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### **Citation**

Navarre, N. H., Mogollón, J. M., Tukker, A., & Barbarossa, V. (2022). Recycled plastic packaging from the Dutch food sector pollutes Asian oceans. *Resources, Conservation And Recycling*, 185. doi:10.1016/j.resconrec.2022.106508

Version: Publisher's Version

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**Note:** To cite this publication please use the final published version (if applicable).



## Review

# Recycled plastic packaging from the Dutch food sector pollutes Asian oceans

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## ARTICLE INFO

## Keywords:

Plastic waste management  
Plastic waste trade  
Marine debris  
Plastic food packaging  
Littering  
Food consumption

## ABSTRACT

Plastic food packaging is a cost-effective tool to minimize food waste. However, plastic food packaging rapidly generates waste and if mismanaged can leak to the environment adversely affecting ecosystems. We quantified the plastic waste leaked to the marine environment due to food consumption in the Netherlands. Combining food consumption patterns, food waste estimates, and plastic packaging data, we estimated the plastic packaging intensity of the Dutch diet. We then mapped the fate of the plastic food packaging waste generated using Dutch plastic waste management patterns. We estimate that a total of 296 kt/yr of plastic food packaging is required in the Netherlands. We model that 6.5 kt/yr is leaked to the marine environment, with 75% of this leakage resulting from the exportation of plastic waste to nations in Asia, 3% from all other nations, and 22% due to littering. We conclude that despite being a high-income nation with a post-consumer plastic packaging waste network reporting a 78% recycle rate, Dutch plastic food packaging waste is leaked to the marine environment at a globally average rate, raising questions about plastic recycle rate metrics and Dutch/EU plastic waste export policies.

## 1. Introduction

Due to plastic packaging benefits, global plastic packaging demand has exceeded 147 million tonnes, and continues to increase annually (PlasticsEurope, 2020). Plastic has become a prominent choice of food packaging material due to its high strength, durability, bio-inertness, and cost effectiveness (Andrady and Neal, 2009). Proper packaging of food reduces losses across all levels of the supply chain by facilitating the handling, containment and transport of food (Wohner et al., 2019). These properties make plastic food packaging a crucial component in reducing global food loss and waste which is estimated to approximately account for 10% of anthropogenic GHG emissions and costs over 1 trillion USD annually (Springmann et al., 2018; IPCC, 2019).

Despite its beneficial properties, plastic packaging rapidly generates plastic waste and if mismanaged can be leaked to the environment causing negative consequences for ecosystems and humans. Plastics have been found to degrade marine ecosystems such as coral reefs by reducing light penetration, entangling branching corals, leaching hazardous chemicals and introducing foreign biota (Pawar et al., 2016). Further, marine animals may ingest plastic debris which inhibits

sensations of hunger leading to starvation. Animals can also be subject to plastic entanglement, which can prevent proper respiration and limit necessary body movements to migrate, catch food, or avoid predators (Dias and Lovejoy, 2012; Li et al., 2016). Plastics are also an important transport medium for toxic chemicals, increasing the concentration of other pollutants (e.g., metals and endocrine disrupting chemicals) in the marine environment by a factor of 1 million (Mato et al., 2001). As a result of these multi-level impacts on marine ecosystems, plastic leakage is likely to become a significant contributor to species population level decline and biodiversity loss (Dias and Lovejoy, 2012).

Today, it is estimated that up to 13 million tonnes of plastic enter the marine environment annually (Boucher and Friot, 2017; Ellen MacArthur Foundation, 2016; Jambeck et al., 2015; Lebreton and Andrady, 2019). Waste management systems have struggled to handle the surge in annual plastic waste volumes (Brooks et al., 2018). The limited capacity of recycling facilities and high purity requirements for reuse have prevented many nations from systematically recycling large volumes of plastic waste (Hahladakis et al., 2018). Instead, a significant portion of plastic waste goes to landfill, incineration, or is exported (Huysman et al., 2017). Exports are a common end-of-life measure in high-income

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nations which constitute 87% of the plastic waste export market. The Netherlands, in particular, plays a crucial role in the global trade plastic waste, ranking as the 3rd largest importer and 7th largest exporter (Brooks et al., 2018). In total, the country has net exported 1.28 million tonnes of plastic waste since 1988. This plastic waste is typically destined for low- and middle-income nations in Asia that have imported 75% of all plastic waste (Brooks et al., 2018). These infrastructural challenges and export patterns have led to only 9% of global plastic waste being recycled, while 80% is landfilled or leaked to the environment (Geyer et al., 2017).

Previous studies have estimated each nation’s contribution to plastic marine debris (Eunomia, 2016; Jambeck et al., 2015; Lebreton and Andrady, 2019; Ryberg et al., 2018). These estimates have used global plastic production data, national waste production statistics, and waste management system efficiencies to estimate fractions of mismanaged plastic waste that may enter the marine environment (Jambeck et al., 2015; Lebreton and Andrady, 2019). However, the models used to estimate total plastic leakage rely on coarse national scale data and do not always include complex trade patterns, limiting our ability to determine the primary national and sectoral sources of mismanaged plastic waste (Boucher and Billard, 2019). These limitations have led to debate regarding the contribution of different sources of plastic waste to ocean plastic debris.

At an estimated 40% of all packaging, single-use plastic food packaging represents the largest share of all packaging and is amongst the most frequently leaked source of plastic due to its short use phase (Ellen MacArthur Foundation, 2016; Schweitzer et al., 2018). Furthermore, plastic food packaging is extremely heterogeneous. At the food item level, plastic packaging quantities and compositions change drastically in order to minimize food waste throughout the supply chain (Majid et al., 2018). Therefore, each food item contributes uniquely to the composition and total generation of plastic packaging waste. However, to the best of our knowledge, the extent to which food items contribute to global plastic marine leakage remains unknown. The lack of resolution on this issue limits the potential for packaging innovations and plastic packaging policies, among other interventions, to effectively minimize the amounts of plastic food packaging entering the marine environment.

In this study, we quantified the global plastic waste potentially leaked to the marine environment due to a nation’s food consumption, at the food item level. In doing so, we aimed to provide a better understanding of how the food sector of a nation contributes to plastic

ocean debris on a global scale. We select the Netherlands as a representative case study of high-income nations due to its large per capita domestic use of plastic packaging and role in the global plastic waste trade (Brooks et al., 2018; Eurostat, 2021). To quantify the leaked Dutch plastic food packaging waste, we estimated the plastic packaging intensity of the Dutch diet by combining food consumption patterns, food waste estimates, and plastic packaging data. We then mapped the fate of the plastic food packaging waste generated using plastic waste management patterns, including litter and global plastic waste trade. We showed that despite efficient domestic plastic waste management, Dutch food consumption remains a significant generator of plastic ocean debris due to its plastic packaging intensity and the vast quantities of exported plastic food packaging waste.

