Land-Based Solutions for Plastics in the Sea

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4	LABORATORIO IBERICO INTERNACIONAL DE NANOTECNOLOGIA	INL	PORTUGAL	RTO
5	KATHOLIEKE UNIVERSITEIT LEUVEN	KUL	BELGIUM	HES
6	HELMHOLTZ ZENTRUM FUR OZEANFORSCHUNG KIEL	GEOMAR	GERMANY	RTO
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Executive summary:	This document corresponds to Deliverable 8.2. Report describing the effectiveness of emission reduction measures of MNP for the two case studies, developed in the framework of Task 8.2 of the LABPLAS project. This report provides information about the research undertaken in the two case studies of WP8: 1. Tyre wear (Lead RU and OU) 2. Single-use plastics (Lead UVI-Erenea) The approach taken for each case study includes the identification of relevant key stakeholders, mapping of the typical supply chain from cradle to grave. In the case of tyre were, estimation of SMNP emissions to the environment at the different stages of the supply chain, the formulation of potential intervention options, the definition of an emission reductions strategy and quantification of the environmental impacts of this emission reduction strategy. In the case of SUPs, estimation of production, recycling and waste, formulation of potential intervention options, proof of their acceptance/agreement by companies and consumers, with final recommendation about policy interventions and how to assess their effectiveness with the participation of stakeholders.

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

ABBREVIATIONS AND ACRONYMS

Abbreviation / Acronym	Description
ASTM	American Society for Testing and Materials
BAT	Best Available Technology
CLSC	Closed Loop Supply Chain
CSR Europe	European Business Network for Corporate Sustainability and Responsibility
DRS	Deposit Return/Refund System
EC	European Commission
EEA	European Environmental Agency
EF	Emission Factor
EoL	End-of-Life
EoP	End-of-Pipe
EPA	United States Environmental Protection Agency
EPR	Extended Producer Responsibility
EQS	Environmental Quality Standards
ETRMA	European Tyre Manufacturers Association
EU	European Union
EUPC	European Plastics Converters
ISO	International Standards Organization
LCA	Life Cycle Assessment
LDPE	Low-Density Poly Ethylene
MNP	Micro- and nano- plastics
MSA	Material System Analysis
NGO	Non-Governmental Organization
PAYT	Pay-As-You-Throw
PBAT	Poly Butylene Adipate Terephthalate
PE	Poly Ethylene
PP	Poly Propylene
R&D&I	Research & Development & Innovation
R&D	Research & Development
SCOR	Supply Chain Operations Reference
SMNP	Small, micro- and nano- plastics
SUP	Single Use Plastic
SUPD	Single Use Plastics Directive
SUV	Sports Utility Vehicle
TRWP	Tyre and Road Wear Particles
TWP	Tyre Wear Particles
UNDP	United Nations Development Programme
WWTP	Waste Water Treatment Plant

1 INTRODUCTION

Plastic is pouring from land into our oceans at a rate of nearly 10 million tonnes a year (UNEP, 2021). Once in the sea, plastics fragment into particles moving with the currents and ocean gyres before washing up on the coastline. The smaller the size the higher the risk posed by these particles to organisms and human health. Because small, micro- and nano-plastics (SMNP) cannot be removed from oceans, proactive action regarding research on plastic alternatives and strategies to prevent plastic from entering the environment should be taken promptly. The LABPLAS project is a 48-month project whose vision is to develop new techniques and models for the detection and quantification of SMNPs Specifically, the LABPLAS project will determine reliable identification methods for a more accurate assessment of the abundance, distribution, and toxicity determination of SMNPs and associated chemicals in the environment. It will also develop practical computational tools that should facilitate the mapping of plastic-impacted hotspots and promote scientifically sound plastic governance.

This report provides an insight into the effectiveness of potential emission reduction measures for two case studies:

1. Tyre wear (Lead RU and OU)
2. Single-use plastics (Lead UVI-Erenea)

The approach taken for each case study includes:

a. Map of the typical supply chain from cradle to grave
b. Identification of relevant key stakeholders
c. Estimate of the typical SMNP emissions to the environment at the different stages of the supply chain (tyre wear) and general production/recycling/waste (SUPs).
d. Identification of potential intervention options.
e. Compilation of emission reduction scenarios in collaboration with stakeholders and determination of emission reductions of the interventions (tyre wear).
f. Quantification of the environmental impact of emissions and emission reductions (tyre wear).
g. Selection of intervention measures and analysis of preferences based on a stated preference approach (SUPs) to test effectiveness/acceptability of potential options.
h. Final intervention proposals and ways of testing their effectiveness in collaboration with stakeholders (SUPs).

This report is an extended version of Deliverable 8.1. *Interim report describing the supply chain of two case studies*.

2 CASE STUDY 1: TYRE WEAR EMISSIONS

Tyre wear is responsible for an important part of the microplastics detected in the environment (Boucher & Friot, 2017; Kole et al., 2017), e.g., in the form of tyre and road wear particles (TWRP). Tyre wear is the result of mechanical forces caused by the contact between tyres and the road surface while driving (Panko et al., 2013; Sieber et al., 2020; Wagner et al., 2018). Even though tyre wear is a major source of microplastics, microplastics release also occurs during other stages of the tyre's lifecycle, e.g., when granulated tyres are being used as infill for artificial turfs (Kole et al., 2017). In the current report, we use the term "tyre microplastics" to refer to all microplastics that originate from tyres.

The important contribution of tyres to microplastics found in the environment triggers the question of how emissions from tyres can be reduced effectively and efficiently. Answering this question is not straightforward as many interventions are possible. These vary from source-oriented measures, such as changing the composition of tyres, to end-of-pipe solutions, such as capturing and treating road runoff (Furuseth & Rødland, 2020; OECD, 2021). Whether an intervention is feasible depends on factors such as its effectiveness in reducing tyre microplastics emissions, its costs and (upstream) implications for important stakeholders, such as the tyre industry. Therefore, the planning of such interventions does not only require detailed insight into the environmental sources, pathways and effects of tyre microplastics (Mitrano & Wohlleben, 2020) but also requires an integrative multi-stakeholder approach (Mian et al., 2022). Stakeholder involvement is critical as it provides a way to better understand the complexity of a problem and the diversity of perspectives around it, and it builds trust for further collaboration necessary for the exploration of, in this case, robust and realistic mitigation measures (Chua, 2016; Pohl & Hirsch Hadorn, 2007). Additionally, it facilitates data gathering and the validation of results (Diedrich et al., 2011; Oreskes, 2004).

The aim of the present case study is to develop a strategy for tyre wear emission reduction in collaboration with stakeholders, while demonstrating the usefulness of the data, models and approaches on tyre wear developed in the LABPLAS project. The case study consisted of the following steps which are explained in more detail in the sections below:

1. Mapping the tyre supply chain to create a systematic overview of the processes associated with the tyre's lifecycle (Section 2.1);
2. Identify key stakeholders involved in the tyre supply chain or the environmental emission of tyre wear (Section 2.2);
3. Identifying and quantifying relevant environmental microplastic emissions along the tyre's lifecycle (Section 2.3);
4. Identifying potential interventions for tyre wear emission reduction (Section 2.4);
5. Selecting emission reduction interventions for tyre wear and quantifying their emission reduction potential (Section 2.5);
6. Quantifying the expected impact of the emission reduction strategies on tyre wear concentrations in the aquatic environment using a draft version of the ePLAS model (Section 2.6).

Although the steps are presented sequentially in this report, in practice, these are interrelated and were therefore performed in an iterative way. For example, the stakeholders were identified and actively contacted in Step 2 but were asked to verify the results of Step 1, i.e., the map of the value chain. The stakeholders were involved in all steps outlined above, except for Step 6. Their level of involvement varied between steps. They played a leading role in Step 5 (i.e., combining interventions into an emission reduction scenario), whereas in other steps (i.e., Steps 1, 3, 4 and 5) their main role was to verify and complement the results initially obtained based on literature review and scientific analysis. The initial plan was to share the results of Step 5 with the stakeholders to optimize the emission reduction strategies and flag the preferred option(s). However, this turned out to be unfeasible within the timeframe of the LABPLAS project. This step will now be performed within the context of the OU ePLAS project which runs until the spring of 2026.

The steps outlined above are typically applied to a particular system, often with distinct geographical boundaries. For the current case study, the system boundaries varied per step. Steps 1, 2, 4 and 5 are generic in nature and the results can be considered representative for the European situation. Step 3, i.e., emission estimation, was performed for the Netherlands. Three types of tyres were included in this step: passenger car tyres (including van and caravan tyres), bus tyres and truck tyres. The last step, i.e., quantification of the expected impact of emission strategies (Step 6), was performed for the Elbe basin, i.e., one of the case study areas of the LABPLAS project.

2.1 Map of the supply chain

2.1.1 Methods

As a starting point, the Closed Loop Supply Chain (CLSC) of a tyre was mapped. The CLSC refers to all forward logistics in the chain, such as extraction and production, while at the same time including the collection and processing of returned (End-of-Life) products and/or parts (Bloemhof-Ruwaard et al., 2002). To describe and map the tyre's supply chain map, the SCOR model was used. SCOR is a process reference model for supply chain management endorsed by the Supply Chain Council (SSC, 2012). SCOR aims to facilitate the mapping, assessment and evaluation of processes and activities in the supply chain to improve and streamline processes (SSC, 2012).

Firstly, the different lifecycle stages present in the supply chain were distinguished. Then the processes in each lifecycle stage were identified and mapped by means of a visual representation. Only processes related to (tyre) material streams were included, thus, excluding those related to information streams, such as receiving orders and customer contact. Information to create the supply chain was initially obtained from peer-reviewed and grey literature. Literature was found via a web-based search engine with keywords including: 'tyres/tyres', 'supply chain', 'manufacturing', 'collection', and 'End-of-Life'. A tyre manufacturing plant and R&D department was visited to obtain insight into the tyre manufacturing process. Open interviews were conducted with specific stakeholders to acquire additional knowledge or to validate information found in the literature. The supply chain map was discussed for validation with stakeholders during a workshop.

2.1.2 Results

The tyre's lifecycle starts with the mining and production of raw materials from which a tyre is constructed. The subsequent manufacturing of a tyre consists of different stages, i.e., mixing, component manufacturing, tyre building, tyre curing and final inspection (Continental, n.d.; Shanbag & Manjare, 2020). After production, tyres are distributed via car manufacturers as part of a new vehicle or via the numerous tyre distributors on the replacement market. After a tyre is disposed of, it is collected and distributed based on its quality. Tyres with more than the legal minimum tread depth can be sold on the internationally used tyre market. Tyres of which the carcass is still of sufficient quality can also be retreaded, which is more common for bus and truck tyres. The remaining tyres are End-of-Life Tyres, of which the main portion is mechanically recycled (RecyBEM, 2022). The rubber granulate that is produced can be used in a number of applications.

Figure 1 shows the supply chain map, in which both the processes per lifecycle stage and the material streams between them are presented. The tyre's lifecycle stages are shown in relation to the primary stakeholder group, i.e., suppliers of raw ingredients, tyre manufacturers, distributors, consumers and processors of used tyres, which includes used tyre collectors. As with most contemporary supply chains, the tyre's supply chain is a global system. The overall forward supply chain system is, therefore, relatively universal. However, the return tyre collection system and diversity of End-of-Life trajectories are specific to the Netherlands. After analyzing all processes in terms of individual inputs and outputs relevant to microplastic release, it was determined that tyre usage by consumers and rubber granulate, when used as infill for artificial turfs, are relevant for tyre microplastic emissions to the environment. Microplastic release from other processes was considered to be negligible, relatively limited or without release to the environment.

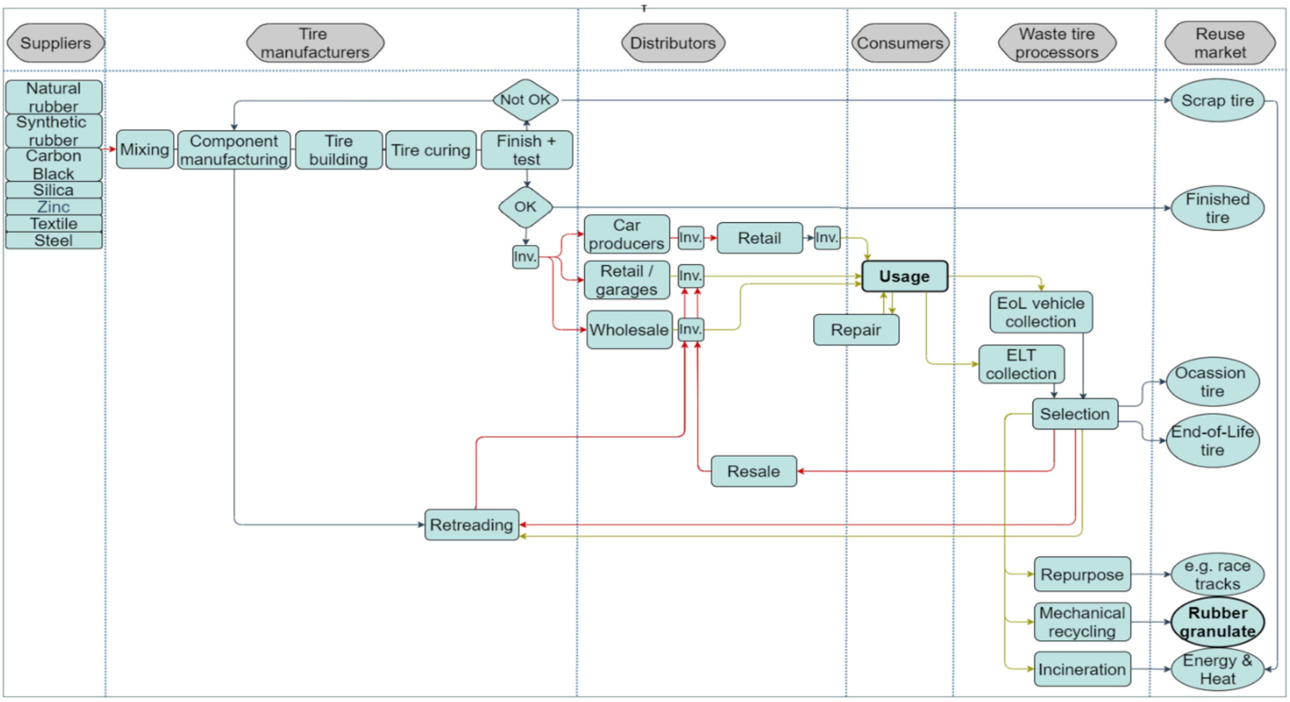

Figure 1. Tyre supply chain map. The supply chain is a global system, yet the presented tyre collection and End-of-Life processes are Dutch-specific. The rectangular boxes represent the processes, with the diamond shapes representing check processes. The boxes on the right side represent the different products that result from the processes on the left. The red arrows show the intercontinental or international streams, the yellow are regional or local streams and the blue are undefined or on-site. The shapes in bold are the processes from which microplastic emissions emerge

2.2 Identification and involvement of relevant key stakeholders

2.2.1 Methods

A stakeholder network analysis was performed, which is a strategy to examine and map the influence of individual actors, their interrelationships and the connectedness and clustering within the network as a whole (USAID learning lab, 2019; Zedan & Miller, 2017). The first step in performing such a stakeholder network analysis was to identify all actors that have an interest in relation to tyre microplastic emissions and categorize them into subsets. Finally, only the most relevant actors from the Dutch and European stakeholder networks were included. Secondly, the respective interest of each subset was formulated as well as their relation to tyre microplastics. Thirdly, the interrelations between stakeholders were defined, using the following relations:

- *Formal reporting*: relationship between same-level authorities or between organizational and executing entities, e.g., formal reporting regarding agreements, legislation or commissions.
- *Trade relationship*: tyre-related trade of financial exchange between actors.
- *Non-financial support*: a strong connection between entities that is based on shared goals rather than financial incentives.
- *Indirect influence*: no strong personal connection, but indirect involvement within a certain topic, e.g., collaboration in a bigger workgroup, lobbying or sharing knowledge.
- *Member-association relationship*: the relationship between an individual company and an association that represents the interests of that specific group.

Lastly, a visual representation of the result was made in the form of a stakeholder network map (Missonier & Loufrani-Fedida, 2014; USAID Learning Lab, 2019). The stakeholder network map was verified via written feedback from several stakeholders with a good understanding of the network.

Individual contact with a number of stakeholders was established and maintained during the study to obtain data and acquire insight into individual stakeholder interests. To facilitate this process, a sounding board group was set up to quickly receive feedback from experts and to make use of their stakeholder network. The sounding board consists of representatives from the tyre manufacturing industry, End-of-Life industry, academia and independent researchers. During the research period, one plenary consultation moment was organized in addition to contact moments with individual members of the sounding board group.

A stakeholder workshop was organized to validate the study's results, i.e., the supply chain map (Figure 1) and the quantified emissions (Figure 3). Thirteen participants attended the workshop, representing most stakeholder subsets. Unfortunately, no representatives from media and governmental institutions were able to join. The workshop was performed in the interactive online platform MIRO. The workshop started with an introduction to the research project and by the participants. This was followed by a brief discussion on microplastic-related challenges observed in the different sectors to learn more about each other's perspectives. Most time was spent on discussing the supply chain map and the quantified emission streams. Written feedback, a poll tool and questions were used to facilitate this process. The workshop ended with participants sharing possible mitigation measures and potential obstacles. Information with supporting figures was sent to the attendees beforehand.

Stakeholder subset	Interest	Relation to tyre microplastics
Suppliers	Making a living from high-quality raw materials.	No strong focus on TWRP/TWP.
Tyre manufacturers	Stay competitive in the market to maintain revenue. Improve products in terms of costs, performance and sustainability.	Dealing with pressure to produce tyres that emit fewer tyre microplastics, partly by funding research, organising knowledge exchange and contact with EU authorities. Prevent factual inaccuracies from causing image.
Distributors	Maintain sales with sufficient profit to make a living, while complying with legislation.	Stay up to date on tyre innovations and legislations, while meeting the wishes of the customer.
Consumers	Being able to buy safe and durable tyres for a good price. Some will value sustainability more than others.	With current tyre labels, it is difficult for consumers to compare tyres in terms of TWRP/TWP release. Might change (driving) behaviour or purchases to limit TWRP release.

End-of-Life industry	Maintain a stable inflow of tyres of a certain quality to make a living from the produced product.	Mechanical recycling is considered a circular option by the industry and is the most common route. This results in the need for a sales market for granulation.
Science	Provide scientific-sound knowledge to citizens, policy-makers and the industry.	Distinguishing facts from beliefs by filling in the data gaps around tyre microplastics.
Authorities	Provide and execute guidelines and legislation to protect both citizens and the environment.	Balancing economic and environmental needs based on the information available.
Builders & directors of roads	Provide safe roads that require minimal maintenance.	No strong focus on the role of asphalt on TWRP/TWP release. Innovating asphalt involves financial risks as builders are responsible for maintenance for the first number of years.
NGOs	Protect the environment and the health of citizens	Aims to limit the amount of tyre microplastic release as much as possible, though none have tyre microplastics as their main focus.
Reuse product market	Being able to buy safe and durable reuse products, such as granulate.	Need to manage new regulations and public opinions on the reuse product.
Media	Draw attention to topics that are considered socially relevant and/or that the public is interested in.	Broadcast specific journalistic items and highlight new research developments related to tyre microplastics.

Table 1. Identified stakes regarding the project per stakeholder subset

2.2.2 Results

Table 1 shows the different identified stakeholder subsets, including their interest and relation to tyre microplastic emissions. The stakeholder network map is shown in Figure 2. The network can be seen as having two planes, of which the Dutch network forms the lower national level and the European the higher overarching level. Between the planes, there are several points where the two levels are linked, e.g., by specific collaborations between actors, such as between the European Tyre Manufacturers Association (ETRMA) and the RecyBEM, but also through universities and research institutes which act on both levels. Furthermore, the national and European planes both have different objectives in relation to tyre microplastics. The European level aims to change the landscape through a top-down approach, e.g., by drafting and implementing European regulations around tyres, infill material and vehicle emissions, but also through developing universal testing and modelling methodologies. The Dutch level, on the other hand, has a strong national focus that also gives space for more direct initiatives, such as the Choose the Best Tyre campaign focused on responsible tyre purchase and maintenance. In addition to these two planes, several clusters can be distinguished within the network, such as a cluster related to the supply chain map and a cluster around governmental institutions. Specific initiatives or collaborations, such as the TWRP platform at the European level and the *Choose the Best Tyre* campaign at the Dutch national level, connect these clusters by bringing together individual stakeholders. Moreover, specific actors can be identified that form a main axis through which clusters are connected. At the Dutch level, the RecyBEM is an important central stakeholder by having different connections to a number of stakeholders and by being involved in several tyre-related initiatives in the Netherlands. Another central stakeholder is the ETRMA at the European level. The overall connectedness of the stakeholder network is relatively high due to existing initiatives and collaborations.

Both individual conversations and the stakeholder workshop revealed a shared feeling of urgency among stakeholders to reduce tyre microplastic release. This is also reflected in the high number of studies and research projects carried out by universities and research institutes (e.g., LEON-T, LABPLAS Project) and the activities initiated by the industry, such as funding research (e.g., Tyre Industry Project) and CSR Europe being the European TWRP platform's facilitator. Despite these shared ambitions, it appears as if stakeholders have different ideas on how to tackle the issue. Some of these ideas rely on technology, such as improved tyre labels and end-of-pipe innovations (e.g., the Tyre Collective), whereas others see a bigger role in societal change, such as interventions to reduce driving and the use of SUVs. The divergence in prioritized ideas is possibly the result of underlying interests that form the boundaries in which innovations or changes are considered desirable.

