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Plastic packaging flows in Europe

A hybrid input-output approach

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Abstract

The European Union (EU) set ambitious goals toward more sustainable use of plastics, but the basis for measuring performance and monitoring progress toward these goals remains inadequate due to a limited understanding of the complex systems behind plastic consumption. In this work, we study the region-wide material flows of plastics related to packaging in 2014 using a hybrid approach that combines data on the production and end-of-life management of plastic packaging with a monetary input-output model for the EU. The approach enables us to gain insight into interindustry flows and the connection between production and final demand. We map supply chains with a relatively high resolution, including polymer types, packaging forms and application categories. Results estimate the total packaging placed on the market (POM) and then discarded amounted to 18,000 kt., excluding a net increase in stocks of 500 kt. This means that waste generation could have been up to 15% higher than accounted in official statistics, reinforcing potential underreporting accounts as well as remaining data gaps. Thirty-five percent of postconsumer packaging waste was directed toward recycling. However, only 5% contributed to new domestic packaging production, a reflection of the broad challenges to plastic circularity. Although first steps are taken in this work, we point to an acute lack of information on industrial streams, compounded by missing policy focus, for example, on transport packaging. We suggest areas for deeper investigation and emphasize the potential of hybrid approaches to establishing baselines and assessment of both production and consumption-side mitigation strategies.

KEYWORDS
circular economy, EU-28, hybrid input-output, industrial ecology, material flows, plastic packaging

1 | INTRODUCTION

The environmental, economic, and potential health costs to society brought by the current linear plastics economy have gained substantial global attention (Jambeck et al., 2015; Smith et al., 2018; The Ellen MacArthur Foundation, 2017; Zheng & Suh, 2019). The significant advantages of plastics over other materials in many societal applications are counterbalanced by their persistent negative impacts on the environment due to improper end-of-life management (Molina-Besch et al., 2019; Villarrubia-Gómez et al., 2018). Globally, packaging is the main plastic application and is characterized by short lifetimes, low value, and high technical complexity inhibiting recycling. In Europe, packaging accounts for 40% of plastic demand and

constitutes 60% of the total generated plastic waste (Geyer et al., 2017; PlasticsEurope, 2018). To curb their negative impact, the European Commission (EC) has elevated plastics to a priority material in its first Action Plan for the Circular Economy (European Commission, 2015), followed by a comprehensive Strategy for Plastics in a Circular Economy (European Commission, 2018). The Strategy aims to promote recycling and influence the design of products to be fully and easily recyclable by 2030 and facilitate the creation and functioning of a robust market for secondary plastics in Europe.

To measure the effects of planned strategic actions and targets, the baseline region-wide production, consumption, and waste management chains of plastics should be certain and well documented. Regarding packaging, EU member states report the amounts placed on the market (POM) in a year to Eurostat, including imports and excluding exports, which are then considered equal to packaging waste generation. Member states also report recycling and recovery rates for packaging waste. This system has been shown inconsistent and prone to abuse, leading the EC to tighten reporting rules over time, the latest taking effect in 2020 (European Commission, 2020). Previous reporting indicates a gap between packaging production and waste generation every year, accounting for around 3000 kt or 15% of estimated EU consumption (Eurostat, n.d.; PlasticsEurope, 2015, 2018). Considering the relatively stable yearly growth of packaging at around 2%, this gap cannot be explained by stock differences in longer lived or reusable packaging. On the contrary, a study commissioned by the EC confirmed reporting issues, suggesting the gap may be explained by significant underestimation of POM (Hogg et al., 2017).

Material flow analysis (MFA) including dynamic MFA (stock and flow accounting over time) has been used to estimate consumption and disposal of plastics, mostly in country-wide assessments. Economy-wide studies of production, use, and waste generation include the early dynamic analysis of plastic flows in Germany by Patel et al. (1998), Spain (Sevigné-Itoiz et al., 2015), and static analyses in Austria by Van Eygen et al. (2017) and Switzerland by Kawecki et al. (2018). Higher resolution, polymer-specific MFA models addressed the end-of-life management of plastic packaging in Austria (Van Eygen et al., 2018), the Netherlands (Brouwer et al., 2018, 2019), and Germany (Picuno et al., 2021). Regional European studies include the dynamic stock and flow analysis of PVC in Europe between 1960 and 2012 (Ciacci et al., 2017) and a detailed static, steady-state analysis for seven polymers and their major applications in Europe by means of probabilistic MFA (Kawecki et al., 2018). Also of note are MFA type analyses produced by consultancies, for example, analysis for Germany (Conversio, 2018), EU 28+2 (Conversio, 2019), and the EU-28 packaging waste analysis by Deloitte (2017).

These studies provide valuable understanding of regional material flows of plastics, but their resolution, and geographical, temporal coverage remains very limited. Moreover, MFA does not capture interindustry flows or links to final demand (e.g., households). Representation of applications (sectors) is generally limited, and pinpointing where products containing plastics or packaging are finally consumed in the economy is generally not possible. The fundamental attraction of combining MFA and economic input-output (IO) models stands precisely in the combined ability to capture the interdependence of all parts of the economy while also revealing the underlying physical relationships (Duchin, 2009). Foundations for combining IO with life cycle assessment (LCA) and MFA were laid with the works of Leontief (1970) and Duchin (1990). Input-output tables (IOTs) and supply-use tables (SUTs) capture essential stages that MFA endeavors to describe from the production of materials to the manufacture of products and their final demand. However, the main challenges in the use of monetary IO tables is their resolution, and the fact that they capture only commodity flows while ignoring scrap, waste, and losses that do not have economic value.

To tackle the latter, Nakamura and Kondo (2002) developed the waste input-output (WIO) model that connects in an IO framework monetary flows of products and services with associated physical waste flows and their management. Later, this framework was shown to be equivalent in SUT formulation, in the so-called waste SUT approach (Lenzen & Reynolds, 2014). Nevertheless, WIO does not capture a full mass balance because the physical waste flows interact with interindustry flows which are in monetary units. IO-MFA and in particular the WIO-MFA approach (Nakamura et al., 2007) was developed to address this. It combines physical yield coefficients with the monetary coefficients in input-output tables, to express inter-industrial physical flows. WIO-MFA models have been used to trace the destination of different materials throughout supply chains, as well as to determine material flows induced by specific final demand (Nakamura et al., 2011). However, the approach has been generally limited to countries that have rather sector-detailed IO tables such as Japan and the US. Furthermore, detailed sectoral insight using production statistics and literature was in many cases necessary. Examples include the study of supply chains of metals and alloys in Japan (Nakajima et al., 2013) and the United States (Chen et al., 2016; Ohno et al., 2016). Plastics in particular have been addressed, such as the detailed flow analysis of PVC in Japan (Nakamura et al., 2009), Bisphenol A and polycarbonate flows in China (Jiang et al., 2017), and most recently, plastic products and packaging in Japan (Nakatani et al., 2020). Even earlier studies, which constituted IO-MFA stepping stones, include Duchin and Lange (1998) that used industry trade data to build a physical plastics extension to the IO monetary table for the United States and Joosten et al. (1999, 2000) that developed a SUT framework model to study plastics in the Dutch economy.

To address the lack of resolution of IO tables, various hybrid approaches were developed to model physical layers in an IO framework, such as the input-output analysis with mixed units (MUIO) (Hawkins et al., 2007) and other types of models that combine process knowledge with IO analysis, such as hybrid approaches to LCA (Sangwon Suh, 2004; Sangwon Suh & Huppes, 2005). The general approach in these models is to divide the economy into two sections, of which one represents the (detailed, physical) industrial activities that are directly related to the products or materials studied, and the other represents the rest of the (monetary) economy (Pauliuk et al., 2015). These sections are called foreground and background systems. A notable reference here is the hybrid model presented by Nakamura et al. (2008), which combined an elaborate description of production for a number of metals, with a monetary background and physical waste management.