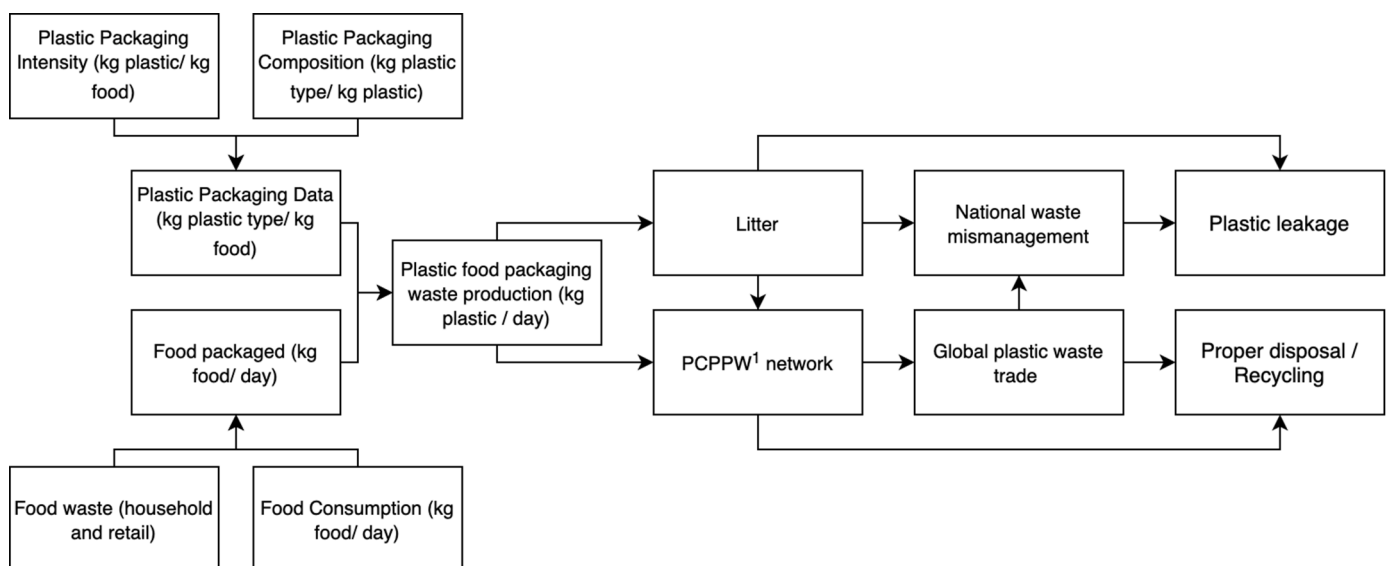
## 2. Methods

To quantify the contribution of food consumption in the Netherlands to global plastic leakage, we first developed a plastic footprint of the current Dutch diet by linking food consumption survey results to plastic packaging data (CONCITO, 2021; van Rossum et al., 2020). The plastic waste generated from food consumption was then mapped through the Dutch and global plastic waste supply chain to estimate both domestic and international plastic leakage (Fig. 1).

**Table 1**

Compilation of data sources used to determine packaging waste generation and the fraction leaked to the marine environment.

	Data Type	Sources
Packaging	Quantity	CONCITO, 2021
	Composition	Duffy et al., 2007; Bouma et al., 2003
Food	Consumption	van Rossum et al., 2020
	Household waste	van Dooren et al., 2019
	Retail waste	Eriksson et al., 2012, 2014; Vollebregt, 2020; WRAP, 2016, Cicatiello et al., 2017
Plastic Network	Recycle Rate	Brouwer et al., 2019
	Export Rate	Hestin et al., 2017
	Export	Gaulier and Zignago, 2012
	Destination	
Mismanaged Fraction	Mismanaged Rate	Jambeck et al., 2015; Lebreton et al., 2018
	Litter	Jambeck et al., 2015
	Leakage	Jambeck et al., 2015



**Fig. 1.** Schematic overview of plastic food packaging waste production and post-consumer supply chain. <sup>1</sup>Post-consumer plastic packaging waste.

The model developed relies on a multitude of data sources (Table 1), with varying degrees of uncertainty and reliability (further detailed in Sections 2.5 and 4). The use and implementation of these data sources into the model is detailed in the following sections.

### 2.1. Plastic packaging of the Dutch food diet

Average daily food consumption in the Netherlands was tabulated using the results collected by the Dutch National Food Consumption Survey conducted by the Dutch National Institute for Public Health and the Environment between 2012 and 2016 (van Rossum et al., 2020). The modeled diet consists of 117 unique food items across 19 food groups which are presented in the supplementary material (Table S1). Information regarding the distinction between the consumption of tap water and bottled water was not specified by the survey, as a result the survey data was supplemented with bottled water consumption in the Netherlands statistics provided by the European Federation of Bottled Water. Combining these two sources we determined the fraction of water reported in the survey which was likely to be bottled. Household food waste rates were applied to determine the amount of purchased food necessary to satisfy household consumption. Food waste rates were gathered from van Dooren et al. (2019), who reported data at a food group resolution based on surveys conducted in Dutch households in 2016. In certain cases, the food categories presented by van Rossum et al. (2020) combined products which were presented in different food categories under the estimates of van Dooren et al. (2019). In such cases, the food group losses were adjusted for the weighted average of the food items reported by van Rossum et al. (2020). For example, van Rossum et al. (2020) reported bread and cakes under the Bakery food group while van Dooren et al. (2019) reported bread and cakes with separate food waste rates. As a result, the Bakery food group is derived from the weighted average waste of bread and cakes. Retail food waste rates were then added to determine the amount of food which must be packaged by the retail food stores in order to meet purchase demand. Total retail food waste was assumed to be 1.7% (Vollebregt, 2020). To account for food categories which did not have reported Dutch retail waste rates, four sources combining Dutch, UK, and Swedish retail food waste along with a meta-analysis of 16 studies quantifying retail food waste were used to approximate the retail food losses in the Netherlands (Eriksson et al., 2012, 2014; WRAP, 2016; Cicatiello et al., 2017; Vollebregt, 2020; Table S2). The final food quantities after the inclusion of household and retail food waste were used as the baseline quantity of food which must be packaged in order to satisfy the consumption of the Dutch food diet in 2019.

