate_to_soil (41 %) * redistribution_rate_to_ocean_from_soil (51 %)
- Final_release_freshwater_1 [%] =
  release_rate_to_freshwater (14 %) * redistribution_rate_to_ freshwater_from_freshwater (30 %)
- Final_release_freshwater_2 [%] =
  release_rate_to_soil (41 %) * redistribution_rate_to_ freshwater_from_soil (22 %)

The mass of plastic losses to water from textiles are summarized in Equation A3.

$$\begin{aligned} Losses_{textiles,water}\ [kton] &= Consumption\_losses_{textiles}[kton] * (Final\_release\_ocean\_1\ [\%] \\ &+ Final\_release\_ocean\_2\ [\%] + Final\_release\_ocean\_3\ [\%]) \\ &+\ Consumption\_losses_{textiles}[kton] \\ &* (Final\_release\_freshwater\_1\ [\%] \\ &+ Final\_release\_freshwater\_2\ [\%]) \end{aligned} \tag{A3}$$

Where:

- $Losses_{textiles,water}$ [ktonne]: represents the total mass of lost plastics from consumption that is finally released in water;
- $Consumption\_losses_{textiles}$ [ktonne]: represents the total mass of lost microplastics estimated for the textiles and clothing sector in the MFA (Section 2.3) during the use phase (i.e., consumption);
- Final_release_ocean_i [%]: represents the share of the total mass that is finally released to ocean (after an initial release to ocean [i = 1], to freshwater [i = 2] or to soil [i = 3]);
- Final_release_freshwater_i [%]: represents the share of the total mass that is finally released to freshwater (after an initial release to freshwater [i = 1], or to soil [i = 2]).

Final release rates to soil were derived as follows, by multiplying corresponding release rates and redistribution rates:

- Final_release_soil [%] =
release_rate_to_soil (41 %) * redistribution_rate_to_soil_from_soil (27 %)

The mass of plastic losses to water from textiles are summarized in Equation A4.

$$Losses_{textiles,soil}\ [kton] = Consumption\_losses_{textiles}[kton] * (Final\_release\_soil\ [\%]) \tag{A4}$$

Where:

- $Losses_{textiles,soil}$ [ktonne]: represents the total mass of lost plastics from consumption that is finally released in soil;
- $Consumption\_losses_{textiles}$ [ktonne]: represents the total mass of lost microplastics estimated for the textiles and clothing sector in the MFA (Section 2.3) during the use phase (i.e., consumption);
- Final_release_soil [%]: represents the share of the total mass that is finally released to ocean after an initial release to soil.

The amount of microplastics lost from textiles that are assumed to be recollected and sent to incineration was estimated as the differences between the total consumption losses and the amount finally released to water and to soil.

The losses of microplastics and macroplastics (to water, to soil and recollected to incineration) from packaging, building and construction, EEE, agriculture, healthcare and other were estimated based on the mass values indicated in Kawecki and Nowack (2019). This study was employed as a proxy to model consumption losses as it represents one of the most detailed literature sources providing detailed information for such plastic flows. However, it must be noted that the scope of the analysis carried out by Kawecki and Nowack (2019) could differ from the one of the present study (for instance, the losses from “consumption” of the construction sector included in the study by Kawecki and Nowack (2019) referred to “construction and demolition sites, buildings in use”). To model the total amount of losses as well as the micro/macroplastics fate in the environment, a set of TCs were calculated from Kawecki and Nowack (2019), as reported in Annex 3. In the case of the fishing sector, the total amount of fishing gear lost to sea was derived from Deshpande et al. (2020) and assumed to be released to ocean (90%) but also to be washed up on shore and released to soil (10%).

All shares and assumption employed in the present study to model losses from consumption are summarized in Table 26.

Table 26. Main parameters and assumption employed to estimate the fate of lost plastics from consumption. (Note: P = Packaging; C = Construction, T = Transport, E = Electrical and Electronic Equipment (EEE), A = Agriculture, C&T = Clothing and textiles, H = Healthcare, F = Fishing, O = Other).

Flow details	P	C	T	E	A	C&T	H	F	O	Reference
Losses (from consumption) [1]	[*] 4.94%	[*] 0.56%	[**] 0.0003%	[*] 0%	[*] 1.13%	[**] 0.09%	[*] 7.24%	[*] 3.80%	[*] 0.07%	[*] Calculated from Kawecki and Nowack (2019) [**] Calculated from Peano et al. (2020)
Losses (microplastic) [2]	[*] 0.08% of [1]	[*] 9.28% of [1]	[**] 100% of [1]	-	[*] 10.13% of [1]	[**] 100% of [1]	-	-	[*] 21.15% of [1]	[*] Calculated from Kawecki and Nowack (2019) [**] Calculated from Peano et al. (2020)
Losses (macroplastics) [3]	99.92% of [1]	90.72% of [1]	-	-	89.87% of [1]	-	100% of [1]	100% of [1]	78.85% of [1]	Calculated from Kawecki and Nowack (2019)
Microplastics to water	-	[*] 0.26% of [2]	[**] 17.00% of [2]	-	-	[**] 48.93% of [2]	-	-	[*] 3.36% of [1]	[*] Calculated from Kawecki and Nowack (2019) [**] Calculated from Peano et al. (2020) and Nessi et al. (2020)
Microplastics to soil	[*] 100% of [2]	[*] 100% of [2]	[**] 69.00% of [2]	-	[*] 37.82% of [2]	[**] 11.07% of [2]	-	-	[*] 18.68% of [1]	[*] Calculated from Kawecki and Nowack (2019) [**] Calculated from Peano et al. (2020) and Nessi et al. (2020)
Microplastics to incineration	-	[*] 3.82% of [2]	[**] 14.00% of [2]	-	[*] 62.18% of [2]	[**] 40.00% of [2]	-	-	[*] 77.96% of [1]	[*] Calculated from Kawecki and Nowack (2019) [**] Calculated from Peano et al. (2020) and Nessi et al. (2020)

Flow details	P	C	T	E	A	C&T	H	F	O	Reference
Macroplastics to water	0.27% of [3]	0.38% of [3]	-	-	0.0016% of [3]	-	0.42% of [3]	90.00% of [3]	0.20% of [3]	Calculated from Kawecki and Nowack (2019)
Macroplastics to soil	8.17% of [3]	20.88% of [3]	-	-	51.86% of [3]	-	25.72% of [3]	10.00% of [3]	5.27% of [3]	Calculated from Kawecki and Nowack (2019)
Macroplastics to incineration	91.56% of [3]	78.74% of [3]	-	-	48.14% of [3]	-	73.86% of [3]	-	94.53% of [3]	Calculated from Kawecki and Nowack (2019)

Plastic losses from waste generation and mismanaged waste

Direct losses of macroplastics from the total waste generated, were estimated for packaging and the general "other" sector based on the approach suggested by the PLP method.

The PLP method indicated Littering Rates (LR_items) for different plastic items, differentiated by size (i.e., small or detachable (<5cm), medium size (5-25 cm) and large size (>25cm)) and "use" (i.e., in-house (non-flushable), in-house (flushable) and on-the-go (items are those consumed while on the move in public spaces)). An average of the LR_items for each "use" category was then calculated in the context of the present study:

- Average LR_items (non-flushable): 0%
- Average LR_items (in-home flushable): 1.67%
- Average LR_items (on-the-go): 2.67%.

The average LR_items (on-the-go) was adopted to estimate losses from packaging sector, whilst the Average LR_items (in-home flushable) was adopted to estimate the losses of the waste generated in the aggregated category 'other'. On top of the mass of plastic losses from waste generated, an additional part of plastics was modelled as being lost from mismanaged waste. As described in Section 2.3.1, mismanaged waste is intended as an inadequately disposed waste, which could be either not appropriately disposed (e.g., disposed in open dumps, in unspecified landfills, unaccounted, etc.) and/or inappropriately treated/managed (e.g., by unauthorized third parties) and that could create routes for potential losses and releases in the environment. A certain amount of mismanaged waste could be either recollected and sent to recycling or lost.

