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Life cycle inventory of plastics losses from seafood supply chains: Methodology and application to French fish products

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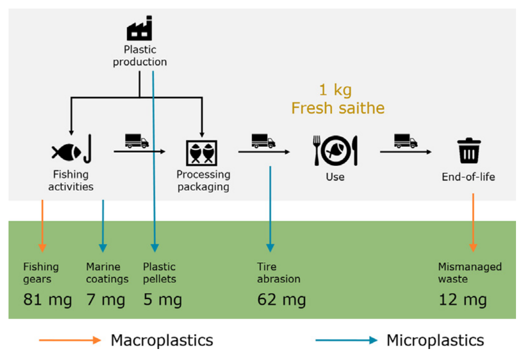
HIGHLIGHTS

- A method to include micro and macroplastic losses in LCI of seafood products is proposed.
- Fishing gear, marine coating, tire abrasion, pellets and mismanaged waste are considered.
- Fourteen fish products from the French Agribalyse database are analysed.
- Plastic losses range from 75 mg to 4345 mg per kg of fish at the consumer.
- Main plastic losses come from lost fishing gears and tire abrasion.

GRAPHICAL ABSTRACT



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ABSTRACT

Plastic debris into the environment is a growing threat for the ecosystems and human health. The seafood sector is particularly concerned because it generates plastic losses and can be endangered by plastic contamination. Life cycle assessment (LCA) does not properly consider plastic losses and related impacts, which is a problem in order to find relevant mitigation strategies without burden shifting.

This work proposes a methodology for quantifying flows of plastics from the life cycle of the seafood products to the environment. It is based on loss rate and final release rate considering a pre-fate approach as proposed by the Plastic Leak Project. They are defined for 5 types of micro and macro plastic losses: lost fishing gears, marine coatings, plastic pellets, tire abrasion and plastic mismanaged at the end-of-life. The methodology is validated with a case study applied to French fish products for which relevant data are available in the Agribalyse 3.0 database.

Results show that average plastic losses are from 75 mg to 4345 mg per kg of fish at the consumer, depending on the species and the related fishing method. The main plastic losses come from lost fishing gears (macroplastics) and tire abrasion (microplastics). Results show high variability: when mismanaged, plastic packaging at the end-of-life (macroplastics) is the main loss to the environment.

As a next step the methodology is to be applied to other fish or shellfish products, or directly implemented in a life cycle inventory database. Further research should characterize the related impacts to the environment when life cycle impact assessment methodologies will be available, and identify eco-design solutions to decrease the major flows to the environment identified.

1. Introduction

Marine debris has been recognized as an environmental concern in the past decades. Large quantities of plastics leak to the ocean (estimations of 4.8 to 12.7 millions of tons in 2010) and generate adverse effects

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on the ecosystems (Jambeck et al., 2015; Ryberg et al., 2019; Werner et al., 2016). The seafood sector is particularly concerned by this challenge. On the one hand, a significant proportion of marine litter originates from fishing activities such as lost gears loss (Lebreton et al., 2018). On the other hand, marine litter contributes to socioeconomic and environmental impacts that have implications on fisheries: contamination of fish with ingested plastics, restricted catch due to litter in nets, vessel damage and staff downtime, reduced earnings and lost fishing time (Werner et al., 2016).

The sustainability of the seafood sector involves reduction of plastic use and losses all along the supply chain. In order to support and strengthen the sector towards a systemic reduction in environmental impacts, a life cycle thinking is required (Ruiz-Salmón et al., 2020). In this context, life cycle assessment (LCA) is the most established methodology to assess environmental impacts of products. LCA has been increasingly applied to assess the environmental impacts of seafood products with more than 60 case studies published in the scientific literature (Ruiz-Salmón et al., 2021). Also, an increase of seafood datasets is observed in life cycle inventory (LCI) databases (ADEME, 2020). However, the quantification of plastic emissions to the environment and their related impacts are still not considered in LCA (in both LCI database and LCIA methods).

Currently, LCA is not adequately addressing the impacts due to marine debris plastics and microplastics (Sonnemann and Valdivia, 2017). The LCI datasets do not take into account plastic leakages to the environment. With regard to a methodology to assess the environmental impacts associated with these plastic emissions Woods et al. (2021) have published a first framework for the assessment of marine litter impacts in life cycle impact assessment (LCIA), which is planned to be made operational as part of the MariLCA working group (Verones et al., 2020). Several set of effect factors have already been developed, e.g., for macroplastic entanglement impact (Woods et al., 2019), or physical impact of microplastics on ecosystem quality (Lavoie et al., 2021). Another challenge is to quantify the transport and the degradation of plastics within the environment in order to provide a complete fate factor (Saling et al., 2020).

Concerning LCI, the Plastic Leak Project (PLP) has been an important step forward as they provide several data and factors that can be used for building life cycle inventories and modelling the pre-fate (Peano et al., 2020). Maga et al. (2021) state that LCA datasets containing product or rather process specific inventory flows to address the initial release of plastics into the environment have not yet been generated, and that developing a stringent methodology to address plastic emissions as part of an LCA bears multiple complex challenges. Also, GreenDelta aims to create a plastic litter extension for the ecoinvent database, as part of its PLEX project (Ciroth and Kouame, 2019). The PLP and the GreenDelta approaches have already been applied and compared by the European Commission in the frame of the LCA of alternative feedstocks for plastics production. In their work, they also expand the PLP approach with an alternative bottom up estimation procedure based on beach litter observations at the EU level (Nessi et al., 2021, 2020).

Activities related to the seafood sector have not been studied yet with regard to considering plastics emissions within life cycle inventory data. This is particularly the case of fishing activities that can entail the release of important amounts of plastics to the oceans through lost fishing gears and marine coatings.

Therefore, the aim of this article is to develop a methodology for quantifying flows of plastics from the life cycle of seafood products (covering fish and shellfish and further on called seafood product life cycle) to the environment. The methodology is validated with a case study applied to French seafood products for which relevant data are available in the Agribalyse 3.0 database. The Agribalyse 3.0 is an open source database that provides several datasets for the seafood sector in France (ADEME, 2020). This approach can be a basis for developing more LCI datasets, for seafood products and beyond, that include plastic emissions to the environment.

2. Materials and methods

2.1. Methodology to account for plastic flows from the seafood product life cycle

The proposed methodology is based on the LCA terminology in terms of scope definition and inventory analysis (Hauschild et al., 2017; ISO, 2006). Firstly, we define the main unit processes of the seafood product life cycle for which plastics can be lost to the environment. Unit processes are the smallest elements considered in a LCI model for which inputs and outputs are quantified. For simplicity, unit processes will be named processes.

The processes may occur either on the foreground system, which are directly related to the seafood product system, or in the background (support activities that supply the foreground system with required goods and services).

The following foreground processes were considered for a typical seafood product life cycle: fishing activities, processing/packaging, consumption, end-of-life, as well as transport activities between these processes. The considered background processes are the plastic production activities for packaging and other plastic materials used in the life cycle.