Plastic packaging information of the food items was retrieved from CONCITO's The Big Climate Database which published plastic packaging weights for the 500 most frequently consumed food items on the Danish market (CONCITO, 2021). The 117 food items comprising the Dutch diet were mapped to the plastic packaging weights found in the CONCITO database to estimate the daily plastic packaging footprint of the Dutch diet. In cases where food items reported multiple packaging alternatives, each alternative was recorded to provide a range of packaging intensities. In the case of eggs, the database only reported paper-based packaging. As a result, a plastic-based alternative was developed assuming six 60 gram eggs were packaged in 28 gs of plastic. The database did not consistently report the plastic type used to package the food items, therefore the plastic composition of each food item was approximated using survey results conducted by The Inspectorate for Health Protection of the Netherlands and Duffy et al. (2007). The survey reported the distribution of each plastic type used to package 606 food items across 13 food categories (Bouma et al., 2003) however, fruits and vegetables were reported as a single category, eggs were not included, and soft beverages had a sample size. As a result, the similar work of Duffy et al. (2007) with a focus on Irish packaging, was used to mitigate these limitations. In their work, fruits and vegetables were disaggregated, eggs were reported, and the sample size of soft drinks was

two orders of magnitude larger than that of the Inspectorate survey. Combining these data sources, the fraction of each plastic type for each food group was estimated in order to disaggregate the total mass of plastic reported by the CONCITO database.

### 2.2. Mapping plastic packaging flows in the Netherlands

The Dutch post-consumer plastic packaging waste (PCPPW) chain developed by Brouwer et al. (2019) was used to estimate the fate of plastic waste in the Netherlands. The transfer-coefficients modeled for each plastic type were extended to the plastic food packaging fraction estimated in the current work. Their model presents four end-of-network scenarios for plastic waste: (1) stock for future recycling, (2) incineration, (3) properly sorted waste, and (4) improperly sorted waste. Improperly sorted waste refers to waste in which polymeric contamination is in excess of the standards required for recycling (e.g., excess PET in a PP recycle stream) and properly sorted when contamination is below the contamination limit (Brouwer et al., 2018). We assumed that the plastics stocked for future recycling would be recycled in the EU, while the incinerated fraction would be sent to incineration. The improperly sorted waste was considered to not be recyclable, and therefore can not be exported legally, resulting in us assuming it would be sent to incineration (European Commission, 2019; Hestin et al., 2017). The remaining pool, properly sorted plastics, was assumed to either be recycled in the EU or exported. To determine the export and recycle fractions of this pool, we derived transfer coefficients from the work of Hestin et al. (2017). Although all exported plastics are exported with the promise of being recycled, verifying this end-of-life fate is largely unfeasible (European Commission, 2018; Leal Filho et al., 2019).

In addition to the fraction of plastic packaging waste directly sent to the PCPPW network through proper disposal, we assumed that 2% of the waste produced in the Netherlands is littered before entering the network (Jambeck et al., 2015).

### 2.3. Estimating Dutch plastic waste exports

The global plastic waste trade market was modeled using the International Trade Database (BACI; version 2). This version of BACI provides disaggregated and balanced quantities of 2019 United Nations International Trade Statistics Database (COMTRADE) bilateral trade data. The level 6 harmonized system (HS) product resolution was used to isolate the mass-based trade data of 'plastic waste, parings, and scrap' for polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), and polymer waste not elsewhere classified such as polyethylene terephthalate (PET; Gaulier and Zignago, 2012). The bilateral trade data does not indicate the final fate of the traded good, however. For example, Slovenia imports a significant amount of plastic waste from Italy, Croatia, Austria, and Hungary, but re-exports the majority of the waste out of the EU (Bishop et al., 2020). To account for this, we assumed that EEA nations, the United Kingdom, Switzerland, and Hong Kong re-exported a fraction of the plastic waste imported from the Netherlands if the total amount of exports exceeded the total amount of imports. This group of countries and administrative regions was selected because they are known to be major intermediary ports (e.g., Hong Kong, Belgium, Ireland), or because waste not financially competitive for recycling within this group of countries and administrative regions is unlikely to be financially competitive for recycling in another within this same group (Bishop et al., 2020; Hsu et al., 2021; Wang et al., 2020). In addition to the financial incentives, the European Commission (EC) incentivizes plastic waste export out of the EU by allowing member nations to classify the exported plastic waste as recycled making this end-of-life option more attractive than incineration or landfilling (European Commission, 2018; Hsu et al., 2021). Trade flows within EEA nations, the United Kingdom, Switzerland, and Hong Kong, were modeled for up to three trading generations (e.g., Netherlands to Belgium, Belgium to Germany, Germany to Malaysia). For each trade

generation, trade partners not belonging to the aforementioned group were assumed to be the final destination. All trades remaining within Europe after the third generation were assumed to be fully recycled. The final fraction of exported plastic food packaging waste attributed to the Netherlands was calculated as the product of the trade fractions between the Netherlands and the intermediaries, and the intermediaries and the final importer.

#### 2.4. Mapping leaked plastic food packaging to the marine environment

To quantify the amount of plastic food packaging leaked to the environment, we compiled national-level mismanaged plastic waste fractions and linked these to the mass of Dutch plastic waste exported to each nation. National level mismanaged waste were compiled from [Lebreton et al. \(2018\)](#) who sourced their data from the *Waste Atlas (2016)* and the estimates presented by [Jambeck et al. \(2015\)](#) derived from the World Bank's 'What a Waste' report ([D. Hoorweg, 2012](#)). The fractions were calculated separately from littering in order to represent the mismanaged fraction of each nation's post-consumer plastic waste network (*Waste Atlas, 2016*; [Jambeck et al., 2015](#)). In the case of exports to 'Other, Asia NES' (Not elsewhere specified), we assumed the mismanaged waste fraction to be 23.25% ([Law et al., 2020](#)).

To estimate the fraction of mismanaged waste that enters the marine environment, we followed the practice of [Jambeck et al. \(2015\)](#) and applied a baseline of 25% as a conversion rate of mismanaged plastic to marine debris, with ranges of 15–40% to account for the uncertainty of this estimation. These conversion rates were applied to both the littered fraction within the Netherlands and the fractions of waste mismanaged in export destinations. Landlocked countries were assumed to have a 0% conversion rate to oceans or seas.

In the case of the waste fraction littered in the Netherlands, the fraction of waste which does not convert to marine debris is assumed to be recaptured by the PCPPW network and sent to incineration. The rate of recapture is then calculated as the complimentary value of the mismanaged plastic to marine debris conversion rate.

#### 2.5. Sensitivity analysis

Scenario ranges were developed using minimum, maximum, and mean reported values at three stages of the model. First, uncertainty ranges of plastic food packaging intensity were developed, as certain food items reported multiple packaging strategies. Minimum packaging intensity scenarios were built using the minimum reported plastic packaging intensity for each food item, maximum scenarios using the maximum reported values, and the mean scenario weighed each packaging alternative equally (Table S3). Secondly, the litter to plastic debris conversion scenarios were developed using minimum, mean and maximum rate of 15%, 25% and 40% ([Jambeck et al., 2015](#)). The complement of these values was used to calculate the fraction of litter recovered by the PCPPW network in each scenario. The wide uncertainty range is due to the fact that this conversion is highly dependent on local topography, climate, land use, plastic type and shape ([Horton et al., 2017](#); [Meijer et al., 2021](#)). Finally, the reported mismanaged plastic waste fraction for each nation varied between the sources reflecting the uncertainty of the data ([Jambeck et al., 2015](#); [Lebreton and Andraday, 2019](#)). A list of minimum and maximum reported values was compiled for each nation with these values weighed equally to develop a mean scenario. Each of these three stages in the model were adjusted independently to develop minimum, mean, and maximum ranges for the entirety of the assessment.