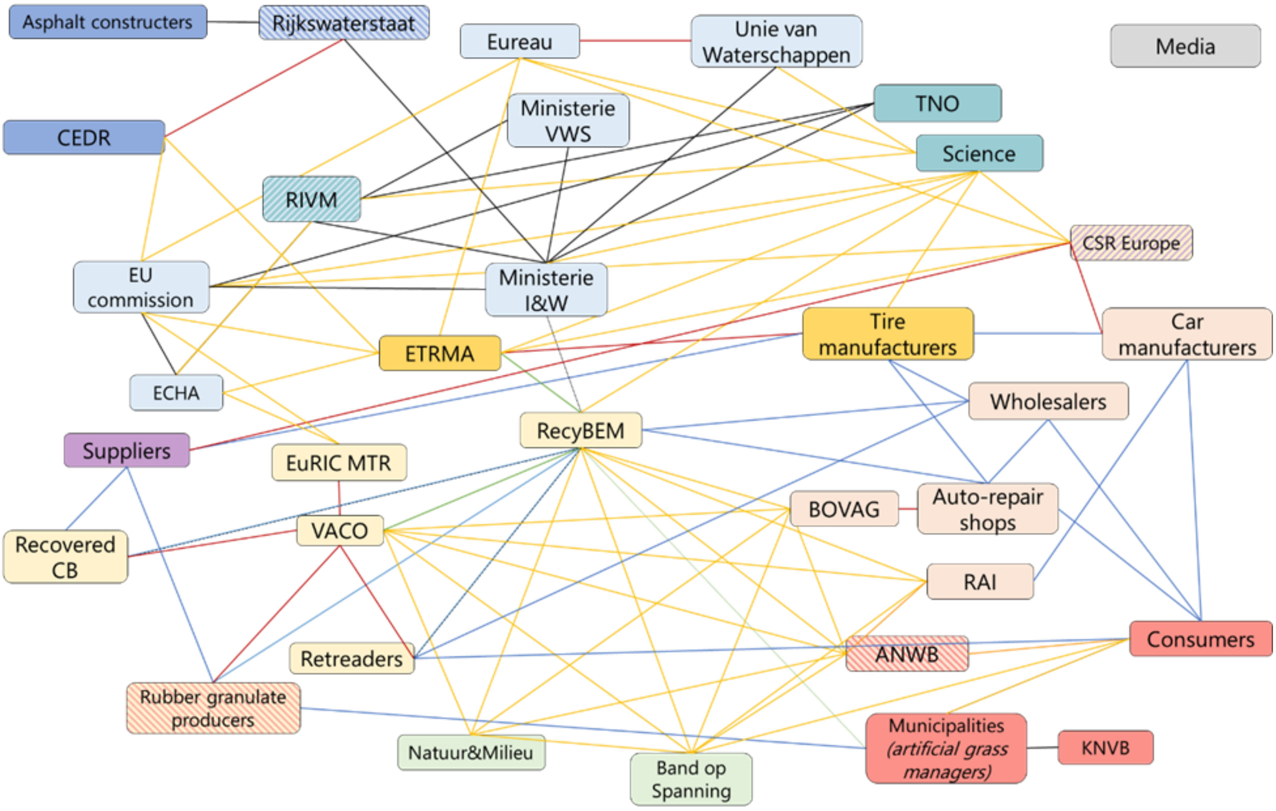

Figure 2. Stakeholder network map. Boxes represent stakeholders, where a different color is given to each subset. Purple refers to suppliers of raw materials; dark yellow to tyre manufacturers; light pink to distributors, dark pink to consumers of tyres and/or artificial turf infill; light yellow to actors in the End-of-Life industry; turquoise to science; light blue to authorities; dark blue refers to the road sector; green to NGOs. Media is shown in grey and as a separate unit due to its character as a communication channel. Striped boxes show actors that can be categorized into two subsets. The lines represent the (dominant) connection: black for formal reporting; blue for trade relationships; green for non-financial support; yellow for indirect influence; and red for member-association relationships.

2.3 Estimate of SMNP emissions

2.3.1 Methods

The tyre microplastics emissions were quantified based on a Material System Analysis (MSA) approach. MSA focuses on the flows of an individual material or natural resource within a system, including lifecycle-wide inputs and outputs, and is a subcategory of material flow analysis (OECD, 2008). The MSA methodology follows a similar procedure as that of a traditional material flow analysis. For each process, the material streams that relate to tyre microplastics emissions were tracked and quantified. Based on the mass of these material streams, the tyre microplastic emissions were quantified using an estimated loss value per mass unit. The initial emission streams from the supply chain were modelled over the environmental pathways to determine the environmental release. Lastly, a visual representation was made to present the results.

2.3.2 Mass flows

Data from the RecyBEM, the Dutch organization responsible for used tyre collection, and the European Tyre Manufacturers Association (ETRMA) was used to determine the number of tyres entering the model's system (ETRMA, 2022; RecyBEM, 2022). To calculate the weight in tonnes, an average weight of 8kg and 80kg for passenger car tyres and bus- and truck tyres was used, respectively (Continental, 2013). The passenger car tyre stock was calculated using data on the number of vehicles in use in 2021 (CBS, 2021). The bus and truck tyre stocks were estimated by multiplying the input of tyres by four representing the average lifespan of a tyre, i.e., 4 years (Hillenbrand et al., 2005). Of the collected passenger car tyres, 71% were mechanically recycled, 26% were sold on the reused tyre market, 1.1% was retreaded, 1.7% was incinerated and 0.2% was used for alternative purposes (RecyBEM, 2022). Of the collected bus and truck tyres, 20% was estimated to be retreaded, 26% to be reused and 54% to be mechanically recycled to rubber granulate (VACO, 23 September 2022). Rubber granulate was, subsequently, used in products, such as molded objects, safety and roof tiles and infill for artificial turf (RecyBEM, 2022).

2.3.3 TWP emissions

To calculate the TWP emissions emitted during the user phase, the Emission Factors (EF) (in mg/km) from Gebbe & Hartung (1997), Luhana et al. (2004) and ADAC (2021) were used. These three studies were selected as these are considered the most trustworthy studies (Mennekes & Nowack, 2022). The average weight loss percentage per tyre type was determined using a formula that included the Emission Factor, the average tyre weight and the average mileage per tyre's lifespan. An average mileage per tyre of 55.000 and 80.000 km for passenger car tyres and bus- and truck tyres were used, respectively (Boulter, 2005; GRPE, 2013). This resulted in an average weight loss of 14% over a tyre's lifespan, which is in line with the 10% to 30% weight loss found in the literature (Grigoratos & Martini, 2014; Wik & Dave, 2009). With an average lifespan of 4 years (Hillenbrand et al., 2005), the estimated weight loss was 3.5% per year per tyre.

TWP can be captured in asphalt, particularly very open asphalt (ZOAB) which covers the majority of the Dutch highways (Geilenkirchen et al., 2022). Its capturing capacity is a side effect of the asphalt's open pores primarily aimed to improve drainage. As the ZOAB asphalt roads are cleaned twice a year and the wastewater is disposed of properly, the captured TWP do not contribute to environmental emissions (Rijkswaterstaat, personal communication, 2 May 2022; Geilenkirchen et al., 2022). The part of the TWP that is not captured in the asphalt will either be transported to the roadside, due to wind, splash water and traffic-induced turbulence, or to the sewer system or surface waters, due to runoff (Baensch-Baltruschat et al., 2020; Verschoor et al., 2016). Another share of the emitted TWP is airborne, contributing to the particulate matter in the air. This fraction likely deposits outside the system's borders (Evangeliou et al., 2020; Kole et al., 2017) and is therefore excluded from the total emission calculations. As there are important differences in pathways between different types of roads, e.g., due to differences in asphalt and connectedness to the sewer, a distinction was made between urban and rural roads and highways.

The sewer system in the Netherlands consists of 66% of combined sewers and 34% of (improved) separate sewers (Liefting & de Man, 2017). In the combined sewer system, the household and industry wastewater is collected together with road runoff and treated in a central wastewater treatment plant (WWTP). In case of large precipitation events, the combined inflow can result in combined sewer overflows in which part of the wastewater could be discharged to surface waters without further treatment (Brombach et al., 2005). In separate sewer systems, the road runoff is collected separately from the household and industry wastewater, limiting the risk of combined sewer overflows. However, the untreated road runoff is often discharged directly to surface waters (Kole et al., 2017). The improved separate sewer system partly bypasses this problem by transporting the sewage water to a WWTP as long as there is capacity (Liefting & de Man, 2017).

2.3.4 Turf emissions

To determine the microplastic emissions from artificial turfs, the mass balance by Kole et al. (2023) was used. This study was used as it is one of the most extensive literature studies available. The emissions as a result of snow clearing were omitted, due to the limited snow days in the Netherlands. The yearly weight loss per m2 of turf was determined using the absolute weight loss per field per year and dividing it by the m2 per field, as provided by Kole et al. (2023). To extrapolate this to the entire Netherlands, it was estimated there were 2688 large turfs and 5052 small turfs in the Netherlands in 2021 (Hann et al., 2018; Oldenkotte, 2017), translating to a total of 2326 ha of artificial turf.

Part of the emitted infill particles will be prevented from reaching the environment, e.g., by collection of infill granules from clothes and shoes or by cleaning maintenance equipment (Løkkegaard et al., 2019). Emitted infill particles that are not captured will be either transported to adjacent soils or paved areas or to the sewer system, as a result of processes such as runoff, movement and housekeeping activities (Løkkegaard et al., 2019; Regnell, 2019). The distribution of the environmental pathways was based on Løkkegaard et al. (2019).

2.3.5 Results

Figure 3 shows the material streams of the MSA and the quantified emissions to different environmental compartments. It shows that in 2021 112,600 t/y of tyres entered the Dutch system, of which 67% are passenger car tyres. The tyre stock counted around 469,500 t/y in that year. Driving resulted in approximately 16,650 t/y of TWP emissions. The emissions from artificial turf in the form of infill granules were estimated to result in approximately 5,940 t/y. Hence, 74% of the initial emissions are caused by the user phase. From the generated emissions, approximately 40% was captured before release to the environment.

The airborne TWP fraction was estimated to be 0.5% for highways and 1% for urban and rural roads (Grigoratos & Martini, 2014; Janssen, 1996). On highways, it was estimated that 80% of the generated TWP is captured by the ZOAB asphalt, 18% ends up at the roadside and 2% is emitted directly to surface waters (Verschoor et al., 2016). On urban and rural roads, 40% of the generated TWP was estimated to end up at the roadside and 60% to be transported to the sewer system (Verschoor et al., 2016). For emitted infill particles it was estimated that 52% ends up in adjacent soils or paved areas, and the remaining share flows into the sewer system (Løkkegaard et al., 2019). Of the tyre microplastics that enter the sewer system, 22% infiltrate into the soil, 52% are captured by the combined sewer system and 26% by the (improved) separated sewer system. From the combined sewer system 8% is discharged directly to surface waters without further treatment, due to incorrect connections or overflows. The remaining portion is transported to the WWTP (Liefting & de Man, 2017). From the (improved) separated sewer system, 82% is released to surface waters without treatment. The remaining 18% joins the sewage from the combined sewer to the WWTP (Liefting E & de Man, 2017). Here, 88% is removed and captured in the sludge, after which it is incinerated. The remaining 12% is released to surface waters as effluent (Iyare et al., 2020; Liefting E & de Man, 2017; van Egmond et al., 2021).

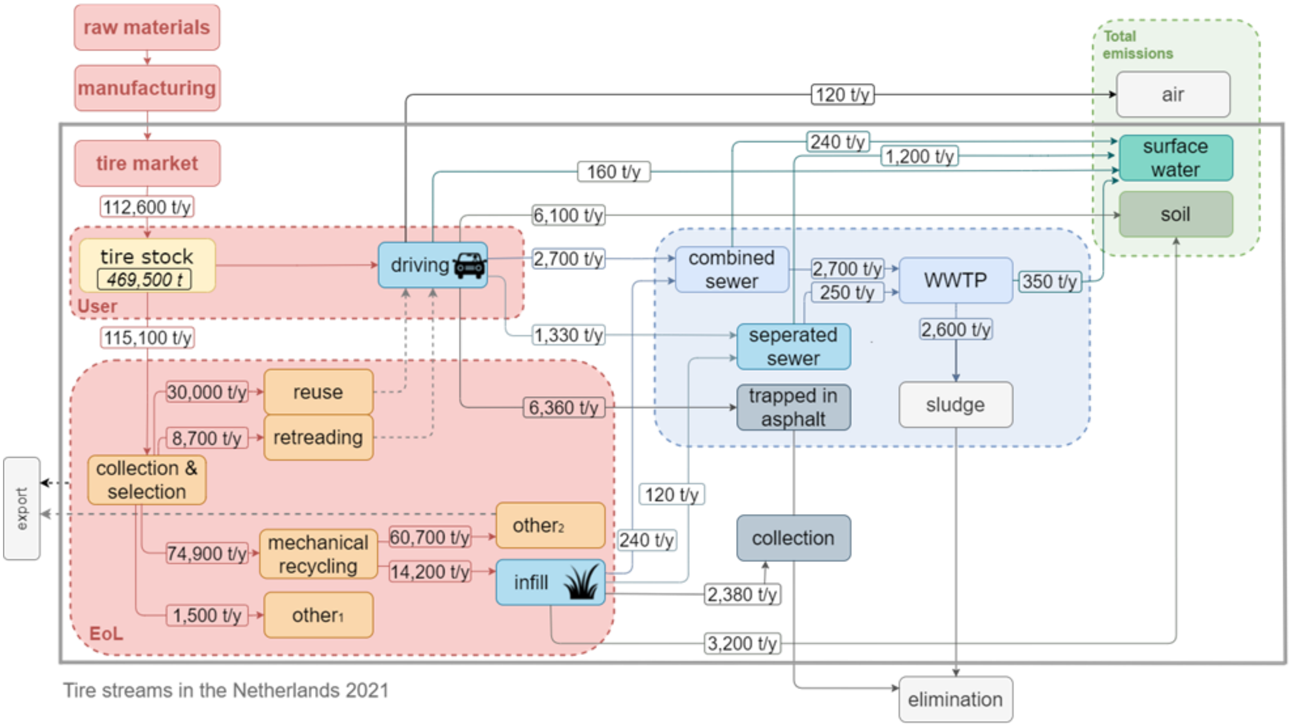

Figure 3. Material System Analysis for the Netherlands, 2021. Streams are shown in tonnes (kg) per year and are rounded. Other1 includes retreading, incineration and repurposing. Other2 includes agricultural mats, rubber tiles, molded objects, bedding construction for artificial turfs, rubber powder, rubber in asphalt and additional purposes.

Table 2 shows both the total mass flow of the estimated emission streams and the emission streams in kg per capita for the year 2021. That year the Netherlands counted 17.533.405 inhabitants (Worldbank, n.d.). As shown in the table, the majority of the tyre microplastics end up in the soil (83%) and 17% is received by surface waters.

Tyre microplastic emission streams in 2021	Mass flow (t/y)	Per capita (kg/cap/year)
Total initial release	22,590	1.29
Initial release as TWP from tyres (user phase)	16,650	0.95
Initial release as granules from infill (End-of-Life phase)	5,940	0.43
Total release to the environment	11,250	0.64
Release as TWP to the environment	7,880	0.45
Release as infill to the environment	3,370	0.19
Release to soil	9,300	0.53
Release to surface water	1,950	0.11

Table 2 Summary table of tyre microplastic streams for the Netherlands with 2021 as year of interest

2.4 Potential emission reduction measures

We identified a list of interventions to reduce tyre microplastics emissions based on a scan of the public literature and dialogues with stakeholders (see below). This is a preliminary list of interventions that will be further expanded and explored regarding feasibility and effectiveness in the next stage of the LABPLAS project. The interventions are organized in four main categories reflecting different stages of the tyre life cycle, i.e., (1) tyre design and manufacturing, (2) tyre use (driving), (3) End-of-Life (EoL) and (4) End-of-Pipe (EoP).

2.4.1 Tyre design and manufacturing

Improving the tyre design/composition and structure of tyres:

- Regulatory instruments in the form of substance bans and Best Available Technology (BAT).
- Economic instruments in the form of subsidies and taxes force companies to set new limits for the wear resistance of their tyres.
- Voluntarily instruments in the form of eco-design initiatives and voluntary commitments from actors.

Implement a legal threshold for tyre wear:

- Regulatory instruments, such as minimum standards, likely in combination with an economic instrument in the form of fines.

Include tyre wear in the tyre label (eco-labelling):

- Regulatory instruments in the form of certification schemes and labelling.
- Economic instruments in the form of subsidies and taxes.
- Voluntarily through enhanced sustainable decision-making of customers

Universal tyre wear test:

- Define definitions and terminology, to then standardize emission factors or methodologies of TRWP release.
- This can be obtained by mandating or encouraging the development of standardized and harmonized microplastic definitions. Set biomarkers to calculate TWRP in environmental samples. Economic by green procurement where companies are paid to develop methodologies.

2.4.2 Tyre use (driving)

Direct capture of generated TRWP:

- An example is the innovation by the Tyre Collective.
- Regulatory instruments through making use mandatory.
- Economic instruments through fines, subsidies and/or taxes.
- Voluntarily instruments were consumers or producers decide themselves to install it through enhanced awareness.

Improve tyre use and maintenance:

- Improve tyre pressure by behavioral change or technological tools, such as the smart tyre pump, PMS in older cars, or changing the settings of PMS.
- Improve correct wheel alignment by making it mandatory in the periodic vehicle inspection or using voluntary instruments, such as behavior.
- Regulate the use, tax or ban studded tyres or raise awareness to reduce unnecessary use could help reduce emissions from the use of studded tyres.

- Prohibit the use, implement fines for incorrect use or raise awareness to prevent/discourage the use of winter tyres in summer.

Eco-driving:

- Promotion by including it in driving lessons or implementing (and checking) speed limits.

Reduce the vehicle weight:

- Promote the use of light vehicles over SUVs by labelling, legal limit, subsidies, taxes.

Reduce driven kilometres:

- Economic: kilometre price (economic instrument) or promoting/subsidizing public transport.

Improve road surface:

- Road innovations aimed at reducing abrasion or include a filter to capture TRWP
- Improve road topography, such as reducing corners.
- Timely road management to repair the surface or improve capturing by road sweeping, snow removal and dust binding.

2.4.3 End-of-Life

Improve turf design (during the laying of the field):

- Improve the design of the carpet (tuft density, thatch zone, shock pads). Reduce the slope of the turf's surface. Can be obtained by green procurement.

Maintenance strategies and good housekeeping:

- Such as regular brushing and drag matting, installation of drainage slit traps, separate collection and treatment of turf runoff and to use dedicated storage areas for snow clearance or piling snow on the pitch. Installing brushing stations for shoe cleaning at entrance points through legal requirements, subsidies or taxes. The installation of physical barriers through legal requirements, subsidies or taxes.

Use alternatives to granulated turf.

2.4.4 End-of-Pipe

Interventions to treat or capture road runoff:

- Implement runoff treatment installations or drainage systems by installing sedimentation, gully pots, filter strips, infiltration chamber systems, bio-retention systems (such as swales) or road runoff treatment procedures. Can be obtained by regulatory instruments, such as environmental quality standards, best available techniques, green public procurement. Economic instruments: Subsidies for improved stormwater management and/or road dust collection, Payments for Ecosystem Services.

Improve WTTP cleaning efficiency:

- Implementing additional cleaning steps or prevent the usage of sludge as artificial fertilizer.
- Regulatory instruments, such as Environmental Quality Standards (EQS); Best available techniques (BAT); wastewater treatments standards; Green public procurement;
- Economic instruments: Wastewater tariffs or taxes for improvements in wastewater, Subsidies for improved wastewater treatment.

Improve waste collection (not super applicable to NL):

- More stringent rules for the separate collection and management of used tyres. Economic instruments: Extended Producer Responsibility (EPR).

2.5 Selected emission reduction interventions

2.5.1 Analyzing stakeholder views on emission reduction interventions

A second stakeholder workshop was organized to assess the views of stakeholders on the potential emission reduction measures. 14 stakeholders participated in the workshop. In preparation to this workshop, an online survey was sent to all participants. In this survey, participants were asked to evaluate a specific list of emission reduction measures based on 3 criteria (i.e., expected effectiveness of the mitigation measure, expected societal acceptance and economic feasibility) by giving each measure a score from 1 to 5 (low to high). In total, 12 participants took the survey. The list of emission reduction measures provided to the stakeholders can be found in Appendix A.1.

Based on the discussions during the workshop, it turned out that the effectiveness of intervention measures was considered the most important factor for their adoption according to stakeholders. When analysing the results of the online survey, four interventions scored highest in terms of effectiveness:

1. Make public and alternative transport cheaper (score 4.4)
2. Improve public and alternative infrastructure (score 4.3)
3. Implement speed limit (score 3.9)
4. Frequent street cleaning at hotspots (score 3.9)

Interventions 1-3 apply to the tyre use phase (2.4.2) while intervention 4 applies to the end-of-pipe (2.4.4) phase. All of these interventions aim at reducing diffuse sources of TWP.

2.5.2 Shortlist of emission reduction interventions selected by LABPLAS researchers

Based on the literature review conducted for MS21, the LABPLAS team selected additionally the following interventions as promising options:

5. Optimal tire pressure + wheel alignment
6. Particle capture devices
7. Improved wastewater treatment plants

Interventions 5 and 6 tackle again the tyre use phase and are expected to mainly reduce emissions from diffuse sources while intervention 7 tackles the end-of-pipe phase, reducing emissions from point sources (i.e., WWTPs) into the rivers.

2.5.3 Quantifying the emission reduction potential per intervention

In this section, the emission reduction potential of shortlisted interventions presented in sections 2.5.1 and 2.5.2 are summarized and quantified. A more detailed description on the advantages and disadvantages of those interventions can be found in Gehrke et al. (2023).

Improvements and reduced costs for public and alternative transport

Interestingly, the two interventions that scored highest in terms of expected effectiveness by stakeholders are often mentioned in studies (e.g., Piras et al., 2024; Verrips and Hilbers 2020; Gehrke et al., 2023) but seem to be difficult to quantify in terms of emission reduction potential for TWP based on literature. This is an interesting finding in itself but challenges the estimation of model-based emission reductions. Since the implications and effects of those two interventions are likely context- and location-specific, evaluating their effectiveness within the ePLAS model seems unfeasible.

Imposing speed limit on highways

Imposing a maximum speed limit can effectively reduce emissions of air pollutants and TWP. A study by Michelin in 2010 suggests that reducing the speed limit from 120-130 km/h to 100 km/h could extend tyre lifetime by 20% to 30%. While an increased life span of tyres does not directly indicate a reduction in tyre wear emissions, it does postpone them and therefore reduces TWP over the course of several years. For this case study, a tyre life span of 4 years was assumed with a 10-30% mass loss over this period, translating into an annual loss of 2.5-7.5%. An increased life span of 20-30% results in a tyre lifetime of 4.8-5.2 years and reduces the annual mass loss to 2-5.8%.

Frequent street cleaning of hotspots

Based on the literature review of Gehrke et al. 2023, mechanical and vacuum cleaning devices for street cleaning remove TWP to varying extents depending on particle size. This intervention seems more effective for larger particle sizes (>100um) than for smaller (e.g., Amato et al., 2010; Vogelsang et al., 2020, Gerke et al., 2023). The in-depth study conducted by Venghaus et al. (2021), investigated the effect of increased street sweeping at main and crossroads in Berlin and reports a reduction potential of 36-42% for TWP entering the sewer system. Amato et al. (2010) reports an average street cleaning efficiency increases from 26% to 64% with increasing particle size. In summary, the effectiveness of more frequent street cleaning at hotspots is likely location-specific and requires an in-depth analysis of traffic hotspots at a high spatial resolution. Despite several publications emphasizing the potential positive effect of this intervention, at the current spatial scale of the ePLAS model it is considered unfeasible to quantify its impact at catchment level for the the Elbe River.