The next step is the identification of inputs and outputs related to plastics materials. Two types of input and output are considered in LCI: intermediate flows which are exchanged within the technosphere, and elementary flows which are exchanged between technosphere and ecosphere. Intermediate flows are already well defined in LCI datasets. However, there is none information on the elementary flows of plastics that reach the environment. These flows are also named plastic losses.

The methodology we propose aims to identify and quantify these flows for seafood product life cycles. Based on existing framework (Peano et al., 2020) we identified five types of plastic losses from the seafood product life cycle:

- Abandoned, lost or discarded fishing gears during fishing activities (macroplastics),
- Marine coatings applied to boats that can leak during fishing activities (microplastics),
- Plastic pellets that can be lost to the environment during plastic production in the background (microplastics),
- Plastics from tire abrasion during transport activities (microplastics),
- Mismanaged plastics during the end-of-life (macroplastics).

Processes and plastic leakages are summarized in Fig. 1.

A typical LCI defines elementary flows that reach the environment in different compartments: ocean, freshwater, soil, other terrestrial environment, air.

Once in the environment, plastic flows can be transported, degraded and fragmented before being exposed and harming human health and ecosystems. This is typically captured during the LCIA phase through characterization factors including fate factor, exposure factor and effect factor. LCIA methodologies for micro and macroplastics are currently under development (Woods et al., 2021). They are out of scope of this paper.

In a previous study done as part of the Plastic Leak Project (Peano et al., 2020) dealing with plastic leakages in the context of LCA, a “pre-fate” modelling is considered to determine the transport of plastics to final environmental compartment. The pre-fate includes two consecutive parameters: initial release compartment and redistribution to the final release compartment.

The methodology proposed in this paper takes into account the pre-fate in order to be in line with the framework proposed by Peano et al. (2020), and with the aim to quantify the final amount of plastics reaching the environmental compartments (ocean, freshwater, soil, other terrestrial environment).

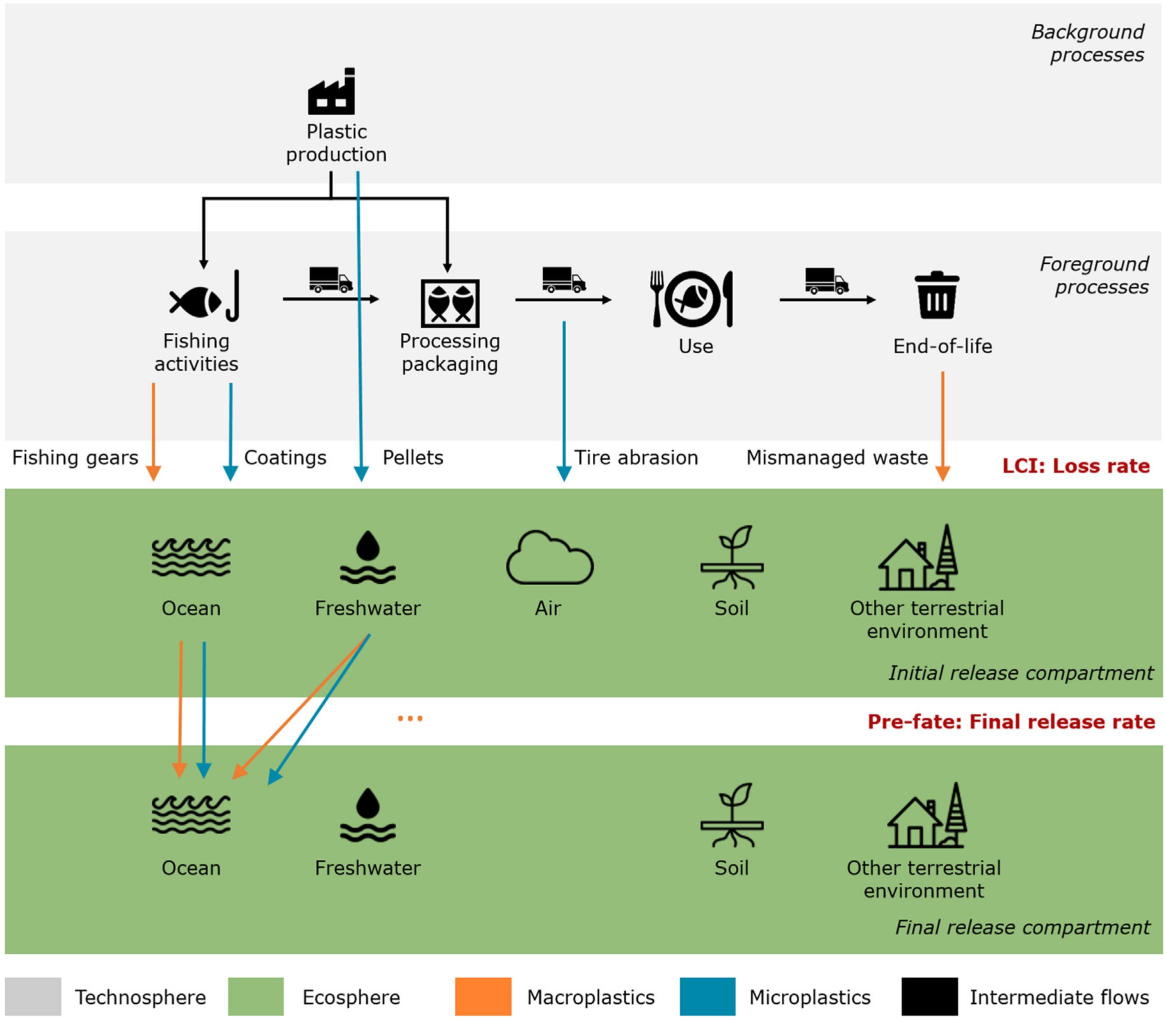

Fig. 1. Identification of plastic losses and final releases from seafood life cycle. Final release flows to environmental compartment are not exhaustive.

In the following section, we define two types of factors for each type of loss as proposed by the PLP approach:

- Loss rate (LR) defined as the relative amount of plastics from the technosphere that leave to the environment. As these loss rates can have a large variability, we identified three scenarios with average, minimum and maximum values found in the literature. When loss rates present geographic variability, France was chosen as representative for the current methodology.
- Final release rate (FRR) to the different environmental compartments (ocean, freshwater, soil, and other terrestrial environment).

These factors are based on the literature presented hereafter and are detailed for the five main types of plastic losses identified for the seafood life cycle.

2.2. Identification of initial plastic loss rates and final release rates

2.2.1. Fishing gear (macroplastics)

Abandoned, lost or otherwise discarded fishing gear represents a significant source of plastic debris in the ocean. It includes macroplastics that have high potential impacts on marine wildlife through entanglement, ensnare or ingestion. They can eventually degrade into microplastics.