### 3. Results

To satisfy a daily food and beverage consumption of 1945 g/day/capita in the Netherlands, our model estimated that 2264 g/day/capita of food must be packaged and available for purchase in retail stores for

the year 2019 ([Fig. 1](#)). Soft drinks and dairy products represented the two primary items consumed by weight, however, liquid products (e.g. soups, stocks, sauces) and bakery products (e.g. bread, pastries) also represented a significant portion of the diet ([Fig. 2A](#)). The model predicted that a 14.2% of the food packaged will go to waste, with household waste accounting for 12.5% of total waste and retail waste accounting for 1.7%.

We estimated that the plastic packaging intensity of the Dutch food diet is 2.1% (i.e., 2.1 gs of plastic per 100 gs of food; range: 2.0–2.2%) ([Fig. 2B](#); full dataset in Table S3). There exists some variation amongst the food groups, however. Bakery products (0.96%; 0.95–0.98%) and potatoes (1.1; 0.2–2.0%) have the lowest plastic intensity, while confectioneries (3.9%; 3.9–3.9%) and grocery products (3.2%; 3.1–3.2%) require the highest ([Fig. 2B](#)).

Overall, to package the food stocked in retail stores, our model reported that a total of 47.0 g/day/capita (44.8–49.1 g/day/capita) of plastic is required, creating a total of 296 kt/yr (283–310 kt/yr) of plastic food packaging waste in the Netherlands ([Fig. 3](#)). We found that soft drinks produced the most plastic packaging waste (61 kt/yr; 61–61 kt/yr), followed by groceries (49 kt/yr; 48–49 kt/yr) and dairy (45 kt/yr; 45–46 kt/yr; [Fig. 3](#)). The plastic packaging waste was primarily composed of PE plastic (131 kt/yr; 125–136 kt/yr), PP (64 kt/yr; 60–68 kt/yr), and PET (62 t/yr; 61–64 kt/yr).

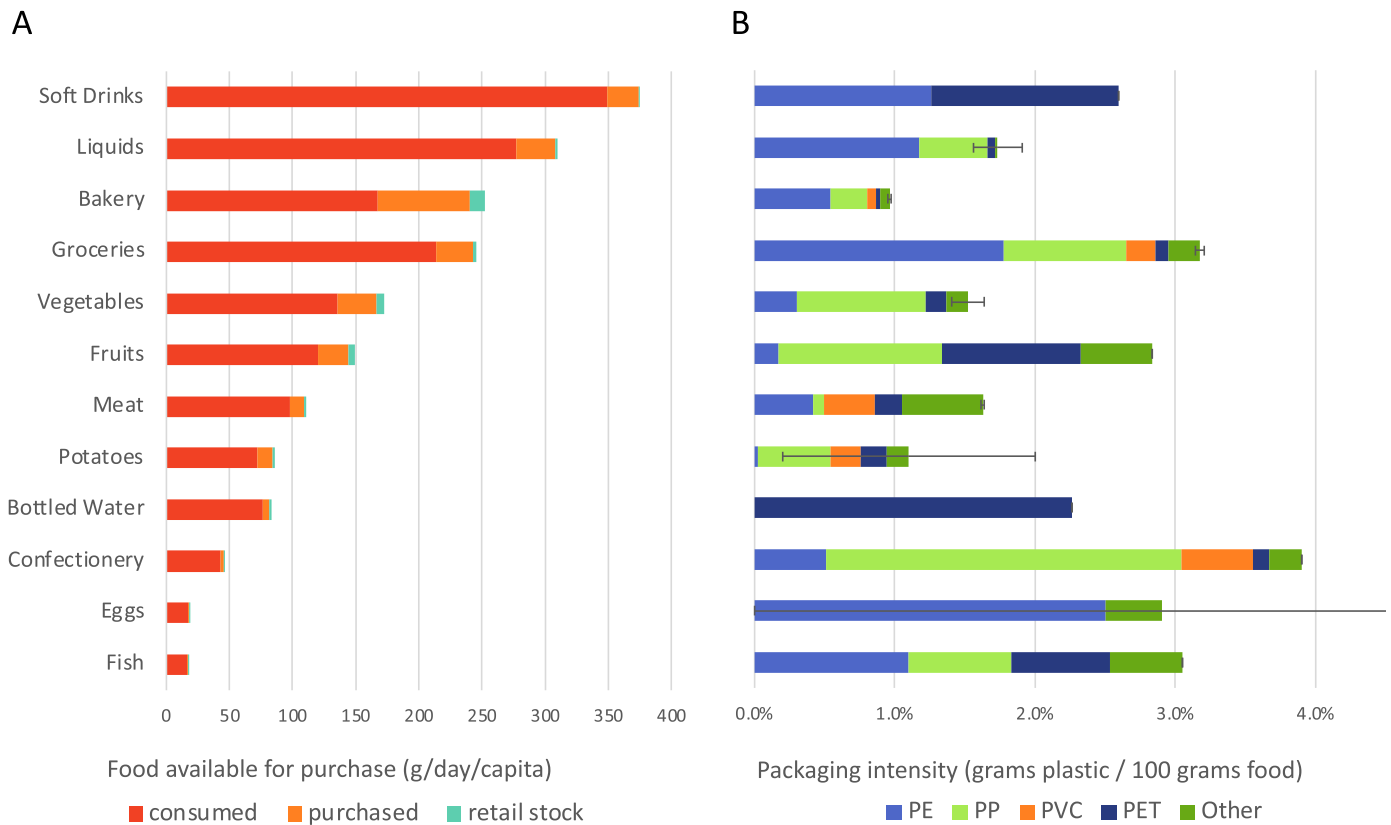
Based on the composition of the waste stream generated and the Dutch PCPPW network, our model showed that 45.6 kt/yr (43.7–47.5 kt/yr) of Dutch plastic packaging waste are exported, of which 37.2 (35.7–38.7 kt/yr) are exported out of the EEA, United Kingdom, Hong Kong, and Switzerland trade block, 198.4 kt/yr (189.8–206.7 kt/yr) are incinerated, 57.6 kt/yr (54.8–60.4 kt/yr) are recycled or disposed of in the EU, and 1.4 kt/yr (0.8–2.3 kt/yr) become unrecovered litter.