In this work, we study the material flows of plastics related to packaging in EU-28 with the objective of gaining insight into interindustry flows and wider to look at the complete process chain efficiency in relation to circular economy. We use a model approach that enables a complete representation of (physical) plastics packaging flows and their connection to monetary demand for products and services in the EU economy for the first time, drawing on the WIO-MFA and hybrid IO approaches. We account losses and waste generation at different points in the lifecycle, multiple waste management steps, and estimate net litter loss to the environment based on the recent work of Kawecki and Nowack (2019). We further address the specific challenge of creating a detailed representation of physical flows, that is, distinguishing different polymers and forms of packaging, when underlaying monetary tables do not support such detail. Using this framework, we estimate the EU plastic packaging chain efficiency, reveal the intensity of packaging use and waste generation by industry, and exemplify the capability of tracing material flows induced by specific units of final demand for monetary products.

2 | METHODS

Before proceeding, a few definitions are necessary:

- Polymers refer to plastics in primary forms before conversion (i.e., manufacture) processes;
- Packaging types are packaging forms after conversion (e.g., films, sacks and bags, bottles);
- Packaging categories represent main applications or categories of products that use similar combinations of packaging types (e.g., food, beverages, transport). We refer to all categories without transport packaging, as sales packaging, also called primary packaging. Secondary packaging, that is, additional packaging used for protection and collation of multiple products, is assumed to be part of primary sales packaging. Transport packaging represents tertiary, also called transit packaging.

In Table 1 we list and describe sets and tables used in the study.

2.1 | Overall approach

The plastic material flows associated with packaging in EU-28 are studied with a modeling framework that has at the core the WIO-MFA approach (Nakamura et al., 2007), extended with a physical representation of upstream production steps based on the MUIO approach (Hawkins et al., 2007) and downstream representation of waste management as WSUT (Lenzen & Reynolds, 2014). Thus, we deal with the aggregated representation of plastics in EU monetary IO tables, by dividing the economy in the model into three sections: (1) one that represents industrial activities directly related to the production of packaging, (2) one representing the rest of the economy, and (3) one that represents the end-of-life stages of packaging. We refer to these sections as: the foreground upstream (1) and downstream (3), and the background system (2). The background system is described in monetary units (Meuro—million euro), and the foreground in physical units (kt). The monetary flows in the background system are used to describe the consumption of packaging in the economy as well as to derive the generation of packaging waste after use. Upstream production is connected to downstream waste management, as the foreground upstream uses inputs (recovered plastics) and treatment service from the downstream. In the complete framework, foreground upstream flows are subtracted from the background as described in Hawkins et al. (2007).

The study aims to capture all important material flows pertaining to packaging in a static representation (with stock) for the year 2014 (Figure 1a). An overall SUT framework allows for explicit representation of all flows (Figure 1b). In this framework, industries producing waste are recorded as using waste treatment service (reflected with the amount of waste generated) and waste management industries are recorded as supplying treatment service (amount of waste treated). Physical flows can be calculated by using both the SUT and IOT representation of the monetary background. The full framework can be arranged similarly to form square coefficient matrices in either SUT or IOT formulation by using the industry technology assumption (Lenzen & Rueda-Cantuche, 2012; Majeau-Bettez et al., 2014).

For the background system, we use the multiregional SUTs (MR-SUTs) of EXIOBASE V3 (current price) for the year 2014 (Stadler et al., 2018). The MR-SUTs were aggregated to a two-region version representing EU-28 and rest of the world (RoW). However, our model is EU-centric, or single-region, as we do not extend the physical system into the RoW. Trade is fully represented and follows the domestic technology assumption, that is, the packaging intensity of imported products is the same as for domestic products. The foreground systems (f, c, pw, and sw sections of Figure 1b) are described with data from different available sources, statistics, reports, and other literature, as elaborated in Section 1, Supporting Information S1. The resolution of foreground flows is given by the eight polymer types included (plm). This means that the full framework can be shown as a layer for each polymer. However, the representation of exchanges between the foreground and the background, that is, packaging use and waste generation, was represented with additional resolution, including five packaging types (pts) and eight packaging categories (pct).

TABLE 1 Description of sets and tables

Description of sets for the model framework		
Symbol	**Description**	**Components**
f	Foreground upstream	Products/industries: primary polymer, secondary preconsumer recycling, secondary postconsumer recycling, conversion to packaging, conversion other, packaging market
b	Background products and industries	EXIOBASE 3 (200 products and 163 industries)
c	Foreground downstream waste generation/collection	Waste types: packing-, retail- and postconsumer waste; Waste industries: collection separate, collection mixed waste
pw	Foreground downstream primary treatment	Waste types: waste for sorting, waste for energy (WtE), and -for landfill; Waste industries: sorting, WtE and landfilling
sw	Foreground downstream secondary treatment	Waste types: conversion waste, sorted plastics, sorting rejects, residuals from preconsumer recycling, residuals from postconsumer recycling, and WtE residue; Waste industries: WtE, landfilling and inert landfilling
w	Denotes the combined c, pw and sw	All components of c, pw, and sw
plm	Types of polymers	PE-LD, PE-HD, PP, PS, PS-E, PVC, PET, Other
pts	Types/forms of packaging	Films, sacks and bags, bottles PET, bottles other, other rigid
pct	Packaging categories	Food, Beverage, Personal and household care, Textiles, Electronics, Other manufactured, Retail, Transport
Description of the tables in the model framework		
Name	**Description**	
S_f, U_{ff}	Supply matrix for physical products and Use matrix of physical products within the upstream foreground	
S_b, U_{bb}	Supply and Use matrices for monetary products and services (background)	
U_{fb}, U_{fc}, U_{fpw}, U_{fsw}	Use of foreground physical products in the background industries, upstream and downstream foreground industries	
U_{bf}, U_{bc}, U_{bpw}, U_{bsw}	Use of background products in the upstream and downstream foreground industries (background to foreground coupling)	
S_c, S_{pw}, S_{sw}	Supply of waste management, that is, collection, primary treatment and secondary treatment	
S_{swf}, U_{swf}	Supply of waste treatment and Use (demand) of treatment by upstream foreground industries (specifically includes recycling and resulting waste)	
U_{cf}, U_{cb}, U_{cc}, U_{cpw}, U_{csw}	Use (or demand) of waste collection by background and downstream waste management industries. These matrices contain essentially waste types generated in the different industries.	
U_{pwc}, U_{swpw}, U_{swsw}	Use (or demand) of waste treatment after collection by downstream waste management industries	
F_f, F_b, F_c, F_{pw}, F_{sw}	Final demand matrices	
B, D	Denote use coefficient matrices for **U** and market share matrices for **S**	
Z, A	Denote the square transaction matrix (product-by-product) and its coefficient form	
P	Multidimensional array of product packaging intensity (plm-pts-pct-b)	
m	Import vector	
y, e	Final demand vector and export vector	
σ	Net addition to stocks	
ε	Loss to environment, representing a calculated amount of packaging which is generated but not captured by the waste management systems	
q, g	Vector of total product output and total industry output	
x	Vector of total domestic output	

The core model calculations that describe interindustry flows and packaging waste generation are similar to those in other WIO-MFA studies. Particular to this work is that the packaging intensity associated with background products (which in WIO-MFA is embodied by the **C** matrix of materials content), was derived by a process of allocation of total converted packaging to background products by using knowledge sources describing packaging content and packaging practices. The steps and data used to estimate packaging intensity is presented in Section 2, Supporting Information S1. In short, packaging intensity was constructed by (1) disaggregating the total physical flow of converted packaging into packaging categories and types, and (2) distribution of packaging categories by background products through bottom-up allocation, using 2014 production statistics and data sources describing product packaging intensity.