The amount of mismanaged waste for packaging, building and construction, agriculture, clothing and textiles, healthcare, fishing and other, was calculated based on the approach suggested by the PLP method (Equation A5).

$$Mismanaged\_waste_{sector\_i}[kton]\ [kton] = Waste_{generated_{sector_i}}[kton] * (Mismanaged\_rate_{sector\_i}\ [\%]) \qquad (A5)$$

Where:

- $Mismanaged\_waste_{sector\_i}$ [ktonne]: represents the total mass of mismanaged waste from a given sector i;
- $Waste\_generated_{sector\_i}$ [ktonne]: represents the total mass of waste generated from a given sector;
- $Mismanaged\_rate_{sector\_i}$ [%]: represents the share of mismanaged waste out of the total waste generated from a given sector i. The mismanaged rate was calculated as suggested by the PLP method, considering the Average LR (calculated above) for non-flushable, in-home flushable and on-the-go "use" categories. Moreover, in the PLP method, a parameter is introduced under the name "Mismanaged Waste Index" (MWI) that represents the share of product waste that is subject to waste mismanagement practices. The average MWI for EU (MWI_EU: equals to 9.25%) was retrieved from Nessi et al. (2020), calculated as a weighted average of the country-specific (EU Member States) default values of MWI reported in Peano et al. (2020), according to the country-specific population:
    - $Mismanaged\_rate_{packaging}$ [%] = (1 – (Average LR_items (on-the-go))) * MWI_EU
    - $Mismanaged\_rate_{other}$ [%] = (1 – (Average LR_items (flushable))) * MWI_EU
    - For building and construction, agriculture, clothing, textiles, healthcare and fishing: Mismanaged_rate [%] = (1 – (Average LR_items (non-flushable))) * MWI_EU

The share of mismanaged waste arising from the total waste generated in the EEE sector (44% after waste trade) was calculated from Huisman et al. (2015) and it includes the waste managed with non-compliant collection systems and the unknown management (excluding exports and scavenged practices outside the EU). The share of mismanaged waste arising from the total waste generated in the transport sector (33% after trade) was derived from Maury et al. (2022) and that indicates how from 1.5 Mt of waste generated from vehicles, 0.5 Mt ends up in unknown whereabouts.

A certain amount of mismanaged waste could be either recollected and sent to recycling or lost to the environment.

The amount of mismanaged waste lost to the environment was modelled according to Ryberg et al. (2019), that suggest a figure of 10% of mismanaged waste being lost (this share was applied for all sectors under the assessment of the present study).
The amount of mismanaged waste which is recollected and sent to recycling was modelled according to the PLP method for packaging, transport, EEE and other sectors. The PLP method indicates how mismanaged waste not released to the environment could be collected by waste pickers and ultimately recycled or reused. To estimate the amount of mismanaged waste released to the environment, it is firstly necessary to calculate the release rates of plastics waste (RR_waste) to water and soil. The PLP methods lists RR_waste rates for different plastic items (namely "Low Value (others + composites, e.g., wrapper, opercula, straw, balloon, plastic bag, cup, meal tray)", "Medium Value (PP, PS, LDPE)", and "High Value (PET, HDPE)"), differentiated by environmental compartment ("ocean and freshwater" and "terrestrial") and size (i.e. small or detachable (<5cm), medium size (5-25 cm) and large size (>25cm)). For each plastic item type and size, a set of RR_waste is provided based on literature review and expert judgment. In the context of the present study, the average of the RR_waste rates for each compartment were calculated as indicated in Table 27.

Table 27. Summary of the release rates of microplastic losses from waste generation (from Peano et al., (2020)) and calculated average rates. Note: [1] Low Value (others + composites, e.g., wrapper, opercula, straw, balloon, plastic bag, cup, meal tray) – derived from Peano et al. (2020); [2] Medium Value (PP, PS, LDPE) – derived from Peano et al. (2020); [3] High Value (PET, HDPE) – derived from Peano et al. (2020); "Avg = Average".

	Ocean and freshwater (small size <5cm)	**Terrestrial (small size <5cm)**	**Ocean and freshwater (medium size 5-25cm)**	**Terrestrial (medium size 5-25cm)**	**Ocean and freshwater (large size > 25cm)**	**Terrestrial (large size > 25cm)**
Low value [1]	40%	60%	25%	75%	5%	95%
Medium value [2]	25%	75%	15%	85%	5%	95%
High value [3]	15%	15%	10%	5%	1%	1%
Calculated average	Avg_1: 27%	Avg_2: 50%	Avg_3: 17%	Avg_4: 55%	Avg_5: 4%	Avg_6: 64%

It was then possible to derive a total average release rate for water (RR_waste_water: 16 %, derived as the average of the calculated release rate "Avg_1", "Avg_3" and "Avg_5" as illustrated in Table 28) and for soil (RR_waste_soil: 56 %, derived as the average of the calculated release rate "Avg_2", "Avg_4" and "Avg_6" as illustrated in Table 28). As suggested by the PLP method it was then possible to calculate the share of mismanaged waste recollected and sent to recycling (MW_recollected: 28%, derived as (1 – RR_waste_soil – RR_waste_water)).

Lastly, the total amount of plastic lost in the environment was distributed between the compartments of final release. The PLP method suggests in this case a redistribution rate equals to 100% and therefore the final release to water was calculated adopting the share RR_waste_water, whilst the final release to soil was calculated adopting the share RR_waste_soil. The remaining mass was modelled as released to environment unspecified.

A summary of the main assumptions and parameters considered for estimating losses from waste generation and mismanaged waste is reported in Table 28.

Table 28. Summary of the parameters adopted for estimating the amount and fate of losses from waste generated and the amount and fate of mismanaged waste. (Note: P = Packaging; C = Construction, T = Transport, E = Electrical and Electronic Equipment (EEE), A = Agriculture, C&T = Clothing and textiles, H = Healthcare, F = Fishing, O = Other).

Flow details	P	C	T	E	A	C&T	H	F	O	Reference
Macroplastic losses (out of all waste generated) [1]	2.67%	-	-	-	-	-	-	-	1.67%	Calculated from Peano et al. (2020)
Macroplastic losses (out of all mismanaged waste) [2]	10% of [4]	10% of [4]	10% of [4]	10% of [4]	10% of [4]	10% of [4]	10% of [4]	10% of [4]	10% of [4]	Ryberg et al. (2019)
Macroplastic total losses [3]	[1] + [2]	[1] + [2]	[1] + [2]	[1] + [2]	[1] + [2]	[1] + [2]	[1] + [2]	[1] + [2]	[1] + [2]	Calculated (for C T, E, A, C&T, H, and F, [1] =0)
Macroplastic total losses to water	16%	16%	16%	16%	16%	16%	16%	16%	16%	Calculated from Peano et al. (2020)
Macroplastic total losses to soil	56%	56%	56%	56%	56%	56%	56%	56%	56%	Calculated from Peano et al. (2020)
Macroplastic total losses to environment unspecified	28%	28%	28%	28%	28%	28%	28%	28%	28%	Calculated from Peano et al. (2020)

Flow details	P	C	T	E	A	C&T	H	F	O	Reference
Mismanaged waste [4]	[*] (1-[1])*9.25%	[*] (1-[1])*9.25%	[**] 33%	[***] 44%	[*] (1-[1])*9.25%	[*] (1-[1])*9.25%	[*] (1-[1])*9.25%	[*] (1-[1])*9.25%	[*] (1-[1])*9.25%	[*] Calculated from Peano et al. (2020) and Nessi et al. (2020) [**] Calculated from Maury et al. (2022) [***] Calculated from Huisman et al. (2015)
Mismanaged waste recollected to recycling	28%	-	28%	28%	-	-	-	-	28%	Calculated from Peano et al. (2020)

Plastic losses from incineration and landfill

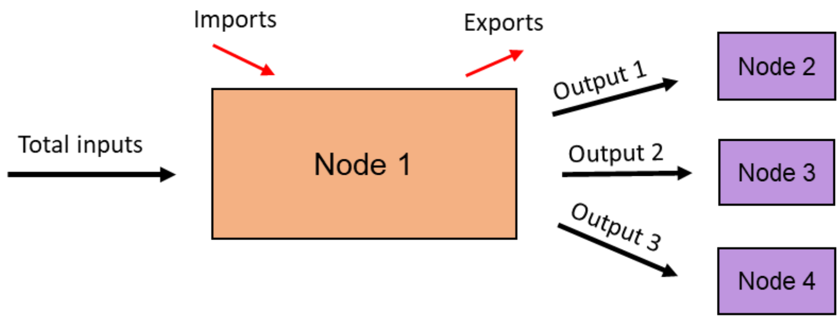
The losses of microplastics the incineration and landfill step were modelled as suggested by ECHA (European Chemical Agency) (ECHA, 2019). In the ECHA report, microplastic general release shares (i.e., not sector specific) from incineration and landfill are suggested, for both water and soil. The suggested values were adopted for all sectors under assessment in the present study, as follows:

- For all sectors under assessment in the present study:
    - Total microplastic losses from incineration: 2% of the total waste modelled as entering the incineration plant;
    - Microplastic releases to water from incineration: 50% of the total microplastic losses from incineration;
    - Microplastic releases to soil from incineration: 50% of the total microplastic losses from incineration;
    - Total microplastic losses from landfill: 2% of the total waste modelled as entering the landfill plant;
    - Microplastic releases to water from landfill: 0.002% of the total microplastic losses from landfill;
    - Microplastic releases to soil from landfill: 99.998% of the total microplastic losses from landfill.

