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Exploring the EU plastic value chain: A material flow analysis

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ABSTRACT

The accounting of plastic flows across the economy is pivotal to assess circularity of production and consumption and to define transitions scenarios at systems level. This study established a top-down mass flow analysis model for the EU27 (2019) plastic value chain, focusing on 9 sectors and 10 polymers. Estimates indicate that 4.46Mt of plastic recyclates are produced and consumed in the EU27 territory. On average, the EU27 recycling rate was equal to 19%. Total plastic losses amounted to 4% of the total plastic production, mostly occurring during the use phase. Future 2025 scenarios were prepared considering expected trends in the plastic value chain and compared with industry targets. In the cases of combined scenarios, the total recyclates consumed by plastic converters in 2025 ranged between 9.11Mt and 11.13Mt. Considering the key commitments for actions at the EU level, an evidence-based transformation of the plastic value chain is essential.

1. Introduction

Plastics represents a fundamental material in the modern world and a crucial asset in the worldwide economy. Plastic products are currently managed in ways that leads to severe environmental impacts and limits a "circular" plastic value chain (EU Plastics Strategy (EC, 2018a)). The negative effects of plastic pollution became highly visible in recent years (Charles et al., 2021). due to the littering of single-use plastics and the rising effects of microplastic on the environment (Welden et al., 2020; Kawecki and Nowack, 2019; Ryberg et al., 2019), humans and the whole food-chain alike (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 (UNEP, 2022). In this context, several EU policies have been put forward to address the considerable challenges represented by plastic (e.g., the above mentioned European Strategy for plastics in a Circular Economy (EC, 2018a), the new Circular Economy Action Plan (EC, 2020), and the European Green Deal (EC, 2019a)).

A deep knowledge of EU plastic material flows is fundamental for achieving such ambitious targets. Material Flow Analysis (MFA) is commonly employed in literature to model material flows (Chen et al., 2020), by systematically assessing them in a system defined in space and time, and to connect them between processes' inputs/outputs (Brunner and Rechberger, 2005). The mass balance of an MFA can be guaranteed by Transfer Coefficients (TCs), which are defined for each input/output flow of a process. TCs add up to 100% and ensure that the total amount of a substance 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 Member States (e.g., 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). Annual statistics (such as the PRODCOM database, Eurostat, 2022) have also been adopted recently (Amadei et al., 2022; Hsu et al., 2021) to assess EU plastic flows, suggesting a potential use of product-based consumption data for MFA. A key asset in enabling the EU foreseen targets in the plastic value chain, is the knowledge about recycled plastics production and recycled plastics fate in the manufacturing process of new products. Few in-depth assessments of recycled plastic generation and fate are available to date. Notably, Watkins et al. (2020) proposed a model aiming at mapping product flows from waste generation to the second life, for investigating the potential fate of the recycled plastic (i.e., sectors of origin and sectors of destination).

This paper aims at assessing the EU27 plastic flows for the year 2019, providing a macro-scale overview at the whole EU level while maintaining a high level of details at the sectors, polymers and flows level. Despite the EU ambitions in the context of the plastics value chain and the growing literature interest on properly addressing such flows, comprehensive studies assessing multiple sectors/polymers along the whole value chain are lacking. To tackle these challenges, a novel top-

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down approach is adopted as a tool for directly linking sector-specific assessments with polymer-specific ones, and its potential strengths and weaknesses are discussed.

The novelty of the study especially concerns the estimation of plastic losses, plastic waste mismanagement and recycled plastics' fate as these flows are commonly unexplored and excluded from typical plastic flows assessment.

Furthermore, the assessment aims at shedding light on the main data gaps and inconsistencies concerning available data and to provide estimates for less explored sectors, such as the textiles and clothing, healthcare, and fishing sectors.

Key hotspots and assumptions needed for generating a balanced MFA starting with literature data are also explored, and the main research needs and data gaps are disclosed towards coming refined assessments.

The estimates for recycled plastics for the year 2019 are extrapolated to 2025 by means of simplified future scenarios. These scenarios serve the purpose of understanding how the plastic value chain could evolve considering the current EU policy and economic background. Future projections are compared not only to the 2019 state of play, but also to industry pledges such as the EU target (endorsed by the Circular Plastic Alliance (CPA)) aiming at ensuring 8.8 Megatonnes of recycled plastics consumed in the EU27 by 2025 (EC, 2018a; CPA, 2022).

Unveiling the state of 2019 EU plastic flows and which future scenarios could ensure a sufficient feedstock for reaching the forthcoming EU targets, could enable a deeper understanding on the required efforts toward ensuring that such EU commitments for the plastic sector will be met.

The structure of the paper and its following sections is summarized as follows:

- Firstly, a Methodology section (Section 2) introduces the underpinning literature research and scope of the analysis:
  - Section 2.1 describes the reviewed literature and how data have been managed and adapted to suit the desired geography and time (i.e., EU27 2019).
  - Section 2.2 illustrates the scope of the sector-specific assessment, by providing a detailed overview of the steps of the value chain and sectors included in the study (Section 2.2.1). Towards assessing how the EU plastic value chain could behave in future, a series of simplified scenarios were hypothesized by projecting flows to the year 2025 (Section 2.2.2).
  - Section 2.3 provides an overview of the main methodological assumptions adopted for the polymer-specific analysis of the EU value chain, especially detailing the employed novel top-down approach (Section 2.3.1).

- Secondly, the main results are presented and discussed in the Results and Discussion section (Section 3):
  - A thorough overview of the sector-specific results is presented in Section 3.1, by following the mains steps of the value chain. Sections are devoted to plastic manufacturing, consumption and waste generation (Section 3.1.1), the management practices of plastic waste (Section 3.1.2) and the mismanagement of plastic waste together with plastic losses and environmental releases (Section 3.1.3).
  - A dedicated section (Section 3.2) illustrates the main results of the scenarios 2025 simplified assessment, contextualized with industry and EU policy targets.
  - Similarly to the sector-specific results, polymers-specific results are presented in a dedicated section (Section 3.3).
  - In Section 3.4, the main challenges and novel aspects of the present assessment are reported. Additionally, to support future research in the plastics MFA field, and to ensure full transparency of the manuscript, the main limitations and assumptions employed in the study are listed.
  - Section 3.5 closes the Results and Discussion section and aims at framing the EU-based results of the present study in the context of the country-specific results, listing potential differences, strengths, and limitations of each.

- Lastly, in Section 4, the main Conclusion of the study are listed and coupled with an outlook concerning MFA studies and the EU plastic-specific policy ambitions.

For sake of clarity a list of key nomenclatures and definitions employed in the present study is reported hereafter:

- 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 microplastic that is lost from plastic management processes or by consumers.
- Plastic environmental release: The amount of macroplastic or microplastic that is lost from plastic management processes or by consumers 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 plastic 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).
- Stock variation: 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 case in which the amount of waste generated is lower than the amount of plastic consumed. A case in which waste generation is higher than the consumed amount was modelled as "negative stock variation": in this case, plastics accumulated within a sector-specific stock is partially or entirely discarded in the year 2019.