The primary food groups generating plastic packaging for exports were soft drinks (10.0 kt/yr; 10.0–10.0 kt/yr), dairy products (6.1 kt/yr; 6.1–6.1 kt/yr), and grocery products (5.5 kt/yr; 5.4–5.5 kt/yr; [Fig. 3B](#)). This was a result of their intensive use of PE and PP plastics, which were less recyclable than PET ([Fig. 3A](#); [Brouwer et al., 2019](#)). Our model found that potatoes (0.5 kt/yr; 0.1–0.8 kt/yr), eggs (0.5 kt/yr; 0.0–1.0 kt/yr), and fish (0.4 kt/yr; 0.4–0.4 kt/yr) generated the least amount of waste for export, largely due to relatively low consumption rates ([Fig. 2A](#)).

The trade model accounted for all exported plastic waste by mass, through 71,736 trade partnerships. This consisted of 40 trade flows between the Netherlands and final importers (direct exports), 132 trade flows between the Netherlands and intermediaries, and 71,564 trade flows between intermediaries and final importers (indirect exports). The ten largest total export destinations (by mass), accounting for 79% of all exports, are presented in [Table 2](#).

The largest export destinations were primarily found to be located in Asia, accounting for 7 of 10 largest trading partners of the Netherlands (as classified by the UN M49 area code standard; [Table 2](#)). Turkey, Indonesia, and Malaysia, the three largest importers, accounted for 57% of all Dutch plastic packaging waste exports. Combined, these three nations received a combined 12.5 kt/yr (12.1–13.0 kt/yr) in plastic packaging waste through direct trades with the Netherlands; however, these nations received an additional 13.8 kt/yr (13.3–14.4 kt/yr) of plastic packaging waste through indirect trade. In particular, Malaysia was found to receive 88% of Dutch plastic packaging waste through indirect trades, primarily from trade partnerships with Belgium, Germany, and the United Kingdom. In total, direct exports accounted for 46% of all Dutch export plastic food packaging waste, while secondary exports account for the remaining 54%.

Using the national scale mismanaged plastic waste estimates of importer nations, we estimated that 6.5 kt/yr (2.8–13.5 kt/yr) of Dutch plastic food packaging are leaked to the marine environment every year, of which 75% (67–79%) are leaked in Asian nations due to waste mismanaged in the PCPPW network of these nations ([Fig. 3](#)). Despite large volumes of exported waste, leakage from waste littered within the



**Fig. 2.** (COLOR) **A.** Daily quantity of food available for purchase in Dutch food retail stores to satisfy Dutch food consumption and **B.** Plastic packaging intensity of Dutch food groups (Bouma et al., 2003). Consumed food represents the amount of food consumed at a household level (van Rossum et al., 2020). Purchased food represents the amount of food a household must purchase in order to satisfy consumption demand while accounting for household food waste (van Dooren et al., 2019). Retail stock represents the amount of food a retail food store must provide to satisfy household purchase demand, while accounting for retail level food waste (Vollebregt, 2020).

Netherlands is the largest contributor to marine debris (Fig. 4). The five largest international sources of plastic leakage to the environment (by mass) were found to be located in Asia, and accounted for 70% (62–76%) of total plastic debris that reaches the marine environment (Fig. 4). The primary final EU trade destinations (Germany, Poland, and Spain) do not feature amongst the top ten leakage points, due to low mismanaged waste rates relative to other nations importing large amounts of Dutch plastic packaging waste. Instead, the largest sources of plastic marine debris are primarily located in Asia, accounting for 8 of the 10 largest sources of plastic marine debris due to higher rates of waste mismanagement and large import quantities (Fig. 4).

#### 4. Discussion

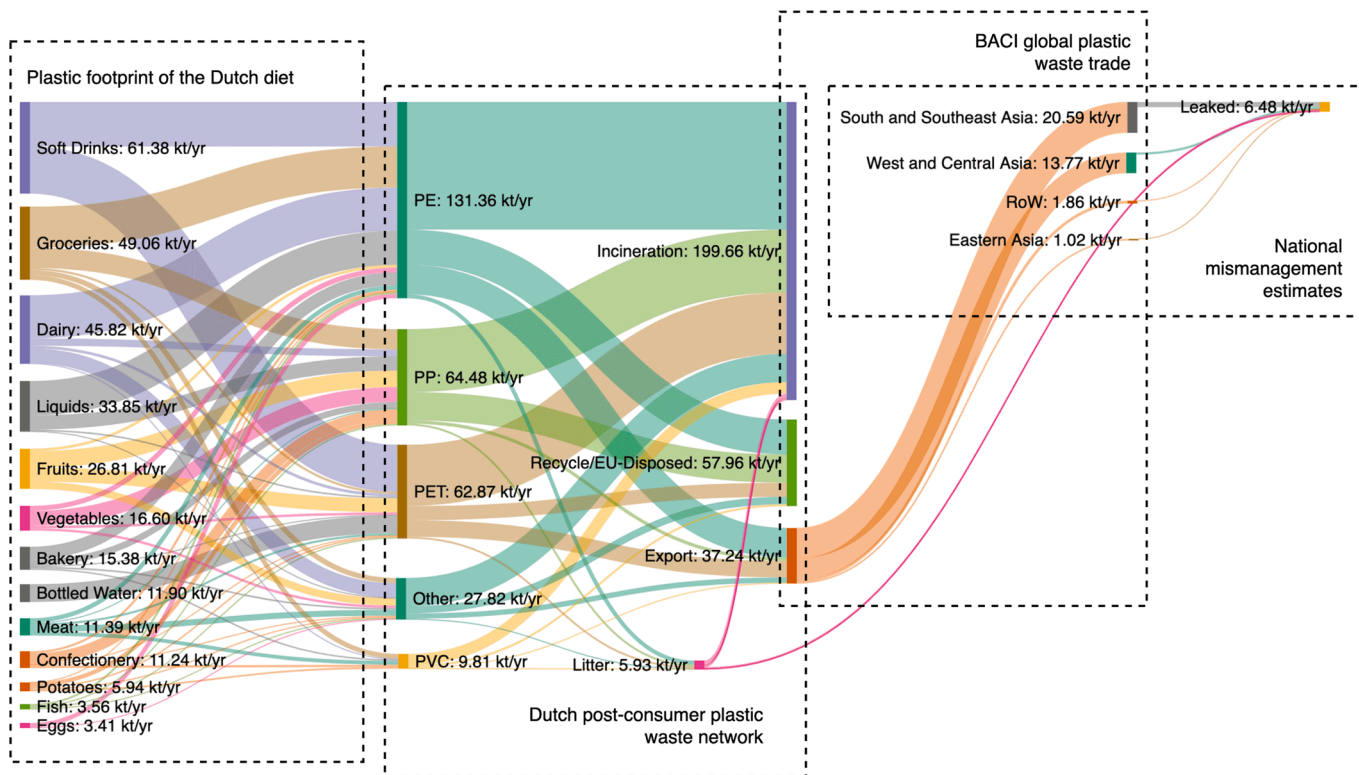
With the approach presented, we were able to link plastic leakage flows around the globe to their original use within the Dutch food network. Our plastic packaging intensity estimate of 2.1% (i.e., 2.1 gs of plastic per 100 gs of food; 2.0–2.2%) was, to the best of our knowledge, the first quantitative estimate of plastic packaging intensity for an entire diet. Our plastic packaging intensity results were in line with the general estimate of 1–3% presented by Andrady and Neal (2009). The predicted plastic packaging intensity, combined with the total food packaged, produced an estimated 296 kt/yr (283–310 kt/yr) of plastic food packaging waste, which is approximately 54% (51–56%) of all plastic packaging waste in the Netherlands (Eurostat, 2021). General estimates have approximated that plastic food packaging accounts for 40% of total plastic packaging, below our model results. However, to the best of our knowledge, this was the first detailed estimate of national scale plastic food packaging waste production compared to total plastic packaging waste generation (Schweitzer et al., 2018).