Optimal tyre pressure and wheel alignment

Research by the Dutch Organization for Applied Scientific Research (TNO) emphasizes the environmental impact of under-inflated tyres, illustrating a direct relationship between tyre pressure and the emissions of nitrogen oxides (NO_x) and particulate matter. Specifically, diesel vehicles exhibit a 0.9% increase in NOx emissions under conditions of tyre under-inflation, while gasoline vehicles show a 1.5% increase. Moreover, the study also indicates that proper tyre inflation alone can prevent 3.2% of all fine dust emissions, highlighting that maintaining the correct tyre pressure can significantly reduce the emission of TWP. Since TWP contribute substantially to PM10 emissions (more so than exhaust form diesel cars (Piras et al. 2024)), it is assumed that this 3.2% reduction to fine dust emissions refers predominantly to reduction on TWP.

Particle capture devices

The intervention measure on particle capture devices is inspired by the ZEDU-1 project of the German Aerospace Center (DLR, 2021). This intervention entails installing a kind of vacuum airflow device into cars and other vehicles. This device collects TWPs while driving and could under ideal circumstances result in a 90% reduction in TWP emissions. While it is unclear how realistic the implementation of this intervention is, given this technology seems promising, it is interesting to calculate its potential impact on catchment level.

Improvements to WWTPs

Reported removal rates of microplastics in general vary depending on treatment technology, plastic material, particle size and shape (Gehrke et al., 2022; Sun et al., 2018; Obermaier and Pistocchi 2022). In general, empirical field measurements for TWPs are scarce (Mennekes and Nowak 2022), especially for WWTPs (Gehrke et al., 2022). The divergent range of reported removal efficiencies is linked to a lack of standardization in sampling and analysis of microplastics (Sun et al., 2018; Obermaier and Pistocchi 2022). Overall, particles larger than 300um are well-removed (around 90%) by conventional treatment systems (Obermaier and Pistocchi 2022). Smaller particles (<300um) and fibres are less well removed and enter the environment in larger numbers. Advanced treatment steps such as membrane filtration or dissolved air flotation increase removal to 99% and 95% respectively (Talvitie et al., 2016, Obermaier and Pistocchi 2022). For this case study, it was assumed that all WWTPs within the Elbe catchment were upgraded with an advanced treatment step. To be conservative, a removal efficiency of 95% was assumed for particles smaller than 300um.

2.5.4 Defining an emission reduction scenario for the Elbe River catchment

Based on the list of identified interventions (2.5.1 and 2.5.2) and their expected emission reduction potential (2.5.3), four interventions were selected and their impact in terms of particle number reduction were calculated within the ePLAS model for the Elbe catchment:

1. Implementing a speed limit at 100 km/h;
2. Optimal tire pressure and wheel alignment;
3. Particle capture devices;
4. Improved particle retention in WWTPs.

2.6 Estimating the emission reduction potential using ePLAS

2.6.1 The ePLAS model in a nutshell

The ePLAS model is a steady-state river network model that simulates the transport of microplastic particles within European river basins. The model uses the infrastructure of the ePiE model which was originally developed to estimate concentrations of pharmaceuticals in European surface waters (Oldenkamp et al., 2013).

The ePLAS model represents a system of connected rivers and lakes. It consists of dots (nodes) which are typically 1 km apart and which can represent different system elements, e.g., a river stretch, a WWTP discharge, a confluence, a bifurcation or a lake. The river hydrology of the ePLAS model relies on the FLOW1K dataset (Barbarossa et al., 2018), providing annual mean flow, and the highest and lowest monthly mean flow based on an ensemble of artificial neural network regressions, with upstream-catchment physiography (area, slope, elevation) and year-specific climatic variables (precipitation, temperature, potential evapotranspiration, aridity index, and seasonality indices) as covariates.

The environmental fate processes of the original ePiE model (e.g., advection, sedimentation and resuspension) were adapted to better represent the fate of microplastics in rivers. Furthermore, hetero-aggregation and bed load transport were added as microplastic-specific fate processes. More details on the ePLAS model are provided in Deliverable 7.1 (Sun et al., 2025).

2.6.2 Case study area: the Elbe River basin

In the current case study on tyre wear, the ePLAS model was used to quantify the environmental impact of the selected emission reduction scenarios (section 2.5). The Elbe River basin, one of the case study areas of the LABPLAS project, was selected to demonstrate the impact of these emission reduction scenarios.

The Elbe is a major river in middle-northern Europe. The river originates in the Giant Mountains in Czech Republic, flows through Germany and ends into the North Sea. It flows through four countries, whereby most of the river basin is located in Germany (65.5%) and the Czech Republic (33.7%) and less than 1% is located in Austria (0.6%) and Poland (0.2%). The Elbe River basin covers a total surface of 148.268 km^2 and is inhabited by approximately 25 million people (Figure 4).

Figure 4. The Elbe River catchment.

This Elbe case study consisted of the following steps:

1. Estimation of current tyre wear emissions into the Elbe River. These emissions were estimated based on national per capita emission data for tyre wear as reported by Sun et al. (in prep.). The database underlying ePLAS provides the number of people living in each WWTP agglomeration. Based on these numbers, the total number of microplastics discharged in the Elbe through WWTPs (= point sources) were calculated. This was done by multiplying the national per capita tyre wear emission with the number of people living in a WWTP agglomeration, the (national) WWTP connection rate and the (national) WWTP removal efficiency. The result reflects the tyre wear emission per WWTP. Furthermore, the total emission from diffuse sources was calculated by multiplying the number of inhabitants from a specific country living in the Elbe basin with the national per capita emission and the national population fraction not connected to a WWTP. Subsequently, this total diffuse load is distributed evenly over all the Elbe River nodes that belong to that specific country. More details on this estimation procedure are provided in Deliverable 7.1 (Sun et al., 2025).

2. Running the ePLAS model to quantify the environmental impact of current emissions. We defined three endpoints of interest to quantify this impact, i.e., (1) the number of microplastics per time unit discharged at the mouth of the basin (Hamburg) into the North Sea, (2) the number of microplastics in the water phase averaged over all Elbe river nodes, and (3) the total number of microplastics in the water phase summed over all Elbe river nodes. In this deliverable we focus on the first endpoint, i.e., the number of microplastic particles discharged at the mouth of the Elbe River. The other endpoints are reported in Appendix A.2.
3. Running the ePLAS model to quantify the environmental impact of the emission reduction scenarios.The impact of each intervention (Section 2.5) was separately quantified. The results are reported in Appendix A.2. These results are discussed below.

2.6.3 Results of the emission reduction scenario for the Elbe River basin

The emission reduction potential was calculated per intervention as outlined in section 2.5. As expected, the largest reduction in particle numbers, approximately 90%, can be attributed to one specific measure, i.e., the installation of particle capturing devices. The impact of the other interventions is substantially smaller with a 3.2% reduction for optimal tyre pressure and wheel alignment, a 20% reduction for a reduced speed limit (i.e., to 100 km/h) and a reduction varying between 0.2-29% for an improved WWTP removal efficiency (i.e., of 95%). The impacts of the individual interventions per particle size and per environmental compartment, i.e., water phase and sediment phase, are specified in Appendix A.2.

For 3 out of 4 interventions, the impact is similar across all endpoints considered. Hence, these interventions result in similar reductions in microplastic numbers, whether the total or average number of microplastic particles in the river water is considered, or the total number of microplastic particles transported to the North Sea. The only exception is the improved WWTP retention capacity, which results in a 1-29% reduction in the number of particles transported to the North Sea, but only a 0.2-2.6% reduction for the total and average number of particles in the Elbe basin. This result can be explained by the dominant role of point source (=WWTP) discharges at the river mouth. In rural areas, diffuse sources dominate over point sources and improved WWTP retention has a relatively small impact on the number of tyre wear particles in the river. Urban areas, like the Elbe River mouth, will be dominated by point sources because of the relatively high population density. In these areas, an upgrade of WWTP retention can have a significant impact on the number of tyre wear particles in river water.

2.7 Evaluation and critical reflection

This case study on tyre wear was set up to illustrate how the tools and estimation techniques developed in LABPLAS can be applied in collaboration with stakeholders to develop an optimal emission reduction strategy for tyre wear. In this section, we first reflect on the results obtained, i.e., the estimated tyre wear emissions and the estimated impact of the interventions on the levels of tyre wear in rivers and the amounts exported to the ocean. Next, we reflect on the involvement of stakeholders in this case study.

2.7.1 Estimation of tyre wear emissions and environmental impacts

We followed a source-to-ocean approach to estimate tyre wear emissions, to describe their fate in riverine systems and evaluate the effectiveness of potential interventions. The results of this case study are as good as the data, the process equations and the assumptions underlying this case study. In the sections below, we first reflect on the emission estimates, followed by the estimation of the emission reduction percentages of the interventions and the fate modelling. We conclude by reflecting on the usefulness of source-to-oceon modelling.

Emission estimation

Emission estimates are the main drivers of source-to-ocean modelling. Any error in emission estimation directly translates into an error in predicted environmental levels. The emission estimates applied in this study were based on Sun et al. (in prep) who estimated average per capita emissions for EU member states. As discussed by Sun et al. (in prep), these estimates are prone to several uncertainties such as the emission estimation method applied, and data used to parameterize these methods (e.g., the emission factor). Differences up to a factor of 3 between methods are common. In this study, we used the average over three alternative estimation methods.

After tyre wear is generated at the interface between the tyre and the road surface, it can reach surface waters through different pathways. We included two major pathways in our estimation approach, i.e. runoff from the road surface to the sewer system, subsequent treatment in a WWTP and then discharge into surface water (point sources), and direct discharge into surface waters (diffuse sources). The number of particles in runoff is difficult to quantify because of the importance of site-specific conditions which can vary strongly from place to place, and because of a lack of empirical data on tyre wear in runoff. Examples of important site-specific conditions include the number of particles captured in the asphalt or in local drainage systems. Furthermore, the retention of tyre wear particles in WWTPs is an important source of uncertainty. Empirical data show considerable variability in WWTP retention and often these data do not specifically to tyre wear but to microplastics in general. The typical characteristics of tyre wear (relatively large particles with a high specific density) might result in a higher WWTP retention than for other microplastics. On the other hand, combined sewer overflows are typically not accounted for in WWTP retention data, resulting in an overestimation of the actual WWTP retention (depending on the frequency and extent of the overflow events).

The (assumed) spatial distribution of emissions is another important source of uncertainty in our case study, especially for diffuse sources. We estimated diffuse emissions based on national per capita emissions and distributed these emissions evenly over the length of the river. In reality, runoff from roads will be highly location-specific depending on factors such as the number of roads, the use intensity of these roads and the drainage infrastructure in place. It is likely that the runoff from roads in urban areas will result in higher tyre wear loads than runoff in rural areas, but the runoff from roads in urban areas is more likely to be led to a WWTP than in rural areas. Since detailed empirical data or proxies on these factors are lacking, we currently adopted a rough approach resulting in considerable uncertainty.

Emission reduction percentages of the interventions

Next to uncertainties in the estimated baseline emissions, there is considerable uncertainty in the estimates of the effectiveness of the different emission reduction interventions. This uncertainty can be caused by a lack of data on empirical data on the technical effectiveness of an intervention, but also by factors such as the success rate of voluntary measures (e.g., for maintaining tyre pressure) and the application domain of the intervention (e.g., the introduction of a speed limit of 100 km/hr will only affect tyre wear emissions on highways and not on rural and urban roads). As such, the expected emission reductions of the four interventions that were considered in the current case study have considerable uncertainty. Before these interventions are applied in practice, we recommend a critical evaluation of these emission reduction percentages, preferably based on the consideration of location-specific data and conditions.

Fate in riverine systems (ePLAS)

We used the ePLAS model to evaluate the fate of the estimated tyre wear emissions in the Elbe River basin. The ePLAS model is a steady-state network model with tailored process equations to model fate processes of plastic particles, such as advection, bed load transport, sedimentation and aggregation. However, it should be realized that the steady-state assumption is debatable for highly dynamic systems such as rivers, and that modelling fate processes of microplastic particles is still in its infancy. The intention is to improve ePLAS over time, e.g., by developing a dynamic version and by updating the process equations. Initial validation exercises indicate that the predictions of ePLAS are within one order of magnitude of measured data. However, this validation exercise was limited in extent and ePLAS should definitely not be used for the prediction of site-specific concentrations at a specific moment in time. The idea is that ePLAS indicates trends and patterns in microplastics transport in European riverine systems.

Usefulness of source-to-ocean modelling

Considering the extensive uncertainties outlined in the sections above, the question arises what the added value of our results is. The uncertainty in the predicted endpoints is at least a factor of 10. Nonetheless, the results provide an indication of the trends and patterns in tyre wear emissions into river systems and the resulting tyre wear levels in riverine systems. The big advantage of source-to-ocean modelling is that the results (in terms of emissions and predicted levels) can be traced back to sources, activities and interventions. In that sense, the prediction of trends and patterns (i.e., the relative performance of the model) can still be useful even if the absolute values (e.g., the predicted number of particles) deviate substantially from reality. An interesting example is the predicted impact of improved WWTP retention, which is larger in densely populated urban areas than in rural areas (section 2.6). This is an insight that emerged after the interpretation of the model results. The result is entirely logical, and the insight could also have emerged without the model, but application of the model and interpretation of its results facilitated the emergence of this insight. It shows that modelling can help revealing patterns and trends that may otherwise remain unnoticed. Within this context, the following conclusions can be drawn based on the simulations of the tyre wear case study:

1. Generic emission reductions at the source translate into an equivalent reduction of environmental impacts, e.g., a 10% emission reduction by traffic will (ultimately) translate in 10% lower tyre wear levels in the environment. As such, interventions at the source, such as the installation of emission capture devices in cars and other vehicles or the development and implementation of wear-resistant tyres, are likely to show the highest effectiveness in terms of reducing environmental impacts.
2. The impact of specific measures, such as the impact of a speed limit of 100 km/h specifically affecting highway-traffic, is more difficult to predict than that of generic measures. This requires data on the relative share of highway traffic compared to urban and rural traffic. Furthermore, this impact can strongly vary depending on location-specific conditions.
3. The emission reduction potential of voluntary and behavioural interventions (e.g., maintaining tyre pressure, wheel alignment, stimulating public transport and stimulating careful driving) is inherently uncertain and this uncertainty directly translates into uncertainty about the expected environmental benefits. In that sense, the gains of hard technical measures (like installing capturing devices) are much more certain than those of soft measures.
4. WWTPs constitute a source of tyre wear that can be relatively well-described and controlled. Their intensity is mainly governed by factors such as population (and traffic) density, treatment level (retention capacity) and the frequency and intensity of overflows. The spatial patterns of these emissions and the impact of emission reduction measures influencing this pathway can be captured

relatively well with the ePLAS model. Emission reductions that specifically target the WWTP-pathway (e.g., increased WWTP retention) tend to have a relatively large impact in densely populated areas.

5. Diffuse sources are more difficult to capture with the ePLAS model than WWTPs, since diffuse sources show considerable variability and are highly dependent on local conditions. Hence, ePLAS is unlikely to identify hotspots dominated by location-specific diffuse sources and accurately predict the impact of emission reductions acting on these sources (e.g., the installation of retention basins along roads draining to surface waters).

2.7.2 Stakeholder involvement

We involved stakeholders in the current case study with the idea of improving the quality and depth of the analysis, to create a common understanding of the tyre wear problem and to stimulate support for potential interventions. Stakeholders were identified and contacted in Step 2 of the case study. At the beginning of the study, considerable efforts were made to involve the tyre production and recycling industry, i.e., through organizing bilateral and group meetings where initial ideas and viewpoints were exchanged. This ultimately resulted in a constructive collaboration where the main researchers regularly contacted industry to obtain industrial data, check results and elicit their views. The contact with other stakeholder groups was less intensive and focused on participation in surveys and workshops. Some stakeholders, especially scientists, were bilaterally contacted in case of questions related to their specific area of expertise.

Stakeholder involvement initially focused on the Netherlands (Steps 1-3) and was later expanded by including more European organizations (Steps 4-6). The focus on the Dutch context made it easier to liaise with stakeholders because some stakeholders were less accustomed to international settings. As a consequence, the results of the case study are likely biased towards the Dutch situation. Nonetheless, we think that the results and conclusions emerging from the case study are also relevant for other EU member states. Many interventions considered in this case study will be generally applicable across the EU, although we advise to always take the specific national context into account when developing a (national) emission reduction strategy for tyre wear emissions.

Our hypothesis at the start of this case study was that stakeholder involvement will improve the quality and depth of the analysis, will create a common understanding of the tyre wear problem and will stimulate support for potential interventions. It is difficult to verify this hypothesis since it would require the comparison of results obtained with and without involving stakeholders. We did not do this. Nonetheless, some general observations on stakeholder involvement in the case study can be made:

1. The identification and involvement of stakeholders requires a substantial investment in terms of time and resources. It took us approximately 1 year to identify, contact, involve and build a trust relationship with stakeholders, especially industry. Understandably, industry first wanted to know what our intentions were. They indicated that they were worried about their reputation being affected in an unjustified manner. Other stakeholders were less concerned and mainly participated because they were interested in the topic and the viewpoints of other stakeholders. Exchange of information, insights and viewpoints seemed the most important reason for stakeholders to participate in the case study.
2. We regularly used stakeholders as a source of information, especially industry and researchers. Other stakeholders were contacted in case we had specific questions that related to their area of expertise. Stakeholders regularly pointed towards information and aspects of the problem that were not on our radar. In that sense, we have the impression that stakeholder involvement deepened and expanded the

scope of the analysis. This probably also fastened the analysis by pointing us to information sources that otherwise might have taken much more time to identify.

3. Exchange of information and insights with stakeholders clearly was a two-way process: the case study benefited from the stakeholders, but the stakeholders also benefited from the case study. During workshops and bilateral contacts, stakeholders regularly indicated that they obtained new insights by participating in the case study. As such, stakeholder involvement in the case study can be characterized as a shared learning experience.
4. Initially, it was our intention to discuss the modelling results of the emission reduction strategy (Step 6) with the stakeholders. We expect that such a discussion will result in new insights among the stakeholders and optimization of the emission reduction strategy. Unfortunately, this discussion turned out to be unfeasible within the timeframe of the LABPLAS project. This step will now be performed within the context of the ePLAS project of the Dutch Open University (OU).

2.8 Guidelines for stakeholder collaboration

Based on the case study on tyre wear, the following guidelines for stakeholder collaboration can be formulated to optimize the effectiveness of emission reduction measures:

1. Before involving stakeholders, it is important to consider potential costs and benefits of stakeholder involvement. Stakeholder involvement requires a substantial investment in terms of time and resources. The potential benefits, e.g., improved analysis and expected support for a common intervention strategy, should outweigh the expected costs.
2. Stakeholder involvement works best if stakeholders see a benefit in participation. This will vary between stakeholders, but an important driver for most stakeholders is the expected gain of information and insights by means of shared learning. Stakeholder participation therefore works best for topics which are still in development and where stakeholders learn through participation. Sharing the results of the study with the stakeholders is considered essential to optimize stakeholder involvement.
3. Be transparent, manage expectations and invest in a good relationship with the stakeholders, especially key stakeholders such as industry, NGOs and researchers. Do this early in the process, e.g., by first organizing bilateral meetings to clarify goals and expectations.
4. Actively control the number of stakeholders. We organized several (online) workshops where participants were expected to actively provide input. We had 10-15 participants in each workshop which was manageable and worked well. Active workshops with >20 participants are discouraged because of the risk of losing stakeholder commitment. In case of a large number of stakeholders, workshops can be combined with surveys. The results of the (larger) surveys can then be used as input to the (smaller) workshops, or the other way around, i.e., surveys can be used to verify the outcomes of the workshop.
5. A combined map of the value chain of the product considered (in our case: tyres) and the environmental impact chain of the related emissions (in our case: tyre wear) is invaluable, i.e., to identify stakeholders and obtain insight in the processes, emissions and environmental impacts involved. Such a combined map can also be used as a communication tool to create a common understanding of the problem at hand. Stakeholders should be provided with the opportunity to criticize and complement this combined map of the value chain and environmental impacts.
6. The identification and quantification of emission reduction measures and subsequent environmental impacts requires detailed technical insight into the emissions, the emission reduction measures and the subsequent environmental processes and impacts. These insights are typically captured in

(technical) estimation methods and models. The development of such methods and models can require a substantial investment in terms of time and resources. Sufficient time and resources should therefore be reserved to develop and/or apply such methods and models.

7. Ultimately, the results of the emission estimation and environmental impact models should be communicated to and discussed with stakeholders. This requires a balanced approach, i.e., communicating limited technical detail, but at the same time providing transparency about scientific uncertainties. Although it is nice to obtain consensus about potential interventions, this is not the main goal and should not come at the cost of disturbed relationships. The most important goal is the development of a common understanding of the problem and mutual recognition of each other's interest. Agreeing to disagree can also be a valuable result.

3 CASE STUDY 2: SINGLE-USE PLASTICS

3.1 Introduction

A single-use plastic (SUP) product is "a product that is made wholly or partly from plastic and that is not conceived, designed or placed on the market to accomplish, within its life span, multiple trips or rotations by being returned to a producer for refill or re-used for the same purpose for which it was conceived" (EU Directive 2019/904). Single-use plastics are goods that are made from fossil fuel-based chemicals and are disposed of right after use, mostly once and in short time after their use. Their use increased exponentially in the 70s when manufacturers replace paper, glass and other potentially re-usable and/or recyclable materials with plastic alternatives, because they were more durable and affordable. However, the short lifetime of SUP undermines one of the key properties of plastics, that is their longevity (Plastics Europe, 2020, 2021).

SUPs are the most common type of plastics produced and are difficult to recycle (Eriksen et al., 2019; Chen et al., 2021). The United Nations Development Programme (UNDP) stated that SUP products make around 86% of beach litter (UNDP, 2018) and the European Commission (EC) found that the 10th most common SUP items on European beaches represent about 50% of all marine litter in the EU. The 10th most common items found on sea shores are: (1) drink bottles, caps and lids; (2) cigarette butts; (3) cotton bud sticks; (4) crisp packets/sweet wrappers; (5) sanitary applications (sanitary towels, tampons, etc.); (6) plastic bags; (7) cutlery, straws and stirrers; (8) drink sups and cup lids; (9) balloons and balloon sticks; and, (10) foods containers, including food packaging.

3.2 EU Legislation on SUPs

Legislation has been adopted worldwide to address this problem an also levies are charged (Xantos and Walker, 2017; Shnurr et al., 2018; Adeyanju et al., 2021). In addition, many scientific articles are published on Life Cycle Assessments (LCA) of plastic products (review in Nessie et al. 2022; dataset from PlasticsEurope https://plasticseurope.lca-data.com).