2. Methodology

The material flow analysis model of plastic in EU has been built via the following steps: (i) a literature review to gather input data for building the MFAs; (ii) data curation and adaptation to a common geographical and temporal reference (EU27 2019); (iii) development of sector-specific MFAs; (iv) development of polymer-specific MFAs for a subset of the different economic sectors selected at point (iii) were derived.

2.1. Literature review and data curation and adaptation for the material flow analysis

Literature studies were collected through a search on the Scopus® database (Scopus, 2022) aimed at gathering documents focusing on material flow assessment (of sectors and polymers in the EU). The full list of sectors included in the study is provided in Supplementary Material (SM) 1 (from now on SMi refers to chapter i of the Supplementary Material). Several keywords were considered for the screening of the documents (titles and abstracts). The list of searched keywords included: (i) keywords related to material flow analysis and plastic flows assessments: "mass flow model/material flow analysis plastics", "plastics/-plastic flows", "plastic polymers flows", "plastic value chain"; (ii) keywords related to specific steps of the value chain: "micro-plastic/macroplastic" releases/losses", "plastic leakages", "plastic waste management"; "plastic consumption"; "plastic export"; "mismanaged waste"; and (iii) keywords combining the searches of points (i) and (ii) with sector-specific and/or polymer-specific terms (e.g., "packaging", "fishing", "healthcare"). These keywords were firstly screened by especially considering the EU geography (e.g., by accompanying the search with "EU/Europe/European Union" terms) and, if needed, by considering other Member States (MS) (e.g., by accompanying the search with "Italy/Austria/Finland" etc. terms). Following a similar screening approach coupled with snowball sampling, other literature sources (such as reports) and additional references were collected and analyzed. The temporal scope of the search was 2000–2022 and EU-based studies or studies providing sector-specific or polymer-specific information were prioritized. The literature review yielded a total of 88 studies, out of which a total of 25 studies referred to the EU (EU28, EU27 or unspecified), whilst most of the others either being studies related to the worldwide plastic economy or dealing with country-specific value chains (predominantly UK, Norway, China, Spain, or other EU countries). The full list of studies analysed is provided in SM2. A data adjustment step was necessary to align the data collected to the same geographical and temporal scope. The correction was based on the Gross Domestic Product (GDP) (The World Bank, 2022), and performed when needed, following a country- or region-specific approach.

2.2. MFA of EU plastic flows at the level of sectors

The MFA model development required: (i) the definition of the MFA system boundaries and assessed sectors (Section 2.2.1); (ii) the generation of a transfer coefficients (TCs) matrix at sectors level based on literature data and specific assumptions (as detailed in SM3); (iii) the calculation of the plastic flows along the value chain (SM3). The MFA model aims at detailing the mass of plastics flows (expressed as ktonne or megatonne) along the main steps of the value chain. A plastic flow is understood as single flow at sector level. A polymer flow is instead understood as a flow expressed specifically at the level of polymers. A plastic flow might be composed of several polymers.

2.2.1. System boundaries and sectors included in the MFA

The system boundary of the present study includes all the main steps involved in the life cycle of the plastics, from pellets production to end-of-life (EOL) management, as illustrated in Fig. 1. As described in SM4, the input mass of the present study was allocated to the various sectors following a top-down approach. Sector-specific MFA models were prepared addressing packaging, construction, transport, Electrical and Electronic Equipment (EEE), agriculture, textiles and clothing, healthcare, fishing, and "other". In the "other" sector are included plastic products and the plastic components not classified in any of the other sectors, hence the MFA model is representative of the entire EU market. Details on each of the sectors included in the present work are provided in SM1. Each box included in the MFA (Fig. 1) is considered as a "node" or "step" of the plastic value chain.

Each node in Fig. 1 could either represent (i) a simplification of an industrial process/collection of industrial processes (being (i) in Fig. 1 represented with a rectangular shape); (ii) a "step/action" of the value chain of plastics (for instance, the node "waste generation" represents the moment in which a plastic waste is generated from consumption), or (iii) an output of a process (being (ii) and (iii) in Fig. 1 represented with an oval shape). In Fig. 1 the same color was used to differentiate between steps in the plastic value chain. To ensure that the mass balance is preserved, input flows equal output flows from each node. Other raw materials (e.g., required for the manufacturing steps) or plastic additives (e.g., employed during the manufacturing of plastic products) were not included in the assessment.

Primary plastic and secondary plastic are considered within the step production of plastic pellets which represents the input mass to the overall model. Plastic pellets are handled by plastic product manufacturers. During the manufacturing/conversion step, pellets are assumed to be transformed into either "finished" or "semi-finished"/

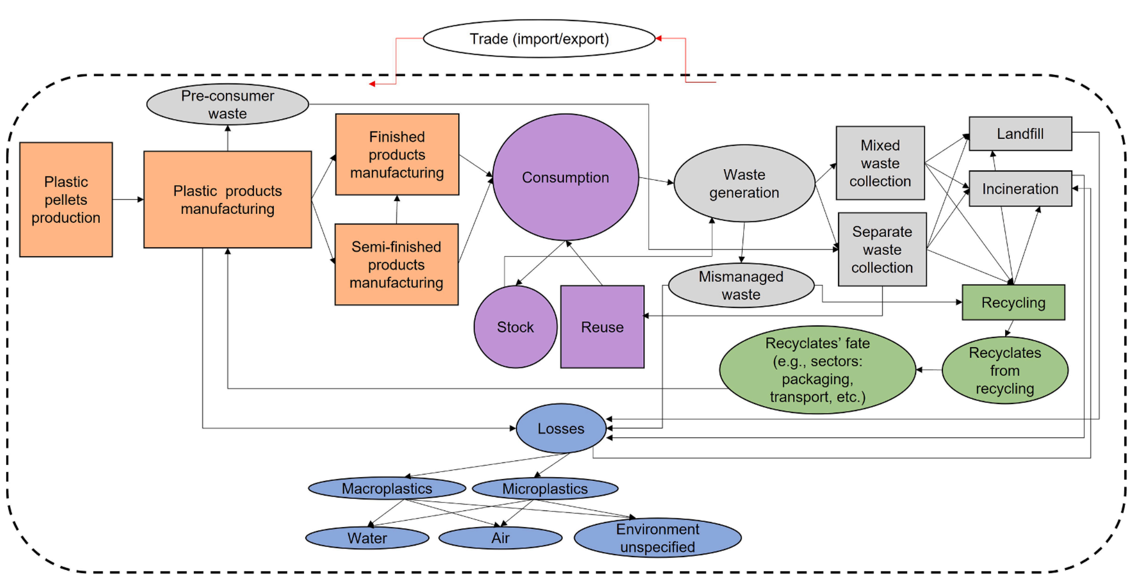

Fig. 1. System boundaries of the MFA model. *Note: the same color was used to differentiate between steps in the plastic value chain: orange for plastic production and products manufacturing; violet for consumption; gray for waste management/mismanagement, green for recycling, and blue for losses and releases.*

"intermediate" products. Semi-finished products are intended as products that could be either used as inputs for other finished goods, or products that could be directly sold to consumers (Amadei et al., 2022). 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 directly available for consumption (SM5). Plastic losses may occur during the manufacturing phase: such losses and the related environmental releases/amounts being recollected were estimated based on the methodology detailed in the 'Plastic Leak Project' (PLP) (Peano et al., 2020; SM6). The present study covers microplastics (intended as small sized plastic debris of less than 5 mm in diameter) and macroplastics (intended as plastic debris of diameter equal or greater than 5 mm). The analysis of nanoplastics flows and of any potential fragmentation of macroplastics into smaller debris were excluded from the assessment.