Interestingly, fruits and vegetables, frequently presented as examples of excessive plastic packaging, were only the 5th and 6th largest contributors to plastic packaging waste in the Netherlands (Fig. 3B; White and Lockyer, 2020), indicating there may be a disconnect between the primary sources of plastic food packaging and policies targeting fruits and vegetable plastic packaging. On the other hand, policies addressing water quality have been very effective at reducing bottled water consumption (Tosun et al., 2020). The Netherlands is the fourth smallest consumer of bottled water in Europe, with other countries consuming more than seven times more bottled water (European Federation of Bottled Water, 2019). Such low rates of bottled water consumption help significantly reduce the plastic footprint of the Dutch diet. If the Netherlands observed the same bottle water consumption patterns as Italy, we expect this plastic flow would increase to 83 kt/yr making it the largest source of plastic packaging of the Dutch diet.

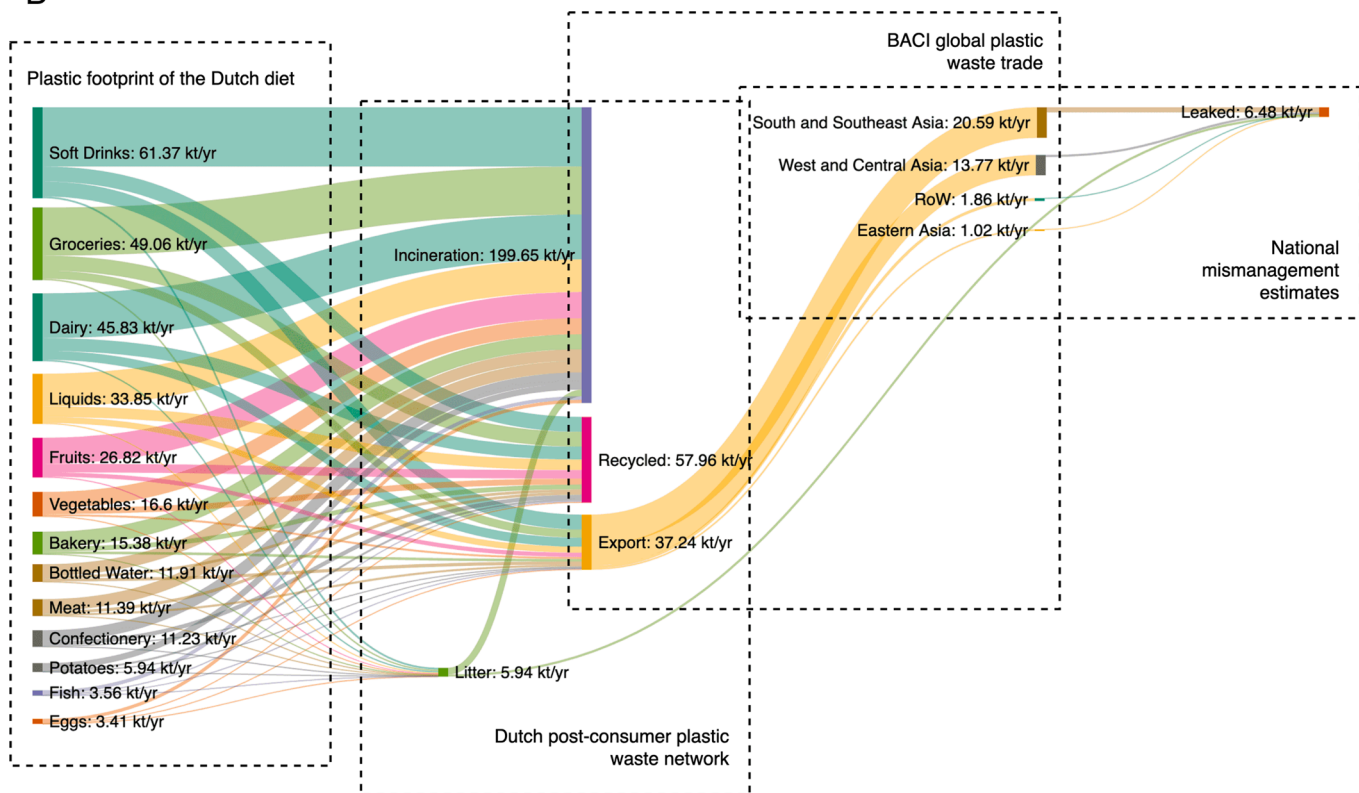
In addition to isolating each food category, we were able to analyze plastic types independently. In the case of PE and PET plastics, the combination of high use to package soft drinks, groceries and dairy, along with a relatively high recycle rates, paradoxically make these the most likely plastics exported out of the EU. This is because only properly sorted plastics can be exported out of the EU, while improperly sorted plastics are sent to incineration (European Commission, 2019; Hestin et al., 2017). These two plastic types accounted for 77% of all plastic food packaging exports, where they are more likely to become ocean debris. As such, innovations and policies addressing the use of PET and PE plastics to package these food items hold significant potential to reduce the plastic leakage footprint of food consumption in the Netherlands.

Overall, our model results indicated that plastic food packaging generated in the Netherlands contributes 6.5 kt/yr (2.8–13.5 kt/yr) of

A



B



**Fig. 3.** (COLOR) A. Fate of post-consumer plastic food packaging by plastic type in the Netherlands and B. The direct relationship of food items to fate of plastic packaging waste. All values are presented in kt/yr. Leaked values indicate the quantities of plastic leaked to the marine environment only. The nations composing the macro-geographical regions presented are classified in accordance with the United Nations UN M49 area code standard (The United Nations Statistics Division, 2018). Minimum and maximum scenarios are reported in the supplementary material Figure S1 and S2.

**Table 2**

Top ten trade partners of total Dutch plastic waste exports that account for 79% of all exports by mass. Indirect exports are shipped through intermediary partners while direct exports are shipped directly from the Netherlands to the final import destination. The top intermediary partners are ranked by mass of plastic waste passing through each nation (full dataset of all trade patterns is presented in Table S4).