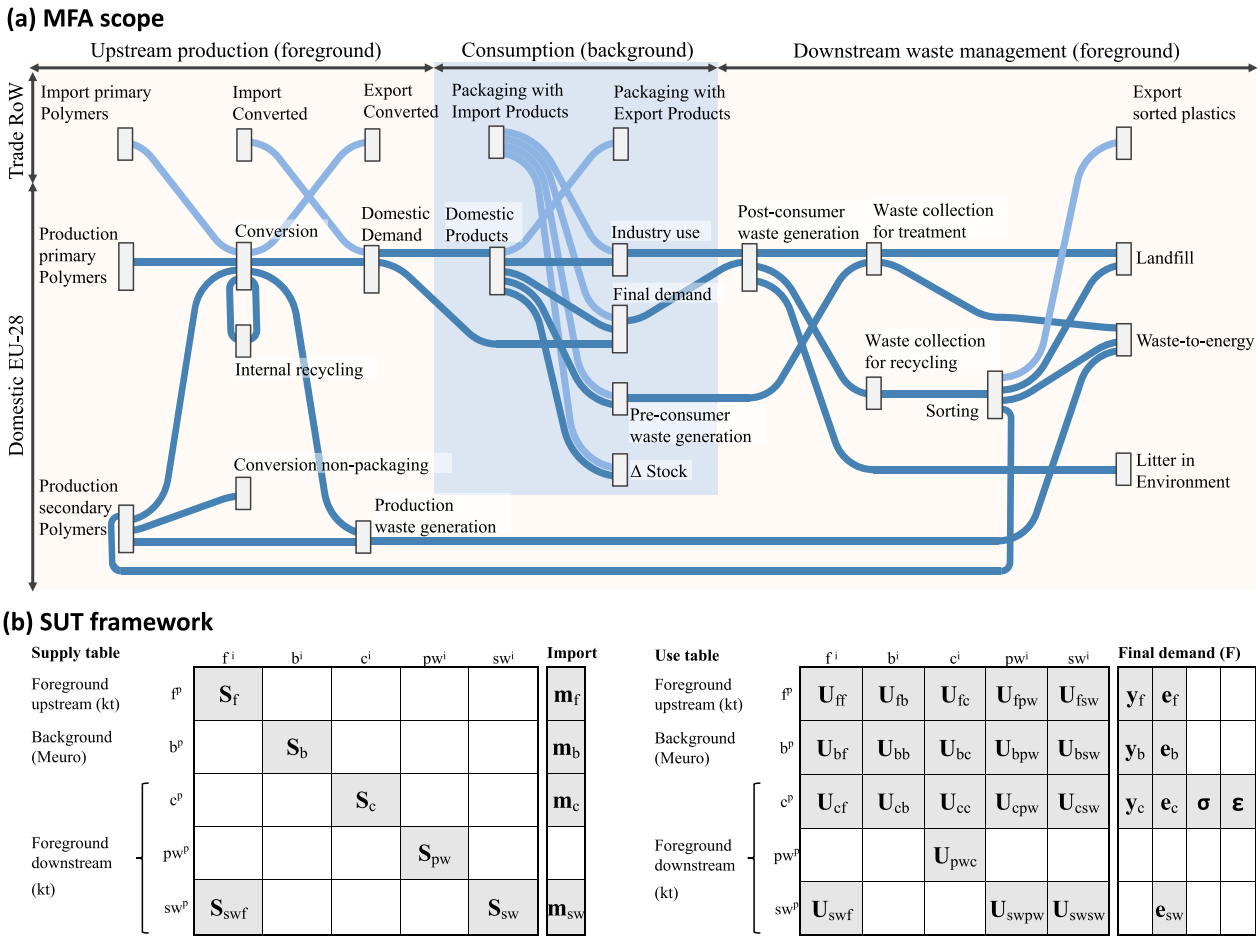

FIGURE 1 (a) The material flows included in the MFA scope, with the light blue rectangle highlighting flows determined with monetary flow data, (b) The SUT framework used in compiling the hybrid model. Superscripts p and i denote products and industries, respectively

2.2 | Interindustry physical flows and waste generation

2.2.1 | Packaging in supply chains

The approach used in the WIO-MFA model (Nakamura et al., 2007) is that physical input to an industry is partly incorporated in its supplied products and partly lost/discarded as production waste (computed with yield coefficients). A modified approach is needed when studying packaging due to its specific behavior within supply chains. Converted packaging constitutes input to certain production and service sectors, and then (typically) becomes attached to product output (e.g., by product packing). However, packaging associated with products does not become a physical component when the product is consumed, and therefore the yearly amount of packaging inflow (attached to consumed products) to sectors can be considered equal to generated waste. This behavior constitutes the base for the calculation of interindustry flows and postconsumer waste generation. However, the above is not uniform as packaging may be discarded in part or fully before the final consumer or depending on characteristics of destination sectors and types of packaging applications. Below we list these exceptions and their implementation:

- Goods transferred between production sectors use primarily transport packaging as they are generally consumed in bulk, compared to goods consumed by service sectors and households. This was implemented by limiting waste in production sectors to transport packaging.
- Transport packaging associated with products consumed by households is discarded at the point of retail. This was implemented by transferring such packaging to the retail sector.
- Direct consumption of packaging by households is implemented, limited to sacks and bags representing packaging used to carry products from retail to households (e.g., plastic carrier bags, thin bags for loose products) and waste bags.

We account waste arising at different points in the packaging lifecycle, namely: (1) production waste (recycling residues/rejects and conversion waste), (2) preconsumer waste (packing and transport/wholesale-retail waste), and (3) postconsumer waste (industry and final demand). In the case of preconsumer waste (managed in the EU), packing waste was accounted for domestic products but not for imported ones, and retail waste was accounted for both domestic and imported products, but not for exported products. Furthermore, the model enables accounting of net additions to stock that reflect (1) an average lifetime of 10 years for rigid transport packaging, and (2) that part of products/goods produced will not be sold and/or consumed in the same year, which leads to a discrepancy between production and waste generation of sales packaging. The determination of stock rates is detailed in Section 1.3, Supporting Information S1.

2.2.2 | Deriving main physical flows

Below we present the equations used to derive the core packaging consumption and waste generation. All equations are applied per polymer layer, with additional dimensions being used in some cases as described below (noted by superscripts). The equations can be implemented both in an IOT and SUT framework. For brevity, we present the equations for the IOT framework, while the equivalent SUT equations are given in Section 3, Supporting Information S1.

With **P** the packaging intensity associated with background products, the superscript "sales" and "trans" denote selection of the sales or transport packaging categories. γ^{pack} and γ^{retail} denote vectors of packing and retail loss rates per product, with elements taking values between 0 and 1. γ^{env} denotes a vector of litter loss to environment applied to certain packaging forms. φ is a scalar representing a rate for net addition to stocks. $\mathbf{A}_{\text{bb}}$ denotes the monetary input coefficients matrix and $\mathbf{x}_{\text{b}}$ denotes domestic monetary output. Further, we use the superscript ^{T} to denote transposition, *expresses the Hadamard product, and the notation "diag" before a vector refers to the diagonalized matrix. In the equations following, to calculate flows associated with imported products, $\mathbf{x}_{\text{b}}$ is replaced by $\mathbf{m}_{\text{b}}$, while $\mathbf{A}_{\text{bb}}$ domestic is replaced by its import counterpart. The waste streams are noted with Γ and calculated sequentially as follows:

$$\Gamma_{\text{b}}^{\text{pack}} = \mathbf{P}_{\text{b}}^{\text{sales}}\text{diag}\left(\mathbf{x}_{\text{b}} * \gamma_{\text{b}}^{\text{pack}}\right) \tag{1}$$

$$\Gamma_{\text{b}}^{\text{retail}} = \mathbf{P}_{\text{b}}^{\text{sales}}\text{diag}\left(\left(\mathbf{x}_{\text{b}} - \mathbf{x}_{\text{b}} * \gamma_{\text{b}}^{\text{pack}}\right) * \gamma_{\text{b}}^{\text{retail}}\right) \tag{2}$$

$$\sigma = \mathbf{P}_{\text{b}}\text{diag}\left(\left(\mathbf{x}_{\text{b}} - \mathbf{x}_{\text{b}} * \gamma_{\text{b}}^{\text{pack}} - \left(\mathbf{x}_{\text{b}} - \mathbf{x}_{\text{b}} * \gamma_{\text{b}}^{\text{pack}}\right) * \gamma_{\text{b}}^{\text{retail}}\right) * \varphi\right) \tag{3}$$

Below we refer to the $\mathbf{x}_{\text{b}}$ shares representing packing waste in (1) retail waste (2) and stock (3) with $\mathbf{x}_{\text{b}}^{\text{pack}}$, $\mathbf{x}_{\text{b}}^{\text{retail}}$, and $\mathbf{x}_{\text{b}}^{\text{stock}}$ respectively (e.g., $\mathbf{x}_{\text{b}}^{\text{pack}} = \mathbf{x}_{\text{b}} * \gamma_{\text{b}}^{\text{pack}}$).