The specific apparent consumption of each sector was calculated as the mass of plastic produced minus the amount of plastic exported plus the amount of plastic imported. Consumed plastics could either be discarded as waste, lost (see SM6) or maintained in "stock".

The total amount of waste generated could be either: (i) separately collected, (ii) collected as mixed waste, (iii) mismanaged (see SM6), (iv) lost (see SM6) or (v) exported/imported.

Plastic that is kept separate from other materials and managed as a specific stream solely of plastic falls under the "separate collection" stream, and could either be: recycled, incinerated, landfilled, or prepared for reuse and reused (both included in the "reuse" step). By contrast, plastic managed within a mixed materials stream is not kept separate from other materials and managed as a mixed stream of waste. Mixed waste for all sectors was either incinerated or landfilled, apart from a certain amount of packaging waste assumed to be sorted from the mixed fraction and sent to recycling. Additional steps such as sorting and cleaning are intended as included within the separate collection/mixed collection steps and were not modelled individually.

Recycling of plastic waste includes all the activities/processing steps aimed at converting waste into recyclates. Mechanical recycling of plastic was not distinguished from chemical recycling of plastics in this study.

The inflow of secondary plastic to the plastic manufacturing step was also detailed in term of final receiving sector (e.g., recyclates from the packaging sector could be destined to the packaging sector, the construction sector, etc.). In the incineration step, waste is converted into energy, flue gas and heat. The landfill is considered as final disposal of waste. From both the incineration and the landfill steps losses to the environment may occur, as described in SM6. An overview of all nodes and transfer coefficients, as well as the various data and assumptions employed for the MFA models at sectors' level is provided in SM4. A hotspot analysis was performed on the sector-specific MFAs to identify the most relevant assumptions on the modelled flows. The hotspot analysis enabled the identification of key TCs and their variation was tested by a sensitivity assessment (described in SM7).

2.2.2. Scenarios for the year 2025

A series of simplified scenarios for the year 2025 were also assessed to identify potential room for improvements in the overall circularity of the plastic system, and to understand under which conditions the 8.8 million tonnes recycled plastics target of the EU could be achievable. Based on the findings of the sensitivity assessment (SM7) and on the plastic value chain future trends, a series of simplified scenarios for the year 2025 were drafted and analysed. In particular, these scenarios included: (i) a reduction of waste exported (scenario A); (ii) an improvement in waste collection (scenario B), especially considering a boost in the total amount of separately collected waste and a reduction in waste mismanagement; (iii) an improvement in the management of separately collected waste (scenario C), with higher amounts sent to recycling; (iv) an improvement in waste recycling performances (scenario D) and (v) a combination of all scenarios including a + 10% (scenario F1), −10% (scenario F2) and 0% variation in plastic production (scenario F3). Such scenarios were inspired by key literature sources (e.g., Systemiq et al., 2022) and by an analysis of the current EU plastic policy background. All scenarios are described in detail in SM8. This exercise aims at understanding how the plastic value chain could evolve, bearing in mind the 2025 EU goal (EC, 2018a; CPA, 2022) of 8.8Mt recyclates' consumption. To enable a fair comparison with the results of the present study, the EU 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.

2.3. MFA of EU plastic flows at the level of polymers

The polymers-specific MFA models were based on sectors-specific MFAs following a three-stepped approach: (i) selection of polymers and sectors to be analysed based on available literature information; (ii) allocation of the total plastic production per sector to the most relevant polymers within a sector (top-down approach); (iii) generation of a polymer-specific TC matrix and MFA models (SM9).

2.3.1. Top-down approach for polymers MFA

To establish a polymer-specific MFAs a literature screening was performed aiming at gathering (i) the main polymers contributing to each sector-specific value chain and (ii) the comprehensive end-of-life data of polymer flows, detailing the management approach and recyclates' production and fate. For each sector, the flows of 10 polymers were detailed, namely: 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 sector, a top-down approach was adopted. Each sector-specific plastic demand was detailed at the level of polymers demand by means of demands shared (a polymer-specific share indicates the amount (%) of the polymer plastic demand within a sector). The polymer-specific shares were calculated for packaging, building and construction, EEE and agriculture sectors based on the information available from Plastics Europe (PlasticsEurope, 2021), whilst for the transport sector, an average of the polymer-specific shares derivable from PlasticsEurope (2020) and Maury et al. (2022) was applied. By contrast, the polymer-specific assessment was not performed for the textiles and clothing, healthcare and fishing sectors since data in literature was not sufficient to establish polymers specific MFAs as for the other sectors (SM10).

3. Results and discussion

The material flow model developed following the methodological steps is illustrated in Fig. 2. The results of the specific estimates at sector and polymer levels, as well as the scenarios are reported in the next sections.

3.1. Material flow analysis and sector-specific results

Results indicated that packaging was the most important sector in terms of plastics flows, both concerning consumed plastics (33% of a total of 44.7Mt), and the generated post-consumer plastic waste (49% of

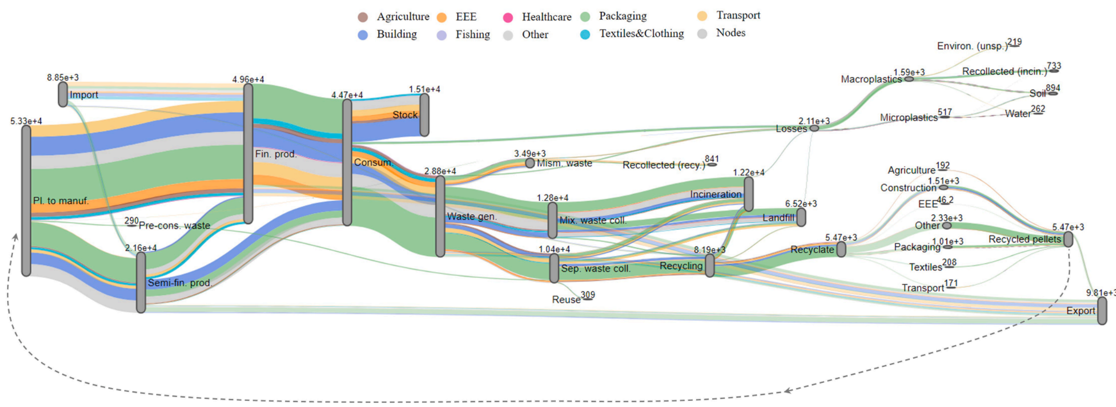

Fig. 2. General overview of the material flow assessment of EU plastic flows at the level of sectors. All data are expressed in [ktonne]. *Note: "Consum." = Consumption; "Pre-cons. Waste" = Pre-consumer waste; "Fin. Prod." = Finished products manufacturing; "Semi-fin. Prod." = Semi-finished products 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.*

a total of 28.8Mt of post-consumer plastic waste generated). An overview of the main nodes and sector-specific flows is provided in Fig. 2, whilst an overview of the main material flows of the MFA is provided in Table. 1. As described, in SM4, the input mass of the present study was allocated to the various sectors following a top-down approach by means of TCs. All data in Table 1 have been calculated by employing the TCs reported in SM4 (Table SM3, where all details concerning the underpinning data sources, assumptions and data-gaps are described) starting with the plastic demand and sector-specific shares illustrated in SM4 (Table SM1) and moving from plastic production towards recyclates generation. In the following sections, results of the main steps of the value chain under examination are commented and analysed.