PLP guidelines acknowledge that fishing gear is an important source of direct plastic loss but they do not include loss rates due to lack of data. There is limited literature on the quantification of sea-based plastics leakages that include fishing gears, but a recent review proposes fishing gear loss rates at a global scale based on a meta-analysis (Richardson et al., 2019). They present several types of fishing gears, which is useful information in the LCA context in order to compare different product systems based on diverse fishing activities.

The authors define average loss for nets, pots and trap, and lines. We selected the fishing gears most commonly found in Agribalyse 3.0 LCI datasets. Fishing boats also use plastic fishing boxes, that can also be lost to the sea. However, there is no available data on this type of loss. Therefore, plastic items used on boats that are not fishing gears were considered with the same loss rates as packaging material (see Section 2.2.5).

For active fishing activities, data for loss rates are reported as fragments of nets lost, as opposed to whole net loss (Richardson et al., 2019). This is because such nets are fixed to the boats and an entire net loss is rare for these gear types, while the incidence of net tear offs is more common. Nevertheless, the size of these fragments in relation to the total size of the net is not defined by the authors. We therefore assumed an average value of 50%, a minimum value of 10%, and a maximum value of 100%.

In its turn, data for passive fishing activities are directly reported as net loss rates. Also, fishing aggregating devices (FADs) that are gears used to attract ocean-going pelagic fish are made of plastic based buoys and can be lost. Richardson et al. (2019) considers a unique value of 9.9% as loss rate.

Table 1
Summary of loss rate and final release rate to the environmental compartments.

Type of losses (and source of data)	Variations	Loss rate LR (%)			Final release rate FRR (%)			
		Average	Min	Max	Ocean	Fresh water	Soil	Terrestrial
Fishing gears (macroplastics) (Richardson et al., 2019)	Dredge	50%·1.8% =.9%	10%·1.60% =0.16%	1.90%	100%	0%	0%	0%
	Gillnet/Trammel net	5.8%	5%	6.50%				
	Longline	20%	19%	22%				
	Purse seine	50%·6.60% =3.3%	10%·5.90% =0.59%	7.30%				
	Seine	50%·2.30% =1.15%	10%·1.90% =0.19%	2.80%				
	Trap/pot	19%	18.00%	20%				
	Trawl bottom	50%·1.80% =0.9%	10%·1.60% =0.16%	1.90%				
	Trawl pelagic	50%·0.70% =0.35%	10%·0.58% 0.058%	0.82%				
	FADs	9.90%	9.90%	9.90%				
Marine coatings (microplastics) (Verschoor et al., 2016)		1.20%	0.50%	3%	100%	0%	0%	0%
Plastic pellets (microplastics) (Peano et al., 2020)		0.01%	0.001%	0.10%	11.74%	5.09%	65.66%	3.61%
Tire abrasion (microplastics) (Peano et al., 2020)	Truck 16–32 t (kg/tkm)	2.74E−05	1.51E−05	5.79E−05	1.68%	15.15%	65.66%	3.61%
	Truck 7, 5–16 t (kg/tkm)	2.59E−05	2.10E−05	3.40E−05	1.68%	15.15%	65.66%	3.61%
Mismanaged plastics at the end-of-life (macroplastics) (Peano et al., 2020)	France	0.02%	0.02%	4%	25%	0%	0%	75%

We considered that 100% of these losses are initially and finally released to the oceans since fishing activities occur directly in this environment compartment. We acknowledge that part of fishing gears can be transported from the ocean to the terrestrial environment (beaches). Due to lack of data, we did not consider this redistribution from ocean to terrestrial environment.

Table 1 summaries the loss rates and final release rates for active and passive fishing activities.

2.2.2. Marine coatings (microplastics)

Marine coatings are protective layers applied to surfaces, as fishing boats, exposed to or immersed in salt water. They are composed of polymer-based paints and can generate microplastics when it migrates to the ocean. According to Verschoor et al. (2016), emissions from paint particles occur during:

- maintenance of the boats because of sanding and abrasive blasting of the coating;
- use of the boats due to regular wear of the coating and occasional damage.

Verschoor et al. (2016) considered that 1% of the coating is emitted during maintenance, and that 1% additional is emitted during use. Based on the same reference, we considered that 60% of the paint is composed of polymer as the solid phase.

Consequently, the initial plastic leakage rate from coatings is equal to 1.2% of the total mass of coatings. We considered variability from 0.5% to 3%.

We also acknowledge that the report of Boucher and Friot (2017) considers 6% losses from marine coatings but their estimation is based on a former reference (OECD, 2009). PLP report did not include marine coatings due to lack of data.

As presented in Table 1, we assumed that this leakage is fully released to the ocean.

2.2.3. Plastic pellets (microplastics)

Plastic goods, such as packaging, are manufactured from small pellets that are melted to produce the final product. Pellets can be considered as primary microplastics with an average size of 5 mm. PLP methodological guidelines estimates leakages associated to pellets entering drains near plastic facilities: at compounders, master batch makers, distributors, resellers, storage locations, processors and recyclers (Peano et al., 2020). Although other types of losses may occur, such as at the periphery of plastic facilities, due to lack of data they were not considered in PLP.

Based on this assumption, Peano et al. (2020) assume leakage rates of pellets from 0.001% to 0.1% along their supply chain. From this range, we considered in the present methodology an average of 0.01% initial leakage rate from pellets for all plastics produced and involved in the product seafood life cycle (mainly for fishing gears and plastic packaging). Final release rates are also taken from PLP and are reported in Table 1.

2.2.4. Tire abrasion during transport (microplastics)

Abrasion of tire on road surfaces is one of the main sources of microplastic losses to the environment (Jan Kole et al., 2017). Resulting particles are a mix of polymers including styrene butadiene rubber, natural rubber and other additives. They are found in the environment as embedded with pavement particles, forming tire and road wear particles (TRWP). However, the fraction from road only includes mineral material and do not participate in plastic leakages.

Peano et al. (2020) also estimate leakages from tire abrasion, considering a broad range of parameters including type of vehicle, type of road, among others. They also propose two modelling strategies for tire-related and non-tire related studies. We used the second type of modelling strategy and considered the case "Goods transport by truck (light, medium and heavy trucks)" for computing LR, which is also recommended by the European Commission (Nessi et al., 2021):

$$LR_{truck\ tires} = \frac{D_{truck\ prod} * M_{prod}}{Load_{average}} * Loss_{truck\ tires} * ShPolymer_{truck\ tires}$$

where $D_{truck\ prod} * M_{prod}$ is the distance over which the products are transported multiplied by the mass of product transported (in t·km). This is usually provided in LCI.

$Load_{average}$ is the average load from trucks. It is considered to be 12,000 kg per medium or heavy truck.

$Loss_{truck\ tires}$ is the loss of tired tread per kilometre travelled by the vehicle. It is considered to be 517 mg/km for a medium/heavy truck long haul and 658 mg/km for a medium/heavy truck short haul.

$ShPolymer_{truck\ tires}$ is the share of polymer (synthetic rubber + natural rubber) in tire tread. It is considered to be 60% for medium/heavy truck long haul and 50% for medium/heavy truck short haul.