Final Importer	Top intermediary partners	Indirect exports (kt/yr)	Direct exports (kt/yr)	Total exports (kt/yr)
Turkey	Germany, Belgium, United Kingdom	6.3	7.0	13.4
Indonesia	Germany, Belgium, United Kingdom	1.8	4.8	6.6
Malaysia	Belgium, Germany, United Kingdom	5.7	0.7	6.5
India	Germany, Belgium, United Kingdom	1.7	1.4	3.1
Viet Nam	Hong Kong, Belgium, Germany	1.3	1.3	2.7
Germany	France, Belgium, Czech Republic	1.1	0	1.1
Poland	United Kingdom, Germany, Czech Republic	0.8	0	0.8
Spain	France, Ireland, Portugal	0.8	0	0.8
Asia (NES)	Poland, Belgium, United Kingdom	0.4	0.2	0.7
South Korea	United Kingdom, Belgium, Germany	0.4	0.2	0.7
RoW	–	8.7	0.8	9.5
Total	–	24.4	21.2	45.6

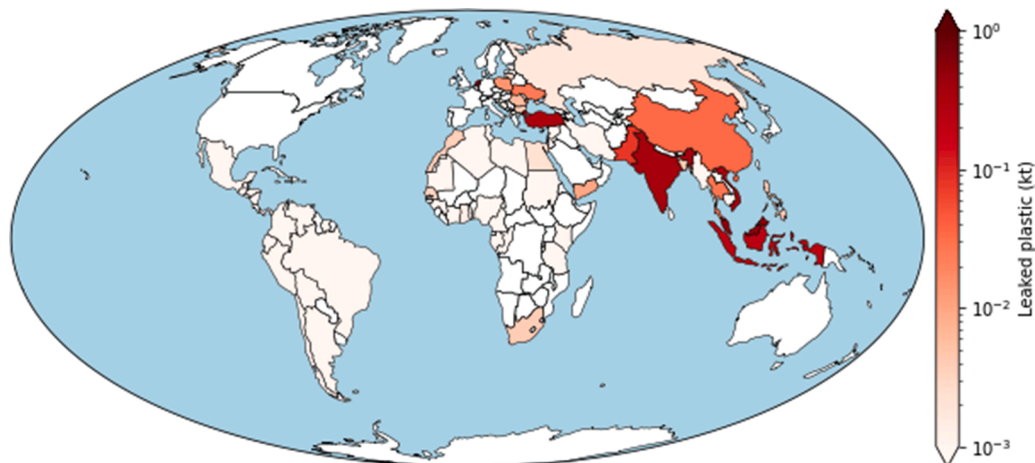
plastic ocean debris, with a leakage rate of 2.1% (1.0–4.3%). Previous estimates analyzing global plastic to ocean found leakage rates to range between 1.0–4.7% (Boucher and Friot, 2017; Ellen MacArthur Foundation, 2016; Jambeck et al., 2015; Lebreton and Andrady, 2019). Jambeck et al., (2015) and Lebreton and Andrady (2019) estimated 27.7–30.6 kt/yr of plastic debris in the oceans could be traced to plastic waste produced in the Netherlands. Plastic packaging is estimated to account for 42% of total plastic usage (Geyer et al., 2017), of which we estimated 54% (51–56%) is associated with food packaging. Using these coefficients and the total plastic waste reported in these previous studies, 6.3–6.9 kt/yr of Dutch plastic food packaging is expected to generate marine debris. Further, Bishop et al., (2020) estimated that 4.8 kt of PE plastic waste produced in the Netherlands resulted in the plastic debris found in oceans, an estimate largely in line with our own of 3.4 kt/yr (1.4–7.1 kt/yr).

The aforementioned studies relied on disaggregating plastic waste from national scale waste accounts, while our approach focused on combining individual food item packaging and consumption data to generate a national scale plastic waste estimate (Jambeck et al., 2015; Lebreton and Andrady, 2019). Despite these different approaches relying on independent data sources, the similar results obtained, indicate that our approach provides a reasonable estimate of plastic waste leaked to the ocean. However, by improving the resolution of the sources of plastic waste, our method can identify key generators of marine debris unique to a country’s plastic food packaging sector. Such a method can support researchers and policymakers develop targeted solutions to combat plastic pollution in their respective countries.

The ranges developed in our analysis are primarily driven by the rates of mismanaged plastic waste in the final importing nations. Particularly in Turkey and Malaysia, where the estimated mismanaged fraction range from 16 to 69% and 55–85%, respectively (Jambeck et al., 2015; Lebreton and Andrady, 2019). In Turkey alone, this uncertainty shifts the final estimate of plastic leakage to the oceans by 3.4 kt/yr. In addition to affecting the total amount of plastic leaked to the oceans, the mismanaged waste fraction ranges affect which nations are the primary leakage points of plastic (Fig. 4). For example, depending on the national mismanaged rates used for each nation, Turkey could be the most intense leakage point or fall out of the top four. As such, improving national mismanaged waste estimates of key plastic waste importers should be a key objective to refine future global plastic leakage estimates.

Including indirect trades in the analysis revealed the importance of re-exports in the fate of Dutch food packaging. Our results indicated that only 46% of exports were directly shipped to their final destination, while the remaining 54% passed through an intermediary (Table 2). This result is in stark contrast to data presented by the United Nations COMTRADE, who reported that only 9.3% of plastic waste is re-exported (Brooks et al., 2018). This discrepancy could be due to the fact that nations are not required to label re-exports as such (Gaulier and Zignago, 2012; United Nations International Trade Statistics Knowledgebase, 2016). Further, the three largest importers of plastic waste trade from Netherlands are Germany, the United Kingdom, and Belgium. These nations host some of the largest ports on the globe, and have a combined net export of over 30 million tonnes of plastic waste, indicating that re-exports are likely more frequent than what is currently documented (Spapens et al., 2018).

The inclusion of re-exports was a crucial consideration as we found that 78% (71–83%) of plastic ocean debris generated from Dutch plastic food packaging was the result of mismanaged exports, while the remaining 22% (17–29%) were the result of domestic littering. Without



**Fig. 4.** (COLOR) Amount of Dutch plastic food packaging leaked to the marine environment from each country connected to the Dutch plastic waste trade (full dataset used to generate this figure found in Table S5).

accounting for indirect exports, we estimated that over 58% of leaked Dutch food packaging may have been unaccounted for, as only 42% of leakage is the result of trade interactions directly linked with the Netherlands. The waste was primarily exported to low- and middle-income nations in Asia, where plastic waste management infrastructure is not yet sufficiently developed to handle such international surges in waste volumes (Brooks et al., 2018).

These results indicate a need to improve Extended Producer Responsibility (EPR) policies in the Netherlands and the EU, as plastic waste exported out of EU nations can currently be labeled as recycled despite the fact that complex trade networks make tracking the fate of exported waste extremely arduous (European Commission, 2018; Leal Filho et al., 2019). In an attempt to address this problem, EU countries have implemented policies to reduce the total quantity of plastic waste generated and improve the quality of exported plastics. The European Commission's *European Plastics Strategy* helped implement strategies banning single-use plastics in participating countries by 2021, while the Basel Convention introduced amendments imposing stricter standards on the quality of plastic waste exported out of EU countries (Basel Convention COP, 2019; Wang et al., 2019).