3.1.1. Plastic manufacturing, consumption, and waste generation

The total amount of plastic pellets being demanded by EU converters was as high as 53Mt (including virgin and non-virgin pellets), out of which around 20-26% (Eurostat, 2022) is currently imported (calculated from Hsu et al. (2021) and Eurostat (2022). Results related to the manufacturing and consumption of semi-finished and finished underlined the leading role of packaging and construction sectors: packaging

Table 1

Overview of the main steps of the plastics flows modelled in the sector-specific material flow assessment (expressed in [ktonne]). *Note: the column "TOT" indicate the plastic flow as a sum of all the assessed sectors, namely Packaging ("P"), Construction ("C"), Transport ("T"), Electrical and Electronic Equipment ("E"), Agriculture ("A"), Clothing and textiles ("C&T"), Healthcare ("H"), Fishing ("F"), Other ("O"). Recyclates "consumed" refer to recyclates "used" by manufacturers in the EU.*

MFA step	P	C	T	E	A	C&T	H	F	O	TOT
Semi-finished products manufacturing	8610	4128	1077	46	315	797	0	0	4368	19,341
Semi-finished products net trade (import-exports)	−339	−114	−35	−21	−8	119	0	0	−186	−584
Consumed semi-finished products	2481	3612	104	3	277	121	0	0	2400	8998
Finished products manufacturing	12,199	6741	4038	3257	1497	1007	86	153	4671	33,647
Finished products net trade	4	−61	423	322	−12	954	4	−2	470	2103
Consumed finished products	12,203	6680	4461	3579	1484	1961	90	151	5141	35,750
Consumption	14,684	10,292	4565	3582	1761	2082	90	151	7541	44,748
Waste generated	13,959	3740	2449	1823	881	1354	85	69	4421	28,780
Waste generated exported	476	317	100	434	28	420	0	0	166	1942
Waste collected (mixed)	6193	1824	0	258	374	568	40	32	3542	12,831
Waste collected (separate)	6006	1283	1566	523	400	280	37	30	255	10,380
Mismanaged waste	1214	317	783	608	79	86	8	6	387	3488
Mixed waste to recycling	372	0	0	0	0	0	0	0	0	372
Mixed waste to incineration	3530	1094	0	155	224	341	24	19	2125	7513
Mixed waste to landfill	2291	730	0	103	150	227	16	13	1417	4947
Separate waste to reuse	0	0	131	10	0	168	0	0	0	309
Separate waste to recycling	4527	822	273	338	322	28	23	19	158	6508
Separate waste to incineration	1051	328	589	124	55	42	10	8	69	2276
Separate waste to landfill	428	134	574	51	23	42	4	3	28	1286
Recycling losses (to incineration)	1406	393	141	239	124	14	8	7	105	2437
Recycling losses (to landfill)	163	46	16	28	14	2	1	1	14	286
Recyclates produced from recycling	3851	559	368	267	198	23	14	11	176	5466
Imported waste to recycling	180	176	34	26	14	10	0	0	28	468
Recyclates employed in the packaging sector	750	10	88	64	45	5	3	3	42	1012
Recyclates employed in the construction sector	561	513	170	123	37	11	6	5	81	1506
Recyclates employed in the transport sector	145	0	11	8	0	1	0	0	5	171
Recyclates employed in the EEE sector	29	0	7	5	0	0	0	0	4	46
Recyclates employed in the agriculture sector	0	0	48	35	80	3	2	1	23	192
Recyclates employed in the textiles sector	206	0	0	0	0	3	0	0	0	208
Recyclates employed in the 'other' sector	2160	35	44	32	36	0	2	1	21	2331
Exported recyclates	707	103	68	49	36	4	3	2	32	1004
Total recyclates (consumed in the EU27, after exports)	3144	456	301	218	161	19	11	9	143	4462

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 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. 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 to 51% in all other sectors (excluding those sectors for which no stock was assumed, such as the packaging sector). Losses from consumption were also estimated (SM6). A detailed overview of the resulting plastic flows for the steps described in this section is provided in SM11.

3.1.2. Management of plastic waste

Results of the study indicated a total amount of post-consumer waste generated from all sectors equal to 28.8Mt, out of which 1.94Mt were exported. In particular, export of post-consumer plastic waste was equal to 31% out of 1.35Mt waste generated for textiles and 24% out of 1.82Mt of waste generated for EEE, with lower values for construction (8% out of 3.7Mt of waste), packaging and agriculture (3% out of 14.0Mt of waste and 3% out of 0.9Mt of waste, respectively).

Considering all sectors under examination, the total amount of waste being separately collected amounted to 10.4 Mt, with 12.8Mt being instead collected as mixed waste. In the case of packaging, a comparable amount of plastic was either collected separately (42% of 13.5Mt waste after trade) or as mixed stream (46% of 13.5Mt waste after trade), whilst the remaining fraction was either lost or mismanaged. Only 0.37Mt of mixed waste arising from the packaging waste was assumed to be sent to recycling, thanks sorting operations of valuable fractions, and equalling 6% of the total mixed (from all sectors). In the case of construction, only 37% of plastics was separately collected (out of 3.4Mt waste generated for this sector, after trade). Most of the separately collected plastic waste was sent to recycling, especially for packaging (75% of the total separately collected waste), agriculture (81%, out of 0.4Mt separately collected waste), EEE (65% out of 0.5Mt separately collected waste) and construction (64% out of 1.3Mt separately collected waste).

The total plastic reused was equal to 0.31Mt. Reuse exhibited a relevant role not only for clothing and textiles (18% of all waste generated, amounting to 0.9Mt after trade) but also for transport (6% of 2.3Mt of waste generated after trade), whilst its contribution remained negligible for all other sectors (1% maximum). Cumulatively, 3.49Mt of the total post-consumer waste generated was mismanaged. The highest share of mismanaged waste (44% of the total waste generated, equal to 1.4Mt after trade) was related to EEE, followed by transport (with 33% of the total waste generated, equal to 2.3Mt after trade), highlighting the much higher relevance of mismanaged waste for these two sectors compared to the other ones.