The EU approved in 2019 a pionneer legislation, EU Directive 2019/904, derived from the EU Plastic Strategy (European Commission, 2018) or SUPD (Single Use Plastics Directive). This directive focused on the 10 following products (Kiessling et al. 2023), selected for being the most common litter objects found on European beaches, which were also selected for having easily available alternatives (Addamo et al., 2017). An implementing regulation linked to the SUPD was approved in 2020 by the European Commission.

The banned products are the following:

- Cotton bud sticks
- Cutlery, plates, straws and stirrers
- Balloons and sticks for balloons
- Food containers
- Cups for beverages
- Beverage containers
- Cigarette butts
- Plastic bags (lightweight plastic carrier bags)
- Packets and wrappers
- Wet wipes and sanitary items

The Directive also covers oxo-degradable plastics. Oxo-degradable plastics are usually conventional polymers (e.g. Low-Density Polyethylene, LDPE) to which additives (chemicals) are added to accelerate oxidation and fragmentation of the material. They are neither bioplastic nor biodegradable plastics. They may generate some confusion and a serious environmental and health problem, which will be explained in section 3.5 because it would be relevant for our case study, due to the use of this technique in some new SUPs and plastic bags, in particular.

For non-banned products in the SUPD, the focus is on prevention, through consumption reduction, marking and product design requirements and improved waste management.

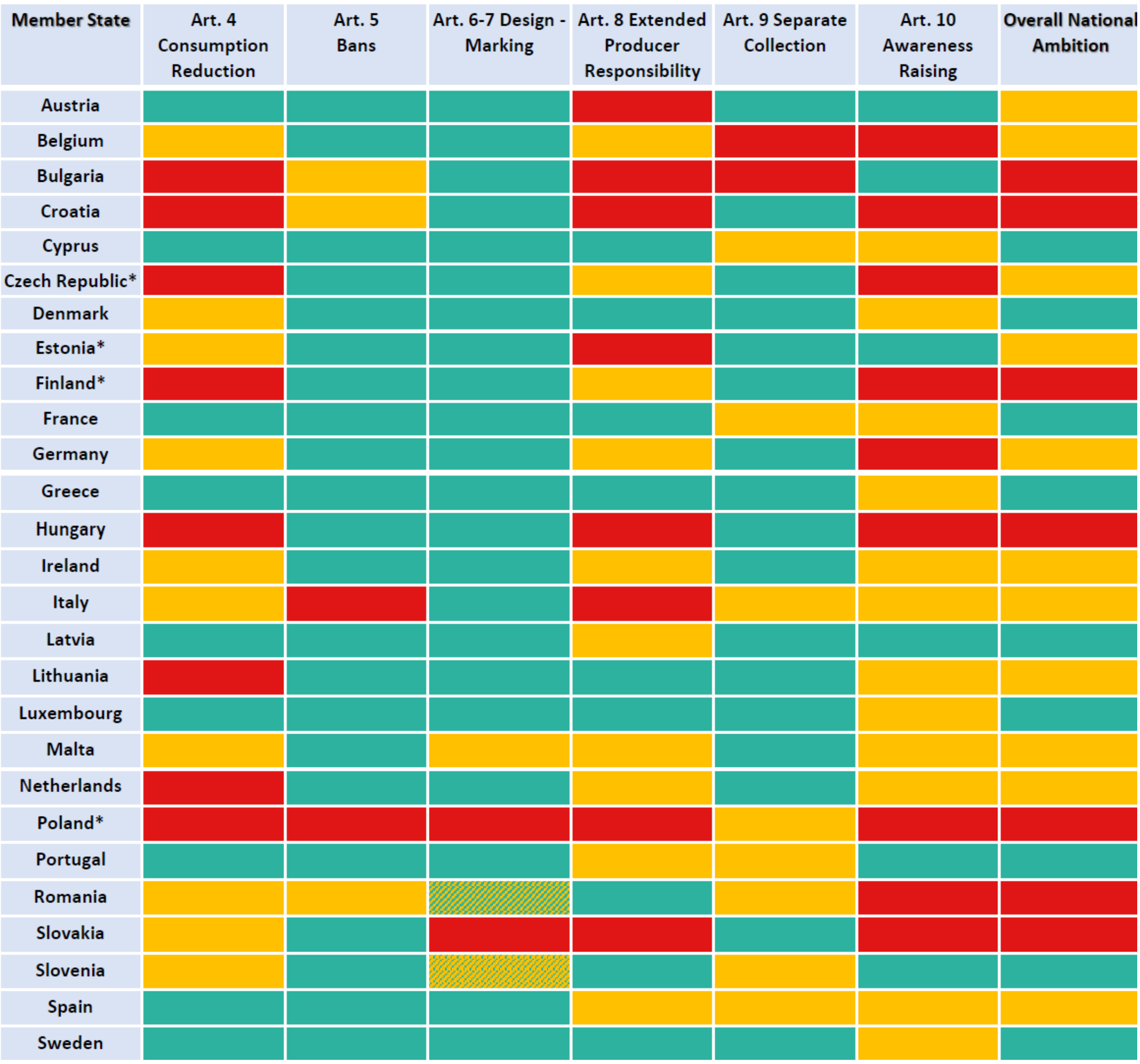

Figure 5. Implementation status of SUPD Directive per measure (Source: Rethink Plastic, September 2022)

This 2019 Directive is being transposed to national regulations. Each member state should have transposed the directive into their national law before July 2021 to be operational by 31 December 2024. Rethink Plastic

(2022), in a report on SUPD implementation, shows that three years after the adoption of the SUPD and one year after the end of the transposition period, most of the EU member states have now transposed the Directive and are already implementing the first batch of measures. However, the report highlights large differences among countries: some adopted ambitious measures to take up the challenge (i.e. France, Greece, Luxembourg, Sweden, Ireland, Cyprus or Portugal), but others show delays in implementing the Directive or are unambitious and had still not adopted all the measures needed, in the time the report was published, in September 2022 (Figure 5). Spain, for example, reported to the European Commission the transposition of the SUPD, through Law 7/2022, 8th April 2022, de *Residuos y Suelos Contaminados para una Economía Circular* (Waste and Polluted Soils for a Circular Economy) with a considerable delay and a lot of work still to be done.

On 19th December 2024, a new regulation (Regulation (EU) 2025/40 of the European Parliament and of the Council of 19 December 2024 on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC) was approved. This new regulation advances on the articles of SUPD Directive with more concrete and strict requirements, mainly for companies, regarding packaging.

3.3 SUP case study: Selection of products

Plastic bags, among other plastic goods, end up constituting a major fraction of the marine debris (Borrelle *et al.*, 2020). Their presence in the oceans brings ecological impacts, affecting marine organisms by smothering, entanglement or ingestion, apart from the toxicity caused by their chemical additives. Low-density PE bags are the most common consumer products, and these materials are one of the most abundant marine litter items in the coast (UNEP, 2021) and the seafloor (Maes *et al.*, 2018).

Plastic bags can be divided into two categories based on their use: carrier bags and garbage bags. Carrier bags are found mainly in supermarkets, bookstores and clothing stores and they are the subject of most of the publications due to the recent bans worldwide (Nielsen et al. 2019).

A garbage bag (also named bin bag, rubbish bag, bin liner, trash bag or refuse sack) is a disposable bag used to contain solid waste. Most of them are useful to line the insides of waste containers to keep them sanitary by avoiding contact with the garbage. Usually, they are made of polyethylene (PE), a soft and flexible plastic with high resistance and strength. Trash bags of different thicknesses, colours and sizes are available and affordable. They are used in several places and areas including homes, markets, restaurants, schools, offices, commercial buildings, hospitals, industries, or agriculture, as they control the odour from waste, reduce toxicity and aid in sanitation.

Garbage bags are usually thicker than carrier bags because they must support a higher weight (López Gómez and Serna Escobar, 2021). There are various standards and regulations specifying the thickness of plastic bags for different purposes, including those from the American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO). There are also specific regulations for regions and countries. In Europe, the European Plastics Converters (EUPC) offer information on the characteristics of plastic packaging and bags.

Martinho et al. (2017) stated that many consumers were used to using carrier bags as waste bags but, since the taxes and bans on these last ones, the consumption of garbage bags has increased and is expected to continue growing in the following years.

However, garbage bags are a type of SUP that is explicitly excluded from the 2019 Directive (COM, 2021 and section 4.6.2 of the 2019 Directive) and, also, of regulations for packaging (Directive 94/62/EC or Packaging and Packaging waste directive, and amending Directives EU 2015/720, on Plastic Bags, and EU 2018/851).

As far as waste generation is increasing (Eurostat, 2024), with 513 kg of municipal waste per capita in 2022 (500 kg per capita in 2004), 220 million tons in the EU (2 million tons more than in 2017), consequently, the purchase and use of garbage bags is expected to increase. The data (EEA, 2023) show a decrease in total waste generation per capita between 2010 and 2020, by 4,2% in the EU, with a similar trend for municipal waste. However, this decrease is recent (2018-2020) and coincides with the slowdown of the EU economy due to the COVID-19 pandemic. Predictions do not show a decline by 2030.

Thus, the second case study of WP8 is focused on garbage plastic bags, in coordination with LCA of WP5. They are commonly used products, well known by consumers (what makes the future analysis of preferences easier), and there are environmentally friendly substitutes (less fossil-based – hybrid origin, but biodegradable). Although garbage bags are excluded from the current European SUP Directive, they have the potential to cause at least the same environmental and health problems as carrier bags. This case study is designed and applied to serve as an example of analysis which may be applied to other SUP products currently excluded from the SUPD.

Table 3 summarizes the material, source, biodegradability and volume of the products selected. Although initially garbage bags of 50 l. were selected as the object of study, posterior results from Beiras et al. (2024), based on the methodology described in Beiras and López-Ibañez (2023) and Beiras et al. (2021), show that those large bags are quite different in composition and characteristics, and less common-used than smaller ones.

Table 4 summarizes some degradation and ecotoxicity results. The results show that PE materials are non-toxic but also non-degradable and compostable materials show decaying mechanical properties but limited biodegradability and, in some instances, marine toxicity. This result claims for more research to improve the composition (materials, additives) and, consequently, the toxicity and degradability of PE potential substitutes.

Product	Material	Source (bio/fossil)	Biodegradability*	Volume
Garbage bag	PBAT and PHA	Hybrid	Biodegradable	50 L
	PE	Fossil	Non-biodegradable	50 L
	Mater-bi (PET and polyester)	Hybrid	Biodegradable	10 L
	PE	Fossil	Non-biodegradable	10 L

Table 3. Selected products for SUP case study. Source: data from table 3 of D5.6 LCA Methodology to compare plastics.

Description	composition	Biodegradation	Mechanical degradation	Ecotoxicity
		BOD28 (%C+)	60-d Strength at break MPa)	Seaurchin 1 g/L TU
PE materials				
Conventional PE trash sac (10 L)	PE	0.0	30.6*	< 1
Recycled PE trash sac (30 L)	PE, CaCO3	0.4	9.4	<1
Compostable materials				
Home compostable trash sac (30 L)	PBAT+starch	12.4	0	**2.41**
Compostable trash sac (10 L)	PBAT+starch+PLA	13.4	0	**5.24**
Industrial compostable trash sac (30 L)	PBAT+starch+PLA	15.6	0	**2.07**

*from a conventional (single-use, not recycled) PE carrier bag of the same thickness

Table 4. Comparison of biodegradability, mechanical degradation and ecotoxicity of garbage bags. Source: Beiras et al (2024)

In addition, D5.7 *LCA Report*, section 3 (*Comparative LCA for garbage bags*) offers a comparison of garbage bags made from different materials. For this case study, the results for low-density polyethylene (LDPE) and the industrial compostable polybutylene adipate terephthalate (PBAT) are relevant to define intervention measures. Conclusions for LCA on plastic bags show manufacturing of biodegradable garbage bags should be improved, due to the high impact values found in the PBAT manufacturing phase. Materials used in the production (amount, proportion) and the additives used, are key factors that producers may use to improve the environmental performance of garbage plastic bags.

3.4 Map of the supply chain

To map the supply chain of plastic bags, a methodology similar to that of car tyres was used. The supply chain operations reference (SCOR) model was used to describe and map the garbage plastic bag supply chain. The process is similar to the case study 8.1., starting with the identification of stages in the supply chain, and then the processes inside each stage, representing the information visually, with connections among processes. Only material streams were included (avoiding information streams). All the information was obtained from published literature, found through web-based search engines about rubbish/garbage/trash/bin bags and linked to production, management, LCA, waste, supply-chain mapping, plastic supply chain and value chain analysis.

The supply chain map (Figure 6) goes from providers of raw materials to disposal of these SUPs. The supply chain was organized into six stages: (1) suppliers of raw materials, plastic bag manufacturers, (3) distribution (wholesale and retail), (4) consumers, with special attention to end-of-life stages, that are, waste plastic processors (5) and secondary products (6). The map of the supply chain is a key issue to identify key stakeholders (Figure 7).

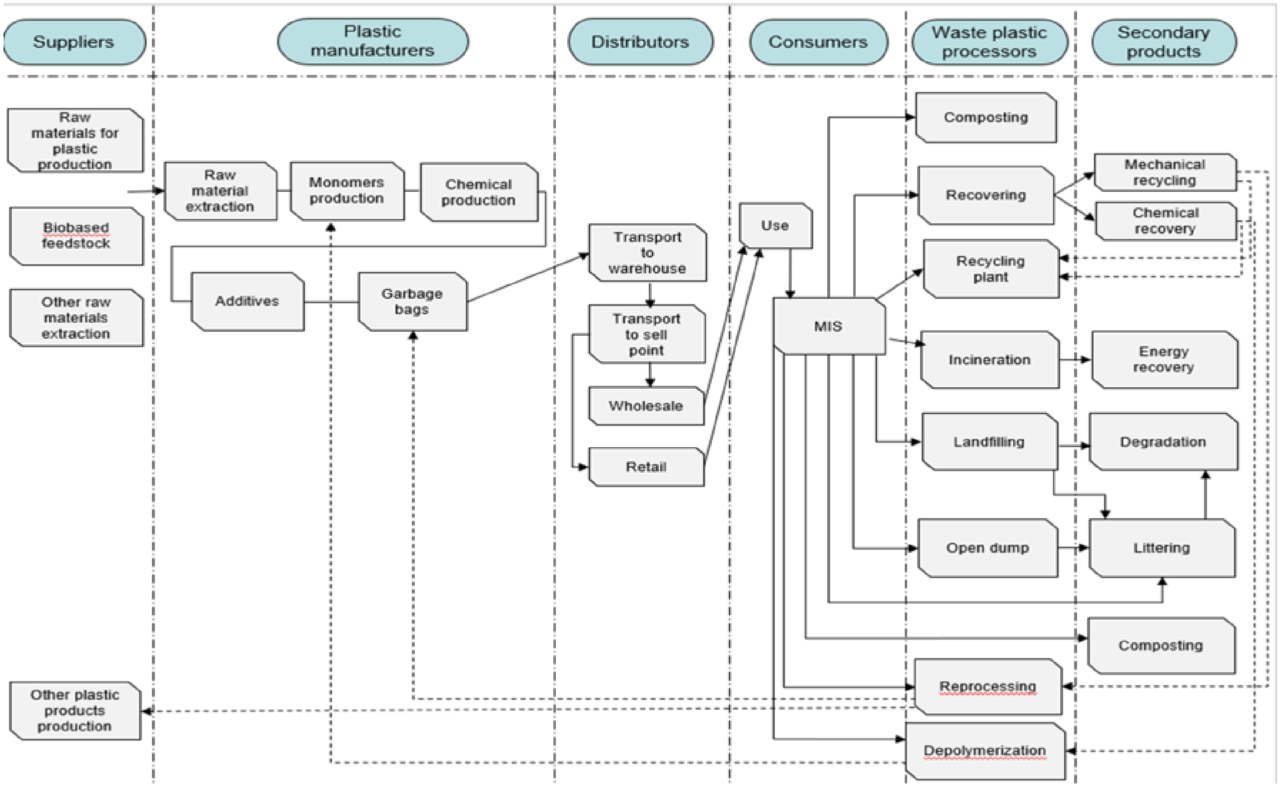

Figure 6. Plastic bags supply chain map

3.5. Identification of relevant key stakeholders

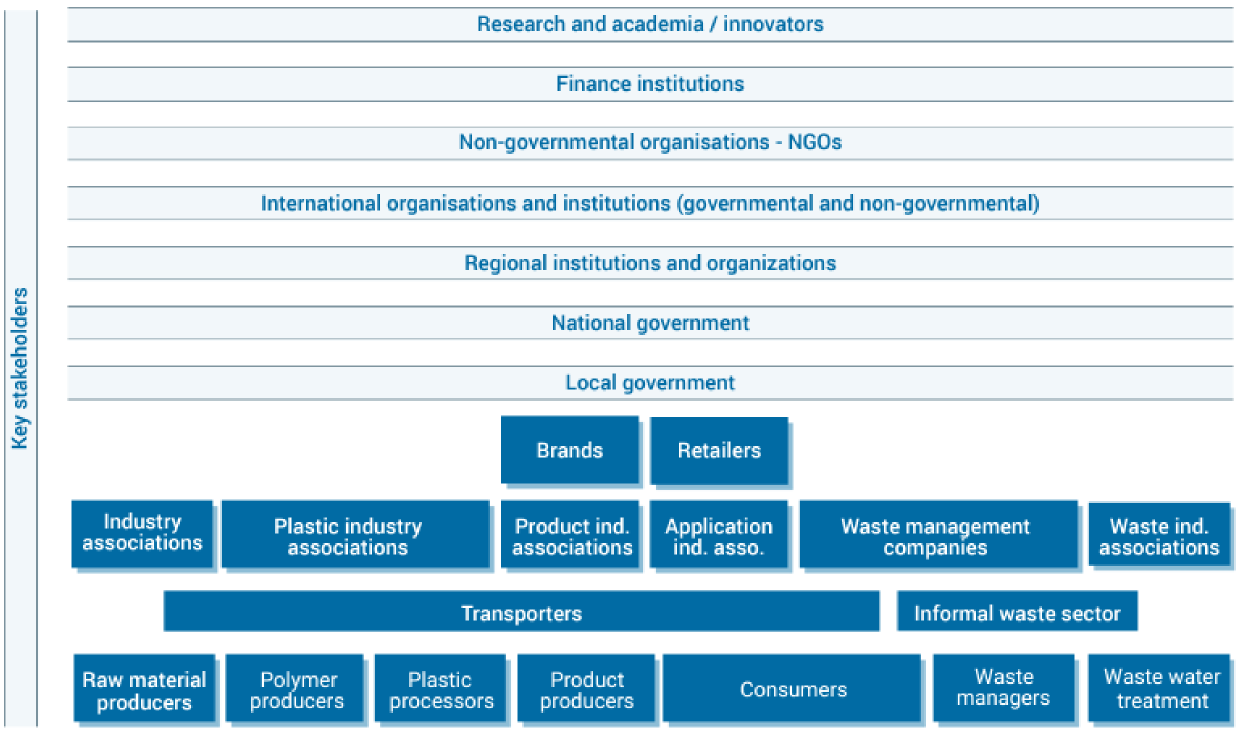

Figure 7. Overview of stakeholders/interest groups associated with each supply chain stage (UN Environment, 2018).

The supply chain map indicates the key stakeholders linked to each of the stages. Key actors are, clearly producers (both of raw materials, intermediate and final consumption products) and here, plastic industry associations, like PlasticsEurope, are relevant to participate in decisions regarding mitigation measures. Consumers, as final users of the products, have been introduced because they make purchase decisions and market choices among different available products, and after consumption, they decide the disposal strategy they prefer. They are the more relevant actors because they may also influence and put pressure on plastic producers based on their consumption preferences and choices, or through NGOs. It also includes International, National, Regional and Local governments, as responsible for the legal framework, and for the collection and treatment of municipal solid waste. These actors, different from the industry, can influence all parts of the plastic value chain and are transversal to the whole process.

The EU recommends, in "A European Strategy for Plastics in a Circular Economy" (EC, 2018), previous to the EU 2019 Directive, stakeholder involvement, including citizens and NGOs, as a key component in the transition to a circular plastic economy. Taking into account this requirement, Clausen et al. (2020) carried out a stakeholder analysis of active stakeholders within the regulatory microplastic debate, with identification, understanding of their interests and relationships and finally, using this information to evaluate the applicability of proposed measures. They use also the following definition of stakeholder, which we assume in this work: "*An individual or group influenced by–and/or with an ability to significantly impact (either directly or indirectly)–the European Union (EU) regulation of microplastics and which have actively participated in the regulatory debate*".

The starting point for the identification of SUP plastics, and garbage bags in particular, was the article of Clausen et al., (2020), which presents a stakeholder analysis concerning the new microplastics regulation in Europe. Table 5 above is extracted from this article, which presents 28 groups of stakeholders. Their abbreviations, corresponding stakeholder groups and descriptions are included. Also, they include the categorisation of primary, secondary and tertiary. Clausen et al. (2020) define primary stakeholders as direct beneficiaries, primary production (industry) and consumers. Secondary stakeholders support or provide services to the primary stakeholders, and they are, for example, NGOs, researchers and local authorities. Finally, tertiary stakeholders include all governmental bodies, national authorities and international authorities. This is a means to ensure that stakeholders on all levels are included in the analysis.