Annex 3. Overview of nodes, TCs, literature data and assumption for the MFA model at sectors level

The approach followed for ensuring a closed mass balance of the TCs of a node (Figure 15) is described by the following equations. TCs add up to 100%, serve the purpose of detailing the total amount of a substance that is transferred from a process to another one, and are calculated in the present study as the ratio between outputs and inputs of a given node.

Figure 15. Simplified diagram of the nodes and flows of the material flow analysis as intended in the present study.



For each node, the mass balance was conserved (total inputs equal to total outputs) as described by Equation A6.

$$\sum Inputs\ (Total\ inputs + imports)\ [kton] = \sum Outputs\ (Total\ outputs + exports)\ [kton] \tag{A6}$$

All TCs were either (i) directly derived from literature (i.e., a TC for a specific step in the value chain and a specific sector was available from literature and already expressed as percentage), (ii) calculated based on a ratio between data (expressed as mass; Equation A7) available from literature, or (iii) assumed (if no other information was available). All TCs were calculated according to Equation A7 unless otherwise specified in the below text.

$$TC_{Output_1}[\%] = \frac{Output\ 1\ [kton]}{(Total\ inputs\ - Exports + Imports)\ [kton]} \tag{A7}$$

The TCs for import and exports were calculated as a ratio on the total inputs as described by Equations SM8 (as it is noticeable from Equations A8, TCs related to trade could therefore be higher than 100%).

$$TC_{Export}[\%] = \left(\frac{Export\ [kton]}{Total\ inputs\ [kton]}\right);\ TC_{Import}[\%] = \left(\frac{Import\ [kton]}{Total\ inputs\ [kton]}\right) \tag{A8}$$

For each node, the mass of each output was calculated through its assumed TCs, on the total inputs after trade (as described by Equation A7) so to ensure a total sum of all TCs for all outputs would be equal to 100% (Equation A9). An output from a node was considered as the input to another subsequent node along the modelled value chain.

$$\sum TCs_{Outputs} = 100\% \tag{A9}$$

As described in Section 2.3.3, the total plastic raw material demand was derived from Plastics Europe (PlasticsEurope, 2019). To allocate the mass to each sector, shares were estimated following a top-down approach (based on data from Plastics Europe (PlasticsEurope, 2020) and Amadei et al. (2022)). A summary of the employed share is summarized in Table 29.

Table 29. Summary of the estimated shares to allocate the total raw material demand for the European Union (EU27) in the year 2019. (Note: EEE = Electrical and Electronic Equipment).

Sector	Plastic demand and sector-specific shares	Reference
Total (All sectors)	5.33E+04 [ktonne/year]	Derived from PlasticsEurope (2019).
Packaging	39.60%	Derived from PlasticsEurope (2020).
Construction	20.40%	Derived from PlasticsEurope (2020).
Transport	9.60%	Derived from PlasticsEurope (2020).
EEE	6.20%	Derived from PlasticsEurope (2020).
Agriculture	3.40%	Derived from PlasticsEurope (2020).
Clothing and textiles	3.39%	Calculated from Amadei et al. (2022).
Healthcare	0.16%	Calculated from Amadei et al. (2022).
Fishing	0.29%	Calculated from Amadei et al. (2022).
Other	16.96%	Calculated from Amadei et al. (2022).

For each life cycle step and sector, a summary of the main assumption and literature sources considered for estimating the TCs (Table 30) is reported hereafter. The amount of lost and mismanaged plastics as well as their fate in the environment was modelled as detailed in Annex 2.

Plastic pellets and plastic products manufacturing

The total plastic demand to the manufacturing step was modelled as described in Table 29. Only in the case of packaging, a datum concerning pre-consumer plastic waste production was retrieved from Cimpan et al. (2021). All the estimated pre-consumer waste for packaging was assumed to be treated as a separately collected waste stream.

As described in Annex 1, the total production and trade of both semi-finished and finished products for each sector under exam in the present study was modelled based on the data reported by Amadei et al. (2022).

Consumption, waste generation and waste collection

The total consumed plastic for each sector (calculated as the sum of the finished products and semi-finished products to consumption) could be either lost (as described in Annex 2), discarded as waste (i.e., "waste generated") or ending as plastic stock. As this study only looks at one-year static MFA, the stock accumulation for each sector was estimated based on the mass balance principle between plastic consumption and plastic waste generation. For the packaging sector, no stock was modelled as it was assumed that all the packaging mass is discarded after consumption. Beside a stock accumulation, a stock reduction was also possible, in case the waste generated amount was higher than the consumed amount (e.g., in the healthcare sector). In this case, to close the mass balance, it was assumed that a reduction of stock for the year under exam explained the increase in waste generation.

The total amount of post-consumer waste generated was derived as a share of the total consumption of plastics for each sector. The exported and imported amounts of plastic waste were modelled by combining the data available from Eurostat (2022a) with the information on polymer-specific shares were applied to sectors demands in EU27 (estimated from PlasticsEurope (2021)). It was assumed that the total waste imported in EU27 was directly sent to recycling plants, whilst waste is exported directly after its generation.

To derive the total waste export and import, the following approach was adopted (for the sectors: packaging, construction, transport, EEE, agriculture and other):

- The data (expressed in mass) of traded waste (import and export) for EU27 in the year 2019 were gathered from the online data code ("EU trade since 1988 by HS2,4,6 and CN8 [DS-645593]"; Eurostat, 2022a) for "Waste, parings and scrap, of polymers of ethylene", "Waste, parings and scrap, of polymers of styrene", "Waste, parings and scrap, of polymers of vinyl chloride", "Waste, parings and scrap, of polymers of propylene", and "Waste, parings and scrap, of plastics (excl. that of polymers of ethylene, styrene, vinyl chloride and propylene)". The data from Eurostat (2022a) is not detailed at the level of sectors, and a series of calculations were necessary to derive the sector-specific import and export amount leveraging on polymer-specific plastics converters demand from Plastics Europe (2021).
    - Firstly, to enable a direct comparison of the data available at polymer level from Plastics Europe (PlasticsEurope, 2021) and Eurostat, the polymers HDPE, LDPE and PET were considered to be included under the Eurostat label "Waste, parings and scrap, of polymers of ethylene"; the polymers PS, EPS, and ABS were considered to be included under the Eurostat label "Waste, parings and scrap, of polymers of styrene"; the polymer PVC was considered to be included under the Eurostat label "Waste, parings and scrap, of polymers of vinyl chloride"; and the polymer PP was considered to be included under the Eurostat label "Waste, parings and scrap, of polymers of propylene".
    - Secondly, the total exported and imported plastic waste for the Eurostat label "Waste, parings and scrap, of polymers of ethylene" was distributed between the polymers HDPE, LDPE and PET based on the data available from polymer-specific plastic converters demand for each sector from PlasticsEurope (2021). Leveraging on the data from Plastics Europe, it was possible to calculate the average relative share (i.e., non-sector specific) of HDPE, LDPE, and PET out of the total demand of these three polymers in the sectors of packaging, construction, transport, EEE, agriculture and other. An analogous approach was adopted to distribute plastic waste from the Eurostat label "Waste, parings and scrap, of polymers of styrene" between PS, EPS, and ABS.
        - As a result, the total trade from Eurostat was at this stage allocated to each polymer (namely: HDPE, LDPE, and PET; PS, EPS, and ABS; PVC; PP and other) starting from the mass categorized under each more general Eurostat label.
    - Thirdly, the mass of each polymer (i.e., total non-sector specific mass from Eurostat at polymer-level) was then allocated to each sector through the polymer-specific plastic converters demand for each sector from PlasticsEurope (2021), expressed as percentages.
        - As a result, the total polymer-specific trade from Eurostat was at this stage allocated to each sector.
    - Lastly, the sum of imports and exports of all polymers under each sector was calculated, resulting in the total sector-specific trade for each sector.