The total amount of plastic waste entering recycling facilities was equal to 8.19Mt. Around 37% of the total post-consumer waste was recycled for the packaging and agriculture sectors; with an average of 18% for the remaining sectors (Fig. 3). The performance of the recycling step ranged from 50% (for EEE) to 71% (for packaging), whilst the non-recycled plastic was mostly sent to incineration (35% on average across sectors) or landfill (5% on average across sectors). On average, the EU27 end-of-life recycling rate was equal to 19% (16.6% when export was considered).

Overall only 82% of plastic recyclates were consumed within the EU27 boundaries (4.46Mt), whilst the remaining 18% were exported (1.01Mt). Most of plastic waste was found to still be incinerated or landfilled (covering on average 36% and 23% of all waste management options, respectively). An overview of the main plastic flows related to plastic waste generation and management are listed in SM11.

3.1.3. Mismanaged plastic, losses and environmental releases

A total of 2.11Mt of plastics were lost in the year 2019; with 39% being lost during the use phase, 20% being waste losses, 2% pre-consumer plastics losses, 17% arising from mismanaged waste, 12% losses from incineration and 10% from landfill. For the packaging, construction, agriculture, healthcare and fishing sectors, the losses due to plastic consumption manifested the highest relevance (ranging from 35% of 0.2Mt total losses in case of construction, to 74% of 0.01Mt total losses in case of fishing). Losses due to plastic consumption are intended as the losses of plastic products or fraction of plastics products during the use phase; for instance, in the case of the clothing and textiles sector, potential loss and release of micro-plastics from the abrasion of synthetic textiles and textile products during laundering (as suggested for instance by Kawecki and Nowack, 2019 and Ryberg et al., 2019); in the case of the transport sector, losses due to tire abrasion during transport (as suggested for instance by Sieber et al., 2020 and ECHA, 2019). Losses of waste were relevant for the packaging sector (25% of 1.4Mt of total losses) and the "other" sector (33% of 0.2Mt of total losses). Losses of waste are linked to the amount of the generated plastic waste subject to littering events; e.g., plastic waste products such as cups, plastic shopping bags, or plastic wrappers/lids that are that are littered (as suggested

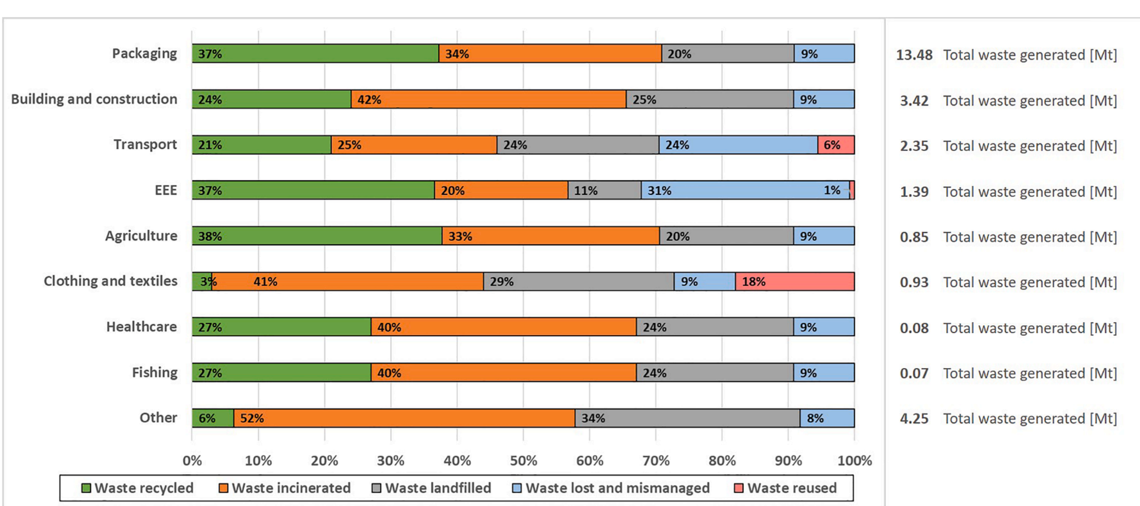

Fig. 3. Rates [%] of total plastic recycled, incinerated, landfilled, reused or lost/mismanaged for each sector. *Note: the rates are calculated considering waste being generated and trade of waste; EEE = Electrical and Electronic Equipment.*

by Peano et al. (2020) Mismanaged waste losses were significant for the transport and EEE sectors (69% and 74% of the total losses, respectively), compared to the remaining sectors, due to the significant amount of waste mismanagement for these two sectors.

In the case of microplastics releases, the highest contribution to soil releases derived from landfill losses (56%), incineration losses (33%) and losses from manufacturing step (10%). Losses of waste (mostly due to macroplastic losses of packaging and losses of mismanaged waste) were responsible for 84% of the total macroplastics' losses to soil and 94% to water, calculated as explained in SM6 as leveraging the information from Peano et al. (2020) and Ryberg et al. (2019). An overview of the total losses per sector and per environmental compartment of the final release (including potential recollections) is reported in Table 2. Thanks to the flexibility of the top-down approach described in the present study, data visualization was not only possible for the flows of the whole value chain, but also for specific steps or sectors (as described in SM11 for instance in the case of losses-related flows).

3.2. Results for the analysis of scenario for 2025

The main results of the scenarios assessment for the year 2025 (described in Section 2.2.2 and detailed in SM8) are reported in Fig. 4.

According to Scenario B focusing on improvement in waste management, a total of 6.47Mt would be consumed in EU27 achieving a recyclates' consumption rate of 24.1%). This scenario was drafted considering the ambitious EU policies' goals (EC, 2018a, 2019a), although several barriers could significantly challenge the fulfillment of such goals. These barriers would be mostly linked to: (i) factors limiting the application of certain collection procedures (e.g., door-to-door) due to the intrinsic differences in MS territories; (ii) the economic feasibility of new collection practices and (iii) a much-needed shift in consumers behavior, especially for the less righteous EU MS. In Scenario B a reduction was assumed concerning waste mismanagement for the transport and EEE sectors, resulting in a significant amount of plastics made available to EU recyclers. Few information is however available to date regarding the fate and the precise amount of mismanaged plastic waste, and tracing and deviating flows of plastics currently mismanaged towards separate collection system would require a significant effort for the EU.

Scenario C would in principle adhere to the expected outcomes of the Landfill Directive (EC, 1999). in terms of reduced landfilling. A competitive effect could reduce recyclates' consumption rates, if waste incineration would be preferred in place of recycling for the additional separately collected waste (a potential scenario suggested for instance by Systemiq, 2022). Following the goal of many EU policies (e.g., EC, 2008, 2018a, 2018b) the effects of Scenario D ("Improved recycling performance") would be in the order of 5.57Mt being consumed in the EU and a recyclates' consumption rate around 20.8%. The assumptions on improved recycling performances of this scenario might however lead to an overestimation of its overall effects. The most adopted technologies for handling plastic waste (e.g., mechanical recycling plants) are already well-known and optimized, and room for improvement could be narrow. Processes such as chemical recycling could represent solutions leading to either higher or lower overall recyclates' consumption rates in the EU when compared with mechanical recycling. 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, a total of 11.13Mt recyclates consumed and a recyclates' consumption rates of 35.5% are achieved, therefore surpassing by 2.33Mt the EU target. Despite a future trend is expected for future plastic production (e.g., EC, 2018a), 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. This is also suggested by Systemiq (2022) that indicates a 5% reduction in plastic demand by 2030 could be envisaged. When a reduction of 10% in plastic production is assumed (for the combined Scenario F2), a total recyclates' consumption (9.11Mt) would be achieved. Similarly, when a stagnation on plastic production is assumed (0% demand variation, Scenario F3) the resulting recyclates being consumed (equal to 10.12Mt) would still be sufficient to meet the EU target.