Type	*Stakeholders/stakeholder sub-groups*	*Abbreviation*	*Group*	*Description/Examples*
Primary	Large Companies	L Companies	Large Companies	Consists of all companies with more than 250 employees.
	Small and medium-sized enterprises	SMEs	SMEs	All companies with up to 250 employees.
Secondary	European Oilfield Speciality Chemicals Association	EOSCA	ITA	Association that responds to regulatory requirements for approval of offshore chemicals and drilling muds.
	European Plastics Converters	EuPC	ITA	The trade association of the European plastics converting industry.
	International Association of Oil and Gas Producers	IOGP	ITA	The petroleum industry's global forum.
	International consumer NGOs	IC NGOs	International NGOs	E.g. the European Consumer Organisation (BEUC) and the Center for International Environmental Law (CIEL).
	International environmental NGOs	IE NGOs	International NGOs	Encompasses a range of NGOS including: Beat the microbeat; ECOS; Earthwatch Europe; ChemSec; ClientEarth; WWF, EEB and Greenpeace.
	International Pharmaceutical Excipient Council Europe	IPEC Europe	ITA	Global organisation that represents producers, suppliers and end users of excipients.
	National environmental NGOs	NE NGOs	National NGOs	National rooted environmental NGOs such as the Scottish Fidra and the German Nature and Biodiversity Conservation Union.
	National sport association NGOs	NSA NGOs	National NGOs	Consists of national and regional football associations e.g. Deutscher *Fußball*-Bund (DFB)
	Other national NGOs	ON NGOs	National NGOs	National NGOs whose focus is not directly related to the environment. The group includes: Ellen McArthur Foundation; Breast Cancer UK.
	Regional authorities	RA	National authorities	Encompasses municipalities, regional councils and other local authorities.
	Researchers	Researchers	Academia and researchers	Includes scientists, college professors and researchers.
	Union of European Football Associations	UEFA	International NGOs	The administrative body for football, futsal and beach soccer.
	Arctic Monitoring and Assessment Programme	AMAP	International authorities	International organisation that implements components of the Arctic Environmental Protection Strategy.
	European Chemical Industry Council	CEFIC	ITA	Main European trade association for the chemical industry.
Tertiary	European Chemicals Agency (Including RAC and SEAC)	ECHA	International authorities	Responsible for managing REACH and includes the Committee for Risk Assessment (RAC) and Committee for Socio-Economic Analysis.
	European Environment Agency	EEA	International authorities	The EU agency that provides information on the environment.
	European Commission	EC	International authorities	The executive branch of the EU, including SAPEA.
	European Council	Ecouncil	International authorities	EU body that defines the political direction and priorities of the EU.
	European Food Safety Authority	EFSA	International authorities	EU agency that provides scientific advice and communicates on risks associated with food.
	European Parliament	EP	International authorities	The legislative branch of the EU, and the 751 elected members from the 28 member states.
	International Union for Conservation of Nature	IUCN	International authorities	International organisation working for use of sustainable nature resources in the field of nature conservation.
	National elected politicians	NEP	National authorities	Politicians in EU countries.
	National environmental governmental bodies (E.g. DK EPA)	NEGB	National authorities	These include national environmental protection agencies as well as forestry, conservation and other governmental environmentally-related bodies.
	National governments	NG	National authorities	Governments in Europe.
	Nordic Council of Ministers	NCM	International authorities	Body for intergovernmental cooperation of the Nordic Region.
	United Nations	UN	International authorities	Intergovernmental organisation responsible for maintaining peace, international relations and international cooperation. Includes UNEP, UNEA and WHO.

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Table 5. Stakeholders categorisation (Clausen et al., 2020)

Based on the supply chain map and the work of Clausen et al. (2020), examples of stakeholders of the different stages have been organized into four groups:

1. Producers (suppliers and plastic manufacturers). Primary stakeholders.
2. Distributors (secondary stakeholders).

3. Waste processors (secondary stakeholders). Secondary stakeholders.
4. Public institutions (tertiary stakeholders), NGOs, and research (secondary stakeholders).

These stakeholders will be consulted (through a representative sample) to test proposed policy measures to act in different stages of the supply chain to reduce the presence of plastics for SUP and garbage bags in the environment. Due to cost and time restrictions, group 4 has not be included in the sampling process.

3.6. Conceptual Framework

To estimate emissions to the environment and propose intervention measures, some definitions should be introduced, moreover related to concepts usually misused by producers and misunderstood by consumers. Those are oxo-degradable, biodegradable and compostable plastics. The information presented in this section has been mostly obtained from Greendotbioplastics.com and European-bioplastics.com and is relevant to clarify concepts and detect some problems of information regarding substitute materials of PE.

Some products, including bags, are made from conventional plastics and supplemented with specific additives to mimic biodegradation. In truth, however, these additives only facilitate fragmentation of the materials, which do not fully degrade but break down into very small fragments that remain in the environment – a process that would be more accurately described by the term “oxo-fragmentation”. However, they claim to be “degradable”, “oxo-degradable”, “oxo-biodegradable”, or “oxo-fragmentable”, and sometimes even “compostable”, without providing any sort of proof for the claims made.

Oxo-degradable plastics quickly fragment into smaller and smaller pieces, called microplastics, but don’t break down at the molecular or polymer level like biodegradable and compostable plastics. The resulting microplastics are left in the environment indefinitely until they eventually fully break down.

No currently internationally established and acknowledged standard or certification process proves the success of oxo-degradation. Without verifiable proof or certification for the claim, the term “oxo-degradable” is just an appealing marketing term.

Biodegradability, compostability and oxo-degradability are often used interchangeably but are not synonymous, and the confusion may have serious implications for the disposal and treatment of products at the end of their life. Companies need to have information, understand and be honest about their products.

Bioplastics are plastics sourced from biomass at the beginning of their life (bio-based), metabolized into organic biomass at the end of their life (biodegradable), or both. Biodegradable plastics are a small subset of bioplastics. Biodegradation is the process of conversion of plastics into water, carbon dioxide and biomass over time with the help of micro-organisms. The biodegradability of a plastic depends on the chemical properties of the polymer. Bioplastics can be bio- or petroleum-based.

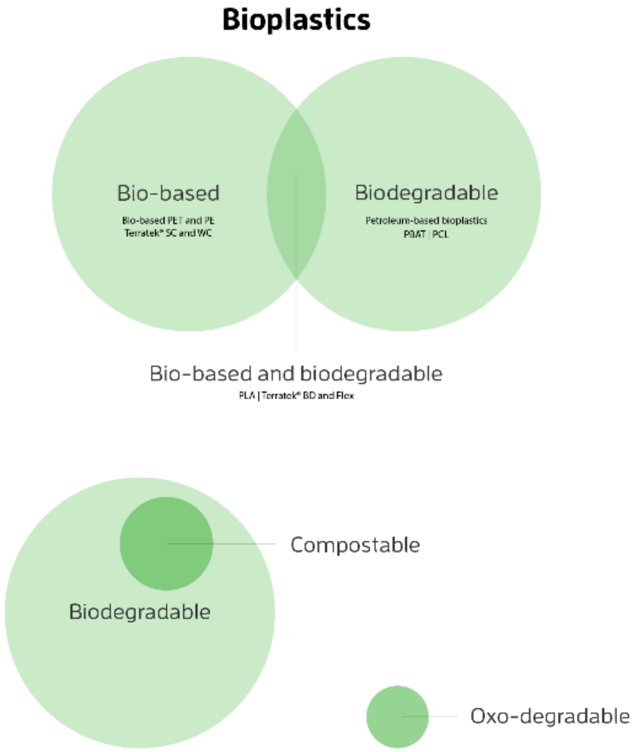

Figure 8. Bioplastics, biodegradable, compostable and oxo-degradable plastics. Source: Greendotbioplastics.com

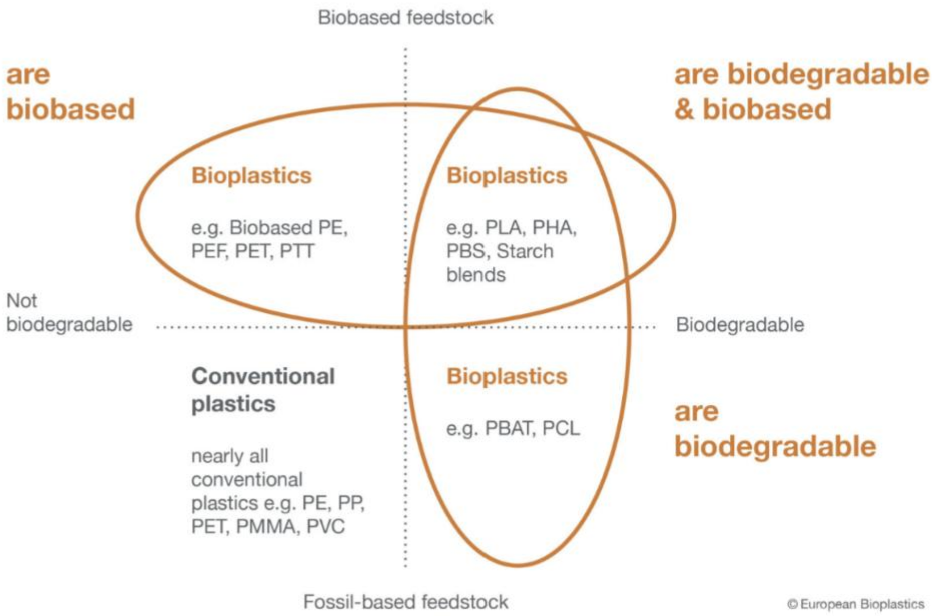

Figure 9. Conventional plastics vs. bio-plastics and their subtypes. Source: European-bioplastics-org

Compostable plastics are a subset of biodegradable plastics, defined by the standard conditions and time under which they will biodegrade. All compostable plastics are biodegradable but not the inverse. Moreover, compostable plastics must be certified by a third party, to adhere to international standards such as EN 13432 for biodegradation in an industrial composting facility. This is also important for the SUP case study because certified compostable materials must be disposed of in a designated composting facility, never at home. The reason is that they require higher temperatures for the materials to biodegrade (totally or almost totally) quickly enough. The waste of bio-based plastics must be managed like conventional plastics.

In the EU there are not enough industrial composting facilities (europeanbioplastics.org) which is an important shortcoming to incentivise the substitution of PE garbage bags for compostable ones. In some European countries (Austria, Belgium, Germany, Italy and the Netherlands) industrial composting is already well established but other countries still need to achieve an equivalent level. However, a separate waste collection system is fundamental to industrial composting.

3.7. Additives in single-use plastics (SUPs)

Single-use plastics (SUPs) often contain a variety of additives to enhance their performance, durability, and aesthetic appeal. Through the revision of several published works (Costa et al, 2020; Al-Malaika and Wilkie, 1999; Andrady, 2003; Biron, 2012; Chanda and Roy, 2007; Ebnesajjad, 2012, Kutz, 2011; Mark and Erman, 2013, Scheirs, 2000; Wypych, 2001) we can describe the different types of common additives used in the production of single-use plastics.

These additives play a crucial role in the production and performance of single-use plastics, tailoring their properties for specific applications and improving their usability in various conditions. However, some have proved effects on the environment and health as shown in Table 6.

Additive	**Objective**	**Risks**	**Selected studies for risks**
Plasticizers	Flexibility and workability. Ex. phthalates and adipates.	Plasticizers, particularly phthalates, can leach into the environment, causing endocrine disruption in wildlife and humans. They are persistent and can bioaccumulate.	Rahman, M., & Brazel, C. S. (2004). The plasticizer market: An assessment of traditional plasticizers and research trends to meet new challenges. *Progress in Polymer Science*, 29(12), 1223-1248. Staples, C. A., et al. (1997). The environmental fate of phthalate esters: A literature review. *Chemosphere*, 35(4), 667-749.
Stabilizers	Prevent degradation from heat, UV light, and oxidation. Ex:UV stabilizers, antioxidants, and heat stabilizers like calcium stearate and zinc stearate.	Some stabilizers, like lead and cadmium compounds, are toxic to aquatic life and can persist in the environment, leading to bioaccumulation and potential human health risks.	Fergusson, J. E. (1990). *The heavy elements: Chemistry, environmental impact, and health effects*. Pergamon Press.
Colourants	Add color. Ex. Titanium dioxide for white.	Certain colourants can be toxic and carcinogenic. They may leach into soil and water, affecting ecosystems and potentially entering the food chain.	Davis, S. N., & Wilkerson, C. L. (1998). Environmental considerations of dye pollution. *Journal of the Society of Dyers and Colourists*, 114(7-8), 250-254.

Fillers	Improve mechanical properties and reduce production costs. Ex: calcium carbonate, talc, glass fibres.	Fillers like calcium carbonate and talc are generally considered inert, but mining and processing can cause significant environmental disruption, including habitat destruction and dust pollution.	Wypych, G. (2016). *Handbook of fillers* (4th ed.). ChemTec Publishing.
Flame retardants	Reduce flammability. Ex: brominated flame retardants, antimony trioxide, phosphorus compounds.	Brominated flame retardants are persistent organic pollutants (POPs) that can bioaccumulate, potentially causing endocrine disruption and neurodevelopmental issues.	de Wit, C. A. (2002). An overview of brominated flame retardants in the environment. *Chemosphere*, 46(5), 583-624. Alaee, M., et al. (2003). An overview of commercially used brominated flame retardants, their applications, their use patterns in different countries/regions and possible modes of release. *Environment International*, 29(6), 683-689.
Antimicrobial agents	Prevent the growth of bacteria and fungi. Ex. Silver ions, triclosan.	Antimicrobials like triclosan and silver nanoparticles can lead to antimicrobial resistance and toxicity to aquatic organisms.	Daughton, C. G., & Ternes, T. A. (1999). Pharmaceuticals and personal care products in the environment: Agents of subtle change? *Environmental Health Perspectives*, 107(Suppl 6), 907-938. Benn, T. M., & Westerhoff, P. (2008). Nanoparticle silver is released into water from commercially available sock fabrics. *Environmental Science & Technology*, 42(11), 4133-4139.
Antistatic agents	Reduce static electricity buildup. Ex. Quaternary ammonium compounds, ethoxylated amines.	Quaternary ammonium compounds used as antistatic agents can be toxic to aquatic life and are known to persist in the environment.	Ying, G. G. (2006). Fate, behaviour and effects of surfactants and their degradation products in the environment. *Environment International*, 32(3), 417-431.
Lubricants	Reduce friction during processing. Ex. Stearic acid, polyethylene waxes.	While generally less toxic, certain lubricants can still cause environmental harm through bioaccumulation and persistence, particularly in aquatic environments.	Wypych, G. (2013). *Handbook of lubricants*. ChemTec Publishing.
Blowing agents	Create foam structures in plastics Ex. Azodicarbonamide, pentane.	Some blowing agents, particularly CFCs, are known to deplete the ozone layer and contribute to global warming. Alternatives like hydrocarbons can still have significant environmental impacts.	Andersen, S. O., et al. (2012). *The Montreal Protocol: Progress, challenges, and perspectives*. Ambio, 41(1), 91-98.
Processing aids	Improve de processability. Ex. Fatty acid amides and silicone oils.	Processing aids can be toxic to aquatic life and may persist in the environment, leading to long-term ecological impacts.	Goodship, V. (2007). *Introduction to plastics recycling*. Elsevier.
Impact modifiers	Enhance the toughness and impact resistance.	These can leach out of plastics and cause environmental contamination, potentially	Al-Malaika, S., & Wilkie, C. A. (Eds.). (1999). *Additives for plastics*. Springer.

	Ex. Butadiene, rubber, ethylene propylene diene monomer (EPDM).	leading to toxicity in aquatic organisms.	
Nucleating agents	Control de-crystallization, and improve clarity and mechanical properties. Ex. Sodium benzoate, talc.	Generally considered less harmful, but their environmental impacts can still be significant, particularly during the manufacturing process.	Karger-Kocsis, J. (Ed.). (1995). *Polypropylene: Structure, blends and composites*. Chapman & Hall.

Table 6. Additives and their risks

3.8 Emissions of SUP plastics

In the 1970s-1980s decade, plastic use, including plastic bags, began to rise significantly, replacing paper bags. In the 1990s, increased awareness of plastic pollution led to more data collection. In this century, the global production of plastics continued to rise significantly with more robust data collection and reporting by environmental agencies. Despite the increasing amount of information available, data on emissions specifically from garbage bags is limited. We will focus on plastic bag data, when available, and on SUP data in general, when no access to plastic bag data is possible.

According to a study by Geyer, Jambeck, and Law (2017) for the U.S.A., approximately 8.3 billion metric tons of plastic have been produced since the 1950s, with a significant portion ending up in landfills or the natural environment. The United States Environmental Protection Agency (EPA) 2020 report on municipal solid waste indicates that plastic waste generation was about 35.7 million tons, with a recycling rate of only 8.7%. Also, EPA states that in 2020, approximately 4,2 million tons of plastic bags, sacks and wraps were generated in the municipal solid waste stream in the U.S. alone. Recycling rates for plastic bags have historically been low. The EPA reported a recycling rate of around 10% for plastic bags and wraps.

Figure 10 illustrates the trends in SUPs and plastic bag production, from 1970 to 2022 for Europe. The total production of SUPs in Europe increased from 2 million tons in 1970 to 42 million tons in 2022. Plastic bag production (in million tons) has shown a steady increase over the past 52 years, rising from 200.000 tons in 1970 to 4.2 million tons in 2022. This increase reflects the growing demand for plastic bags in various sectors, despite efforts to reduce plastic usage.

The figure shows the recycling rate for SUPs and plastic bags in Europe. The recycling rate for plastic bags specifically is generally lower than for plastics overall due to contamination and collection challenges, and this could be a bigger problem for garbage bags. SUPs recycling rate has increased from 0,5% in 1970 to almost 22% in 2022. For plastic bags, the percentage is lower, rising from 0,1% to 17% in the same period (European Commission, 2018). This indicates enhanced efforts and initiatives to recycle plastic bags, although the rate is still relatively low compared to the total production. The increase in recycling rates can be attributed to EU Directives and national policies aimed at improving recycling infrastructures and practices.

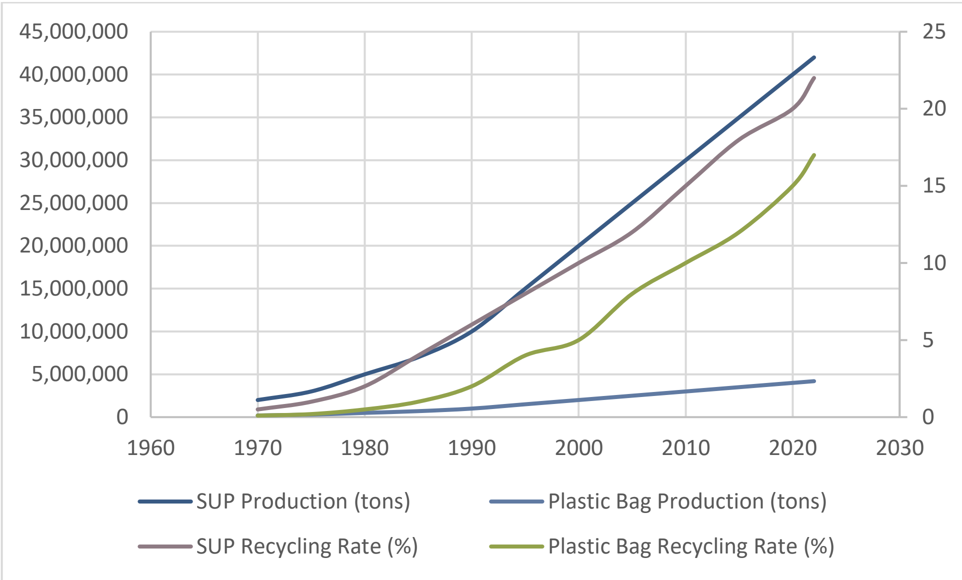

Figure 10. Plastic bag production, recycling rate for plastic bags and ocean waste in Europe (1970 – 2020). Source: data from EEA (2020, 2021), PlasticsEurope (2020), European Commission (2018) and UNEP (2021)

Finally, the contribution of SUPs to ocean waste is a significant concern, but specific data for plastic bags or even for SUPs is harder to find as most studies focus on total plastic waste. Based on several studies, emissions from SUP to oceans in Europe have been summarized in the following table (note that different sources and methodologies may differ) but it shows some figures that may illustrate the gravity of the problem. The data shows an increasing trend from 2010 to 2022, reflecting the growing environmental challenge of managing plastic waste. The sources for data are official reports from European institutions and global organizations that monitor and report on the environmental impacts of plastic pollution.

Year	SUP Emissions to Oceans in Europe (tons)	Source
2010	500,000	European Environment Agency (EEA)
2015	600,000	UNEP (2021)
2020	700,000	EEA (2020)
2021	720,000	European Commission (2018)

Table 7. Estimated SUP emissions to oceans in Europe

3.9 Prevention/mitigation measures for SUPs

With the aim of reducing emissions of SMNPs to the marine environment, in this case study, we aim to act on domestic-used conventional (PE) garbage bags, reducing their use, and increasing the use of improved compostable garbage-bags, acting in the production, consumption and end-of-life stages of the supply chain. We use garbage bags as an example of not regulated SUP and, consequently, most of the results and recommendations found may be applied to other SUPs, which are currently out of the European legal framework. These first set of measures, obtained from previous literature and previous contacts with stakeholders, include three levels (as shown in Table 8): the (1) production/manufacturing, (2) use/consumption, and (3) the end-of-life (EoL).

Production/ manufacturing	1. Research on the generation of microplastics and potential impacts 2. Change to industrial compostable garbage bags, institutionally/legally supported 3. Creation (or incentives to the use of existing) official, third party, certification and labelling schemes 4. Ban/penalize confusing claims about characteristics of garbage bags (bio, eco, degradable, …) 5. Legal framework for additives 6. Promotion of information transfer from public/private research to the production sector
Use/consumption	1. Encourage responsible consumption to diminish domestic waste generation 2. Economic incentives 3. Information and awareness campaigns to the consumers to substitute conventional PE garbage bags 4. Legal framework to substitute conventional PE bags
End of Life	1. New investments in waste treatment infrastructures 2. Legal framework on disposal

Table 8. Potential interventions to mitigate the emissions of single use plastics

3.9.1. Production/manufacturing of garbage bags

3.9.1.1. Research on the generation of microplastics and potential impacts

In previous WPs of this project, several commercial brands of compostable bags and brands of polyethylene (PE) bags were assessed in terms of major components of the polymeric matrix and quantitative composition in additives of bags, and ecotoxicological effects on some marine species (Beiras *et al.*, 2024). Compostable plastic items showed a particularly complex composition; when plastic additives are specifically targeted, number of chemicals and concentrations are generally higher in compostable bags than in the PE counterparts. But, among additives remarkably more abundant in compostable than in PE bags there are chemicals registered in the EU as toxic in aquatic environments at level 1 and 2. Likewise, recycled PE bags showed much higher Cu and Zn levels than single use PE and compostable bags; however, no differences in short term aquatic toxicity were found between recycled and single use PE materials. In summary, current compostable bags cannot be considered chemically or ecotoxicologically safer products than PE bags. More research is needed on the generation of microplastics and potential impacts (biodegradability, ecotoxicity), considering their composition (materials, additives) and way of release/treatment to improve alternatives to conventional PE plastics, with special focus on compostable bags.

3.9.1.2. Legal and institutional support to change to compostable bags, with improved characteristics.

Legal and institutional support to incentive the change to compostable bags must be based on previous R+D+I (Research, Development, Innovation) to improve some characteristics of garbage bags. Firstly, most compostable bags currently in the market do not have enough resistance to withstand organic waste, compared to conventional PE bags. Therefore, deeper research on design and composition of compostable bags is required to make them more competitive/substitutive of PE bags. Secondly, more research on Eco-design is necessary, to improve biodegradation and lower ecotoxicity of compostable garbage bags. This could include not only industrial compostable bags but also home compostable ones. Based on current EU legislation, and in order to promote reduction, reuse, recycling and recovery of waste, producers may have their responsibility extended (EPR) and be obliged to design products and product components in such a way that their environmental impact and waste generation are reduced throughout their life cycle, both in its manufacture and in its subsequent use (Ministry for Ecological Transition, 2022). However, this legal framework does not always favour the manufacture of more resistant compostable products, and it may be necessary to establish minimum densities for compostable garbage bags and/or encourage industrial research in that direction. In this case, the benefits of some increase in density could compensate the higher use of materials through making compostable bags more attractive and useful for consumers.