We considered two types of trucks for transport in the seafood product life cycle, with the resulting LR (computed with data from PLP):

- Freight lorry (16 t–32 t), considered to be long haul: 2.74E−5 kg/tkm (min: 1.51E−5, max: 5.79E−05)
- Freight lorry (7.5 t–16 t), considered to be short haul: 2.59E−5 kg/

tkm (min: 2.10E−5, max: 3.40E−05)
- Data for other types of trucks not included in this study (such as light truck) are available in the PLP report (Peano et al., 2020).

The final release rates are presented in Table 1.

2.2.5. Mismanagement at the end-of-life (macroplastics)

Plastic waste that leaks to the environment at the end-of-life includes uncollected and poorly managed waste. PLP methodological guidelines proposes loss rates for both mechanisms.

Uncollected waste includes (i) littering which is the disposal of small, one-off items in the environment (such as throwing a cigarette), and (ii) fly tipping which is the deliberate disposal of larger quantities of litter in the environment outside of official waste collection and treatment locations. Poorly managed waste includes (i) dumping, which mainly occurs in low-income countries where waste can end up in open dump and (ii) non-sanitary landfills where waste can end up being mismanaged.

For littering, they differentiate several size of plastic products (small or detachable, medium and large), and different types of use (in-home non flushable, in-home flushable and on-the-go). Plastic packaging are considered as in-home (non-flushable) medium size for which the litter rate is considered to be 0%. PLP guidelines only considers littering for on-the-go (e.g., cups) or flushable plastics (e.g., cotton swabs).

For fly-tipping, dumping and non-sanitary landfills, PLP guidelines propose loss rates that are geographically differentiated (on a country level). These rates are based on a previous report from the World Bank Group (Kaza et al., 2018). For example, France presents a loss rate of 0.02%, which is the value that was considered for minimum and average scenario. PLP also considers a default value for high income countries which is defined to be 4.3%, and is considered for the maximum scenario.

Final release rates (considering initial rate and redistribution) for all mismanaged waste are gathered for medium size plastics which have low value (since there are packaging materials). The rates are presented in Table 1.

2.3. Application to French fish products of the Agribalyse database

Aiming to validate the approach presented in Section 2.2, we have applied the factors to existing LCI datasets in Agribalyse 3.0 database.

For this case study, the functional unit (FU) is "the consumption of 1 kg of fish". System boundaries are the ones presented in Fig. 1. The quantities of plastics in the technosphere were extracted from the Agribalyse database.

Agribalyse contains more than 200 specific LCI datasets of raw products, including agricultural but also fishery products. LCI datasets of fishery products were collected through the specific project ICV Pêche (Cloâtre, 2018). It provides specific data for the fishing activities (including quantity of fishing nets and fishing boats). Data are available for 12 different species (Table 2), through the definition of triplets related to: target species, fishing area and fishing gear. It should be noted that two species originally referred as "seine" fishing (skipjack and yellowfin tuna) were considered as "purse seine" fishing because they also rely on fishing aggregating devices that are usually used with purse seine.

Agribalyse also provides reference data on 2500 food products consumed in France. These data rely on many assumptions and approximations and correspond to "medium/standard" products that are detailed in the Agribalyse methodological report (ADEME, 2020). It includes data related to: transport, processing, packaging (only primary), household consumption and end-of-life of food products. Product losses are also considered with generic values (from the Agribalyse methodological report) at the processing stage, retail stage and consumer stage.

Thus, the LCI provides elements related to flows of plastics in the technosphere during these stages of the seafood supply chain. It is to be noted that Agribalyse is composed of unit processes interconnected for the agri-food value chain. Supporting products and services such as energy, packaging materials and infrastructure are modelled based on ecoinvent 3 system processes (Wernet et al., 2016).

After identifying the different processes of the seafood supply chain, the goal is to identify and quantify the relevant unit and/or system process that may have plastic losses. For doing so, these processes should be associated with one of the five type of plastic losses presented in Section 2.2. The list of processes and related type of plastics losses is provided in SI ("Plastic LCI" tab). It mostly includes foreground processes but also background processes related to plastic production, as defined in the methodology.

The collection of these processes as well as the computation of plastic losses has been automated in an Excel tool (available in SI), with the different steps explained hereafter (Fig. 2):

- All process requirements for 1 kg of Fish are obtained through openLCA software and imported in the Excel tool.
- The relevant processes are automatically identified in the Excel tool. The quantities of each process are multiplied with the correct LR and FRR from Table 1.
- Resulting quantities of plastic loss and final release are assessed through Sankey diagrams, contribution analysis (to identify the stages that generate most plastics into the environment) and comparison analysis between different types of fish products.

We selected 14 different fish product life cycles to be analysed (Table 2): 12 of them for the different species with a common packaging (polystyrene-PS); 2 additional datasets were selected to study the effect of packaging and processing. In order to simplify the analysis of results, one specific fish product was also selected to show all plastic flows in detail (Fresh saithe).

Table 2
List of selected fish products life cycles for plastic flows quantification.

Fish species	Fishing area	Fishing gear	Processing	Packaging
Mackerel (*Scomber scombrus*)	Northeast Atlantic	Trawl pelagic	Filleting	PS
Saithe (*Pollachius virens*)	North Sea	Trawl bottom	Filleting	PS
Albacore (*Thunnus alalunga*)	Northeast Atlantic	Trawl pelagic	Filleting	PS
Herring (*Clupea harengus*)	Northeast Atlantic	Trawl pelagic	Filleting	PS
Yellowfin tuna (*Thunnus albacares*)	Eastern Central Atlantic	Purse seine	Filleting	PS
Anchovy (*Engraulis encrasicolus*)	Eastern Central Atlantic	Seine	Filleting	PS
Swordfish (*Xiphias gladius*)	Mediterranean Sea	Longline	Filleting	PS
Scallop with coral (*Pecten maximus*)	Saint-Brieuc Bay	Dredge	No preparation	PS
Gadidae-cod (*Gadus morhua*)	Celtic Sea	Trawl bottom	Filleting	PS
Eur. Pilchard (*Sardina pilchardus*)	Eastern Central Atlantic	Seine	Filleting	PS
Skipjack tuna (*Katsuwonus pelamis*)	Eastern Central Atlantic	Purse seine	Filleting	PS
Sole (*Solea solea*)	Bay of Biscay	Gillnet	Filleting	PS
Mackerel (*Scomber scombrus*)	Northeast Atlantic	Trawl pelagic	Filleting + caning	Aluminium
Albacore (*Thunnus alalunga*)	Northeast Atlantic	Trawl pelagic	Filleting + caning	Aluminium