Overall, results indicated how the application of a single action (e.g., scenarios from A to D) would not be sufficient to ensure the 8.8Mt EU target. Only by pursuing combined efforts (scenario F1, scenario F2 and scenario G) it would be possible to reach the 8.8Mt target by 2025. The scenarios' assessment results should be considered a tool for discussing how variations in some key steps of the value chain could hypothetically provide benefits/disadvantages to future EU goals for plastics. However, it must be noted how results are affected not only by the employed hypothesis on these variations, but also by the effects of unprecedented world events on plastics masses and flows (e.g., the COVID-19 pandemic outbreak and the war in Ukraine).

3.3. Material flow analysis and polymer-specific results

The sectors included in the polymer-specific analysis contributed to around 80% of the overall EU27 demand. Results indicated how a major role was played by HDPE, LDPE, PP, PVC, PET covering 70% of the total demand, and contributing to a total of 84% recyclates out of the total waste generated. In particular, LDPE, HDPE, PET and PP amounted to a total 92% of the total polymer demand needs for the packaging sector, as is also illustrated in Fig. 5.

3.4. Challenges, novel assumptions and limitations of the present study

The analysis of literature information suggested several relevant issues and challenges related to the information currently available in the context of sector-specific and polymer-specific MFAs. Data-gaps were recognized not only for certain unexplored flows (e.g., waste mismanagement and recyclates' fate), but also for whole sectors (e.g., healthcare and fishing). Incoherences between certain steps of the value chain (e.g., plastic consumption and plastic waste generation) were also acknowledged, as certain important gaps between subsequent steps in the value

Table 2
Sector-specific releases [ktonne] of plastics (sum of all releases along the value chain) per sector and per environmental compartment or potential recollection routes (excludes losses from mismanaged waste, landfill, and incineration). *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
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 environment (unspecified)	135.2	8.9	22.0	17.1	2.2	2.4	0.2	0.2	30.8	219.0

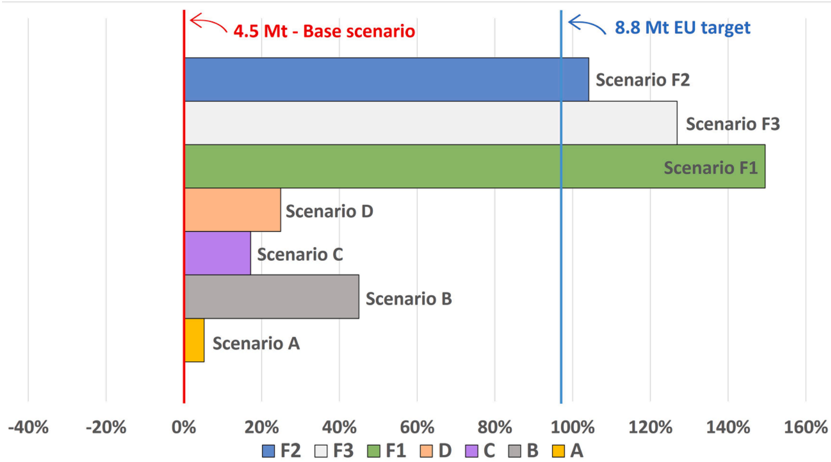

Fig. 4. Percentage variation of the total recyclates production for the sector-specific material flow analysis for the scenarios for the year 2025, compared to the results of the "base" sector-specific material flow analysis (expressed as megatonnes). *Note: description of the scenarios: scenario A = "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 SM8.*

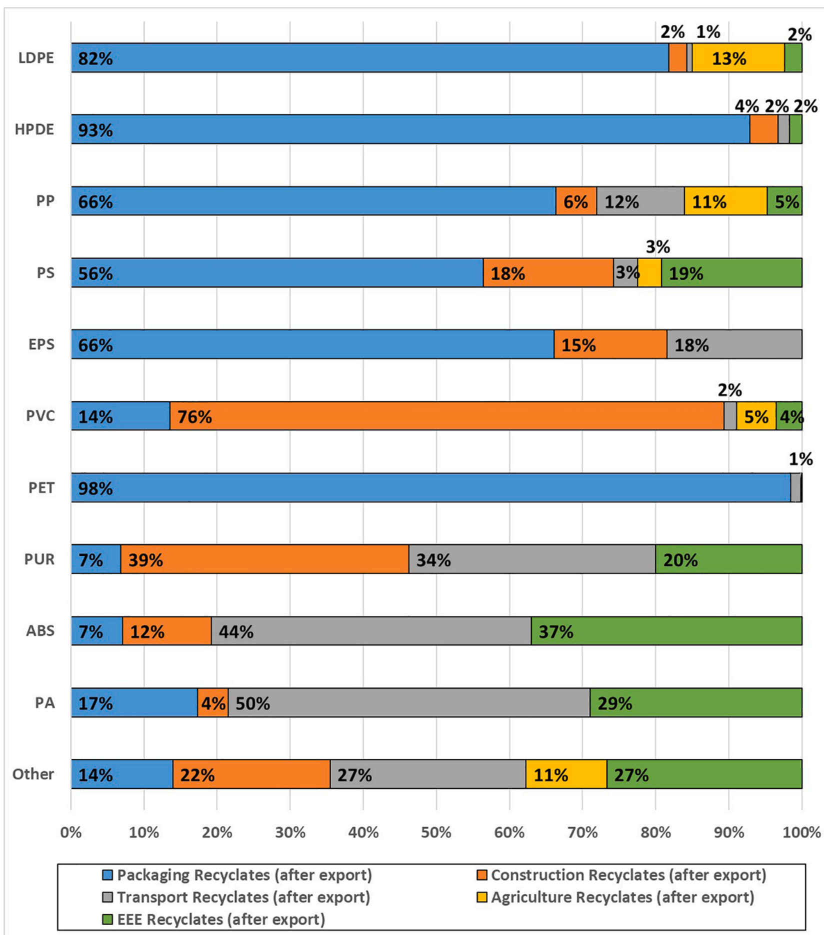

Fig. 5. Polymer-specific contribution of each sector regarding the total recyclates produced. Polymer-specific shares for each sector are expressed as [%]. *Note: EEE = Electrical and Electronic Equipment.*

chain are currently still in need of dedicated and proper explanations. A lack of direct links between comprehensive overviews at polymers-/sectors-levels was also evident, with no consistent underpinning approaches employed for deriving such estimates.