3.9.1.3. Create (or incentive the use of existing) official, third party, certification and labelling schemes.

Low-density PE bags are one of the most common plastic consumer products and, in an attempt to solve the problem of accumulation of plastic litter in the marine environment, potentially biodegradable plastic in compliance with multiple certification schemes and labels have been introduced (Emadian et al., 2017; Kranz et al., 2006). In EU, the EN-13432 (CEN, 2000) sets the standards for packaging to be considered as compostable in industrial composing facilities, whereas the EN-17427 (CEN, 2022) is normally used to test biodegradability in home composting installations. Promoting the design of eco-labels and official, third party certification systems that reflect these standards can help mitigate the use of conventional SUPs.

3.9.1.4. Avoid confusing industrial claims about characteristics of garbage bags (green, bio, degradable, etc.) and regulate the information provided.

Some “green” or “bio” or “degradable” claims usually found in labels of plastic products and of garbage bags, should be banned and penalized because they are general, out of real content/confusing for consumers, aim to “greenwash” products and companies, and are used without scientific evidence supporting them. Compulsory official certification and labelling schemes (proposal 3.9.1.3) should be promoted instead.

Producers of garbage bags must be compelled to inform in a concise and clear way where to deposit them according to their composition. That is, the manufacturer's label should indicate that PE bags should go to the recycling bin while compostable bags should go to the compost bin. In otherwise, the policymakers could have the possibility of implementing regimes of sanctions or fines on producer liability.

3.9.1.5. Legal framework on additives

As previously mentioned, SUPs often contain a variety of additives to enhance their performance, durability, and aesthetic appeal. These additives play a crucial role in the production and performance of single-use plastics, tailoring their properties for specific applications and improving their usability in various conditions. However, some have proved effects on the environment and health as it has been shown. In this case study, both PE and compostable bags have levels of toxicity, the latter cannot in their current state be considered ecotoxicologically safer than PE bags. It is necessary to update the legal context on the prohibition of additives in those cases in which there is sufficient and contrasted empirical evidence.

3.9.1.6. Promotion of information transfer from public/private research to the production sector

The transfer of public/private research results to the production sector is essential to improve governance, in any area, especially in order to achieve sustainability objectives. In addition, increasing the participation of producers and allowing them to express their opinion would allow regulatory measures to be implemented with a higher level of success and compliance with rules, also increasing their responsibility towards the preservation of marine ecosystems and, so, improving the level of legitimacy of related institutions (Österblom and Folke, 2013).

3.9.2. Use/Consumption

3.9.2.1. Encourage responsible consumption to reduce domestic waste generation

To break the link between economic growth and the impacts on human health and the environment associated with waste generation, governments must go further in the implementation of waste prevention/reduction policies. Among them, promoting and supporting sustainable and circular consumption models is essential. In this line, to encourage responsible consumption, reducing the generation of food waste and other materials is essential to reduce the use of garbage bags. Developing and supporting information campaigns to raise awareness about waste prevention is a critical mitigation measure. In this sense, promoting the reduction of waste generation also in the field of commerce through the sale of bulk products, the sale and use of reusable packaging, among others, may contribute to reduce the use of garbage bags.

3.9.2.2. Economic incentives

In addition to possible new regulations or bans on garbage bags depending on their environmental and health effects, economic instruments have proved to influence agents' behaviour in an efficient way and are a cost and time efficient way of achieving public policy objectives. There is a broad set of potential economic incentives, aimed at reducing PE bags, increasing the consumption of biodegradable or compostable ones, and reducing waste (and plastic) generation in general. Examples could include the following:

- Increasing the current fees for the use of garbage bags, including negative taxes for the use of compostable bags.
- Generalization in Europe of pay-for-generation or pay-as-you-throw (PAYT) schemes for home waste.

- Implementation, following already applied experiences in some countries of the EU, DRS (Deposit-Refund Systems) for containers/packaging.
- Higher taxes on more environmentally damaging materials and additives.

The introduction of an SDR is considered one of the most effective measures to reduce plastic waste in the environment, as it encourages consumers to return empty containers and packaging, ensuring their proper collection and subsequent recycling and significantly contributing to waste reduction and environmental protection. It seems to be a significant correlation between the implementation of deposit, return, and refund systems (DRS) for plastic packaging and containers and the percentage of collection and recycling. For example, in Europe, DRS achieve an average recycling rate of 94% for PET bottles, compared to other systems, which result in an average collection rate of 47% (Reloop Platform, 2022). In addition, European countries that have adopted DRS typically achieve recycling rates for single-use beverage containers exceeding 85%.

EU countries that have implemented deposit return systems (DRS) for beverage packaging, offering economic compensation to consumers who return empty containers, include Germany, Sweden, Finland, the Netherlands, and, soon, Spain. In Germany, since 2003, there has been a DRS known as "Pfand" for beverage containers made of glass, plastic, and aluminium cans. It has helped the country maintain high recycling rates for beverage packaging (The Times, 2025). DRS in Finland is one of the most successful in the world, with a return rate of 97%. This system is financed through a tax on beverage containers. In Spain, in 2023, only 41.3% of plastic beverage bottles were collected for recycling, falling short of the 70% target set for that year. This low percentage has led the Ministry for Ecological Transition to conclude that it is necessary to implement an SDR nationwide within two years, as stipulated by Law 7/2022 on Waste and Contaminated Soil for a Circular Economy. The Deposit Return System which is being implemented, would require a minimum deposit of €0.10 for plastic bottles, cans, and cartons, which consumers can recover when returning empty containers. This measure addresses the failure to meet European recycling targets and is established under Royal Decree 1055/2022.

It is important to note that the financing structure and producer responsibility in these systems vary depending on the specific legislation of each country. For example, in Finland, The Deposit Return System is financed through a tax on beverage containers. In Spain, Royal Decree 1055/2022 establishes that producers must finance the management of waste generated by the products they place on the market. Finally, recent reports indicate challenges in proper waste separation by consumers, which affects the system's efficiency, therefore these systems should be applied together with information campaigns to improve classification of domestic waste.

Regarding PAYT (pay-as-you-throw) systems to manage waste, several European countries have implemented them, aiming to incentivize waste reduction and enhance recycling rates. In these systems, households are charged based on the amount of waste they produce, encouraging better waste sorting and recycling practices. For example, in France, in 2013, approximately 5.4 million French citizens were part of PAYT schemes. These programs have led to significant reductions in household waste and improvements in recycling rates. For instance, areas with PAYT reported a 28% decrease in household waste per person and a 33% increase in sorted waste compared to national averages (euractiv.com). In Italy, cities like Parma have adopted PAYT systems, resulting in notable successes. Parma achieved an 80% recyclable waste collection rate, significantly surpassing the European target of 55% by 2025. The city employs door-to-door collection and an incentive-based pricing system to encourage residents to minimize waste (lemonde.fr). In Spain, some municipalities such as Esporles in Mallorca have become European benchmarks in waste management by implementing PAYT systems. Esporles achieved a recycling rate of 80%, significantly higher than the national average of 36%. The Spanish law 7/2022 mandates that by April 2025, all municipalities must implement similar systems where fees cover the costs of waste collection, treatment, and management.

The European Environment Agency (EEA) notes that economic instruments like PAYT are effective in encouraging citizens to separate waste at the source and generate less waste overall. The EEA's report indicates that PAYT systems typically have a positive impact on recycling rates (EEA, 2023).

3.9.2.3. Information and awareness campaigns direct to consumers to substitute conventional garbage bags.

Authorities should take the necessary measures to inform consumers and to encourage them to behave responsibly. Measures such as the availability of reusable alternatives (certified and improved compostable bags, as an example), available reuse systems and waste management options, information about the impact of litter abandonment and other inappropriate forms of conventional PE bags disposal.

3.9.2.4. Legal framework to substitute PE bags

Conventional PE carrier bags have already been banned in the EU. Improved compostable bags, decreasing the toxicity of compostable bags and the energy consumption for their degradation, and increasing their resistance, could be the best alternative to conventional or even recycled PE bags. It is necessary to ensure a legal context that encourages research into the use of safer materials in compostable bags and ban the use of all types of PE bags.

3.9.3. End-of-Life (EoL)

3.9.3.1. New investments in waste treatment infrastructures

In addition to reducing the generation of waste that is not suitable for preparation for reuse, recycling or reincorporation into sub-product value chains, new investments in waste treatment infrastructures may be necessary. It would be desirable to increase the number of industrial composting facilities; and, simultaneously, promote (in municipalities where it does not exist) or expand separate garbage collection systems (in municipalities where it already exists), and increase the number of compostable garbage containers. PAYT schemes and DRS for containers/packaging would contribute to improve separation of waste at home and enhance the success of the different strategies implemented.

3.9.3.2. Legal framework on disposal

Consumers should have clear information when making purchasing decisions to know how to manage different materials at their end-of-life. Policymakers should establish additional protocols for the correct collection, transport and treatment of waste, both for compostable and non-compostable garbage. There must be stronger institutional support for research and innovation in product design and development to take into account the entire life cycle, and bag labels must properly reflect this information, so that consumers will be able to differentiate types of garbage bags, according to their characteristics and correctly classify them for their final treatment/recovery. Misleading or lack of information must be banned and penalized.

3.10. Methodology to test the effectiveness/acceptance of reduction/mitigation measures on stakeholders.

To analyse the effectiveness of the intervention options described in section 3, social research methodologies, based on questionnaires, to assess preferences of stakeholders in the supply chain for SUPs were used. Surveys are a widely used quantitative methodology in social research to collect data on perceptions, behaviours, and attitudes of target populations. They are employed to evaluate the effectiveness of public policies by measuring key indicators before and after implementation, identifying gaps, and gathering opinions to guide future decisions (Fowler, 2014; Bryman, 2016; Babbie, 2020). Types of surveys applied to evaluate the effectiveness of public policies are longitudinal, cross-sectional, experimental or perception/satisfaction survey. Among this last ones, stated-preference methodologies to elicit and value preferences have been broadly used (Louviere et al., 2000; Hanley et al, 2001; Bateman et al, 2002). These social research methodologies have been applied in the EU for example, taking the most recent works, to know the plastic waste problem perception (Boca et al., 2023), the public preferences for marine plastic litter reductions (Khedr et al, 2021), or the impact of the SUP Directive (Meyer, 2021),

To test the effectiveness and acceptance of the reduction/mitigation measures described in section 3 to stakeholders of the different stages of the supply chain, two questionnaires were designed and applied. The first questionnaire was focused on obtaining information from companies, closely related to garbage bags, if possible, or to plastics in general, in some or all the parts of their production process. Questions include perceived effects of the current legal framework on SUP and their opinion regarding the measures applied; difficulties that may found in compliance with it; and preferences about new policies/measures, taking into account their role in the value chain and their experience. We surveyed firms from four stages of the supply chain: (1) input suppliers; (2) producers; (3) distributors (wholesale and retail) and (4) waste plastic processors (including recovery of secondary products). This implies that we elicit opinions of three of the four types of stakeholders described in section 3.4., and only the 4th type, that is, public institutions (tertiary stakeholders), NGOs, and research (secondary stakeholders), are out of the scope of our study.

Special emphasis has been placed on consumers, an essential part of the supply chain and crucial for the success of public measures/policies, with an extensive questionnaire to know purchase habits regarding packaging, waste separation and recycling, use and purchase of garbage bags, information about the types of bags available, their current knowledge about the environmental/health problems derived from plastic use and disposal, opinion about the current legal framework and finally, opinions and preferences about future public measures to advance in the solution.

Both questionnaires were applied between December 2024 and January 2025 obtaining 602 responses from consumers 151 from firms/companies, in Spain. The consumers' sample was proportional regarding the population of different Spanish regions, taking the person responsible of purchasing decisions at home as responder, and with age quotas. Telephone and online interviews were used. Firms were selected considering the stage of the supply chain (input suppliers, producers, distributors and waste plastic processors), from different regions, with previous telephone contact to invite them to fill in the online questionnaire.

3.11. Results

3.11.1. Results from companies

Use of plastics

Of the 151 companies that agreed to answer the questionnaire, 11,3% were input suppliers, 18% were producers of final goods, 25% were distributors/transporters, 22% were wholesale sellers, 13% were retail sellers, 3% were recycling/waste treatment companies and 7% were recycling/recovering byproducts from plastic production companies. We have representation of three different categories of stakeholders from almost all the stages of the supply chain (consumers have a different questionnaire, whose results will be described in the next section). About 37% of the sample are international companies.

About 54% of the interviewed companies used PE in some part of their activity, 56% used PP and 4% other types of conventional plastic (ABS, Nylon, Polyamide, PVC, etc.), 37% used bioplastics (vegetal origin) and 48% used recycled plastic. In addition, 36% say they used plastic as an input for production, and 64% for containers and packaging.

Through an open question, they were asked to explain how the current legal framework has affected the company. Some of the answers obtained were the following (ordering by frequency): increasing of bureaucracy, increasing in costs, changes in the type of selected materials, changes in the production process to reduce the quantity and type of plastic used, and need of new investments. The laws have had positive effect on recycling firms and some companies stated that the new laws on plastics have changed completely their environmental policy.

Most of the sampled companies (50%) are in favour of the measures already applied in current EU Directives and national laws, because the problem generated by plastic waste is serious and even 26% defend that more ambitious measures are necessary. About 20% do not agree with the current laws and policies, although admit that intervention is necessary and finally, only 4% believe that the problem does not exist and are against any intervention.

When asked about the better option to substitute conventional plastics, about 54% choose biodegradable (bio-based) plastics in general, 19% compostable plastics and 25% recycled plastics.

A majority of companies (56% of the sample) think that everybody is responsible for the problem (consumers, firms and governments), the most frequent answer; 39% say that companies themselves have more responsibility, 31% mention governments as more responsible and 27% say that responsibility is on consumers (more than one option was possible).

Opinions about future interventions/measures

The questionnaire included the question “In your opinion, what prevents companies that use or produce plastics from transitioning to the use or production of materials with less environmental impact than conventional ones?” and the alternatives (they could choose more than one) were the following:

1. Costs are higher.
2. New materials do not have the necessary quality or characteristics.
3. The materials exist but are not available or not available in sufficient quantity.
4. We do not have enough information about alternative materials or their characteristics.
5. More research on new materials is needed.
6. Production processes are technically difficult to change.
7. We consider the situation somewhat alarmist and do not see the need for change.
8. We cannot find suppliers of these materials.
9. Our clients do not demand them. There is not enough public awareness of the problem.

Figure 11 summarises the answers to this question. Cost is the most important shortcoming facing by companies that difficulties transition. Changing production processes is complex and expensive, and this is coherent with the second reason, technical difficulties, mentioned by more than 30% of the respondents. With near 30% of responses are also the deficient characteristics of new materials and the need of more research to improve those characteristics and the environmental effect (toxicity, biodegradability) of new materials. Finally, about 28% say that new materials are frequently not available. It is remarkable that only 13% believe that there is no need for change or 9% that there is no social awareness about the problem.

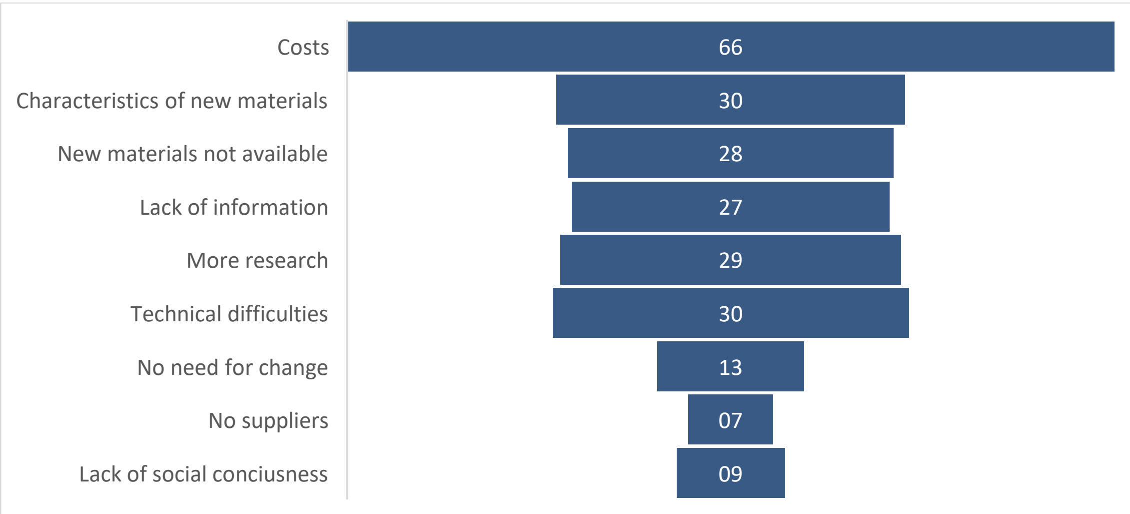

Figure 11. Companies’ difficulties in transitioning to new materials

About 42% of interviewed companies are currently participating in some initiative, alone or in collaboration with other firms or institutions, related with the decrease in quantity or change of type of plastics they used, 72% of these projects are individual. They mention some public administrations or sectorial associations as main partners and the objective of the projects were (1) developing new materials; (2) looking for new products (recycled, biodegradable, compostable); (3) design and apply changes in production processes to substitute conventional for new plastics; (4) decrease the use of plastic in production or distribution (packaging); (5) increase re-use, separation and recycling

Finally, the last question explained that both the European Union and Member States are proposing advancements in community policies to continue reducing plastic waste. A series of possible measures were proposed and respondents were asked to indicate their level of agreement or disagreement, taking into account the situation and adaptability of their company to these new measures (on a scale from 1 = strongly disagree to 5 = strongly agree). The proposals presented were the following:

1. Prohibit the use (and therefore the production) of all types of conventional plastics (PE, PP, PVC, and others).
2. Advance research on new materials and their effects.
3. Apply taxes on the use of more harmful plastic materials (PE and others) or the use of proven dangerous additives to increase their cost, thereby incentivizing the use of more environmentally friendly options.
4. Design and implement measures to reduce waste generation in households/companies, such as pay-as-you-throw (PAYT) systems.
5. Improve product labelling with clear information about the type of plastic used (compostable, biodegradable, recyclable, recycled, etc.) and its advantages/disadvantages (Official Eco-labelling – Certification Program).
6. Information campaigns for consumers/companies about the risks of using conventional plastics and the possibilities for their replacement.
7. Prohibit/penalize misleading advertising by companies regarding the eco, bio or degradation characteristics of different products.
8. Extending companies or producers' responsibility, making it mandatory to take care of the waste associated with their products (with specific and more ambitious collection-recycling targets).
9. Regulations limiting the use of plastics in production/transport/sale (companies), with specific goals (in % and time) and penalties.
10. Economic support/advisory services for companies to use new materials that replace conventional plastics.
11. More and clearer information on how to handle plastic products (based on their composition) at the end of their life cycle.

Results are summarised in Table 9 and Figure 11. About 65% of the companies participating in this study think that advancing in research on improved or new materials to substitute conventional plastics is the key issue regarding public policy in the near future. The mean score of this option is 4.6 and if we consider 4 and 5 positions in the scale, 90% of companies would agree or fully agree with this measure. Policy options related to improving information are the next better classified. These are improving information on how to handle plastic products at the end of their life (4.37), financial and information support to companies to replace conventional plastics, prohibit/penalise confusing or wrong information from companies about characteristics of their products (like degradable, eco, bio, green, etc.), improve labelling with reliable officially certified information about plastic used and its effects, and information campaigns about the risks of conventional plastics and substitution possibilities. All these policies were rated with about 4.3.

Extending companies or producers' responsibility and measures to reduce waste generation in households/companies, such as PAYT systems are punctuated with 4.2 and 4.1, respectively.

Finally, the options with less agreement by part of companies are bans on all types of conventional plastics, stablishing limits to the use of plastics and applying new taxes.

		1	2	3	4	5	Mean
1	**Ban conventional plastics**	13,25	12,58	24,50	31,79	16,56	3,30
2	**Research**	0,00	0,66	7,95	25,17	64,90	4,58
3	**Taxes**	9,93	8,61	21,19	33,11	23,18	3,63
4	**Reduce waste**	4,64	4,64	12,58	36,42	41,06	4,07
5	**Labeling**	0,66	2,65	11,26	42,38	41,72	4,26
6	**Information**	1,32	1,32	14,57	37,09	44,37	4,26
7	**Penalize wrong inf.**	0,66	3,31	13,25	33,11	47,68	4,30
8	**Companies Responsibility**	0,00	5,30	18,54	32,45	41,06	4,17
9	**Limits to use**	6,62	6,62	18,54	36,42	31,13	3,81
10	**Support to companies**	1,99	1,99	8,61	39,07	46,36	4,32
11	**Information on waste handling**	0,00	1,32	11,26	37,09	49,67	4,37

Table 9. Companies' preferences about new measures (Likert Scale, from 1, fully disagree, to 5, fully agree; % of total responses)

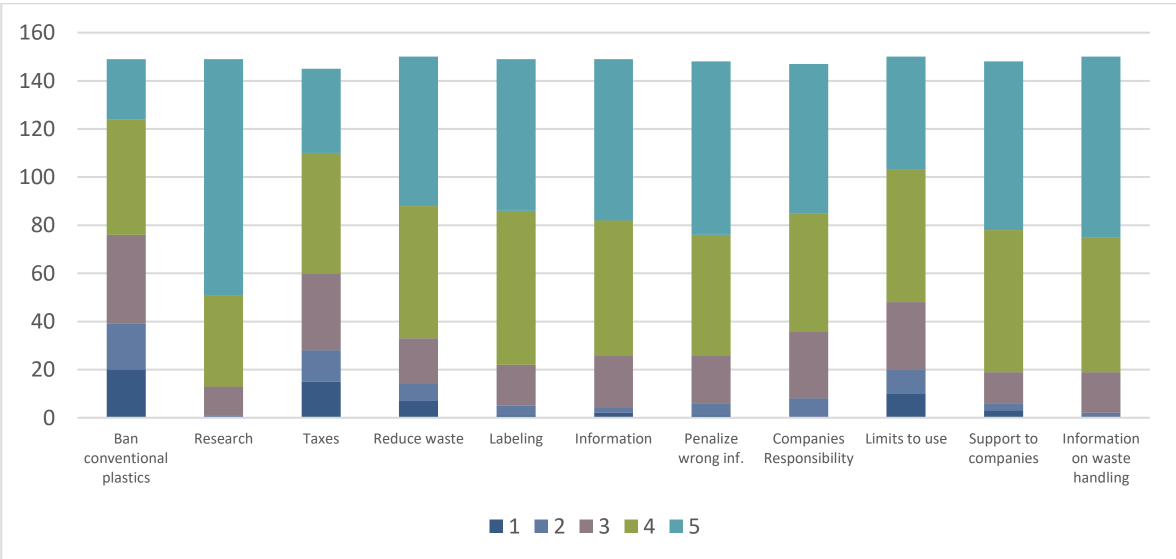

Figure 12. Companies' preferences about new measures *(Likert Scale, from 1, fully disagree, to 5, fully agree; number of responses)*

Figure 12 show that those proposals obtaining an agreement or full agreement (4 and 5) of more than 80% of interviewed companies are, apart from research (with more than 90%), improving the information on waste handling, economic and information support to companies, labelling (official certification schemes on new products) and finally, they claim for more and better information, with information campaigns for consumers/companies about the risks of using conventional plastics and the possibilities for their replacement and also they are in favour of prohibiting/penalizing misleading advertising by companies regarding the eco, bio or degradation characteristics of different products.