At this point, after subtraction of preconsumer waste and accounting of stock, the amounts of packaging in interindustry flows according to the WIO-MFA approach would be represented by the multiplication product: $\text{diag}(\mathbf{P}_{\text{b}})\mathbf{A}_{\text{bb}}\text{diag}(\mathbf{x}_{\text{b}} - \mathbf{x}_{\text{b}}^{\text{pack}} - \mathbf{x}_{\text{b}}^{\text{retail}} - \mathbf{x}_{\text{b}}^{\text{stock}})$. However, because packaging waste associated with input to sectors depends on the type of sector and type of packaging (i.e., sales or transport), as described in Section 2.2.1, we use transfer matrices **G**, similar to (Nakatani et al., 2020). Thus, postconsumer waste generation is calculated as follows:

Waste generated in industry sectors (b) and final demand (F):

$$\Gamma_{\text{bb}}^{\text{sales/trans}} = \mathbf{P}_{\text{b}}^{\text{sales/trans}}\text{diag}(\mathbf{x}_{\text{b}} - \mathbf{x}_{\text{b}}^{\text{pack}} - \mathbf{x}_{\text{b}}^{\text{retail}} - \mathbf{x}_{\text{b}}^{\text{stock}})\mathbf{G}_{\text{bb}}^{\text{sales/trans}} \tag{4}$$

$$\Gamma_{\text{bF}}^{\text{sales/trans}} = \mathbf{P}_{\text{b}}^{\text{sales/trans}}\text{diag}(\mathbf{x}_{\text{b}} - \mathbf{x}_{\text{b}}^{\text{pack}} - \mathbf{x}_{\text{b}}^{\text{retail}} - \mathbf{x}_{\text{b}}^{\text{stock}})\mathbf{G}_{\text{bF}}^{\text{sales/trans}} \tag{5}$$

The transfer matrices are presented below. Θ denotes a filter matrix (binary) for the selection of final consumption sectors in $\mathbf{A}_{\text{bb}}$. Production sectors are given the value 0 (the first 125 products in the 200 EXIOBASE products) and the rest 1. **R** denotes the filter matrix (binary) selecting the retail sector. **R** is used to transfer the transport packaging from households back to the retail sector in Equation (8). $\mathbf{y}_{\text{b}}$ denotes final domestic demand (mainly households) excluding exports, while $\mathbf{F}_{\text{b}}$ is the matrix of final demand with exports explicit. **I** is a matrix of ones and **i** is a summation vector of ones of appropriate dimensions.

Transfer matrices for sales packaging:

$$\mathbf{G}_{\text{bb}}^{\text{sales}} = \left((\mathbf{A}_{\text{bb}}\text{diag}\,(\mathbf{x}_{\text{b}}) * \theta_{\text{bb}})^{\text{T}}\text{diag}(\mathbf{x}_{\text{b}} - (\mathbf{A}_{\text{bb}}\text{diag}\,(\mathbf{x}_{\text{b}}) * (\mathbf{I} - \theta_{\text{bb}}))\,\mathbf{i}_{\text{b}})^{-1}\right)^{\text{T}} \tag{6}$$

$$\mathbf{G}_{\text{bF}}^{\text{sales}} = \left(\mathbf{F}_{\text{b}}^{\text{T}}\text{diag}(\mathbf{x}_{\text{b}} - (\mathbf{A}_{\text{bb}}\text{diag}\,(\mathbf{x}_{\text{b}}) * (\mathbf{I} - \theta_{\text{bb}}))\,\mathbf{i}_{\text{b}})^{-1}\right)^{\text{T}} \tag{7}$$

Transfer matrices for transport packaging:

$$\mathbf{G}_{\mathrm{bb}}^{\mathrm{trans}} = \left(\left(\mathbf{A}_{\mathrm{bb}} \mathrm{diag}\left(\mathbf{x}_{\mathrm{b}}\right)\right)^{\mathrm{T}} \mathrm{diag}(\mathbf{x}_{\mathrm{b}})^{-1} \right)^{\mathrm{T}} + \mathrm{diag}\left(\mathbf{y}_{\mathrm{b}} * (\mathbf{x}_{\mathrm{b}})^{-1} \right) \mathbf{R}_{\mathrm{bb}} \tag{8}$$

$$\mathbf{G}_{\mathrm{bF}}^{\mathrm{trans}} = \mathbf{e}_{\mathrm{b}} * (\mathbf{x}_{\mathrm{b}})^{-1} \tag{9}$$

In (9), as households do not generate transport packaging waste, this is only associated with exports ($\mathbf{e}_{\mathrm{b}}$). Finally, packaging waste lost in the environment due to littering upon use of sales packaging, is calculated as a fraction of postconsumer waste, where the superscript $^{\mathrm{sales.pts}}$ denotes the selection of the packaging types dimension (pts) associated to sales packaging:

$$\varepsilon = \gamma^{\mathrm{env}} * \Gamma_{\mathrm{bb}}^{\mathrm{sales.pts}} + \gamma^{\mathrm{env}} * \Gamma_{\mathrm{bF}}^{\mathrm{sales.pts}} \tag{10}$$

2.3 | Analysis

The compiled model enables a representation of packaging material flows for EU-28 in the reference year 2014. Packaging flows are then extracted and illustrated in Sankey diagrams, including interindustry flows and flows to final demand sectors. For illustration of interindustry flows we aggregate the 163 EXIOBASE industries to activity categories, that is, a custom version based on the International Standard Industrial Classification (ISIC) (UN, 2008). The associated concordance matrix can be found in Supporting Information S2. Further, we use the background monetary dimension to show sectoral intensity per output in the use of packaging and waste generation. Finally, we present the flows induced by demand for some specific products (Nakamura et al., 2011).

IO-MFA models have particularly high complexity and size (number of flows) posing challenges to uncertainty quantification. Results are affected by uncertainty pertaining to data sources as well as assumptions and model choices. To address this, we (1) performed a data quality evaluation using the framework put forward by Laner et al. (2016) and (2) tested the sensitivity of results to main data concerns and to important model choices. We refrained from propagating uncertainty by applying a statistical approach, which would entail rather arbitrary definitions of uncertainty ranges (Schwab & Rechberger, 2018). The sensitivity runs addressed (1) sector packaging intensity and the distribution of packaging categories, and (2) the limitation of sales packaging flows between production sectors, and the transfer of transport packaging from household consumption to retail. Details on and results from the data evaluation and sensitivity runs are found in Sections 5 and 6, Supporting Information S1.

3 | RESULTS

3.1 | EU-28 plastic packaging flows

The overall picture for plastic flows related to packaging in 2014 is illustrated in Figure 2. The amount of primary and secondary plastic input to packaging production was estimated to 19,000 kt, with a majority of 95% input of primary plastic, or 18,300 kt (PlasticsEurope, 2015). The contribution of secondary plastic varied substantially between polymers, leading with PET at 10% (of total PET converted) and PE-HD at 4% and a lower contribution at 3% for PE-LD and 2% for PP. Production waste, which includes net residuals from conversion (after internal recycling) and postconsumer recycling waste, represented a combined 670 kt. The import and export of converted packaging changed only marginally the input to domestic production of packaged goods. After including packaging attached to imported goods, POM in 2014 could be estimated at around 18,000 kt, which excluded additions to stock of 540 kt. The inflow of packaging into European industries and households was estimated to be 8300 kt and 9600 kt, respectively. Preconsumer waste generation, including packing and retail losses, was estimated at around 300 kt.

Postconsumer waste, both industry and households, accounted for a total of 17,900 kt. A net loss into the environment, not differentiating between soil and water, was estimated to 140 kt. The contribution to this loss was made up of 30 kt foils, 55 kt of sack and bags, 35 kt of various bottles, and 20 kt of other rigid packaging. Collection of waste for recycling captured 6400 kt of packaging waste accounting for around 35% of postconsumer waste. Subsequently around 80%, or 5000 kt, were recovered and sent to domestic reprocessing/recycling (60% of sorted plastics) or exported outside the EU for further processing (40%). Summing production waste, preconsumer, and postconsumer streams, we estimated that 8000 kt of plastics were treated by different thermal processes, while 5700 kt were landfilled.