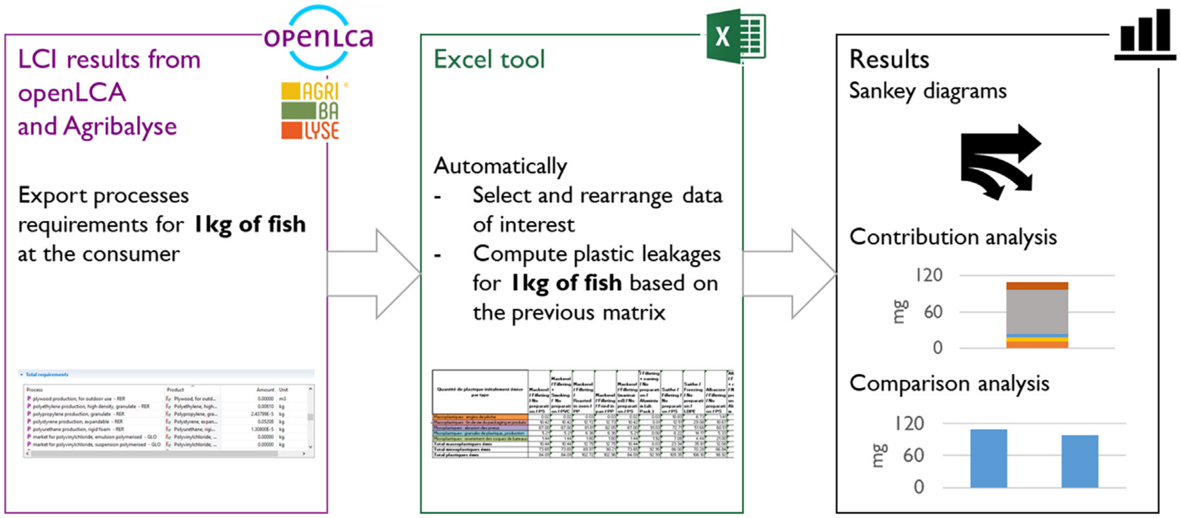

Fig. 2. Procedure to compute plastic losses and final release rates from existing LCI datasets.

3. Results and discussion

3.1. Typical plastic requirements within the life cycle of a specific fish product

This section focuses on the results for one specific fish product life cycle, i.e., fresh saithe packaged in polystyrene (PS), the functional unit being 1 kg of fish at the consumer.

Fig. 3 shows the flows of plastics within the technosphere, which are directly available from Agribalyse datasets. The FU requires 63.7 g of plastics/kg of fish at the consumer. The highest plastic requirement is the polystyrene packaging (52 g). This value is higher than the packaging mass involved during the packaging phase (50 g of packaging/kg of fish) due to products losses in the distribution chain.

The second highest plastic requirement is the fishing gear as it represents 9 g of plastics/kg of fish at the consumer. Fresh saithe is fished with bottompair trawl (63 m of headline) which is composed of 350 kg ethylene vinyl acetate copolymer, 5000 kg polyethylene high density, 3500 kg synthetic rubber (as well as 5934 kg of steel). Such bottompair trawl can fish up to 2185 t of saithe over its life time, resulting in 4 g of plastics/kg of fish at fishery. In this case, 2.23 kg of fish at the fishery is required for 1 kg of fish at the consumer (considering the losses and non-edible parts of fish).

Remaining flows of plastics in the technosphere are below 1.5 g/kg of fish at the consumer and include plastics for marine coatings, other plastics materials in the fishing boats, and truck tires. As the Agribalyse datasets is connected to ecoinvent 3 system process, it is not possible to identify all plastic requirements in the background (for example within the infrastructure). We assume these plastics flows are minor.

Quantity of plastics at the end-of-life should be the sum of all plastic requirements (i.e., 63.7 g/kg of fish) since Agribalyse and ecoinvent do not consider emissions of plastics to the environment. However, the reported value is 60.05 g/kg of fish. This is because the datasets do not necessarily consider plastics waste management at the end-of-life or they do not provide correct mass balance for plastics.

3.2. Initial plastic losses from the life cycle of a specific fish product

Fig. 3 also shows plastic losses to the environment calculated based on factors from Table 1. The average value of plastic losses is 168.8 mg/kg of fish at the consumer, which represents 0.27% of the total plastic requirements (63 g).

Major plastic losses are macroplastics from lost fishing gears (81.3 mg) and microplastics from tire abrasion during transport (62.6 mg). The value for tire abrasion can also be compared with ecoinvent dataset that considers "tyre wear emission" for transportation. The dataset "transport, freight, lorry 16–32 metric ton, EURO6 {RER}" considers 2.2E−04 kg/tkm of tyre wear emissions (Spielmann et al., 2007). Considering 60% of this emission as plastic, this is 5 times higher than the average loss rate considered by PLP guidelines (which is 2.74E−05 kg/tkm for 16–32 t truck as shown in Table 1).

The three remaining sources of losses are in the same order of magnitude: macroplastics from mismanaged waste (12.5 mg), microplastics from marine coatings (7.1 mg) and microplastics from plastic pellets (5.4 mg).

Plastic losses for average, min and max scenarios are shown in Table 3. The losses of macroplastics from mismanaged plastic waste presents a large variability depending on the different scenarios. In the max scenario, this value is 2689.7 mg, which is 4.3% (default value for high income countries as presented in Section 2.2.5) of the mass of plastic at the end-of-life, mainly composed of packaging. In the average and min scenarios, 0.02% (value for France) of plastic at the end-of-life is considered to be lost in the environment. This is 215 times less than the default value for high-income countries. Once these data originally come from a single source, it should be refined (Kaza et al., 2018). Furthermore, in two case studies conducted by PLP (dairy and textile sectors) as well as in the case studies conducted by Nessi et al. (2020) on plastic products, most of the plastic losses were macroplastics occurring during the end-of-life of the products (Peano et al., 2020).

Microplastics from pellets production also presents a high variability (2 orders of magnitude between min and max values) but remains a low contributor in all scenarios.

Macroplastics from lost fishing gears presents one order of magnitude variability because of the uncertainty associated with the size of net fragments that is reported by Richardson et al. (2019).

3.3. Final environmental compartments for plastics from the life cycle of a specific fish product

Fig. 4 shows the final release to the environmental compartments after application of the pre-fate factors. Such factors consider initial release rate and redistribution in different environmental compartments. Most plastics end up into the ocean (84.38 mg), mainly because of the direct loss of fishing gears (i.e., macroplastics).

A significant amount of plastics is released into the soil (51.82 mg) and other terrestrial environment (12.23 mg). Both environmental compartments have been merged in Fig. 4 for clarity reasons. Tire abrasion is the main source of release of microplastics to these environmental compartments.