There were finally invited to provide suggestions or proposals to try to solve the environmental problem of plastics and, additionally to the list we previously presented them, they mentioned the following:

1. More recycling and waste treatment infrastructure, new incentives for recycling and education campaigns.
2. Information and education to consumers, both about the problem and likely solutions.
3. Changes in lifestyle: decrease consumption, increase in separation for recycling, etc.
4. Ban all types of SUPs.
5. Incentives to separate/recycling (PAYT, SDR, etc.)
6. Plastic (containers/packaging) must be 100% compostable.
7. Incentives to the use of bio-degradable/compostable plastics.
8. More collaboration/dialogue among stakeholders (companies – governments)

3.11.2 Results from consumers

Purchasing behaviour

Consumers use tote bags (about 48% of the sample) to take their daily supermarket purchase home, followed by plastic reusable bags (37%). Only 3% usually buy SUP plastic bags in the market. When buying fruits and vegetables the preferred options are compostable plastic bags (29.6%), reusable bags (25.4%), paper bags (19.3%) and conventional plastic bags, made of PE (18.6%). More than 50% buy some products in bulk (mainly oil, rice, legumes, nuts or seeds) and those who do not buy in bulk products explain that the reason is that there are no products available or they are not used to buy them.

Waste separation and recycling

Regarding waste separation at home, most or respondents separate waste at home (87%), most of them packaging waste (87%), glass (77%), paper (80%), organic (60%), batteries (64%), oil (45%). The majority of respondents have among 2 and 4 waste bins at home (82%), with 40% having 3 bins (the most frequent value).

Of those who separate organic waste, 48% use the "brown container" or brown bin, is collected by the local council and treated at industrial composting facilities. 27% do home composting (in a home compost bin) and 19% do community composting (in neighbourhood, street, or building composters)

There are two main reasons why 11% of the sample do not separate waste fractions. The first is the need of enough space at home to store the different waste containers (34%), and the second is the lack of habit/they are unaccustomed to doing waste separation for recycling (31%).

Garbage bags

In the sample, 35% buys one size of garbage bags (bins of the same size), 32% buys two sizes, 14 % buys three sizes and 19% four sizes. When asked about the size, respondents combine small garbage bags (10-20 litres) with big ones (40-60 litres) (65% of the sample). The small bags are mainly used to store organic waste, glass (and small fractions like batteries, etc.), and the big bags are used mainly for packaging waste (plastic, paper/cardboard, etc.).

Respondents were asked about how they choose the type of garbage bags, and they were presented different characteristics (they could select more than one). Those characteristics where price, colour (for different waste fractions), resistance, self-sealing system, scented, dripless, and biodegradability/compostability/recycled. Of those options, the price is the most mentioned criteria (48%), followed by resistance (44%) and self-sealing (36%). Colour were mentioned by 22% of the sample, scented by 24%, dripless by 25% and remarkably, biodegradability/compostability/recycled were selected by the 22% of the sample.

When asked which of the former characteristics is more influential in their purchase decision, answers are quite divided among resistance (26%) and price (25%), followed by self-sealing (19%). In this case, biodegradability/compostability/recycled, that is environmental effects, are selected as key reason for purchase for the 11.6% of individuals.

About 60% of interviewed individuals say that they know the meaning of “biodegradability”, 54% state that they know what “recycled” is, but only 35% say they know the meaning of compostability. However, when those to claim knowledge were asked to define the concepts, almost 100% of those correctly define “compostability” and “recycled”, although those trying to define “biodegradability” show more variability and misunderstanding. In this case, there are general answers like “better for the environment”, “ecological”, “not toxic” “sustainable” or “higher quality”; others more concrete but not correct like “organic”, “soluble in water”, “used as fertilizer” and about a 60% gave the right answer.

Respondents usually (33% of the sample) buy biodegradable garbage bags (bio-based), conventional PE garbage bags (30%) and recycled/recyclable bags (20%), and the less frequent purchase is of compostable bags (only 6.5% of the sample). Those who continue using conventional PE bags explain that they do it because the other types are more expensive (32%) or because they do not have enough information to choose (31.5%). In addition, about 15% say that other types of garbage bags are no available.

It was also found that about 60% of the sample previously re-used carrier bags as garbage bags, before the current EU Directive that banned those for free.

Knowledge of the problem and preferences for mitigation measures

The most extensive part of the questionnaire focused on the previous knowledge of the environmental/health problem derived from the use and disposal of plastics and of the likely solutions already applied and to be applied in near future.

When facing to different environmental problems, 18.4% of respondents choose as one the most important problems sea pollution derived from plastics (second chosen option), when the most frequently chosen option is climate change (50%). Regarding effects on health of those problems, climate change is mentioned again as the most relevant for the 31.2% of the sample, but 21% mentioned pollution of water from industries and cities, 20% choose air pollution from industry and transport, and 16% mentioned plastics at the sea.

The questionnaire then focused on the problem of plastics at the sea and its consequences. Figure 13 show that the mean rating is over 4 for all the problems, with the higher mean rate for losses of marine biodiversity, 4,56, followed by losses on fisheries (4,52), human health effects (4,45) and marine landscapes (4,37).

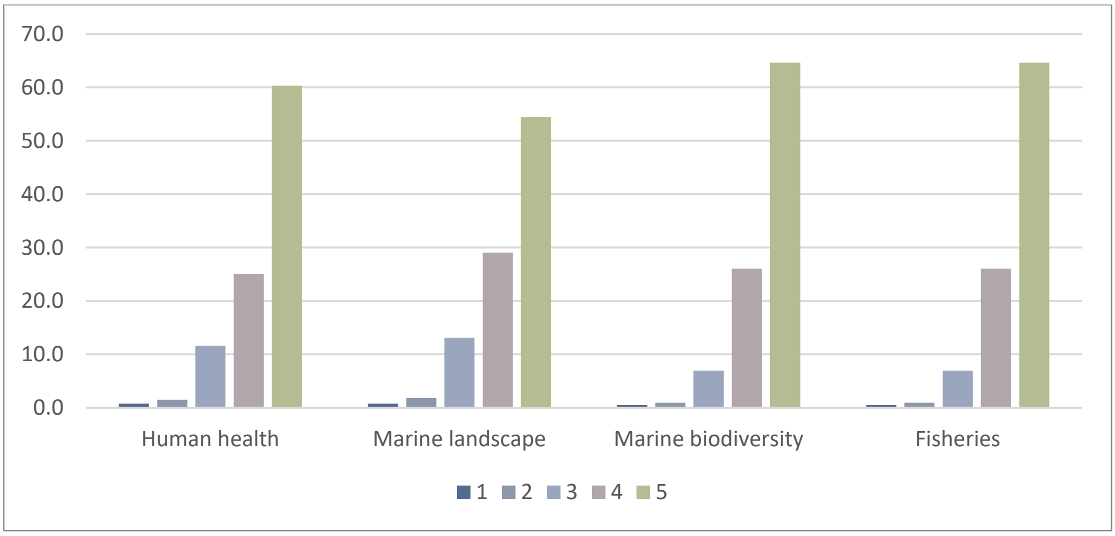

Figure 13. Consumers' opinions about the importance of consequences of plastic marine pollution

When asked their opinion about why plastic waste is harmful, most of respondents (46%) say that plastic waste is difficult to degrade and remains in nature for a long time, 27% say that they broke and generate micro-plastics that enter in the food chain, and 12% point out that they float in the ocean and avoids sunlight to enter, damaging biodiversity.

Respondents also consider that everybody (consumers, firms and governments) is responsible of the marine pollution form plastics (62%), although 42% think firms are more responsible, and a similar percentage, 33% thinks that the responsibility is on consumers and governments.

Opinion about the current legal framework:

Most of the sample (68%) consider as positive the ban of free carrier bags. Those who are not in favour doubt about the effectiveness of the measure and think it generates more expenditure for consumers and profits for supermarkets. About 78% also consider as positive the ban on some SUP. People in favour of the current legal framework explain that those measures incentives reusing, lowers plastic consumption and therefore the amount of waste generated, being positive for the environment and health.

They were also asked about the scope of the current regulations on plastics in the EU. More than half of the sample (53.2 %) think "It is not enough. Further progress in needed", 18.6% needs more information to have an opinion, 13% thinks it is too demanding and 10% is not in favour of regulations. More focused on garbage bags, 65.8% of respondents would be in favour of banning PE/conventional garbage bags, allowing only other bags with proved lower negative effects at the end-of-life stage. About 22% does not have an opinion and 13%

would not support this measure. Those who do not support it, doubt about the availability of alternatives that offer similar characteristics, including similar prices.

In the questionnaire, explanations about what biodegradability(bio-based), compostability and recycling were provided and then, individuals were asked whether they will purchase some of them if they have access to these types of bags, at a similar price compared to conventional PE garbage bags, and maintaining similar characteristics. About 77% of respondents would buy some alternative, with the preferred ones being biodegradables (bio-based), with 35%, followed by compostables, with about 30% and recycled 11.5%. If the price of compostable bags would be higher than conventional ones 70% will accept and if compostable bags were cheaper, 81.2% would buy them.

The final question was about preferences regarding different future policy measures/regulations on the use of SUPs and in special of those not included in the current European legal framework, like garbage bags. The proposed policies were the following:

1. Ban de use of conventional/PE plastic
2. More research about new materials and their effects
3. New taxes on harmful materials or the use of dangerous additives, raising their price, to encourage the use of more environmentally friendly options.
4. Implementation of PAYT systems to encourage the reduction of household waste, as well as the use of bags.
5. Improve bag labelling with clear information about alternative plastic types (compostable, biodegradable, recyclable, recycled, etc.) and their advantages/disadvantages (official eco-labelling).
6. Conduct information campaigns for consumers about the risks of using conventional plastics and their alternatives.
7. Ban/penalize misleading advertising by companies regarding the eco or bio characteristics of different products.

	1	2	3	4	5	Mean
Ban PE plastic	4,65	4,15	19,10	26,58	44,19	4,05
Research on materials and effects	0,66	1,00	9,14	22,59	65,95	4,54
Taxes on materials or additives	8,14	6,31	15,45	27,41	40,86	3,92
PAYT systems	8,80	6,81	13,62	29,57	38,87	3,90
Bag labelling	1,33	2,66	13,12	30,90	50,00	4,32
Information	2,16	2,33	12,29	26,74	54,98	4,35
Penalize ilegal claims	2,49	1,83	12,13	21,43	61,30	4,40

Table 10. Consumers' preferences about different future policy measures.

Likert scale (1, fully disagree to 5, fully agree), % of total answers.

Table 10 presents the results obtained. Analysing the mean punctuation assigned, all the alternatives have a mean over 3.5, which means that are highly approved by consumers. However, the preferred measures (over

4 over 5) are the research on materials and their effects (4.5), penalize illegal claims of products (4.4), followed closely by information campaigns about risks of plastics and alternatives and, with 4.3., improve bag labelling with clear/official/reliable information about the type of plastic and its advantages/disadvantages. It is remarkable that the most preferred options are related to research (knowledge) and reliable information, that would allow consumers to undertake the correctly informed decisions.

Ban PE plastic is also highly supported (but with previous research and information) and finally, taxes and PAYT systems are close to 4, but we could conclude that consumers think they are interesting but kind of next step in the intervention policy, with priorities focused clearly on research advances and reliable information.

Figure 13 represents the answers to the same question but, in this case in a more visual way, taking into account the number of responses (frequency) to each option and the five points of the Likert Scale (and not the mean). Taxes on materials and additives show the higher number of 1 and 2 scale responses, although this percentage is, in both cases, not more than 15%. The rest of measures are under 5% of disagreement, except banning of plastics that is about 9%.

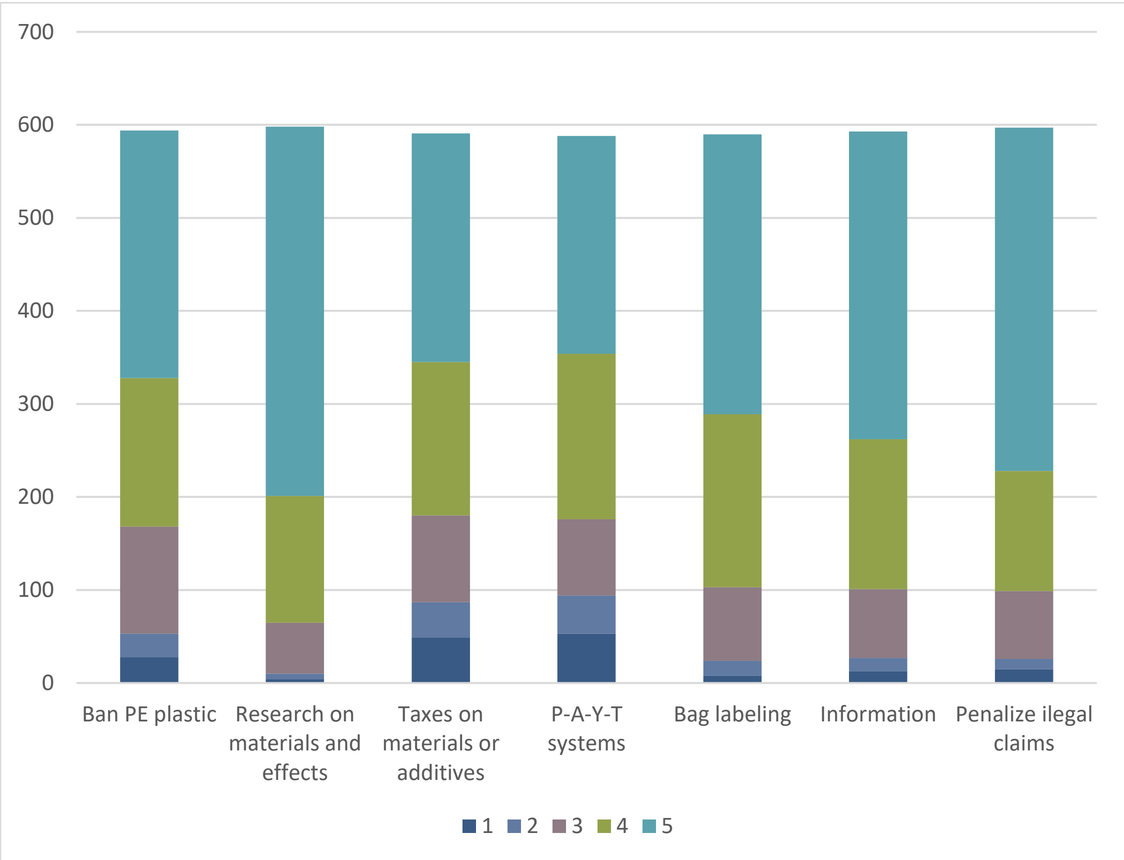

Figure 14. Consumers' preferences about different future policy measures.

Likert scale (1, fully disagree to 5, fully agree), number of answers.

Finally, we search for suggestions to improve the current system of for separating/sorting, depositing, collecting, and processing plastics. The proposals presented were the following:

1. Measures to reduce waste at the source (e.g., PAYT systems, where each household/company pays for the waste they generate)
2. Measures to improve the separation of plastic materials in households and increase recycling
3. Improvements in the plastic containers and packaging collection service, such as systems with SDR, etc.
4. Taxes on the use of plastics in manufacturing/packaging/transportation of products, which would increase their price
5. Greater responsibility for companies, establishing mandatory management of waste associated with their products
6. Regulations limiting the use of plastics in production/transportation/sales (companies)
7. Financial support for companies to use new materials that replace conventional plastics

Again, a Likert scale (1 to 5) of social preferences to improve the current system of for separating/sorting, depositing, collecting, and processing plastics, was used and results are presented in Table 11 and Figure 14. Results show a high interest in those policies, with mean punctuation over 3.5 for all of them. The highest position in the scale, considering the mean, is for improving the collection system for containers and packaging waste using SDR or other systems (4.45), and increasing responsibility of producers (4.40), which are coherent with the use of those SDR, supported by companies. Very similarly scaled, with among 4.2. and 4.3. are measures to improve the separation in households to increase recycling, limits to the use of plastic in production/distribution/sales and financial support for using new substitutive materials in production. Measures for reducing waste and taxes obtained less support, although mean punctuation is still very high (about 4).

	1	2	3	4	5	Mean
Reduction	6,48	3,99	19,10	30,23	36,71	3,97
Separation	1,66	2,33	14,45	29,07	51,00	4,30
Collection	1,83	1,16	8,14	29,07	58,31	4,45
Tax on use	6,98	5,81	17,61	30,07	36,05	3,93
Companies	1,99	1,66	11,46	25,91	57,48	4,40
Limits/regulations	2,33	2,82	13,46	28,74	50,00	4,29
Financial support	2,82	3,65	13,62	27,74	50,17	4,25

Table 11. Consumers' support of new measures to improve the waste collection and treatment systems

Likert scale (1, fully disagree to 5, fully agree), % of total answers.

In Figure 14, the responses by option and point of scale are visually shown. The options more punctuated with 5 are improving collection systems and increasing responsibility of producers (extended producer responsibility), with about 60% of the sample. If we sum up responses with give them 4 or 5 points, we have that almost 90% and 85% of the sample, respectively, agree or fully agree with these two policies. With 80% of the sample giving 4 or more points to improving separation, and limiting/regulating the use of plastics and financial support for substitute materials in production.

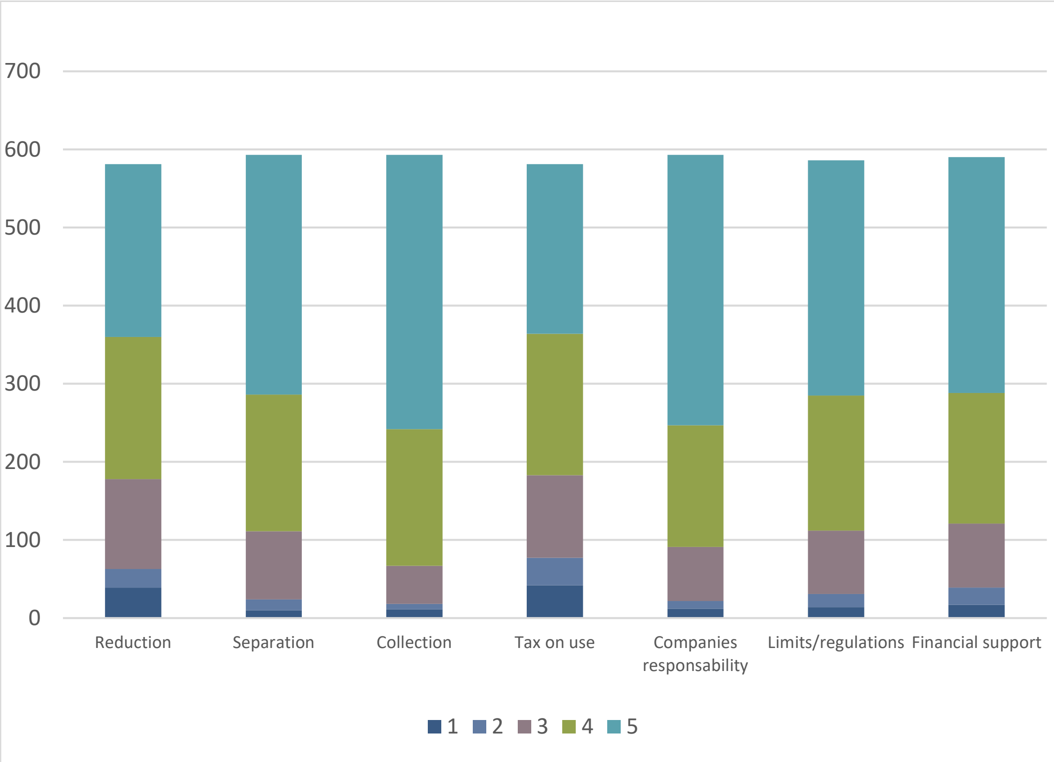

Figure 15. Consumers' support of new measures to improve the waste collection and treatment systems

Likert scale (1, fully disagree to 5, fully agree), number of answers.

3.11.3. Summary

Companies (66%) found cost difficulties in transitioning to new materials, both regarding financial costs and bureaucracy, technical difficulties to change production processes (30, problems to find substitutes with suitable characteristics (29%) and lack of information about possibilities (28%). A remarkable result is that an important number of companies is already participating in initiatives to decrease the use of change the type of plastics they use. Both, consumers and companies, think that everybody is responsible for the environmental problem of plastics (56% of companies and 62% of consumers).

Regarding consumers, there is still possibility of improving the classification of domestic waste, particularly organic waste and containers/packaging (11% of the sample say that do not separate any waste fraction). They show misinformation and misunderstanding about types and characteristics of currently marketed garbage bags, being the dominant characteristics in their purchase decisions, price and resistance. Although PE garbage bags are the most bought type (conventional and recycled), both biodegradable and compostable have already an important market chare (about 40%). Information here appears again as a difficulty to change.

Most participants in both surveys agree with the current legal framework and with the ban on carrier bags and even some think that a deeper intervention is required (e.g. 53% of consumers say that further progress is needed). 66% that would be in favour of banning conventional PE garbage bags, if suitable alternatives were available. 77% of respondents will buy alternative garbage bags. When facing to choose among garbage bags alternatives (PE vs improved compostable bags), if the price of compostable where higher, 70% will be willing to pay that price and buy them, and this percentage increased to 81% if prices were lower.

Research on improved materials, acting on their functional and degradability characteristics is the most supported intervention policy (90% of companies and consumers agree of fully agree, with 4.6 mean rate). Measures related to information are the next highly supported ones, about handling of products at the end of their life, information support to help in the change and also banning and penalize misleading information provided in labels and marketing campaigns, improving labelling information through official certification programs (mean rating over 4.2., both companies and consumers). Companies and consumers also support EPR and PAYT systems (mean rate about 4).

Finally, consumers highly require changes in the current systems of classification/collection/treatment of waste. They claim for improvement in the collection system for containers and packaging and generalize the ERP (more than 85% agree or fully agree), which seems to be in favour of extending SDRs. Enhance measures to improve classification through incentives, regulate the use of plastics in production, helping companies to substitute materials are also highly punctuated (80% agree of fully agree).