Zooming into the aggregated flows between production and use (Figure 3), some overall differences were revealed, in terms of the types and categories of packaging and their destination. In terms of packaging types, a larger share of films accompanied products to industry, and this was

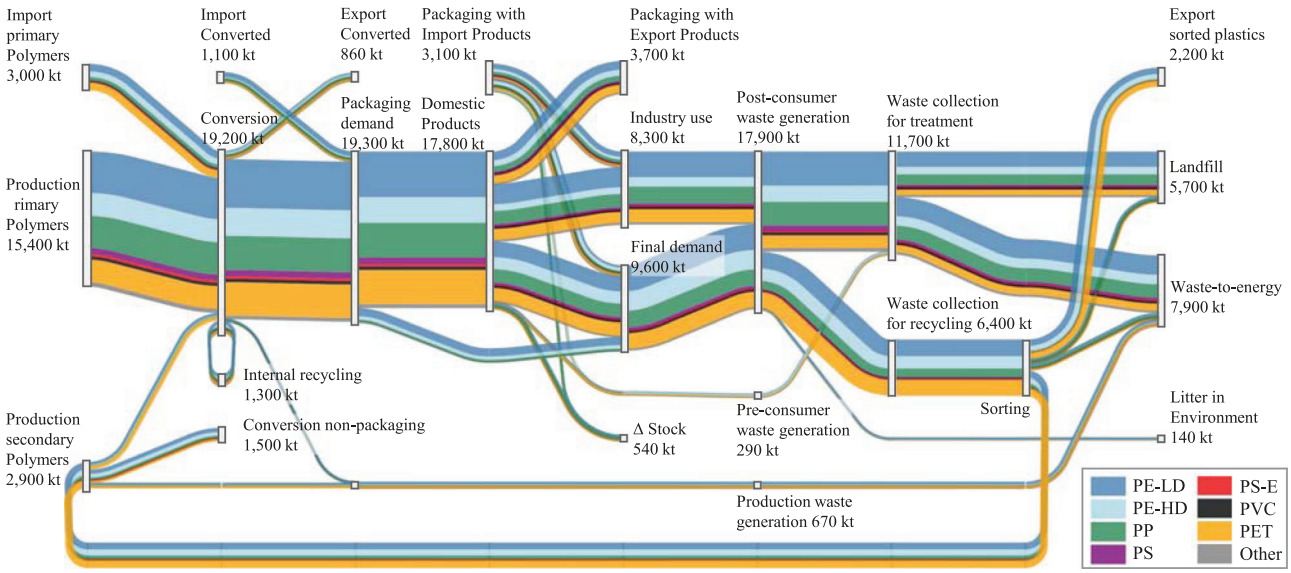

FIGURE 2 Overall picture of packaging flows in 2014 for EU-28, kt rounded two/three significant digits. Sankey diagrams were created with floWeaver (Lupton & Allwood, 2017). The underlying data for this figure can be found in Supporting Information S2

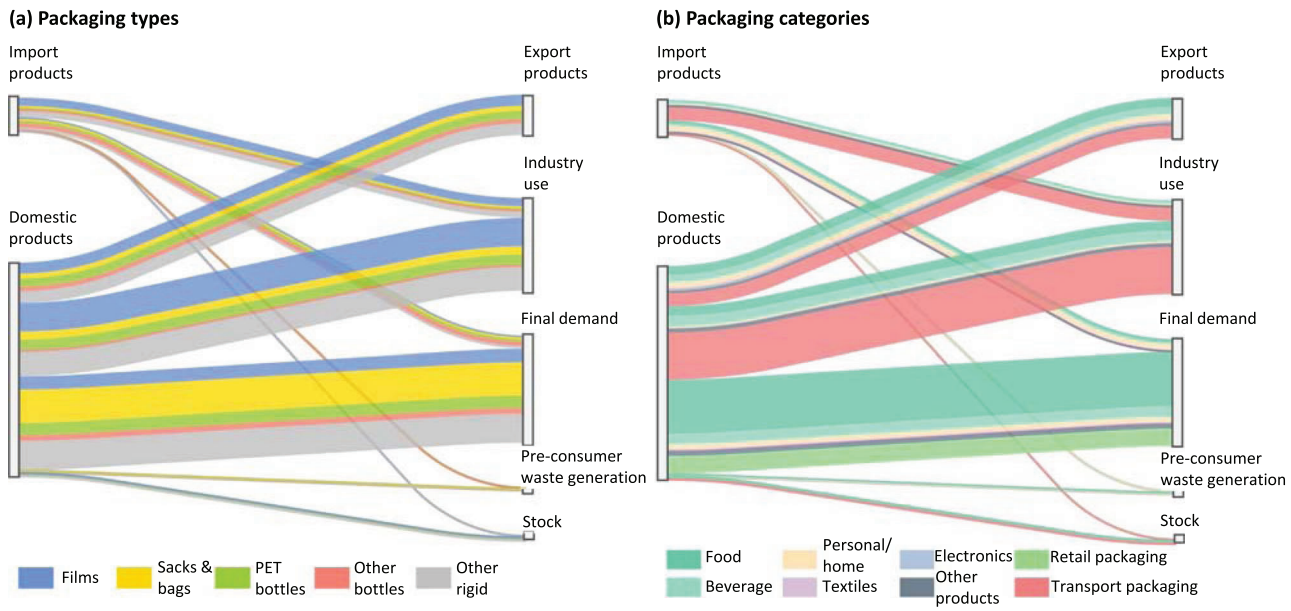

FIGURE 3 Flows of packaging types (left) and packaging categories or application archetypes (right). The underlying data for this figure can be found in Supporting Information S2

associated with transport packaging (i.e., wrapping foil), while a larger share of sack and bags were used by households. This constitutes sack and bags consumed directly by households and large quantities of flexible plastic packaging associated with food products. This difference between industry and households is important as packaging films represent large quantities of a relatively homogeneous material with better opportunities for recycling compared to flexible sales packaging that may have complex functional designs such as multiple layers of different polymers (Kaiser et al., 2017). Flexible packaging made up 47% of packaging reaching final demand. Food and beverage packaging constituted around 65% of the total packaging absorbed by final demand and only 22% of packaging absorbed by industry. Around 65% of the packaging absorbed into the industry was made up of transport packaging. Transport packaging also constituted 60% of the total net addition to stocks, in the form of PP and PE rigid packaging.

Intersectoral flows of plastic packaging in absolute values are shown in Table 2. Some of the more prominent flows were associated to goods sold by food (MF) and beverage (MB) industries to hotels and restaurants (HR) and to education and healthcare (EH) sectors. Substantial packaging amounts accompanied chemical manufacture (MC) products to wholesale/retail (WR) and to education and healthcare sectors (EH), as well as flows

TABLE 2 Industry to industry flows (18 ISIC aggregated categories) in kt

		AG	MF	MB	MT	MP	MC	MG	MM	MV	MO	SE	CO	WR	HR	TC	FR	PA	EH	H-O	E
AG	Agriculture, forestry and mining	30	114	30	1	1	6	14	2	2	1	2	29	154	65	2	9	5	38	242	120
MF	Man. of foods	16	88	2	1	0	4	1	0	0	1	3	8	489	574	10	47	33	334	4427	887
MB	Man. of beverages	4	7	2	0	0	1	0	0	0	0	3	9	35	354	9	29	19	181	989	425
MT	Man. of textiles and apparel	0	0	0	17	1	2	0	1	2	1	1	5	34	4	0	3	2	13	255	88
MP	Man. of wood, paper, and printing	8	44	13	8	245	21	20	19	18	53	15	111	166	12	4	61	14	74	74	179
MC	Man. of chemicals, plastics, and rubber	46	28	8	27	25	354	37	56	69	16	47	109	678	24	10	31	15	650	988	1024
MG	Man. of glass, ceramic, cement, and metal	10	14	5	3	9	25	168	78	65	9	12	273	53	4	3	19	10	25	28	121
MM	Man. of machinery and electronics	7	3	2	1	5	9	19	153	50	3	18	63	98	3	11	26	13	72	71	384
MV	Man. of transport equipment	1	1	0	0	1	1	3	12	54	1	1	5	74	0	3	4	8	7	23	111
MO	Man. of furniture and n.e.c.	1	1	0	1	2	1	2	2	2	5	2	11	65	3	2	7	3	18	226	81
SE	Supply of electricity, gas, water, and waste	0	0	0	0	0	0	0	1	0	0	0	1	1	1	0	1	0	2	5	4
CO	Construction	0	0	0	0	1	1	1	2	1	0	0	4	2	0	0	1	0	1	4	5
WR	Wholesale, retail, repair of motor vehicles	5	10	1	2	3	8	4	6	4	1	3	13	64	92	4	17	7	64	1926	149
HR	Hotels and restaurants	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	1	0	2	17	5
TC	Transport, storage, and communications	1	2	1	0	1	2	2	3	2	0	3	3	12	2	30	14	4	8	43	8
FR	Financial, real estate, and business	0	0	0	0	0	1	0	2	1	0	9	23	10	6	14	114	15	44	61	41
PA	Public administration and social security	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	1	2	114	2
EH	Education, health, other services	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	0	8	93	2

Addition to stock is not included in the flow values. H-O, households and other final demand; E, exports

from manufacture of glass, ceramics, cement, and metals (MG) to the construction sector (CO). Similarities can be seen between the prominent flows in the EU drawn in this work and the flows described for Japan recently by Nakatani et al. (2020).