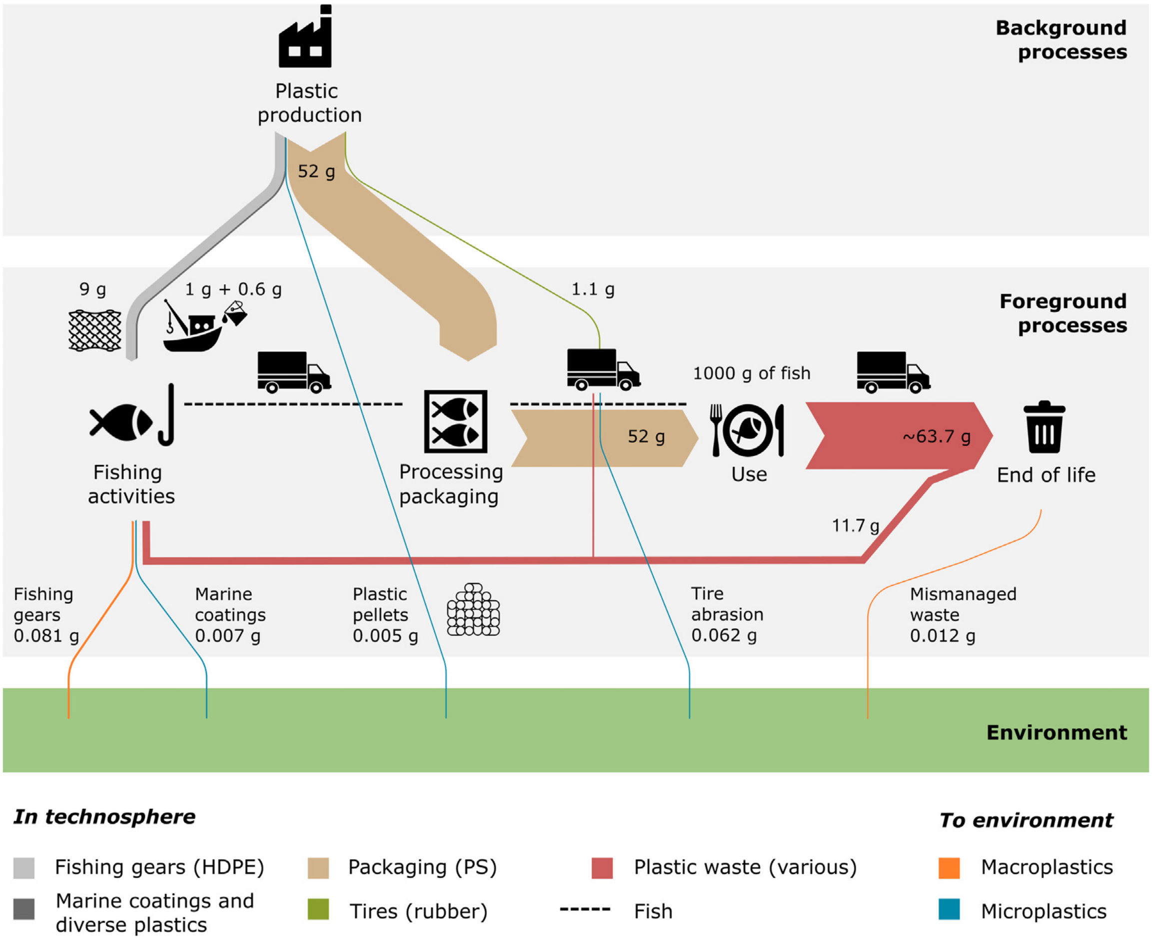

Fig. 3. Major plastic flows in the technosphere and leaching to the environment from the life cycle of Saithe packaged in PS (FU: 1 kg at the consumer, scenario: average loss rates as indicated in Table 1).

Final releases to freshwater represents 11.33 mg, as 11 mg (out of the initial loss of 22.3 mg) are removed from wastewater treatment plant.

The model does not consider any final release to the air compartment because all plastics initially emitted to air have low residential time, and end up in one of the other compartments.

3.4. Comparison between different life cycles of fish products

Table 4 shows the plastic requirements, and the plastic losses for the 12 different fish species studied from the Agribalyse datasets, computed with average loss rates. The downstream life cycle stages (processing, packaging and use) are considered equivalent in all life cycles: filleting, polystyrene (PS) packaging, no preparation at the user. Total plastic losses vary from 74.1 mg/kg of fish (mackerel/pelagic trawling) to 4344.9 mg/kg of fish (sole/gillnetting).

The life cycles of two fish species product systems (sole/gillnet and swordfish/longline) generate plastic losses with one order of magnitude higher than the other ones. This is because they rely on high quantity of fishing gear per kg of fish (72.1 g and 14.9 g, respectively) and their fishing gears have high loss rates (5.9% for gillnet and 20% for longlining).

The other species rely on bottompair trawl, pelagic trawl, seine or purse seine that have lower loss rates. In addition, less fishing gear is required for 1 kg of fish with these techniques, except for cod (39.9 g/kg of fish). In general, there is a high variability in the quantity of plastics required for fishing gears.

Marine coatings requirements and associated losses also present high variability because they depend on the fishing boats (size and quantity of fish per boat). The microplastics losses from marine coatings range from 4.5 mg (mackerel/pelagic trawl) to 187.6 mg (swordfish/longline).

Plastic pellets microplastics losses are similar for the different species (around 5 mg) because they rely on the same PS packaging mass which is the main plastic produced. However, scallop is associated with a packaging mass 7 times higher than the other species because it is distributed and sold with shells and requires more packaging for 1 kg of fish at the consumer. It results in 33.1 mg of pellets losses.

Microplastics from tire abrasion are also similar for all species once Agribalyse considers similar transport distances and mass of products for all species, with the exception of scallops. Similarly, to what we observed with the packaging, this is because shells are also transported and generate 7 times more microplastics from tire abrasion than the other seafood product life cycles.

Table 3
Average, min and max plastic leakage flows from the life cycle of fresh Saithe packaged in PS (FU: 1 kg at the consumer).

mg of plastics/kg of fresh saithe at the consumer	Average	Min	Max
Fishing gears (macroplastics)	81.3	14.4	171.5
Marine coatings (microplastics)	7.1	3.0	17.7
Plastic pellets from production (microplastics)	5.4	0.5	53.5
Tire abrasion from transport (microplastics)	62.6	50.9	82.6
Mismanaged plastic waste (macroplastics)	12.5	12.5	2689.7
Total macroplastics	93.8	27.0	2861.2
Total microplastics	75.0	54.3	153.8
All plastics	168.8	81.3	3015.0
% of plastic leakage to the total plastic requirements	0.27%	0.13%	4.76%