On the other hand, in the case of clothing and textiles sectors, the waste trade (imports to recycling, and generated waste exported) was estimated from Hsu et al. (2021). Waste trade for the healthcare and fishing sectors was not estimated due to absence of suitable data.

The total amount of waste generated (after trade) was modelled to be either: collected separately (separate waste stream), collected with other waste fractions (mixed waste stream), lost or mismanaged. For each sector, the total amount of waste generated was therefore calculated as the sum of the collected waste (separate and mixed stream), the total losses and the total amount of mismanaged waste. Whilst losses and mismanaged waste were modelled as described in Annex 2, a sector-specific approach was adopted to estimate the total waste collected separately and collected as a mixed waste stream:

- In the case of packaging, construction, and agriculture: from the study of Watkins et al. (2020) it was possible to estimate the total amount of waste separately collected and collected as a mixed waste stream. However, in the study of Watkins and colleagues, the total estimated mass for these two streams was calculated only on selected subset of "priority products". The process of selecting the priority products was guided by the EU/CPA goal of 8.8 million tonnes of recycled plastics to be used annually in the EU27 by 2025 (adjusted from 10Mt for EU27+UK to enable a fair comparison with the results of the present study) considering the current situation and the foreseeable future developments (Watkins et al., 2020). As the scope of the present study would be to cover the overall mass of plastic for each sector, an additional amount of waste mass (either separately collected and collected as a mixed waste stream) was added to the estimates from Watkins and colleagues by comparison with the amount reported by Plastics Europe (PlasticsEurope, 2019).

- In the case of transport: from the study of Maury et al. (2022), it was estimated that 67% of the waste generated in this sector was separately collected, whilst the remaining 33% was modelled as mismanaged waste. It was assumed that the waste generated in this sector would only be either properly managed (i.e., following the fate of separately collected waste) or mismanaged.
- In the case of EEE: from the study of Huisman et al. (2015) it was possible to estimate not only the total amount of mismanaged waste electrical and electronic equipment (WEEE) (44%) but the amount of WEEE separately collected (38%) and the amount of WEEE managed as a mixed waste stream (19%).
- In the case of clothing and textiles: from Köhler et al. (2021) and the report of the European Environment Agency (EEA) (EEA, 2021b), it was estimated that only 33% of textiles and clothing waste are separately collected. Beside the mismanaged amount (Annex 2), the remaining mass was assumed to be collected as mixed waste.
- In the case of fishing and healthcare: due to lack specific data for these two sectors, the share of separately collected and mixed waste collected were estimated based on PlasticsEurope, (2019). The amount of mismanaged waste was instead modelled as described in Annex 2.
- In the case of the heterogeneous 'other' sector: from the study of Maury et al. (2022), it was possible to estimate that 6% of the total waste generated is separately collected. The remaining part could be either mismanaged (Annex 2) or collected as mixed waste.

Management of collected waste

The total amount of mixed waste could be either sent to incineration or landfill. In the case of the packaging sector, a certain amount (6%) of plastic waste collected as mixed waste was assumed to be sorted and sent to recycling (according to the data available from PlasticsEurope, (2019)). For all other sectors, the entirety of mixed waste could be either sent to incineration (60%) or landfill (40%), as suggested by Plastics Europe (PlasticsEurope, 2019) and excluding the recycling route.

In the context of the separately collected waste, a certain amount of plastic could be prepared for reuse and reused. In the current study, both phases are considered together, and sector-specific estimates were considered to model the amount of reused waste (ultimately sent again to consumption). A reuse rate of the plastic waste generated was modelled for the transport, EEE and textiles and clothing sectors. In the case of transport, the total mass of reused plastic was estimated from Maury et al. (2022) by considering passenger cars. In the case of the EEE sector, the amount of WEEE reused was derived from the report European Commission on WEEE recovery targets (Seyring et al., 2015). Lastly, in the case of textiles and clothing, an estimate of the reuse amount of plastic waste discarded in this sector was obtained by combining the information available in Köhler et al. (2021) and the EEA (EEA, 2021b).
The amount of separately collected waste that was not reused, could be either sent to incineration or landfill. Each plastic waste fate was modelled specifically for each sector:

- In the case of packaging, construction, EEE and agriculture: from the study of Watkins et al. (2020) it was possible to estimate the total amount of waste separately collected destined to recycling, landfill or incineration. As previously mentioned, the study of Watkins et al. (2020) was mostly focused on the separately collected waste sent to recycling. On the other hand, a general "disposal" step was included in the model of Watkins et al. (2020), as other destinations of waste were not included in the boundaries of the study. The total amount of separately collected waste sent to "disposal" was hence differentiated between separately collected waste to incineration or landfill according to Plastics Europe (PlasticsEurope, 2019).

- In the case of transport: from the study of Maury et al. (2022), it was possible to estimate that only 19% of the total separately collected waste was destined to recycling, whilst the remaining part was either incinerated (41%) or landfilled (40%).
- In the case of textiles and clothing: from Köhler et al. (2021) it was derived that a total of 25% of separately collected waste was sent to recycling. The remaining 75% was assumed to be equally allocated between incineration and landfill (38% each).
- In the case of healthcare, fishing and other: no specific studies were gathered in the literature review for the healthcare and fishing sectors which provided sufficient details for modelling the fate of separately collected waste in these two sectors. It was assumed that the separately collected waste could be either recycled, incinerated, or landfilled by employing the non-sector specific shares of these three fates as described by Plastics Europe (PlasticsEurope, 2019). The same approach was followed for modelling the fate of waste under the heterogeneous 'other' sector.

Recycling and recyclates production

The total amount of plastic waste sent to recycling was calculated as the sum of the amount of recycled plastic waste separately collected, the amount of recycled waste from collected mixed waste (only in the case of packaging) and a share of the total mismanaged waste assumed to be recollected (Annex 2). For each sector, the total amount of plastic waste entering the recycling step could either be recycled (and generate a specific amount of secondary plastics, i.e., recyclates) or sent to incineration or landfill. Sector specific modelling approaches were followed at this stage:

- In the case of packaging, construction, transport, EEE and agriculture: from the study of Watkins et al. (2020) it was possible to estimate the total amount of recyclates produced from the recycled waste, and the amount of waste "disposed". The total amount of recycled waste sent to "disposal" was differentiated between incineration and landfill by employing assumptions derived from Hsu et al. (2021) for these sectors.
- In the case of textiles and clothing, healthcare, fishing and 'other': from the study of Watkins et al. (2020) it was possible to estimate the total amount of recyclates produced from the packaging, construction, transport, EEE and agriculture sectors. The total amount of recyclate produced for these sectors (i.e., packaging, construction, transport, EEE and agriculture) was compared to the total amount of plastic sent to recycling to derive a proxy share of recyclates produced for textiles and clothing, healthcare, fishing and 'other' (60%). The remaining 40% were distributed between incineration and landfill by employing assumptions derived from Hsu et al. (2021).

The fate of recyclates was also considered in the present study. The total amount of recyclates produced within a sector could feed the converters' demand of the same sector (e.g., recyclates generated by the management of plastic packaging waste, being an input of plastic packaging products manufacturing) or the demand of converters of other sectors (e.g., recyclates generated by the management of plastic packaging waste, being an input of plastic products manufacturing in the field of construction, transport, EEE, etc.). The following sectors were included as potential destinations of produced recyclates: packaging, construction, transport, EEE, agriculture, textiles and 'other'. In the case of packaging, building and agriculture, information from Watkins et al. (2022) were employed to model the sector of destinations of recyclates arising from these sectors. On the other hand, in the case of transport, EEE, textiles and clothing, healthcare, fishing, and 'other', the destinations of recyclates produced from these sectors were derived from Plastics Europe (PlasticsEurope, 2019) by employing reported data in the context of how plastic recyclates re-enter the economy. In the case of the textiles and clothing sector, the total amount of recyclates destined the 'other' sector (estimated based on the sectors "Others" and "Houseware, leisure, sports" from the Plastics Europe report (PlasticsEurope, 2019)) was assumed to be employed in the manufacturing of new textiles or clothes instead. For each sector, a certain amount of recyclates produced (18%) was assumed to be exported outside the EU as indicated by Plastics Europe (PlasticsEurope, 2019), and therefore only 82% of the total recyclates are assumed to be available for the manufacturing of new plastic products within the EU borders.