3.2 | Intensity of industry packaging use and waste generation

The absolute and intensity (normalized to industry monetary output) of plastic packaging use and waste generation by industry group is shown in the bar graphs of Figure 4. The graph includes the final demand components that were normalized by their total monetary value. The blue bars on the left sides of the figure represent the plastic packaging used by each industry group in association with sales of product output. The orange (domestic products) and gray (imported products) bars on the right sides represent inflows of plastic packaging into each industry group with the purchase of (packaged) products, packaging that becomes waste once products are received/consumed.

In absolute terms, food sectors display the highest use of packaging at around 35% of total packaging, followed by manufacture of chemicals (including plastics) at around 15% and beverages at 10%. Waste generation was dominated by households at around 55% and was followed by significant industry waste from wholesale and retail sectors (10%), education and healthcare services (7%), hotels and restaurants (5%), and the construction sector (3%).

Packaging use intensity was highest for the beverage and food sectors with just under 12 t/Meuro and 8 t/Meuro, respectively. Waste generation intensity among sector groups was highest for wholesale/retail and hotels and restaurants, both around 1.5 t/Meuro. Waste intensity per Meuro of household consumption was similar at 1.5 t. Packaging use intensity values can be compared with the recent study from Japan where, after currency conversion, intensity of the beverage sectors appeared at 10.5 t per Meuro and food sectors at 3.5 t per Meuro (Nakatani et al., 2020). In this reference study, the second highest intensity is displayed by plastic products at 9.5 t per Meuro. Another comparison can be made with values from UNEP (2014) where an IO model was used to estimate global plastic intensity for economic sectors. Here packaging intensity for beverages appeared at around 15 t per Mdollar and food at around 5 t per Mdollar.

3.3 | Plastic packaging chain efficiency

According to packaging waste management statistics from Eurostat (n.d.), the recycling rate in 2014 stood just under 39% of the reported plastic packaging put on the market. This rate is a result of inhomogeneous calculation approaches used in the 28 member states and probably falls

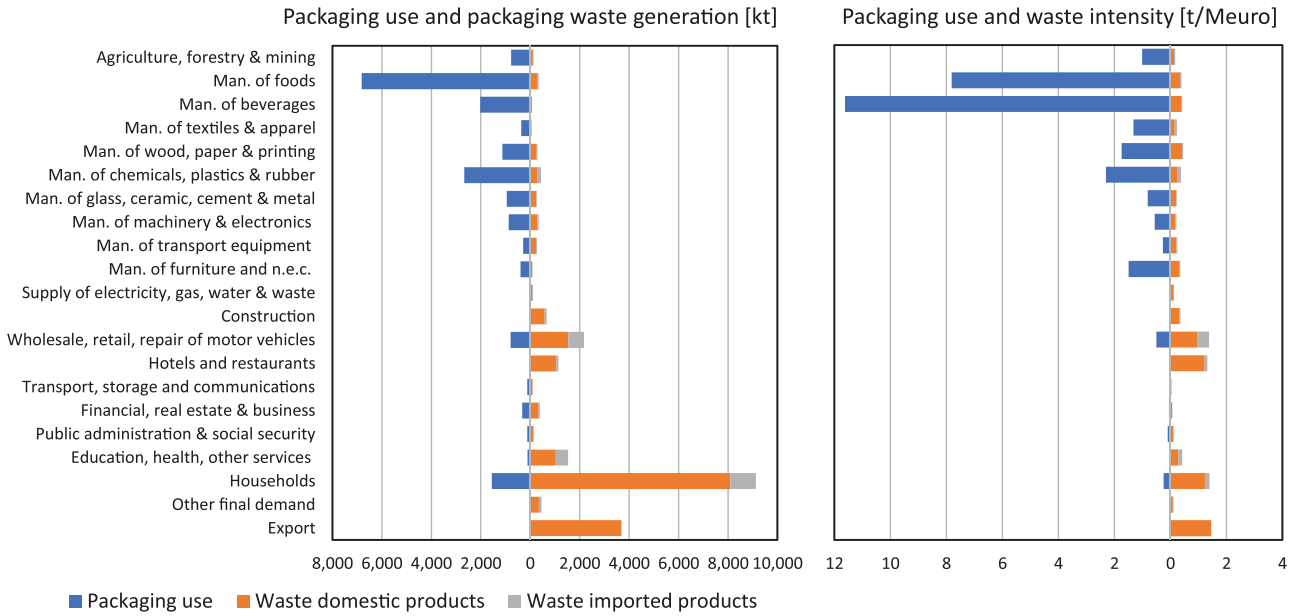

FIGURE 4 Absolute (kt) and normalized (t/Meuro) packaging use and packaging waste generation by sector. Stock occurring between consumption and waste generation is removed from the right-side bars. The underlying data for this figure can be found in Supporting Information S2

somewhere between a rate that would represent collection for recycling and a rate representing output after sorting processes (Hogg et al., 2017). Plastics Europe, the association for plastic manufacturers, anticipates that after implementation of stricter reporting requirements, the EU plastic packaging waste recycling rate will correctively be reduced by around 10% points (PlasticsEurope, 2019). The present work indicated an overall collection for recycling rate of 35% and sorting output rate of 30% when related to the estimated amount of POM packaging. Collection efficiency and subsequent management steps varied significantly by plastic type. Collection was highest for PET (56%), followed by PE-HD (43%), PE-LD (32%), PP and PS-E (27%), PS (11%), and PVC (10%).

Figure 5 illustrates the final destination of packaging waste by polymer type. Overall, only around 14% of the waste generated was converted domestically to secondary plastic (or recyclate) and 12% was exported outside the region as sorted plastics, presumably for recycling. Around 35% of recyclate (800 kt) was used to produce new packaging, with the remaining 65% (1500 kt) finding use in the construction, automotive, and other manufacturing sectors. Most of the minor polymers, such as PS, PVC, and Others, ended in waste treatment with other residual waste. From the perspective of circularity, the packaging sector was in 2014 far from closing materials loops, with secondary input constituting less than 5% of packaging production. The only plastic type with a relatively high chain efficiency was PET, where established systems already exist that preserve quality, including for food grade closed loop recycling (Geueke et al., 2018; Welle, 2011).

3.4 | Plastic flows induced by final demand

The model can be used to examine plastic flows induced by units of final demand for background products. Two examples are illustrated with Sankey diagrams in Figure 6. In the figure, domestic production includes the share supplied by imports, reflecting thus a full footprint of packaging, under the assumption that supply is fully furnished under European conditions.

The plastic flows induced by demand for beverage products consisted largely of PET polymer and PET bottles specifically. Secondary polymer input to conversion accounted for 7%. The flows also reveal that most of the plastic would be absorbed by final demand and exports, with relatively minor inflows into industry. For beverage products, the collection of postconsumer waste for recycling was well above the average of all products, at just above 50%, and sorting output at 45%. In contrast, the plastic flows induced by the demand for furniture and other n.e.c. products were substantially smaller and consisted of a majority of PE and PP polymers. Secondary polymer input to conversion accounted for less than 3%. Packaging was absorbed more equally between final demand and industry and collection for recycling captured only around 30% of postconsumer waste.