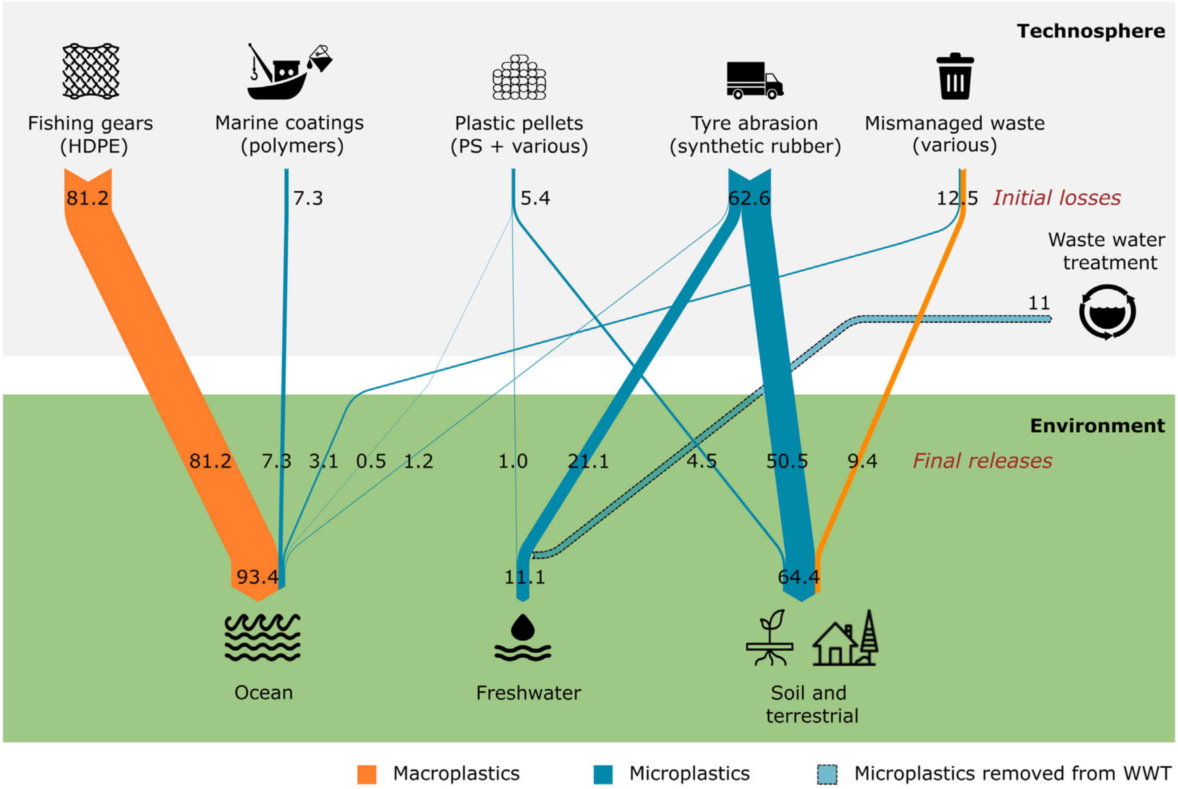

Fig. 4. Final plastic releases to environmental compartments after redistribution, in mg (FU: 1 kg at the consumer, scenario: average)

Mismanaged waste losses are mostly dependent on the packaging mass. Also, species that rely on higher quantity of fishing gear (swordfish, sole, cod, and saithe) generate higher macroplastics from mismanaged nets at the end-of-life.

The influence of packaging and processing is shown in Fig. 5. As it can be noticed, seafood products packaged in aluminium do not generate less plastic losses over the life cycle (for 1 kg of fish at the consumer). This is because the studied aluminium products require more

Table 4
Summary of plastic requirements and plastic losses from the life cycle of 12 fish species product systems (FU: 1 kg of fish at the consumer, scenario: average).

Species		Mackerel	Saithe	Albacore	Herring	Yellowfin tuna	Anchovy	Swordfish	Scallop with coral	Cod	Sardine	Skipjack tuna	Sole
Fishing method		Trawl pelagic	Trawl bottom	Trawl pelagic	Trawl pelagic	Purse seine	Seine	Longline	Dredge	Trawl bottom	Seine	Purse seine	Trammel net
Packaging		PS	PS	PS	PS	PS	PS	PS	PS	PS	PS	PS	PS
Technosphere plastic flows (g/FU)	Fishing gear (g)	0.0	9.0	1.2	0.0	5.2	2.2	14.9	0.0	39.9	0.9	5.1	72.1
	Marine coatings (g)	0.1	0.6	2.2	0.1	0.5	0.6	17.2	1.9	3.0	1.1	0.5	6.3
	Packaging (g)	52.1	52.1	52.1	52.1	52.1	52.1	52.1	372.0	52.1	52.1	52.1	52.1
	Plastic production others (g)	0.0	1.0	0.1	0.0	0.0	1.2	20.0	13.0	0.1	0.5	0.0	9.2
	Tire (g)	1.1	1.2	1.0	1.1	1.0	1.1	1.0	4.9	1.4	1.1	1.0	1.3
	Plastics at the end-of-life (g)	50.0	60.0	51.2	50.0	55.2	53.4	83.8	375.9	89.9	51.3	55.1	131.0
	Total plastic requirements (g)	53.2	63.3	54.3	53.2	58.2	56.7	87.9	389.9	93.4	54.6	58.2	134.7
Environment plastic losses (mg/FU)	Macro: fishing gear (mg)	0.1	81.3	4.1	0.1	179.1	25.7	2976.8	0.0	358.7	10.0	176.4	4184.5
	Micro: marine coating (mg)	1.4	7.1	21.0	1.6	5.6	5.8	187.6	15.6	19.7	6.0	5.5	53.3
	Micro: plastic production (mg)	4.5	5.4	4.6	4.5	4.9	4.8	7.5	33.1	7.9	4.6	4.9	11.5
	Micro: tire abrasion (mg)	57.7	62.6	52.1	59.5	52.1	59.5	52.1	265.1	76.2	59.5	52.1	68.4
	Macro: mismanaged waste (mg)	10.4	12.5	10.7	10.4	11.5	11.1	17.5	78.3	18.7	10.7	11.5	27.3
	Total macroplastics (mg)	10.5	93.8	14.8	10.5	190.6	36.9	2994.2	78.3	377.4	20.7	187.9	4211.7
	Total microplastics (mg)	63.6	75.0	77.7	65.5	62.7	70.0	247.1	313.9	103.8	70.1	62.5	133.2
	All plastics (mg)	74.1	168.8	92.5	76.0	253.2	106.9	3241.3	392.2	481.2	90.8	250.4	4344.9
	Ratio between plastic losses and plastic requirements	0.14%	0.27%	0.17%	0.14%	0.34%	0.09%	3.69%	0.10%	0.52%	0.17%	0.34%	3.23%

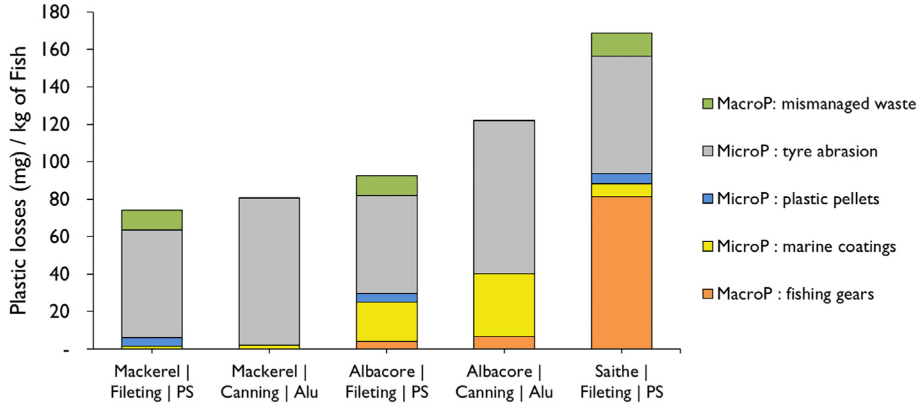

Fig. 5. Plastic losses from the life cycle of fresh saithe as reference and 2 fish species product systems with different packaging/processing (FU: 1 kg of fish at the consumer, scenario: average).

processing stages and therefore more raw fish (because of fish losses), thus resulting in an increase of fishing activities and transport requirements. For fish products which are fileted and packaged in PS, the plastic losses associated with plastic production and end-of-life are higher but do not counterbalance the other plastic flows.