Incineration and landfill

The total amount of waste entering the incineration step was calculated as the sum of plastic waste sent to incineration out of the total separately collected waste or waste collected as a mixed waste stream. A certain amount of plastic waste entering the incineration step could be ultimately sent to landfill: to estimate this amount for each sector, the data from Van Eygen et al. (2017) were employed. Beside losses (estimated as described in Annex 2) no additional destinations were considered for the waste entering the incineration step (i.e., and “elimination” of the waste was assumed). Similarly, for landfill, beside losses (Annex 2) no additional destinations were considered for the waste entering the landfill step.

Table 30. Summary of the Transfer coefficients (TCs) adopted for modelling plastic material flows at sectors level in the European Union (EU27) for the year 2019. The approach followed for modelling losses, losses fate, mismanaged waste and mismanaged waste fate is described in Annex 2. (Note: P = Packaging; C = Construction, T = Transport, E = Electrical and Electronic Equipment (EEE), A = Agriculture, C&T = Clothing and textiles, H = Healthcare, F = Fishing, O = Other).

FROM	TO	P	C	T	E	A	C&T	H	F	O
Plastic pellets production	Plastic products manufacturing	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Plastic products manufacturing	Pre-consumption waste	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Pre-consumption waste	Separate waste collection	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Plastic products manufacturing	Semi-finished products manufacturing	40.8%	37.9%	21.0%	1.4%	17.4%	44.1%	0.0%	0.0%	48.3%
Plastic products manufacturing	Finished products manufacturing	57.8%	62.0%	78.9%	98.5%	82.5%	55.8%	99.9%	99.9%	51.6%
Plastic products manufacturing	Losses	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Losses	Microplastics	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Microplastics	Water	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%
Microplastics	Soil	69.0%	69.0%	69.0%	69.0%	69.0%	69.0%	69.0%	69.0%	69.0%
Microplastics	Incineration	14.0%	14.0%	14.0%	14.0%	14.0%	14.0%	14.0%	14.0%	14.0%
Semi-finished products manufacturing	Export	19.1%	8.5%	18.3%	69.0%	4.9%	27.6%	0.0%	0.0%	8.3%

FROM	TO	P	C	T	E	A	C&T	H	F	O
Import	Semi-finished products manufacturing	15.1%	5.7%	15.0%	24.0%	2.6%	42.5%	0.0%	0.0%	4.1%
Semi-finished products manufacturing	Finished products manufacturing	70.0%	10.0%	90.0%	90.0%	10.0%	86.8%	0.0%	0.0%	42.6%
Semi-finished products manufacturing	Consumption	30.0%	90.0%	10.0%	10.0%	90.0%	13.2%	0.0%	0.0%	57.4%
Finished products manufacturing	Export	7.3%	17.7%	26.8%	9.3%	0.9%	14.0%	10.2%	5.4%	8.9%
Import	Finished products manufacturing	7.3%	16.8%	37.3%	19.2%	0.1%	108.7%	15.1%	3.9%	18.9%
Finished products manufacturing	Consumption	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Consumption	Waste generation	95.1%	36.3%	53.6%	50.9%	50.0%	65.1%	94.4%	45.6%	58.6%
Consumption	Losses	4.9%	0.6%	0.0003%	0.0%	1.1%	0.1%	7.2%	3.8%	0.1%
Losses	Microplastics	0.1%	9.3%	100.0%	0.0%	10.1%	100.0%	0.0%	0.0%	21.1%
Losses	Macroplastics	99.9%	90.7%	0.0%	0.0%	89.9%	0.0%	100.0%	100.0%	78.9%
Microplastics	Water	0.0%	0.3%	17.0%	0.0%	0.0%	48.9%	0.0%	0.0%	3.4%
Microplastics	Soil	100.0%	95.9%	69.0%	0.0%	37.8%	11.1%	0.0%	0.0%	18.7%
Microplastics	Incineration	0.0%	3.8%	14.0%	0.0%	62.2%	40.0%	0.0%	0.0%	78.0%

FROM	TO	P	C	T	E	A	C&T	H	F	O
Macroplastics	Water	0.3%	0.4%	0.0%	0.0%	0.0016%	0.0%	0.4%	90.0%	0.2%
Macroplastics	Soil	8.2%	20.9%	0.0%	0.0%	51.9%	0.0%	25.7%	10.0%	5.3%
Macroplastics	Incineration	91.6%	78.7%	0.0%	0.0%	48.1%	0.0%	73.9%	0.0%	94.5%
Consumption	Stock	0.0%	63.1%	46.4%	49.1%	48.9%	34.9%	0.0%	50.6%	41.3%
Stock	Waste generation	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.6%	0.0%	0.0%
Waste generation	Export	3.4%	8.5%	4.1%	23.8%	3.2%	31.0%	0.0%	0.0%	3.8%
Import	Waste generation	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Waste generation	Mixed waste collection	45.9%	53.3%	0.0%	18.6%	43.9%	60.8%	47.2%	47.2%	83.2%
Waste generation	Separate waste collection	42.4%	37.5%	66.7%	37.7%	46.9%	29.9%	43.6%	43.6%	6.0%
Waste generation	Losses	2.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.7%
Losses	Macroplastics	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Macroplastics	Water	15.7%	15.7%	15.7%	15.7%	15.7%	15.7%	15.7%	15.7%	15.7%
Macroplastics	Soil	56.2%	56.2%	56.2%	56.2%	56.2%	56.2%	56.2%	56.2%	56.2%
Macroplastics	Environment (unspecified)	28.1%	28.1%	28.1%	28.1%	28.1%	28.1%	28.1%	28.1%	28.1%

FROM	TO	P	C	T	E	A	C&T	H	F	O
Mismanaged waste	Recycling	28.1%	0.0%	28.1%	28.1%	0.0%	0.0%	0.0%	0.0%	28.1%
Waste generation	Mismanaged waste	9.0%	9.3%	33.3%	43.8%	9.3%	9.3%	9.3%	9.3%	9.1%
Mismanaged waste	Losses	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%
Mixed waste collection	Recycling	6.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Mixed waste collection	Incineration	57.0%	60.0%	60.0%	60.0%	60.0%	60.0%	60.0%	60.0%	60.0%
Mixed waste collection	Landfill	37.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%
Separate waste collection	Reuse	0.0%	0.0%	8.3%	2.0%	0.0%	60.0%	0.0%	0.0%	0.0%
Reuse	Consumption	0.0%	0.0%	100.0%	100.0%	0.0%	100.0%	0.0%	0.0%	0.0%
Separate waste collection	Recycling	75.4%	64.0%	19.0%	65.9%	80.5%	25.0%	62.0%	62.0%	62.0%
Separate waste collection	Incineration	17.5%	25.6%	41.0%	24.3%	13.8%	37.5%	27.0%	27.0%	27.0%
Separate waste collection	Landfill	7.1%	10.4%	40.0%	9.9%	5.6%	37.5%	11.0%	11.0%	11.0%
Import	Recycling	3.4%	21.4%	6.8%	5.1%	4.5%	37.2%	0.0%	0.0%	10.4%
Recycling	Incineration	25.9%	39.4%	26.9%	44.8%	36.9%	35.5%	35.5%	35.5%	35.5%
Recycling	Landfill	3.0%	4.6%	3.1%	5.2%	4.3%	4.9%	4.9%	4.9%	4.9%

FROM	TO	P	C	T	E	A	C&T	H	F	O
Recycling	Recyclates	71.1%	56.0%	70.0%	50.0%	58.8%	59.6%	59.6%	59.6%	59.6%
Recyclates	Packaging [sector]	19.5%	1.9%	24.0%	24.0%	22.7%	24.0%	24.0%	24.0%	24.0%
Recyclates	Construction [sector]	14.6%	91.9%	46.0%	46.0%	18.5%	46.0%	46.0%	46.0%	46.0%
Recyclates	Transport [sector]	3.8%	0.0%	3.0%	3.0%	0.0%	3.0%	3.0%	3.0%	3.0%
Recyclates	EEE [sector]	0.8%	0.0%	2.0%	2.0%	0.0%	2.0%	2.0%	2.0%	2.0%
Recyclates	Agriculture [sector]	0.0%	0.0%	13.0%	13.0%	40.5%	13.0%	13.0%	13.0%	13.0%
Recyclates	Textiles and clothing [sector]	5.3%	0.0%	0.0%	0.0%	0.0%	12.0%	0.0%	0.0%	0.0%
Recyclate	Other [sector]	56.1%	6.2%	12.0%	12.0%	18.3%	0.0%	12.0%	12.0%	12.0%
Recyclates	Export	18.4%	18.4%	18.4%	18.4%	18.4%	18.4%	18.4%	18.4%	18.4%
Recyclates	Plastic products manufacturing	81.6%	81.6%	81.6%	81.6%	81.6%	81.6%	81.6%	81.6%	81.6%
Incineration	Losses	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
Losses	Microplastics	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Microplastics	Water	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%
Microplastics	Soil	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%

FROM	TO	P	C	T	E	A	C&T	H	F	O
Incineration	Landfill	52.9%	52.9%	52.9%	52.9%	52.9%	52.9%	52.9%	52.9%	52.9%
Landfill	Losses	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%
Losses	Microplastics	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Landfill	Water	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Landfill	Soil	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Annex 4. Overview of nodes, TCs, literature data and assumption for the MFA model at polymers level

As described in Section 2.4, the polymer-specific MFAs for each sector were derived by adapting the sector-specific TCs established as described in Section 2.3. In particular, the following sectors were analyzed: packaging, construction, transport, EEE and agriculture. For each of these sectors, the following polymers were detailed: LDPE, HPDE, PP, PS, EPS, PVC, PET, PUR, ABS/ASA/SAN, PA (and a general "other polymers" category).