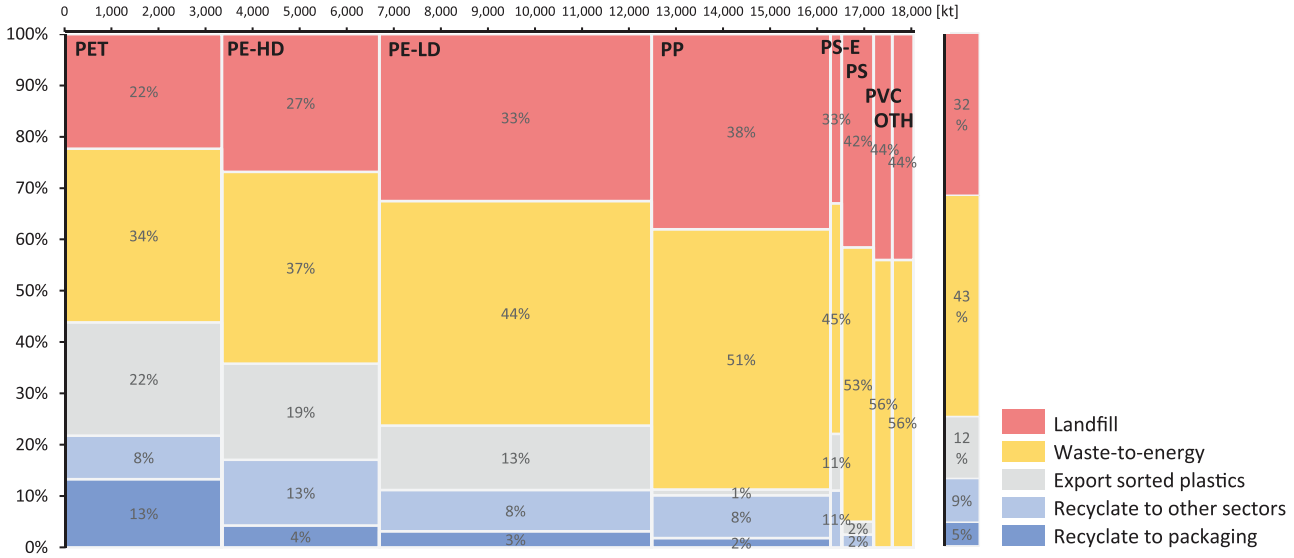

FIGURE 5 Destination per polymer type of generated pre- and postconsumer packaging waste. Loss to the environment is not included (as it represents < 1%). The underlying data for this figure can be found in Supporting Information S2

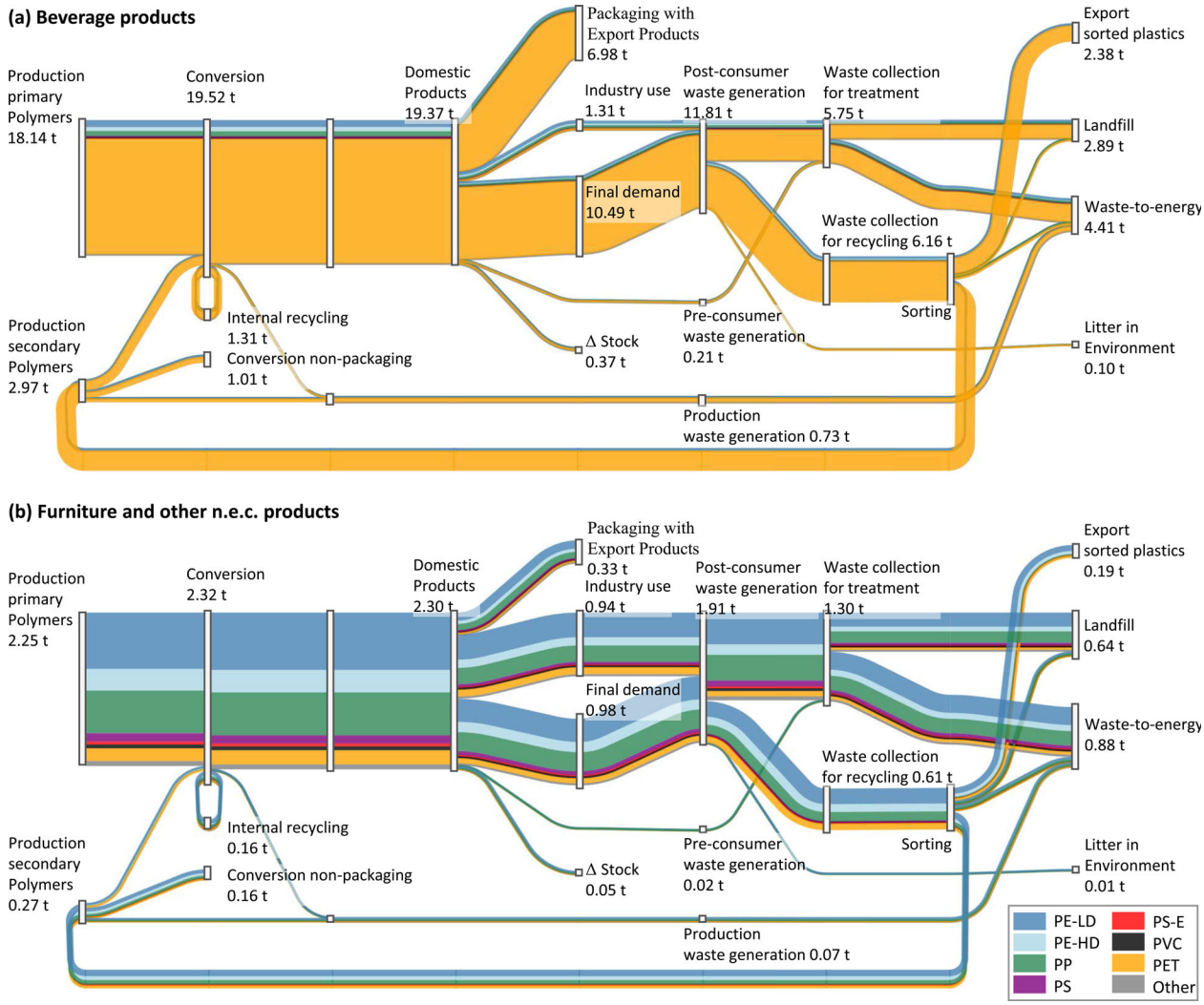

FIGURE 6 Lifecyle induced plastic flows induced by the demand for (a) 1 Meuro of beverage products and (b) furniture and other n.e.c. products. The underlying data for this figure can be found in Supporting Information S2

4 | DISCUSSION

4.1 | Robustness and limitations

This study provides a static or quasi-static (accounting for stock) representation of economy-wide plastic material flows associated with packaging in EU-28 by employing a hybrid approach that combines modeling of physical flows in IO frameworks with more traditional MFA data (Nakamura et al., 2008). At the level of material flows, our results can only be viewed in comparison with the comprehensive study by Kawecki et al. (2018) that endeavored to represent the economy-wide flows for plastic applications related to seven polymers in Europe for 2014. Kawecki et al. (2018) estimated overall packaging entering use in 2014 was around 17,500 kt, which was then equivalent to waste flows under the steady-state assumption. Equivalent packaging consumption in the present work was estimated higher at around 18,500 kt. The difference between the two studies is easily explained by accounting here for production waste recycling in the conversion industry (1000 kt), as documented by Conversio (2019), the inclusion of the plastics polymer category Other (around 500 kt), and the negative product trade balance (around −500 kt).

Our results carry uncertainty pertaining to data sources as well as parameters and model choices, which we discuss in the following.

Overall, the data describing the plastic flows in foreground upstream production and management of waste streams collected for recycling, are relatively robust at an aggregate level. The internal composition of flows, in terms of polymers, is comparably more uncertain. The data quality characterization pointed to several important areas requiring deeper investigation. These include the flows describing generation and management of production and preconsumer waste (which are described by weak data or assumptions), the mechanisms behind net additions of packaging to stocks, packaging loss to environment, and trade flows. Data sources used in the determination of packaging compositions and product packaging intensity can be characterized with relatively low reliability, induced by scarcity in empirical data, that is, generally incomplete, temporally outdated, or missing. For example, product-specific packaging intensity that evolves continuously may be based on single (outdated) data points.