However, in the case of the max scenario where 4% of packaging is mismanaged at the end-of-life (instead of 0.02% in the average scenario), the increase in macroplastics loss at the end-of-life is predominant. It shows again the high variability of plastic losses quantity, which depends on geographical parameter and consumer behaviour.

Full results in terms of final release rates for the studied seafood product life cycles are available in SI ("Results" tab).

3.5. Perspectives

LCI data generated in this paper could be implemented into the Agribalyse datasets concerning the seafood sector. The proposed methodology and procedure presented in Fig. 2 could also be applied for all types of agri-food products studied in Agribalyse. In this case, the plastic loss rates defined in this study for plastic production, processing/packaging and end-of-life processes could be used for the agri-food products. New loss rates should be developed for specific activities that use plastic such as aquaculture (e.g., loss of plastic buoys at sea for oyster production) and agriculture (e.g., loss of plastic mulching in the soil). However, we acknowledge that the implementation of plastic losses would be partial because it only includes losses in the foreground system, and on some processes in the background (plastic production).

Wider database such as ecoinvent should also be updated to consider plastic emissions in all sectors and in all background processes. This is an important step towards the consideration of plastic related impacts in LCA. A more general challenge is to develop mass balanced unit processes regarding intermediate and elementary inputs and outputs. This is also the case for other types of materials such as metals for which their dissipation is not well accounted yet (Beylot et al., 2021). Past initiatives have shown that existing database can be fully updated to consider mass balance of a specific material or resource, e.g., water (Pfister et al., 2015).

In order to expand data on plastic flows, several data sources can be used. Maga et al. (2021) classify 4 types of data sources: survey, statistical data, empirical measurement and probabilistic models. This paper mostly includes statistical data on consumption of products or littering and mismanaged waste. Further data sources such as empirical measurements of plastic parts found in the environment can be used to improve the quality of the data even if it is complex to link retrieved plastic items to their initial product.

Also, top-down quantification of plastics leaching into the environment have been conducted in the last years (Jambeck et al., 2015; Ryberg et al., 2019). Further research could be conducted to reconciliate top-down data with bottom-up LCIs such as the ones provided here. This would require producing sector specific (such as seafood) top-down data, which is not yet the case.

Complementary to the quantification of the plastic emissions from value chains, it is important to assess its impact in the environment. Several initiatives have been launched to develop LCIA methods in the past years as described before. Most of them are listed under the MariLCA working group (Verones et al., 2020) and can be integrated into the initial framework recently published (Woods et al., 2021). According to their framework, LCI should be the quantity of plastic initially leaked to a specific environmental compartment. Therefore, only the initial loss rate presented in this paper should be considered as LCI, since the final release rate includes the transport factor that is part of the fate modelling. It is to be noted that the fate also includes degradation and fragmentation in the environment. The MariLCA framework and Maga et al. (2021) also recommend to attribute further details to the inventory apart from the mass of plastics: (i) receiving environmental compartment (air, ocean, freshwater, terrestrial), (ii) fragment type (micro, macro, etc.), (iii) material type (PS, PEHD, etc.), and (iv) location. Attributes (i), (ii) are available from our study. The material types (iii) are not specifically discussed in our results, but are available in Supplementary Information. However, further properties on the material such as the shape can have a strong influence on the fate or the effect of the plastic and should also be taken into account (Maga et al., 2021). The location (attribute iv) is not specifically stated here but can be easily specified, at least for the foreground processes.

The application of these LCIA methods to the LCI data presented here would complement the LCA of seafood and show the magnitude of plastic related impacts and/or damages compared to other environmental issues (for example in terms of (eco)-toxicity).

LCI and LCIA results related to plastic can also be used to identify the types of losses that generate most impacts, and therefore to prioritize eco-design initiatives. Considering that lost fishing gears is a major plastic loss in seafood product life cycles, several preventive and mitigation measures have been developed (Gilman, 2015). This includes, for example, gear marking to identify ownership and increase visibility, technology to avoid unwanted gear contact with seabed, etc. Plastic packaging and transport by truck are also two potential sources of plastic losses. Some actions could also be implemented to reduce them, as use of biodegradable packaging, improvement of end-of-life management, and reduction of transport distance through local circuits.

4. Conclusion

This paper proposes a methodology and an automatic procedure to account for plastic losses and final releases from the life cycle of seafood products into the environment. It is based on the guidelines and data from the PLP (Peano et al., 2020) and complements it with loss rates specific to the seafood sector (fishing gear and marine coatings).

Results have shown a high variability in plastic losses depending on the fish species and the associated fishing method. Plastic losses computed with average rates range from 74 mg to 4344 mg per kg of fish at the consumer. Most of the fish species result in plastic losses around 100 mg per kg of fish at the consumer (Mackerel, Saithe, Albacore, Herring, Yellowfin tuna, Anchovy, Sardine and Skipjack tuna). The highest plastic losses are related to species that require high mass of passive fishing gear (e.g. Swordfish and Sole, since such gears present high loss rates). Fishing gear (macroplastics) and tire abrasion (microplastics) are the main plastic losses when considering average rates for all types of losses. When considering maximum rates, mismanaged plastic packaging at the end-of-life is the main plastic loss. The variability of results depending on the parameters (min, max, average) show that there are research needs to better quantify several types of losses, mainly lost fishing gears and mismanaged waste.

This work paves the way to better account for plastic pollution in LCA, more particularly for the seafood sector. Several perspectives are foreseen: broadening the methodology to other products, assessing the associated impacts with preliminary LCIA characterization factors, identifying and prioritizing relevant eco-design solutions to mitigate plastic pollution arising from a seafood product life cycle of seafood.

CRediT authorship contribution statement

Philippe Loubet: Conceptualization, Methodology, Validation, Writing – original draft, Supervision. **Julien Couturier:** Methodology, Investigation, Data curation, Resources, Writing – review & editing. **Rachel Horta Arduin:** Writing – review & editing, Visualization. **Guido Sonnemann:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supporting information to this article includes the Excel tool with 4 different tabs: “Import tool”, “Plastic LCI”, “Models” and “Results”. Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.150117.

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