Polymer-specific shares were applied to sectors demands in EU27 to derive the corresponding polymers demands, as summarized in Table 31. Polymer-specific demands were derived from Plastics Europe (PlasticsEurope, 2021) for the packaging, construction, EEE and agriculture sectors; whilst Polymer-specific demands for the transport sectors were calculated as an average between the information available from PlasticsEurope (2021) and Maury et al. (2022).

For each polymer in each sector, specific TCs were prepared to precisely model the end-of-life management and recyclates fate (Table 32). The set of polymers-specific TCs was prepared to:

- Model the waste collection step, calculating specific TCs for the separate waste collection or the mixed waste collection of each polymer within a sector.
- Model the separately collected waste management, calculating specific TCs for the management of separately collected polymers (that could be either sent to recycling, incineration, or landfill).
- Model the recycling process, calculating specific TCs for the recycling process (distinguishing between recyclates produced, and the fraction of waste sent to incineration or landfill).
- Model the fate or recyclates produced, calculating TCs to model the amount of recyclates that could be employed in the production of new products in the packaging, construction, transport, EEE, agriculture, textiles and 'other' sectors.

For each polymer in the construction, transport, EEE and agriculture sectors, the TCs were adapted based on the information available from Watkins et al. (2020). In the case of the packaging sector, an average of the TCs calculated on data retrieved from and Antonopoulos et al. (2021) was applied. If no specific information from literature was available for modelling polymers-specific TCs in a given set, the TCs modelled for the whole sector were adopted.

Table A polymer-specific share indicates the amount (%) of the polymer plastic demand within a sector. The polymer-specific shares were calculated based on the information available from Plastics Europe (PlasticsEurope, 2021) for the packaging, building and construction, EEE and agriculture sectors. In the case of the transport sector, an average of the polymer-specific shares derivable from PlasticsEurope (2020) and Maury et al. (2022) was employed instead.

Table 31. Summary of the polymer-specific shares applied to each sector-specific demand to derive polymer-specific demands within each sector following a top-down approach. (Note: EEE = Electrical and Electronic Equipment (EEE).

Sector (calculated total demand according to sector-specific MFA; expressed as [ktonne/year] EU27, 2019)	**Polymer-specific share [%]**											**Reference**
	LDPE	**HDPE**	**PP**	**PS**	**EPS**	**PVC**	**PET**	**PUR**	**ABS**	**PA**	**Other polymers**	
Packaging (2.11E+04 [ktonne/year])	29.78	17.96	23.44	2.92	1.41	2.01	20.62	0.25	0.10	0.30	1.21	Derived from PlasticsEurope (2021).
Construction (1.09E+04 [ktonne/year])	4.58	13.83	8.06	2.49	12.54	34.03	0	9.95	1.19	0.50	12.84	Derived from PlasticsEurope (2021).
Transport (5.12E+03 [ktonne/year])	1.96	3.81	29.35	0.69	4.12	1.73	4.00	14.54	6.50	9.00	24.28	Calculated average (PlasticsEurope, 2021) and Maury et al., 2022).
EEE (3.31E+03 [ktonne/year])	9.24	5.61	16.17	5.61	0	4.29	0.33	10.56	7.59	7.26	33.33	Derived from PlasticsEurope (2020).
Agriculture (1.81E+04 [ktonne/year])	33.97	2.56	33.97	1.28	0	8.97	0.64	0	0	0	18.59	Derived from PlasticsEurope (2020).

Table 32. Summary of the polymer-specific Transfer Coefficients (TCs) considered for each sector-specific Material Flow Analysis (MFA). (Note: P = Packaging; C = Construction, T = Transport, E = Electrical and Electronic Equipment (EEE), A = Agriculture; poly. = polymers).

Sector	**FROM**	**TO**	**Polymer-specific transfer coefficients [%]**											**Comment on underlined TCs (all other TCs values are taken from the sector-specific TCs)**
			LDPE	**HDPE**	**PP**	**PS**	**EPS**	**PVC**	**PET**	**PUR**	**ABS**	**PA**	**Other poly.**	
P	Waste generation	Mixed waste collection	55.2%	49.6%	57.3%	38.8%	45.9%	70.7%	35.1%	45.9%	45.9%	45.9%	45.9%	Calculated from Watkins et al (2020) and Antonopoulos et al. (2021).
P	Waste generation	Separate waste collection	33.1%	38.7%	31.0%	49.5%	42.4%	17.7%	53.2%	42.4%	42.4%	42.4%	42.4%	Calculated from Watkins et al (2020) and Antonopoulos et al. (2021).
P	Waste generation	Losses	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	TCs for overall P sector (Annex 2).
P	Waste generation	Mismanage d waste	9.0%	9.0%	9.0%	9.0%	9.0%	9.0%	9.0%	9.0%	9.0%	9.0%	9.0%	TCs for overall P sector (Annex 2).
P	Separate waste collection	Recycling	81.7%	83.0%	53.4%	27.8%	75.4%	62.5%	80.6%	75.4%	75.4%	75.4%	75.4%	Calculated from Watkins et al (2020) and Antonopoulos et al. (2021).
P	Separate waste collection	Incineration	13.0%	12.1%	33.1%	51.3%	17.5%	18.8%	13.8%	17.5%	17.5%	17.5%	17.5%	Calculated from Watkins et al (2020) and Antonopoulos et al. (2021).
P	Separate waste collection	Landfill	5.3%	4.9%	13.5%	20.9%	7.1%	18.8%	5.6%	7.1%	7.1%	7.1%	7.1%	Calculated from Watkins et al (2020) and Antonopoulos et al. (2021).
P	Recycling	Incineration	36.8%	14.5%	28.2%	39.3%	25.9%	8.9%	21.5%	25.9%	25.9%	25.9%	25.9%	Calculated from Watkins et al (2020) and Antonopoulos et al.

Sector	FROM	TO	Polymer-specific transfer coefficients [%]											Comment on underlined TCs (all other TCs values are taken from the sector-specific TCs)
			LDPE	HDPE	PP	PS	EPS	PVC	PET	PUR	ABS	PA	Other poly.	
														(2021).
P	Recycling	Landfill	4.3%	1.7%	3.3%	4.6%	3.0%	8.9%	2.5%	3.0%	3.0%	3.0%	3.0%	Calculated from Watkins et al (2020) and Antonopoulos et al. (2021).
P	Recycling	Recyclates	58.9%	83.8%	68.5%	56.2%	71.1%	82.2%	76.1%	71.1%	71.1%	71.1%	71.1%	Calculated from Watkins et al (2020) and Antonopoulos et al. (2021).
P	Recyclates	Packaging [sector]	14.0%	20.0%	10.0%	0.0%	19.5%	19.5%	25.0%	19.5%	19.5%	19.5%	19.5%	Calculated from Watkins et al (2020).
P	Recyclates	Construction [sector]	10.0%	80.0%	20.0%	100.0 %	14.6%	14.6%	36.5%	14.6%	14.6%	14.6%	14.6%	Calculated from Watkins et al (2020).
P	Recyclates	Transport [sector]	0.0%	0.0%	50.0%	0.0%	3.8%	3.8%	0.0%	3.8%	3.8%	3.8%	3.8%	Calculated from Watkins et al (2020).
P	Recyclates	EEE [sector]	0.0%	0.0%	10.0%	0.0%	0.8%	0.8%	0.0%	0.8%	0.8%	0.8%	0.8%	Calculated from Watkins et al (2020).
P	Recyclates	Agriculture [sector]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	Calculated from Watkins et al (2020).
P	Recyclates	Textiles and clothing [sector]	0.0%	0.0%	0.0%	0.0%	5.3%	5.3%	0.0%	5.3%	5.3%	5.3%	5.3%	Calculated from Watkins et al (2020).
P	Recyclates	Other [sector]	76.0%	0.0%	10.0%	0.0%	56.1%	56.1%	38.5%	56.1%	56.1%	56.1%	56.1%	Calculated from Watkins et al (2020).