Transport packaging, in particular its longer-lived (> 1 year) and/or reusable segment, is subject to especially sparse documentation on both overall flow sizes and compositions. Available sources indicate large in-use quantities of rigid transport packaging in the EU, but yearly production and waste generation data is not available. Example sources include a study addressing derogations to hazardous substances in transport packaging, which estimated a total quantity of above 4000 kt for the pool of returnable packaging in the EU in 2015 (Jenseit & Gibbs, 2015), while around 850 kt of reusable plastic packaging was reported circulating in 2015 in Spain (Gsell et al., 2019).

Another area of particular interest and active research is loss to the environment. The model output indicated 140 kt, or 0.8% of postconsumer waste generated, was lost in the environment due to littering. The packaging specific litter rates used here were based on Swiss data and could underestimate loss to the environment. Additionally, they do not account for significant illegal activities, such as dumping or open burning, which however are not documented for EU countries. Nevertheless, our estimate is comparable to other studies, such as by UN Environment (2018) that found a litter loss of 200 kt for the combined regions of Western Europe and Eastern Europe & Central Asia, and studies in preparation for the Single Use Plastics (SUP) Directive, which estimated litter due to plastic packaging items at around 140–250 kt before waste management services (ICF & Eunomia, 2018a, 2018b).

Addition to stocks of longer-lived packaging primarily, supplemented by potential differences in packaging accompanying trade and undocumented waste streams, have been pointed previously as the likely causes behind the large gap between production and waste generation data in Europe. Compared to MFAs that generally reconcile additions to stock considering differences between the production side and waste flows data, in this work, we first removed potential additions to stock to reveal the remaining waste generation. The former approach could potentially result in unreasonable additions to stocks, particularly if waste data is unreliable (e.g., due to underreporting), as it is strongly suggested for Europe (Hogg et al., 2017). Here, we determined addition to stocks based on parameters reflecting reasonable mechanisms that induce stock differences, namely the year-to-year general increase in consumption and a potential average lifetime of rigid transport packaging. Still, considering the limitations characterizing transport packaging, it is possible that additions to stock may be underestimated. However, we must emphasize that extant country-based studies either forgo stock related to packaging or document only minor contributions, for example, Austria (Van Eygen et al., 2017) and Germany (Conversio, 2018). The implication, if our estimation is valid, is that total waste generation in 2014 was 2500 kt (or 15%) greater than registered in the Eurostat packaging waste statistics.

The absolute values of interindustry and industry-final demand flows should be interpreted with some caution, as they are contingent on model choices with unavoidable uncertainties. The sensitivity runs indicated that neither the absolute size nor flow intensity of sector-specific waste generation was particularly sensitive to changes in the overall distribution of packaging categories. At the level of specific interindustry flows, there were changes consistent with the new packaging distribution, that is, proportional decrease in flows with food and beverage packaging and increase for other manufactured products. There was also an increase of 15% in transport packaging between manufacturing sectors. With the second sensitivity run, that is, interindustry flows follow strictly monetary flows, the waste generation increased substantially in some manufacturing sectors (e.g., food production) and decreased by 95% in the retail sectors. The former reflects large internal flows within manufacture (likely not accompanied by sales packaging), and the latter indicates the small own consumption of retail sectors (but not the waste generated due to sales: back-of-store waste). This is an indication that basing interindustry flows only on monetary transfers is not always sufficient to simulate packaging flows and

waste generation, because packaging may not follow always monetary flows. As such, we believe our approach, although far from perfect, reflects adequately overall scales and patterns of packaging flows.

Finally, interindustry flows determined with IO-MFA are affected by the implicit assumption of price homogeneity. However, information on price differences for the same product acquired in different sectors is very difficult or impossible to acquire. A more generic simulation of price heterogeneity is likely to reveal general low sensitivity of flow value results, based on the example in the study by Jiang et al. (2017), using random and normally distributed errors,.

4.2 | Challenges to reforming plastic packaging in Europe

Current circular economy strategies and upcoming targets in Europe make it necessary if not crucial to understand the detailed economy-wide supply and demand chains of plastics. Considerable strategic focus is put on upstream production, including creation of a functioning market for secondary plastics, exemplified by recycled content requirements, the call for voluntary industry pledges for the uptake of 10,000 kt of recycled plastics in production by 2025 (European Commission, 2018), and new essential requirements for packaging to be reusable and recyclable (Eunomia & COWI, 2020). At the level of consumption, the use of several types of packaging is expected to be curbed to limit their impact on the environment. Combined with ambitious targets for recycling (i.e., 55% by 2030), these interventions are expected to substantially change the status quo described here for 2014. However, their implementation and monitoring faces enormous challenges, many induced by the exceptional complexity of plastics systems, owing to a great variety of polymers, applications, and supply chains. Compared to other packaging materials, for example glass, metals, or paper, the primary and secondary plastics sectors show practically no level of integration. Despite policy that links them, the plastic packaging market is largely disconnected from the waste management industry, which has resulted in a lack of coordination and consistency in terms of mutual requirements. Ongoing, the development, design, and dissemination of new packaging formats, for example, multimaterial or new materials (e.g., bioplastics), is independent of, and vastly outpaces developments in recovery/recycling technologies (ICF & Eunomia, 2018b; Vanderroost et al., 2014). This disconnect places the secondary sector in mostly a reactive position, which results in the observed high material losses along supply chains, as well as the frequently unusable quality of secondary plastics.

The present work highlights once more, the limited circularity within the packaging sector. Besides overall system complexity, and compared to other plastic applications, packaging is subject to legal restrictions that can affect the use of recycled content. In fact, up to 50% of the packaging supply may be subject to restrictions, including packaging used for food, beverages, and also cosmetics and medicine. Food-contact is a key challenge, as secondary supply must come from processes scientifically assessed by the European Food Safety Authority and approved by the EC. Here, technology development and uptake cannot happen without policy support including streamlining assessment of new processes. Returnable transport packaging constitutes another area of unknown, but likely high, potential for circularity, due to its capacity to retain plastics in use for long periods of time. However, most of current policy focus has been on postconsumer sales packaging, with little attention to industrial packaging streams. For example, there are no reuse targets for transport packaging at the EU level, a strategy that could potentially transform logistic systems.

Overall, the current state of knowledge is inadequate to support the circular economy strategy for plastics. As reviewed by Wang et al. (2021), detailed economy-wide studies addressing plastics are rare, covering a handful of regions with limited resolution in terms of polymer, applications, and consumption sectors. A recurring topic in all reviewed studies was data limitations, that is, inexplicit or missing, inconsistent, or even conflicting. In order to move forward, the complexity of plastics systems needs to be unraveled by new consistent data collection, enhanced reporting, and more data transparency from stakeholders along supply chains.

4.3 | Perspectives

The hybrid IO-MFA approach used in this work enabled a first estimation of interindustry packaging flows, as well as waste generation both in industry sectors and households, at regional level. Further refinement and calibration are warranted considering the data limitations. The full potential of such hybrid approaches is though manifold. First, understanding where plastic packaging is used and discarded, and underlying demand determinants, can highlight potential leverage points to improve system efficiency. More models with high resolution, that is, flows and compositions, are necessary to capture aspects of quality and functionality in different applications. Second, in combination with environmental and social extensions, this framework could be employed to examine potential (future) effects of circularity interventions based on current strategies at the EU level. Integration of upstream production, downstream waste processes, while maintaining economic links to final use, facilitates the investigation of a full range of production, treatment, and consumption-based strategies. Hybrid IO approaches have been proposed as particularly suitable in dealing with some of the complexity in assessing circular economy interventions, particularly due to representation of physical flows and transparency in assessment of effects (Aguilar-Hernandez et al., 2018). Toward this aim, a main weakness of IO approaches is inability to reflect dynamic responses in the economy, which can however be compensated by coupling with input from macro-economic models. Third and last, considering that all EU

countries produce yearly SUTs, hybrid frameworks could be useful tools in establishing comprehensive baselines, developing mitigation strategies, and toward monitoring of different material and product systems, under a more complete mass-balanced and economy-wide perspective.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supporting information of this article.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

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