3.12. Conclusions

3.12.1. Limitations and further research

The research of this case study on SUPs, although both samples are representative and conclusions are robust enough to be extrapolated as social preferences, is limited in some aspects and would require an extended analysis regarding two aspects:

- More countries should be included. The field work of the stated preference analysis was done in Spain, due to cost and time restrictions. Although an important part of companies surveyed develop international activity (about 40%), applying the same or similar questionnaire to other countries of to the EU would provide strong support for the results and will allow them to be extrapolated or taken as representative of social preferences for the EU.
- Opinions from other stakeholders should be captured, among which international, national, regional and local governments (tertiary institutions), as responsible for the legal framework, and for the collection and treatment of municipal solid waste, and NGOs and research (secondary stakeholders).

3.12.2 Recommendations for policy interventions

Stakeholders (companies, consumers) participating in the survey to elicit preferences for intervention measures regarding SUPs agree or fully agree with the options presented. From the literature and data reviewed, and from the answers to the questionnaires, there is a high agreement and acceptance of the EU SUP Directive, and a majority of respondents state that it is necessary to go further in new regulations and policies to solve the problem of plastics in the environment. Studies like Meyer (2021) demonstrate the Directive on single-use plastics has been effective in changing consumer behaviour. Even with the increase in the market of garbage bags, when carried bags, where banned, a net decrease in the total consumption of plastic bags was observed.

Based on the literature reviewed and on stated intensity of their preferences observed in this case study, a list of potential intervention alternatives will be presented, ordered by observed social priority and grouped in sets of measures that could and need be combined.

I. Research + incentives for substituting PE conventional SUPs

- Current substitutes of PE garbage bags (and SUPs) are not innocuous, both in toxicity and degradability, due to materials and additives (e.g. to accelerate oxidation and fragmentation) included in their production. More research is needed to improve composition of alternative plastics.
- Product substitutes currently in the markets do not have the characteristics required by consumers, particularly resistance/thickness to prevent leakages in case of garbage bags. Although more materials would be required, stablishing minimum densities could help increasing the demand and use of alternative plastics, reducing environmental impacts and compensating the highest use of inputs.
- Check and monitor compliance with the current legal framework in all the countries of the EU, avoiding the differences among countries regarding the effort intensity.
- Extend the current regulation to include banning of other types of SUPs made of PE or other conventional plastics not currently controlled, like PE garbage bags, and incentive the use of new improved substitutes, like compostable garbage bags.
- Implement stricter regulations on intentionally added microplastics in products like cosmetic and detergents.

II. Information interventions

- Intensify public awareness campaigns about the effects of plastics on the environment and health, linking the problem to consumption and production decisions, promoting consumption reduction or responsible consumption, efficiency in materials' use in production and going towards a Circular Economy. Public perception studies on plastic waste, such as Boca et al. (2023), highlight the importance of education in fostering sustainable attitudes. Lowering consumption will have an effect on waste generation in general, and on the consumption of garbage bags, in particular.
- Once advances in research have achieved improvements in alternative materials, legal framework about information to consumers and companies about available substitutes, their composition, effects and how to handle them at the end of their life, must be developed.
- Banning and penalizing confusing and misleading claims on plastics characteristics used by companies in labels and marketing campaigns.
- Develop and promote official third-party certification and labelling schemes with internationally recognized standards, which may help companies to modify production processes and consumers to find reliable information.

IV. Interventions to improve the classification, separate collection and recovery/recycling/treatment or waste.

- New infrastructures for industrial composting of organic waste and recycling of plastic materials.
- Involve and support (information, financial resources) local and regional governments to apply a correct collection and treatment policy.
- Intensify the campaigns and incentives to increase social involvement in the correct classification and disposal of waste fractions, including organic waste, using PAYT systems and SDR, which have proved, where applied, to increase percentage of collection and recycling of all fractions and particularly plastic containers and packaging. Encourage reuse with economic incentives and subsidies for refillable or returnable products.
- Prioritize improving waste collection in urban and rural areas, especially in vulnerable coastal zones.
- Move forward do the Extended Producer Responsibility (EPR), making producers responsible for the entire life cycle of their products, including EoL disposal and increasing the current low rate of recovery of plastic products, particularly in the case of plastic bags. This objective would incentive a better Eco-Design, that is, to design products that would be easier to recycle, reuse or be safely disposed.

V. Support to companies

- Administrative/technical and financial support to companies to incentivize or intensify transition to new materials. Costs (economic and in terms of bureaucracy), new investments and technical difficulties are the main shortcomings found by producers/manufacturers, together with deficient characteristics of new materials and the need for research on improved alternatives.
- Promotion of information transfer and collaboration in join research among public/private sectors.
- Promote business models focused on recycling, reuse and use of better inputs for production through subsidies or tax incentives for companies adopting circular economy practices.

VI. Other proposals

- Cross-border policies and regional collaboration. Research by Khedr et al. (2021) underscores the importance of coordinated European responses to marine plastic pollution. Pan-European strategies to reduce plastic pollution in shared seas like the Mediterranean and the Baltic must be developed, and strengthen international collaboration to track plastic waste flows and address cross-border impacts.
- Social preference analysis methodologies, such as those by Khedr et al. (2021), can assess willingness to pay for plastic waste reduction and provide information to design citizen-preferred policies.
- Implement continuous monitoring systems to track plastic waste and its impacts on biodiversity and human health.
- Studies for anticipating effects of policies, both on biodiversity, human health and society.

3.12.3. General guidelines about how to assess policy effectiveness in collaboration with stakeholders

1. **Ensure stakeholder Understanding of the Current Legal Framework**

Key EU regulations addressing plastic waste include:

- **EU Single-Use Plastics Directive (2019/904):** Targets reducing waste from single-use plastics like cutlery and straws.
- **Waste Framework Directive (2008/98/EC):** Establishes waste management principles, focusing on waste reduction and recycling.
- **Marine Strategy Framework Directive (2008/56/EC):** Protects European marine environments and addresses marine litter.
- **Circular Economy Action Plan:** A component of the Green Deal aimed at reducing plastic waste through sustainable design and recycling.

2. **Define Key Policy Objectives**
Focus on clear goals, such as:

- Reducing plastic waste and marine pollution.
- Preventing plastic from entering marine ecosystems.
- Increasing recycling rates and waste management efficiency.
- Raising public awareness and encouraging behavior change.
- Mitigating health and biodiversity risks associated with plastic pollution.

3. **Engage Stakeholders**
Include key groups like:

- **Government authorities:** Responsible for policy enforcement and implementation.
- **Businesses and industries:** Involved in plastic production, consumption, and recycling.
- **NGOs:** Raise awareness and advocate for sustainable practices.
- **Academics:** Provide data and models for evaluating policy outcomes.
- **Citizens:** Essential for gauging behaviour changes and public support.

4. **Identify Key Performance Indicators (KPIs)**
Examples include:

- Reduction in plastic waste generation.
- Increased recycling rates.
- Decreasing use of PE and increasing use of substitutes.
- Decreased marine litter.
- Public awareness and behaviour changes.
- Impacts on biodiversity, such as fewer species affected by plastic pollution.

5. **Data Collection and Monitoring**
   Collect baseline data and track changes over time:
- Monitor plastic waste levels, marine pollution, and public behavior.
- Use existing EU reporting systems like those of the European Environment Agency (EEA).

6. **Comparative Policy Analysis**
   Compare the outcomes of policies across EU member states to identify best practices.

7. **Public and Stakeholder Feedback**
   Gather feedback through surveys, consultations, and collaborations with NGOs.

8. **Conduct Impact Assessments**
   Analyze environmental, health, economic, and social equity impacts.

9. **Evaluate and Adjust Policies**
- Modify policies based on data and stakeholder input.
- Share best practices among EU member states.

10. **Develop a Long-Term Strategy**
- Integrate plastic waste policies with broader EU strategies like the Green Deal.
- Coordinate globally to address transnational marine pollution.

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Appendix

Appendix to case study 8.1

A.1 - List of emission reduction measures for stakeholder survey.

Tire design and manufacturing

Innovations in tire design and composition

Ban residual rubber on tires (vent spews or rubber hairs)

<u>Following two include creating an universal tire wear test</u>

Implement a legal limit for tire mass loss for tires

Include tire mass loss in the already existing EU tire label

Tire use (driving)

Technological approaches and devices to collect particles at vehicle

Educational measures to raise awareness around tire pressure

Improve TPMS and implement it in all vehicle

Impose regulations on regular checking wheel alignment

Invest in (and implement) systems that monitor and correct chassis settings

Educational measures to raise awareness around wheel alignment

A time limit on use of winter tires

Implement speed and acceleration limiters

Implement speed limit

Education measures on eco-driving

Stimulate the development of lighter electric vehicles

Tax according to vehicle weight

Educational measures to make lighter vehicles more attractive

Taxation, fees, subsidies, or incentives to reduce total driven km

Improve public and alternative infrastructure

Make public and alternative transport cheaper

Educational measures to enhance the use of public and alternative transport

Implement an asphalt or road label and optimize road surfaces through green procurement

Frequent street cleaning at hotspots

End-of-Life

Improve turf design (during the laying of the field)

Maintenance strategies and good housekeeping

Use alternatives to granulated turf

End-of-Pipe

Road runoff treatment systems

Roadside vegetation to capture airborne tire wear fraction

Improve WTTP removal efficiency

Avoid spreading sludge on agricultural land

A.2 – Detailed results for ePLAS endpoint calculations

In the following section, the reduction potential per emission reduction intervention (2.5.4) are reported for each of the 3 different endpoints considered. Those endpoints are (1) the number of microplastics per time unit discharged at the mouth of the basin (Hamburg) into the North Sea, (2) the number of microplastics in the water phase averaged over all Elbe river nodes, and (3) the total number of microplastics in the water phase summed over all Elbe river nodes. The considered interventions were:

1. Implementing a speed limit at 100 km/h
2. Optimal tire pressure and wheel alignment
3. Particle capture devices
4. Improved particle retention in WWTPs

Results are specified for the for water phase (tables with blue background) and sediment phase (tables with yellow background) within the Elbe River catchment and for different particle sizes ranging from 5um to 200um. Reductions of total numbers are reported (column 'After') as well as relative reduction (%, column 'Reduction') compared to the baseline of the ePLAS model (no interventions taken, iE business as usual, indicated by column 'Original').

Endpoint 1. The number of microplastics per time unit discharged at the mouth of the basin (Hamburg) into the North Sea.

Results for intervention (1), implementing speed limit at 100 km/h, assuming a 20% reduction in TWP:

3.1 The paticle numbers near the river mouth to sea in water phase			
Size	Orginal	After (20%)	Reduction
5um	3,17E+10	2,53E+10	20,00%
30um	6,67E+07	5,34E+07	20,00%
75um	4,90E+05	3,92E+05	20,00%
125um	1,38E+04	1,10E+04	20,00%
200um	4,21E+02	3,36E+02	20,00%

3.1 The paticle numbers near the river mouth to sea in sediment phase			
Size	Orginal	After (20%)	Reduction
5um	5,09E+13	4,07E+13	20,00%
30um	6,16E+11	4,92E+11	20,00%
75um	1,94E+10	1,55E+10	20,00%
125um	1,21E+09	9,67E+08	20,00%
200um	6,47E+07	5,18E+07	20,00%

Assuming a 30% reduction in TWP:

3.2 The paticle numbers near the river mouth to sea in water phase			
Size	Orginal	After (30%)	Reduction
5um	3,17E+10	2,45E+10	22,72%
30um	6,67E+07	5,16E+07	22,70%
75um	4,90E+05	3,79E+05	22,70%
125um	1,38E+04	1,07E+04	22,71%
200um	4,21E+02	3,25E+02	22,71%

3.2 The paticle numbers near the river mouth to sea in sediment phase			
Size	Orginal	After (30%)	Reduction
5um	5,09E+13	3,94E+13	22,72%
30um	6,16E+11	4,76E+11	22,70%
75um	1,94E+10	1,50E+10	22,70%
125um	1,21E+09	9,35E+08	22,70%
200um	6,47E+07	5,00E+07	22,70%

Results for intervention (2), optimal tyre pressure and wheel alignment:

3.1 The paticle numbers near the river mouth to sea in water phase			
Size	Orginal	After (3.2%)	Reduction
5um	3,17E+10	3,06E+10	3,20%
30um	6,67E+07	6,46E+07	3,20%
75um	4,90E+05	4,74E+05	3,20%
125um	1,38E+04	1,34E+04	3,20%
200um	4,21E+02	4,07E+02	3,20%

3.1 The paticle numbers near the river mouth to sea in sediment phase			
Size	Orginal	After (3.2%)	Reduction
5um	5,09E+13	4,93E+13	3,20%
30um	6,16E+11	5,96E+11	3,20%
75um	1,94E+10	1,87E+10	3,20%
125um	1,21E+09	1,17E+09	3,20%
200um	6,47E+07	6,26E+07	3,20%

Results for intervention (3), cars with particle capture devices:

3.1 The paticle numbers near the river mouth to sea in water phase			
Size	Orginal	After (90%)	Reduction
5um	3,17E+10	3,17E+09	90,00%
30um	6,67E+07	7,34E+06	89,00%
75um	4,90E+05	3,92E+04	92,00%
125um	1,38E+04	1,38E+03	90,00%
200um	4,21E+02	4,21E+01	90,00%

3.1 The paticle numbers near the river mouth to sea in sediment phase			
Size	Orginal	After (90%)	Reduction
5um	5,09E+13	5,09E+12	90,00%
30um	6,16E+11	6,77E+10	89,00%
75um	1,94E+10	2,13E+09	89,00%
125um	1,21E+09	1,21E+08	90,00%
200um	6,47E+07	7,12E+06	89,00%

Results for intervention (4), improved particle retention in WWTPs:

3.1 The paticle numbers near the river mouth to sea in water phase			
Size	Orginal	After	Reduction
5um	3,17E+10	3,14E+10	0,97%
30um	6,67E+07	4,71E+07	29,44%
75um	4,90E+05	3,73E+05	23,86%
125um	1,38E+04	1,18E+04	14,59%
200um	4,21E+02	3,88E+02	7,69%

3.1 The paticle numbers near the river mouth to sea in sediment phase			
Size	Orginal	After	Reduction
5um	5,09E+13	5,04E+13	0,94%
30um	6,16E+11	4,27E+11	30,66%
75um	1,94E+10	1,30E+10	32,94%
125um	1,21E+09	8,31E+08	31,29%
200um	6,47E+07	4,41E+07	31,88%

Endpoint 2. The number of microplastics in the water phase averaged over all Elbe river nodes.

Results for intervention (1), implementing speed limit at 100 km/h, assuming a 20% reduction in TWP:

2.1 Average all river nodes in water phase (unit: particle numbers)			
Size	Orginal	After (20%)	Reduction
5um	1,25E+09	1,00E+09	20,05%
30um	1,57E+07	1,26E+07	20,04%
75um	2,86E+05	2,29E+05	20,02%
125um	1,22E+04	9,75E+03	20,10%
200um	4,64E+02	3,71E+02	20,00%

2.1 Average all river nodes in sediment phase (unit: particle numbers)			
Size	Orginal	After (20%)	Reduction
5um	2,64E+12	2,12E+12	19,98%
30um	2,27E+11	1,81E+11	19,97%
75um	1,29E+10	1,03E+10	20,09%
125um	9,93E+08	7,94E+08	20,00%
200um	6,07E+07	4,85E+07	20,19%

Assuming a 30% reduction in TWP:

2.2 Average all river nodes in water phase (unit: particle numbers)			
Size	Orginal	After (30%)	Reduction
5um	1,25E+09	9,69E+08	22,61%
30um	1,57E+07	1,22E+07	22,63%
75um	2,86E+05	2,21E+05	22,78%
125um	1,22E+04	9,43E+03	22,73%
200um	4,64E+02	3,59E+02	22,71%

2.2 Average all river nodes in sediment phase (unit: particle numbers)			
Size	Orginal	After (30%)	Reduction
5um	2,64E+12	2,04E+12	22,74%
30um	2,27E+11	1,75E+11	22,68%
75um	1,29E+10	9,98E+09	22,80%
125um	9,93E+08	7,68E+08	22,65%
200um	6,07E+07	4,70E+07	22,60%

Results for intervention (2), optimal tyre pressure and wheel alignment:

2.1 Average all river nodes in water phase (unit: particle numbers)			
Size	Orginal	After (3.2%)	Reduction
5um	1,25E+09	1,21E+09	3,20%
30um	1,57E+07	1,52E+07	3,20%
75um	2,86E+05	2,77E+05	3,20%
125um	1,22E+04	1,18E+04	3,20%
200um	4,64E+02	4,49E+02	3,20%

2.1 Average all river nodes in sediment phase (unit: particle numbers)			
Size	Orginal	After (3.2%)	Reduction
5um	2,64E+12	2,56E+12	3,20%
30um	2,27E+11	2,19E+11	3,20%
75um	1,29E+10	1,25E+10	3,20%
125um	9,93E+08	9,61E+08	3,20%
200um	6,07E+07	5,88E+07	3,20%

Results for intervention (3), cars with particle capture devices:

2.1 Average all river nodes in water phase (unit: particle numbers)			
Size	Orginal	After (90%)	Reduction
5um	1,25E+09	1,25E+08	90,00%
30um	1,57E+07	1,57E+06	90,00%
75um	2,86E+05	2,86E+04	90,00%
125um	1,22E+04	1,22E+03	90,00%
200um	4,64E+02	4,64E+01	90,00%

2.1 Average all river nodes in sediment phase (unit: particle numbers)			
Size	Orginal	After (90%)	Reduction
5um	2,64E+12	2,64E+11	90,00%
30um	2,27E+11	2,27E+10	90,00%
75um	1,29E+10	1,29E+09	90,00%
125um	9,93E+08	9,93E+07	90,00%
200um	6,07E+07	6,07E+06	90,00%

Results for intervention (4), improved particle retention in WWTPs:

2.1 Average all river nodes in water phase (unit: particle numbers)			
Size	Orginal	After	Reduction
5um	1,25E+09	1,25E+09	0,23%
30um	1,57E+07	1,56E+07	1,11%
75um	2,86E+05	2,80E+05	1,94%
125um	1,22E+04	1,19E+04	2,39%
200um	4,64E+02	4,52E+02	2,60%

2.1 Average all river nodes in sediment phase (unit: particle numbers)			
Size	Orginal	After	Reduction
5um	2,64E+12	2,64E+12	0,33%
30um	2,27E+11	2,24E+11	1,03%
75um	1,29E+10	1,28E+10	1,35%
125um	9,93E+08	9,81E+08	1,18%
200um	6,07E+07	5,96E+07	1,92%

Endpoint 3. The total number of microplastics in the water phase summed over all Elbe river nodes.

Results for intervention (1), implementing speed limit at 100 km/h, assuming a 20% reduction in TWP:

1.1 Sum up all river nodes in water phase (unit: particle numbers)			
Size	Orginal	After (20%)	Reduction
5um	4,29E+13	3,43E+13	20,05%
30um	5,39E+11	4,31E+11	20,04%
75um	9,79E+09	7,83E+09	20,02%
125um	4,18E+08	3,34E+08	20,10%
200um	1,59E+07	1,27E+07	20,00%

1.1 Sum up all river nodes in sediment phase (unit: particle numbers)			
Size	Orginal	After (20%)	Reduction
5um	9,06E+16	7,25E+16	19,98%
30um	7,76E+15	6,21E+15	19,97%
75um	4,43E+14	3,54E+14	20,09%
125um	3,40E+13	2,72E+13	20,00%
200um	2,08E+12	1,66E+12	20,19%

Assuming a 30% reduction in TWP:

1.2 Sum up all river nodes in water phase (unit: particle numbers)			
Size	Orginal	After (30%)	Reduction
5um	4,29E+13	3,32E+13	22,61%
30um	5,39E+11	4,17E+11	22,63%
75um	9,79E+09	7,56E+09	22,78%
125um	4,18E+08	3,23E+08	22,73%
200um	1,59E+07	1,23E+07	22,71%

1.2 Sum up all river nodes in sediment phase (unit: particle numbers)			
Size	Orginal	After (30%)	Reduction
5um	9,06E+16	7,00E+16	22,74%
30um	7,76E+15	6,00E+15	22,68%
75um	4,43E+14	3,42E+14	22,80%
125um	3,40E+13	2,63E+13	22,65%
200um	2,08E+12	1,61E+12	22,60%

Results for intervention (2), optimal tyre pressure and wheel alignment:

1.1 Sum up all river nodes in water phase (unit: particle numbers)			
Size	Orginal	After (3.2%)	Reduction
5um	4,29E+13	4,15E+13	3,20%
30um	5,39E+11	5,22E+11	3,18%
75um	9,79E+09	9,48E+09	3,21%
125um	4,18E+08	4,05E+08	3,20%
200um	1,59E+07	1,54E+07	3,19%

1.1 Sum up all river nodes in sediment phase (unit: particle numbers)			
Size	Orginal	After (3.2%)	Reduction
5um	9,06E+16	8,77E+16	3,20%
30um	7,76E+15	7,51E+15	3,20%
75um	4,43E+14	4,29E+14	3,20%
125um	3,40E+13	3,29E+13	3,20%
200um	2,08E+12	2,01E+12	3,20%

Results for intervention (3), cars with particle capture devices:

1.1 Sum up all river nodes in water phase (unit: particle numbers)			
Size	Orginal	After (90%)	Reduction
5um	4,29E+13	4,29E+12	90,00%
30um	5,39E+11	4,85E+10	91,00%
75um	9,79E+09	1,08E+09	89,00%
125um	4,18E+08	4,18E+07	90,00%
200um	1,59E+07	1,27E+06	92,00%

1.1 Sum up all river nodes in sediment phase (unit: particle numbers)			
Size	Orginal	After (90%)	Reduction
5um	9,06E+16	9,06E+15	90,00%
30um	7,76E+15	7,76E+14	90,00%
75um	4,43E+14	4,43E+13	90,00%
125um	3,40E+13	3,40E+12	90,00%
200um	2,08E+12	2,08E+11	90,00%

Results for intervention (4), improved particle retention in WWTPs:

1.1 Sum up all river nodes in water phase (unit: particle numbers)			
Size	Orginal	After	Reduction
5um	4,29E+13	4,28E+13	0,23%
30um	5,39E+11	5,33E+11	1,11%
75um	9,79E+09	9,60E+09	1,94%
125um	4,18E+08	4,08E+08	2,39%
200um	1,59E+07	1,55E+07	2,60%

1.1 Sum up all river nodes in sediment phase (unit: particle numbers)			
Size	Orginal	After	Reduction
5um	9,06E+16	9,03E+16	0,33%
30um	7,76E+15	7,68E+15	1,03%
75um	4,43E+14	4,37E+14	1,35%
125um	3,40E+13	3,36E+13	1,18%
20um	2,08E+12	2,04E+12	1,92%