Improving recycling rates within EU countries is also crucial. The Netherlands is actively expanding its domestic recycling capacity, however, unless domestic recyclability becomes more financially favorable than exporting, such a solution may be ineffective in rerouting plastic waste away from exports (Brouwer et al., 2019; Wang et al., 2020). Gradus (2020) has proposed postcollection separation as a measure to improve the cost-effectiveness of plastic recycling in the Netherlands as well as implementing policies targeting design-for-recycling in order to promote recycling within the Netherlands. In addition to domestic considerations, nations like the Netherlands can also implement policies which contribute to reducing the generation of global plastic debris by investing in the plastic waste management systems of its key trade partners (both direct and indirect) to support environmental protection in these countries, as well as economic development (Barnes, 2019). Such investments could expand the capacity of the plastic waste networks of importing nations to ensure their ability to handle the vast quantities of plastic waste exported to them, minimizing plastic leakage to the marine environment.

## 5. Study limitations

The data used in this work to quantify the plastic intensity of food items packaged in the Netherlands relied on information gathered from 500 food items packaged for sale in Danish supermarkets (CONCITO, 2021). These food items may have different packaging approaches in the Netherlands, and depending on the food branding and final point of sale (e.g. a supermarket or an open-air food market; Simmonds and Spence, 2017). The most notable example of this is the almost non-existent use of plastic to package eggs in Denmark, a practice largely unique to that country (Skyggebjerg, 2019). Further, although certain food items used in this study had multiple packaging alternatives, a wider range of reported values could reduce the uncertainty ranges reported in our results of annual plastic food packaging waste produced. Furthermore, only primary packaging was considered. Secondary and tertiary packaging used to import food items in bulk were not considered due to a lack of data (Molina-Besch et al., 2019).

The complexity of the global plastic waste trade constitutes another potential source of uncertainty for the final estimates presented in our study, both in terms of total export quantities, and the final waste destination. In the case of export quantities, our assumption that only properly sorted plastics are available for export may not be true in practice. Improperly sorted plastics may also be exported as their disposal is largely unprofitable within EU markets and the European Circular Economy package incentivizes nations to avoid incineration or landfilling as end-of-life options (European Commission, 2019). As a result, the vast majority of extra EU plastic waste exports are composed

of cross-contaminated plastic waste which cannot be recycled (Hsu et al., 2021). Despite being illegal, illicit export of these contaminated plastic wastes from the Netherlands (and other nations) remained frequent and was considered an important factor in China imposing its ban on plastic waste imports (Brooks et al., 2018; INTERPOL, 2020). As a result, the assumption that only properly sorted plastics are available for exports from the Netherlands can be heavily debated.

To account for the complex interconnections of the global plastic waste trade, and unreported re-exports, we analyzed not only direct trades between two nations, but also indirect trades by including trade partnerships separated by one intermediary; however, certain trade relationships may exist that use no intermediaries, or more than one intermediary. Although including indirect trade may overestimate the quantities of exported plastic waste in certain cases, we expect that the results derived from this study remain a reasonable estimate.

Plastic food packaging tends to have lower recycle rates than other plastic packages due to complex multi-layer structures and contamination. Therefore, the recycle rates predicted from general plastic packaging recreated from Brouwer et al., (2018) may overestimate the generation of properly sorted packaging from food consumption available for export (Ragaert et al., 2017).

Although the mechanisms by which terrestrial plastic waste is leaked to the environment are well understood, a lack of spatially explicit data makes it difficult to determine the spatiotemporal delay of mismanaged waste resulting in ocean debris. The results provided therefore only give a national scale estimate, however, for nations with long coastlines (e.g. India, China, Malaysia, Indonesia), further refining the location of leakage points is critical to better understanding the environmental impacts of the leaked plastic on marine environments (Jenkins and Van Houtan, 2016).

## 6. Conclusion

We quantified the contribution of food consumption in the Netherlands to global plastic leakage by combining food consumption patterns, plastic packaging data, and plastic waste management networks. We found that the average plastic packaging intensity of the Dutch diet is 2.1% (i.e., 2.1 gs of plastic per 100 gs of food), generating 296 kt/yr (283–310 kt/yr) of plastic food packaging waste annually. Of this generated waste, we estimated that 6.5 kt/yr (2.8–13.5 kt/yr) of plastic food packaging waste produced in the Netherlands is leaked to the oceans, primarily as a result of plastic waste exports (78%) rather than domestic littering (22%). From these results, we conclude that despite being a high-income nation with an efficient domestic PCPPW network reporting a 78% recycle rate of packaging waste (Eurostat, 2021), 2.1% (1.0–4.3%) of Dutch post-consumer plastic food packaging waste is leaked to the marine environment at rate compliant with the global average of 1.1 – 4.7% (Boucher and Friot, 2017; Ellen MacArthur Foundation, 2016; Jambeck et al., 2015; Lebreton and Andrady, 2019).

Many strategies which either address the initial generation of plastic waste, address the generation of plastic ocean debris, or address critical leakage points, can be formulated in order to minimize the environmental burdens generated from plastic packaging waste within the food sector. In the case of the Netherlands, we found that soft drinks, grocery, and dairy products contribute most to ocean plastic debris due to their intensive use of PET and PE plastics. These two plastic types are largely exported to Turkey and Malaysia, among other Asian nations. These two countries do not possess the infrastructure to handle the large volumes of waste exported to them from the Netherlands, causing high levels of waste mismanagement potentially culminating into plastic ocean debris released near highly biodiverse marine environments (Brooks et al., 2018). As a result, to most effectively limit the nation's contribution to plastic ocean debris caused by food consumption, the Netherlands should formulate solutions which reduce the plastic packaging intensity of these three food groups, explore alternatives to PET and PE plastics, and support the plastic waste management infrastructure of its two

major plastic waste trade partners, Turkey and Malaysia, or shift its current plastic waste trade patterns to nations with lower mismanagement rates.

### CRedit authorship contribution statement

**N. Navarre:** Conceptualization, Methodology, Data curation, Writing – original draft. **J.M. Mogollón:** Conceptualization, Writing – review & editing, Validation. **A. Tukker:** Writing – review & editing. **V. Barbarossa:** Conceptualization, Writing – review & editing, Validation.

### 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.

### Acknowledgements

This research was funded by the Foundation for Packaging and the Environment (SVM) via the Leiden University Fund (201730821 – LUF W20405-1-99). The SVM had no role in the selection of the funded project nor in the design or execution of the project. The authors declare no conflict of interests.

### Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2022.106508](https://doi.org/10.1016/j.resconrec.2022.106508).

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