Sector	FROM	TO	Polymer-specific transfer coefficients [%]											Comment on underlined TCs (all other TCs values are taken from the sector-specific TCs)
			LDPE	HDPE	PP	PS	EPS	PVC	PET	PUR	ABS	PA	Other poly.	
C	Waste generation	Mixed waste collection	53.3%	53.3%	53.3%	53.3%	53.3%	53.3%	53.3%	53.3%	53.3%	53.3%	53.3%	Calculated from Watkins et al (2020).
C	Waste generation	Separate waste collection	37.5%	37.5%	37.5%	37.5%	37.5%	37.5%	37.5%	37.5%	37.5%	37.5%	37.5%	Calculated from Watkins et al (2020).
C	Waste generation	Losses	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	TCs for overall C sector (Annex 2).
C	Waste generation	Mismanaged waste	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	TCs for overall C sector (Annex 2).
C	Separate waste collection	Recycling	64.0%	22.5%	64.0%	64.0%	9.3%	85.0%	64.0%	64.0%	64.0%	64.0%	64.0%	Calculated from Watkins et al (2020).
C	Separate waste collection	Incineration	25.6%	55.1%	25.6%	25.6%	64.5%	10.7%	25.6%	25.6%	25.6%	25.6%	25.6%	Calculated from Watkins et al (2020).
C	Separate waste collection	Landfill	10.4%	22.4%	10.4%	10.4%	26.3%	4.3%	10.4%	10.4%	10.4%	10.4%	10.4%	Calculated from Watkins et al (2020).
C	Recycling	Incineration	39.4%	25.9%	39.4%	39.4%	26.9%	40.5%	39.4%	39.4%	39.4%	39.4%	39.4%	Calculated from Watkins et al (2020).
C	Recycling	Landfill	4.6%	3.0%	4.6%	4.6%	3.1%	4.7%	4.6%	4.6%	4.6%	4.6%	4.6%	Calculated from Watkins et al

Sector	FROM	TO	Polymer-specific transfer coefficients [%]											Comment on underlined TCs (all other TCs values are taken from the sector-specific TCs)
			LDPE	HDPE	PP	PS	EPS	PVC	PET	PUR	ABS	PA	Other poly.	
														(2020).
C	Recycling	Recyclates	56.0%	71.1%	56.0%	56.0%	70.0%	54.8%	56.0%	56.0%	56.0%	56.0%	56.0%	Calculated from Watkins et al (2020).
C	Recyclates	Packaging [sector]	1.9%	25.0%	1.9%	1.9%	0.0%	0.0%	1.9%	1.9%	1.9%	1.9%	1.9%	Calculated from Watkins et al (2020).
C	Recyclates	Construction [sector]	91.9%	25.0%	91.9%	91.9%	0.0%	100.0 %	91.9%	91.9%	91.9%	91.9%	91.9%	Calculated from Watkins et al (2020).
C	Recyclates	Transport [sector]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	Calculated from Watkins et al (2020).
C	Recyclates	EEE [sector]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	Calculated from Watkins et al (2020).
C	Recyclates	Agriculture [sector]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	Calculated from Watkins et al (2020).
C	Recyclates	Textiles and clothing [sector]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	Calculated from Watkins et al (2020).
C	Recyclates	Other [sector]	6.2%	50.0%	6.2%	6.2%	100.0 %	0.0%	6.2%	6.2%	6.2%	6.2%	6.2%	Calculated from Watkins et al (2020).
T	Waste generation	Mixed waste collection	0.0%	0.0%	14.0%	0.0%	0.0%	13.3%	0.0%	13.3%	0.0%	0.0%	0.0%	Calculated from Watkins et al (2020).

Sector	FROM	TO	Polymer-specific transfer coefficients [%]											Comment on underlined TCs (all other TCs values are taken from the sector-specific TCs)
			LDPE	HDPE	PP	PS	EPS	PVC	PET	PUR	ABS	PA	Other poly.	
T	Waste generation	Separate waste collection	66.7%	66.7%	52.7%	66.7%	66.7%	53.3%	66.7%	53.3%	66.7%	66.7%	66.7%	Calculated from Watkins et al (2020).
T	Waste generation	Losses	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	TCs for overall T sector (Annex 2).
T	Waste generation	Mismanage d waste	33.3%	33.3%	33.3%	33.3%	33.3%	33.3%	33.3%	33.3%	33.3%	33.3%	33.3%	TCs for overall T sector (Annex 2).
T	Separate waste collection	Recycling	19.0%	19.0%	19.0%	19.0%	19.0%	19.0%	19.0%	19.0%	19.0%	19.0%	19.0%	Calculated from Watkins et al (2020).
T	Separate waste collection	Incineration	41.0%	41.0%	41.0%	41.0%	41.0%	41.0%	41.0%	41.0%	41.0%	41.0%	41.0%	Calculated from Watkins et al (2020).
T	Separate waste collection	Landfill	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	Calculated from Watkins et al (2020).
T	Recycling	Incineration	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%	Calculated from Watkins et al (2020).
T	Recycling	Landfill	3.1%	3.1%	3.1%	3.1%	3.1%	3.1%	3.1%	3.1%	3.1%	3.1%	3.1%	Calculated from Watkins et al (2020).
T	Recycling	Recyclates	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	Calculated from Watkins et al (2020).

Sector	FROM	TO	Polymer-specific transfer coefficients [%]											Comment on underlined TCs (all other TCs values are taken from the sector-specific TCs)
			LDPE	HDPE	PP	PS	EPS	PVC	PET	PUR	ABS	PA	Other poly.	
T	Recyclates	Packaging [sector]	24.0%	24.0%	0.0%	24.0%	24.0%	0.0%	24.0%	0.0%	24.0%	24.0%	24.0%	Calculated from Watkins et al (2020).
T	Recyclates	Constructio n [sector]	46.0%	46.0%	0.0%	46.0%	46.0%	0.0%	46.0%	0.0%	46.0%	46.0%	46.0%	Calculated from Watkins et al (2020).
T	Recyclates	Transport [sector]	3.0%	3.0%	100.0 %	3.0%	3.0%	100.0 %	3.0%	100.0%	3.0%	3.0%	3.0%	Calculated from Watkins et al (2020).
T	Recyclates	EEE [sector]	2.0%	2.0%	0.0%	2.0%	2.0%	0.0%	2.0%	0.0%	2.0%	2.0%	2.0%	Calculated from Watkins et al (2020).
T	Recyclates	Agriculture [sector]	13.0%	13.0%	0.0%	13.0%	13.0%	0.0%	13.0%	0.0%	13.0%	13.0%	13.0%	Calculated from Watkins et al (2020).
T	Recyclates	Textiles and clothing [sector]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	Calculated from Watkins et al (2020).
T	Recyclates	Other [sector]	12.0%	12.0%	0.0%	12.0%	12.0%	0.0%	12.0%	0.0%	12.0%	12.0%	12.0%	Calculated from Watkins et al (2020).
E	Waste generation	Mixed waste collection	18.6%	18.6%	25.3%	18.6%	18.6%	18.6%	18.6%	18.6%	18.6%	18.6%	18.6%	Calculated from Watkins et al (2020).
E	Waste generation	Separate waste collection	37.7%	37.7%	30.9%	37.7%	37.7%	37.7%	37.7%	37.7%	37.7%	37.7%	37.7%	Calculated from Watkins et al (2020).