To provide support towards bridging these gaps, the present study proposes a sector-specific and polymer-specific detailed overview coupled with novel approaches. The main novelties of the analysis comprise the following aspects:

- Sector-specific information related to pre-consumer and/or end-of-life plastic flows is either missing (e.g., for sectors such as health-care and fishing) or detailed only for a limited number of country-specific studies. This study provides results for a total of 9 sectors, detailing sector-specific flows for the end-of-life management and pre-consumption steps. Most MFAs available to date do not include less explored sectors such as clothing and textiles, healthcare, and fishing. These are instead analyzed in the present study on an equal

footing compared to other sectors. Additionally, TCs estimated by means of PRODCOM data (Eurostat, 2022), could be yearly updated, enabling the assessment of time trends.
- The analysis of mismanaged waste flows and plastic losses (together with the final environmental compartment in which they are released) is frequently not integrated in plastic value chain studies. Especially for sectors such as transport and EEE, this could overshadow some relevant flows that were instead detailed in this study by employing the most up-to-date methodological approaches and data knowledge.
- The absence of consistent classifications of polymers' flows among literature studies limited their comparability and increased the complexity of understanding polymers-sectors links. The proposed top-down approach represents a potential tool to estimate polymer-specific MFAs starting with sector-specific data, along the whole value chain. Knowledge gaps and boundaries' differences could be bridged by a similar approach to ensure consistent estimates starting with literature data.

The transfer coefficients employed for deriving plastic flows were estimated from several literature references, as described in SM4. In particular, EU-based studies (such as Amadei et al., 2022; and Watkins et al., 2020), represented key sources for estimating consumption-related and end-of-life-related flows. Similarly, other works on plastic MFAs (such as Hsu et al., 2021; and Kawecki et al., 2018) represented key references for the models developed in this study. A comparison of the results of the present study with the most relevant sector-specific and polymer-specific literature sources is provided in SM12.

Beside listing the article novel aspects, this section also aims at providing an overview of the main limitations and assumptions of the present study. These aspects could represent an important added value for supporting future MFAs and EU ambitions and for reinforcing the ongoing research in the plastic flows' field towards analysis that are more and more adhering to reality.

The overall model is strongly dependent on the assumed EU plastic demand (5.33E+04 [ktonne/year]; PlasticsEurope; 2019), being the input to the sectors-specific MFAs. PlasticsEurope (2019) indicated how the Plastics Europe's Market Research Group has provided input information related to plastics production and demand, although no further insights were attainable concerning the underpinning assumptions and employed data to derive such estimate. The Plastics Europe report for the year 2019 was employed as the starting point of the analysis due (i) to the level of details provided not only at the level of plastic demand and waste generation, but also at the level of recyclates' production and fate and to (ii) enable a consistent data source for modeling several steps of the value chain (e.g., TCs related to recyclates' fate). Below are reported other relevant limitations and assumptions of the present study:

- The approach employed to estimate the consumption of semi-finished products builds on the results of the consumption statistics-based approach by Amadei et al. (2022). It introduces a series of own assumptions/expert judgment to calculate the total mass of semi-finished products sent to consumption, needed to overcome the lack of data (SM5). The employed assumption could therefore potentially lead to under/over-estimations of mass flows. Additionally, to date there are no accepted definitions of 'finished products' and 'semi-finished products' in the context of plastics, further limiting comparison with other studies.
- For all sectors included in the present study, the stock accumulation was calculated as the amount of plastics closing the balance between total consumption and the total waste generated within a sector. Results indicate that this assumption covers a gap of about 15Mt. In the case of 2019 Plastics Europe report (PlasticsEurope, 2019) this difference amounted to 18Mt (after correction for the EU27 2019). This gap was recently acknowledged by Material Economics and Agora Industry (Material Economics, 2022), suggesting how a potential explanation could lie in the underestimation of the waste generated (as high as 45%), rather than a stock effect. By considering an increase of 40% of the total waste available in the construction, transport, EEE and agriculture sectors, the total plastic recyclates generated (after export) would be around 1.5Mt higher than the base results of this report. On the other hand, an MFA built for a single year could lead to an underestimation of the stock variation, given the effect of long-lasting lifetimes of certain products (e.g., in the transport, construction and EEE sectors in particular).
- As mentioned in Section 2.2.1, TCs for the recycling steps was modelled excluding chemical recycling technologies. Current literature data is affected by a severe lack of detailed information concerning chemical recycling, especially when sector-specific TCs must be estimated (e.g., in the study by Van Eygen et al. (2017), chemical recycling-specific insights are provided although only for the "total plastic" stream). This aspect, coupled with the current level of penetration of industrial-scale chemical recycling technologies, hindered the possibility of modeling proper TCs specific to chemical recycling in the present study. However future updated plastic MFA models should consider the different recycling efficiencies of chemical recycling and mechanical recycling when estimating recycling-specific TCs.
- Regarding 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 recyclates being produced. This could be captured by other types of analysis, for instance by focusing on the quality of recyclates or their environmental impacts. This aspect could ensure a modelled MFA closer to the real plastic market, where industrial trade looks at plastic quality together with mass volumes.
- 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. (2018). This approach might lead to an overestimation of the amount of plastics landfilled in place of being eliminated.
- As previously mentioned, data availability varied significantly across sectors, with some (e.g., packaging, construction) more investigated than others (e.g., healthcare, fishing). 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. An overview of the most relevant assumptions is provided in SM13.
- Regarding polymer-specific MFAs, some limitations of the top-down approach could be highlighted. Polymer-specific TCs were adopted (Section 2.3 and SM10) to model polymer-specific end-of-life management operations, whilst all other TCs were borrowed from the sector-specific estimates. When polymer-specific TCs in a sector were not available, the sector-specific TCs were employed, introducing a potential over/underestimation of the corresponding polymer-specific flows. By contrast, when polymer-specific TCs are employed to model, 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.
- During the analysis of the available literature information, several issues were recognized concerning the available information at polymers level (e.g., the polymers data were commonly aggregated in different polymer groups with a lack of coherence among sources; a lack of an agreed common classification of polymers/polymers group and the polymer-specific flows details were provided only for few steps of the plastic value chain; etc.). These elements increased the complexity of establishing a polymer-specific coherent overview

by combining different literature sources. As a result, a prioritization of the available sources was performed considering those deemed as the most complete and reliable ones (e.g., the information retrievable from Plastics Europe reports). This approach could influence the article results, as the key assumptions are based only on a shortlisted number of selected data sources. By contrast, it should be considered that a combination of data at polymers level could nevertheless lead to other limitations, especially considering (i) the abovementioned differences in scope and definitions of polymers, and (ii) the details needed to assess certain specific MFA flows (e.g., losses and waste mismanagement).
- Regarding the assessment of the simplified scenarios for the year 2025, assumptions were needed to model each specific scenario (i.e., “Reduced waste export”, “Improved waste collection”, etc.). The economic and social effects of the COVID-19 outbreak and the war in Ukraine have been reflected in the “Combined Scenarios” by assuming variations in the total plastic production. However, it must be acknowledged that these assumptions could only suit simplified future scenarios, and that more recent data should be employed to properly capture the effects of these unprecedented world events.
- Overall, the simplified scenario assessment (Section 3.3) aims at providing insights on foreseeable future trends. 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 assumptions. These assumptions (detailed in SM8) were grounded in the foreseen targets of EU policies (e.g., EC, 2008, 2018a, EC. 2019b) and in industry associations’ pledges (such as the EU/CPA target; EC, 2018a; CPA, 2022). Therefore, these scenarios serve the purpose of discussing how hypothetical future variations in some key steps of the value chain could provide benefits/disadvantages towards EU goals for plastics.