Sector	FROM	TO	Polymer-specific transfer coefficients [%]											Comment on underlined TCs (all other TCs values are taken from the sector-specific TCs)
			LDPE	HDPE	PP	PS	EPS	PVC	PET	PUR	ABS	PA	Other poly.	
E	Waste generation	Losses	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	TCs for overall E sector (Annex 2).
E	Waste generation	Mismanaged waste	43.8%	43.8%	43.8%	43.8%	43.8%	43.8%	43.8%	43.8%	43.8%	43.8%	43.8%	TCs for overall E sector (Annex 2).
E	Separate waste collection	Recycling	65.9%	65.9%	65.9%	65.9%	65.9%	65.9%	65.9%	65.9%	65.9%	65.9%	65.9%	Calculated from Watkins et al (2020).
E	Separate waste collection	Incineration	24.3%	24.3%	24.3%	24.3%	24.3%	24.3%	24.3%	24.3%	24.3%	24.3%	24.3%	Calculated from Watkins et al (2020).
E	Separate waste collection	Landfill	9.9%	9.9%	9.9%	9.9%	9.9%	9.9%	9.9%	9.9%	9.9%	9.9%	9.9%	Calculated from Watkins et al (2020).
E	Recycling	Incineration	44.8%	44.8%	44.8%	44.8%	44.8%	44.8%	44.8%	44.8%	44.8%	44.8%	44.8%	Calculated from Watkins et al (2020).
E	Recycling	Landfill	5.2%	5.2%	5.2%	5.2%	5.2%	5.2%	5.2%	5.2%	5.2%	5.2%	5.2%	Calculated from Watkins et al (2020).
E	Recycling	Recyclates	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	Calculated from Watkins et al (2020).
E	Recyclates	Packaging [sector]	24.0%	24.0%	0.0%	24.0%	24.0%	24.0%	24.0%	24.0%	24.0%	24.0%	24.0%	Calculated from Watkins et al (2020).

Sector	FROM	TO	Polymer-specific transfer coefficients [%]											Comment on underlined TCs (all other TCs values are taken from the sector-specific TCs)
			LDPE	HDPE	PP	PS	EPS	PVC	PET	PUR	ABS	PA	Other poly.	
E	Recyclates	Construction [sector]	46.0%	46.0%	0.0%	46.0%	46.0%	46.0%	46.0%	46.0%	46.0%	46.0%	46.0%	Calculated from Watkins et al (2020).
E	Recyclates	Transport [sector]	3.0%	3.0%	0.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	Calculated from Watkins et al (2020).
E	Recyclates	EEE [sector]	2.0%	2.0%	100.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	Calculated from Watkins et al (2020).
E	Recyclates	Agriculture [sector]	13.0%	13.0%	0.0%	13.0%	13.0%	13.0%	13.0%	13.0%	13.0%	13.0%	13.0%	Calculated from Watkins et al (2020).
E	Recyclates	Textiles and clothing [sector]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	Calculated from Watkins et al (2020).
E	Recyclates	Other [sector]	12.0%	12.0%	0.0%	12.0%	12.0%	12.0%	12.0%	12.0%	12.0%	12.0%	12.0%	Calculated from Watkins et al (2020).
A	Waste generation	Mixed waste collection	1.8%	37.4%	43.0%	43.9%	43.9%	43.9%	43.9%	43.9%	43.9%	43.9%	43.9%	Calculated from Watkins et al (2020).
A	Waste generation	Separate waste collection	88.9%	53.3%	47.8%	46.9%	46.9%	46.9%	46.9%	46.9%	46.9%	46.9%	46.9%	Calculated from Watkins et al (2020).
A	Waste generation	Losses	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	TCs for overall A sector (Annex 2).

Sector	FROM	TO	Polymer-specific transfer coefficients [%]											Comment on underlined TCs (all other TCs values are taken from the sector-specific TCs)
			LDPE	HDPE	PP	PS	EPS	PVC	PET	PUR	ABS	PA	Other poly.	
A	Waste generation	Mismanaged waste	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	TCs for overall A sector (Annex 2).
A	Separate waste collection	Recycling	83.4%	5.4%	98.5%	80.5%	80.5%	80.5%	80.5%	80.5%	80.5%	80.5%	80.5%	Calculated from Watkins et al (2020).
A	Separate waste collection	Incineration	11.8%	67.2%	1.0%	13.8%	13.8%	13.8%	13.8%	13.8%	13.8%	13.8%	13.8%	Calculated from Watkins et al (2020).
A	Separate waste collection	Landfill	4.8%	27.4%	0.4%	5.6%	5.6%	5.6%	5.6%	5.6%	5.6%	5.6%	5.6%	Calculated from Watkins et al (2020).
A	Recycling	Incineration	37.3%	21.1%	32.8%	36.9%	36.9%	36.9%	36.9%	36.9%	36.9%	36.9%	36.9%	Calculated from Watkins et al (2020).
A	Recycling	Landfill	4.3%	2.4%	3.8%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	Calculated from Watkins et al (2020).
A	Recycling	Recyclates	58.3%	76.5%	63.4%	58.8%	58.8%	58.8%	58.8%	58.8%	58.8%	58.8%	58.8%	Calculated from Watkins et al (2020).
A	Recyclates	Packaging [sector]	25.0%	0.0%	0.0%	22.7%	22.7%	22.7%	22.7%	22.7%	22.7%	22.7%	22.7%	Calculated from Watkins et al (2020).
A	Recyclates	Construction [sector]	20.0%	80.0%	0.0%	18.5%	18.5%	18.5%	18.5%	18.5%	18.5%	18.5%	18.5%	Calculated from Watkins et al (2020).

Sector	FROM	TO	Polymer-specific transfer coefficients [%]											Comment on underlined TCs (all other TCs values are taken from the sector-specific TCs)
			LDPE	HDPE	PP	PS	EPS	PVC	PET	PUR	ABS	PA	Other poly.	
A	Recyclates	Transport [sector]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	Calculated from Watkins et al (2020).
A	Recyclates	EEE [sector]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	Calculated from Watkins et al (2020).
A	Recyclates	Agriculture [sector]	35.0%	0.0%	100.0 %	40.5%	40.5%	40.5%	40.5%	40.5%	40.5%	40.5%	40.5%	Calculated from Watkins et al (2020).
A	Recyclates	Textiles and clothing [sector]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	Calculated from Watkins et al (2020).
A	Recyclates	Other [sector]	20.0%	20.0%	0.0%	18.3%	18.3%	18.3%	18.3%	18.3%	18.3%	18.3%	18.3%	Calculated from Watkins et al (2020).

Annex 5. Results of the material flow analysis per step of the value chain

In Table 33 are reported the results related to the plastic manufacturing, consumption and waste generation steps of the MFA, as commented in Section 3.1.1.

Table 33. Plastic flows [ktonne] of each economic sector related to the pre-consumption and consumption key steps. Net trade is calculated as the difference between imports and exports. (Note: P = Packaging; C = Construction, T = Transport, E = Electrical and Electronic Equipment (EEE), A = Agriculture, C&T = Clothing and textiles, H = Healthcare, F = Fishing, O = Other).

MFA step	P	C	T	E	A	C&T	H	F	O
Semif. products	8,610	4,128	1,077	46	315	797	0	0	4,368
Semif. Net trade	-339	-114	-35	-21	-8	119	0	0	-186
Consumed semif. products	2,481	3,612	104	3	277	121	0	0	2,400
Finished products	12,199	6,741	4,038	3,257	1,497	1,007	86	153	4,671
Finish. Net trade	4	-61	423	322	-12	954	4	-2	470
Consumed finish. products	12,203	6,680	4,461	3,579	1,484	1,961	90	151	5,141
Consumpt ion	14,684	10,292	4,565	3,582	1,761	2,082	90	151	7,541
Waste generated	13959	3,740	2,449	1,823	881	1,354	85	69	4,421

In Table 34 are reported the results related to the plastic waste management and fate for the MFA, as commented in Section 3.1.1.

Table 34. Plastic flows [ktonne] of each economic sector related to waste generation and waste management. (Note: P = Packaging; C = Construction, T = Transport, E = Electrical and Electronic Equipment (EEE), A = Agriculture, C&T = Clothing and textiles, H = Healthcare, F = Fishing, O = Other).

MFA step	P	C	T	E	A	C&T	H	F	O
Waste export	476	317	100	434	28	420	0	0	166
Mixed waste coll.	6,193	1,824	0	258	374	568	40	32	3,542
Separate waste coll.	5,717	1,283	1,566	523	400	280	37	30	255

MFA step	P	C	T	E	A	C&T	H	F	O
Mismanaged waste	1214	317	783	608	79	86	8	6	387
Mixed waste to recycling	372	0	0	0	0	0	0	0	0
Mixed waste to incineration	3,530	1,094	0	155	224	341	24	19	2,125
Mixed waste to landfill	2,291	730	0	103	150	227	16	13	1,417
Separate waste to reuse	0	0	131	10	0	168	0	0	0
Separate waste to recycling	4,527	822	273	338	322	28	23	19	158
Separate waste to incineration	1,051	328	589	124	55	42	10	8	69
Separate waste to landfill	428	134	574	51	23	42	4	3	28

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