3.5. Framing of the study in the context of EU countries

The goal of the present study is providing an overview MFA at sectors and polymers level for the whole EU27 plastic value chain. To arrive at such complete overview, EU-specific data were employed by means of a top-down approach (described in Section 2.3). The results of the present study enabled an in-depth overview of the whole value chain, comprising less-known and less-explored flows (e.g., waste mismanagement, plastic losses and recyclates’ fate) and sectors (e.g., the clothing and textiles, fishing and healthcare sectors). The results of the present study provide an overview at the level of the whole EU, whilst the assessment of specific and varying EU MS conditions were excluded from the scope of the analysis. Variations in the relevance of plastic flows between MS should be considered when contextualizing the results of the present study, especially when looking at plastic flows and transfer coefficients at the end of life. A recent study (Picuno et al., 2021) conducted on three different MS (namely: Austria, Germany and The Netherlands) highlighted how country-specific recycling rates could be greatly affected by the management systems in place in each country, and especially altered by the applied strategies on the valorisation of “mixed plastic” streams. As an example, results of the present study suggest how around 24% of the total plastic waste generated (after trade) is recycled on average across the sectors under assessment. This value is closer to the one suggested by Van Eygen et al. (2017) for Austria (28%, calculated after waste trade), whilst is higher than the ones suggested by Pivnenko et al. (2019) for Denmark (13%, calculated after waste trade) and by Sahimaa and Dahlbo (2017) for Finland (14%, calculated after waste trade). However, the granularity of data varies significantly among the available country-specific studies. For instance, the studies from Van Eygen et al. (2017) and Sahimaa and Dahlbo (2017) do not cover the fishing and textiles sectors, whilst the study from Pivnenko et al. (2019) only provide details for the packaging, construction and agriculture sectors. In addition, within country-specific studies, plastic flows are frequently aggregated (i.e., “total plastic”), providing sector-specific details only for few steps of the value chain. Such limitations, coupled with the objective of the present study of covering a wide array of sectors, polymers, and less explored plastic flows, hindered the possibility of employing country-specific data for a EU bottom-up assessment. For these reasons, a top-down approach was applied instead. It should be considered how a country-specific assessment would however enable a thorough assessment of the EU plastic value chain, ensuring a better representativeness of the modelled transfer coefficients, especially for key steps of the value chain (e.g., the recycling step, where recycling technologies vary among MS). Future research should aim at covering this gap to allow for an improved and comprehensive analysis of the plastic value chain, which could be an added value not only for clearly visualizing country-specific scenarios, but also to properly assess EU policy targets.

4. Conclusions and outlook

This study aimed at establishing a mass flow analysis model (MFA) for the whole value chain of plastics in EU27, from pellets production to end-of-life plastic management and recyclates’ production. Estimates for the 2019 and future scenarios for 2025 were analysed in the context of the EU target of 8.8Mt of recycled plastics to be used annually in the EU27 by 2025 (EC, 2018a; CPA, 2022).

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. Of the total amount of post-consumer waste being generated (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 especially from transport and EEE. Out of the total plastic waste sent to recycling, 70% derived from the packaging sector. Overall, 4.46Mt plastic recyclates were produced and consumed in the EU27 territory. On average, the EU27 end-of-life recycling rate (i.e., recyclates produced over waste generated) was equal to 19% (16.6% when trade effects are considered). Losses of plastics (micro/macroplastics) mostly occurred during the use phase (39% of the total 2.11Mt of plastic lost along the value chain). HDPE, LDPE, PP, PVC and PET drove the overall plastic consumption and cover 70% of the total demand.

Results from the scenarios assessment indicated that the EU target could be achieved if (i) a reduction in the waste exported outside of the EU is put in practice across all sectors to increase the amount of available resources for EU end-of-life plants (compared to 2019, 20% improvement for the EEE and textiles and clothing sectors, affected by high amounts of waste exports, and 10% for the remaining sectors); (ii) an improvement on waste collection is put in practice with a reduction of waste mismanagement (for the transport and EEE sectors with a 25% improvement compared to 2019) and reduction of mixed waste collection (compared to 2019, 30% improvement for the packaging sector, and 10% in the remaining sectors excluding EEE and transport); (iii) an increased amount of waste separately collected is sent to recycling plants (compared to 2019, improvement levels of 15% for the packaging sector and 10% for the remaining sectors, at the expense of separately collected waste currently incinerated) and (iv) an improvement in recycling performances is put into action (by reducing of at least 20% for the packaging sector and 10% in the remaining sectors, the recycling losses compared to 2019). The expected plastic production trend could have an important role on plastic recyclates. Despite current estimates suggesting an increasing production, the COVID-19 outbreak and the Ukraine war, coupled with EU and industries’ commitments in reducing plastic consumption, could signify an unprecedented reduction in plastic production. When a future decrease in plastic production is explored in parallel with value chain improvements, the EU target appears to still be reachable, as such scenario would lead to 9.11Mt of recyclates being consumed by 2025 in EU27. This study aims at providing a knowledge base of plastic flows in the EU, and could represent a starting point for corrective options potentially exploring and recommending actions towards future targets in the plastic value chain (for instance, labeling strategies on plastic products, design with recycling, consumers' awareness, etc.).

Despite a growing interest in addressing plastic flows, comprehensive studies detailing plastic flows of multiple sectors/polymers along the whole value chain are currently lacking, especially including estimates on losses, mismanaged waste, and recycled plastics' fate. Understanding the effects of plastic production, consumption, and plastic waste management as well as the consequences of plastic pollution are considered key actions in several ambitious EU policies. To live up to such ambitions, 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 should be explored. Up-to date estimates of both losses and mismanaged waste flows should also not be neglected. An improvement and rethinking of the value chain is mandatory and should be driven by an up-to-date knowledge of all its many hotspots. Additionally, monitoring frameworks could be proposed for evaluating the implementation of current policy efforts in the EU value chain, and more realistically assessing plastic flows in the near future. This could have a strategical role to unveil the untapped plastic recycling potential of the EU value chain.

CRediT authorship contribution statement

Andrea Martino Amadei: Investigation, Methodology, Writing – original draft, Writing – review & editing, Formal analysis, Investigation, Visualization. **Lucia Rigamonti:** Conceptualization, Methodology, Visualization, Investigation, Writing – review & editing. **Serenella Sala:** Conceptualization, Methodology, Validation, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

The underpinning data used in the study are available in the supplementary materials.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.107105.

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