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TRABAJO FIN DE MÁSTER

ENHANCING THE EUROPEAN PLASTICS STRATEGY AT SECTOR LEVEL:

MARINE PLASTICS FROM PET BOTTLES IN GERMANY

Autor: Belén Castro-Rial Resines

Director: Rose Mankaa

Madrid, Mayo 2021

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Enhancing the European plastics strategy at sector level:

Marine plastics from PET bottles in Germany

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

curso académico 2020/2021 es de mi autoría, original e inédito y

no ha sido presentado con anterioridad a otros efectos.

El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido

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Fdo.: Belén Castro-Rial Resines Fecha: 27/04/2021

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Rose Mankaa Fecha:

28/04/21

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To my family, for always providing me with support.

To Rose, for her encouragement and motivation during the project.

ENHANCING THE EUROPEAN PLASTICS STRATEGY AT SECTOR LEVEL: MARINE PLASTICS FROM PET BOTTLES IN GERMANY

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Director: Mankaa, Rose.
Entidad Colaboradora: RWTH Aachen University: Institute of Sustainability in Civil Engineering (INaB)

RESUMEN DEL PROYECTO

El objetivo de este proyecto es identificar las lagunas actuales y las necesidades de investigación para una evaluación cuantitativa de los impactos relacionados con la basura plástica marina.

Para ello, se examina el escenario concreto de Alemania, el país europeo con mayor consumo de plástico y con escasez de datos cuantitativos sobre sus fugas de plástico a los océanos. Además, sus resultados se comparan con los de Indonesia.

Palabras clave: Plásticos, Microplásticos, Alemania, Indonesia, Fugas, Océanos.

1. Introducción

La creciente producción de plástico en todo el mundo es un aspecto crítico del siglo XXI. Debido a su bajo precio, su comodidad y sus buenas propiedades, es conveniente para todo tipo de aplicaciones. Sin embargo, la mayoría de dichos plásticos no se gestionan adecuadamente tanto durante su producción y uso como en su fase de fin de vida, por lo que acaban entrando en el medio ambiente (Boucher et al., 2019).

"Las fugas de plástico se definen como el plástico que sale de la tecnosfera y se acumula en el medio natural" (Peano et al., 2020). Se estima que las fugas de plástico marino representan el tres por ciento de la producción mundial de plástico, lo que implica aproximadamente 12 millones de toneladas al año, como se muestra en la *Ilustración 1* (Boucher et al., 2020).

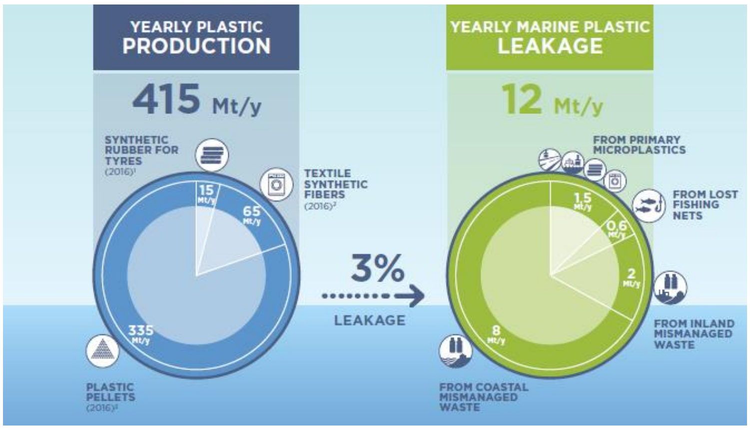


Ilustración 1: Producción de plásticos y fugas de plásticos marinos según su origen: Las mejores estimaciones actuales a escala mundial. Fuente: Boucher et al., 2020.

Los dos principales caminos de entrada del plástico en el medio ambiente son:

- Los macro plásticos visibles procedentes de residuos mal gestionados, definidos como fragmentos de plástico con un diámetro superior a 5 mm (Peano et al., 2020).
- Microplásticos invisibles, fragmentos de plástico con un diámetro inferior a 5 mm. Tienen formas más discretas de llegar al medio ambiente, produciendo efectos potencialmente nocivos para los ecosistemas y la salud humana. Pueden provenir de añadidos de carácter voluntario en diversos productos, como en los geles de ducha o en los productos de limpieza, o ser el resultado de la abrasión involuntaria de objetos de plástico a lo largo de su ciclo de vida, como los neumáticos al conducir o la ropa sintética durante el lavado (Boucher and Friot, 2017).

La basura plástica marina es dominante en los países costeros, y en particular en los que carecen de instalaciones de gestión de residuos, como se muestra en la *Ilustración 2* (Boucher and Friot, 2017). En cuanto a los vertidos de microplásticos en los océanos del mundo, los principales contribuyentes son Asia, África y Oriente Medio, debido al lavado de textiles sintéticos, y América, Europa y Asia Central, debido a la abrasión de los neumáticos al conducir, como puede observarse en la *Ilustración 3* (Boucher and Friot, 2017).

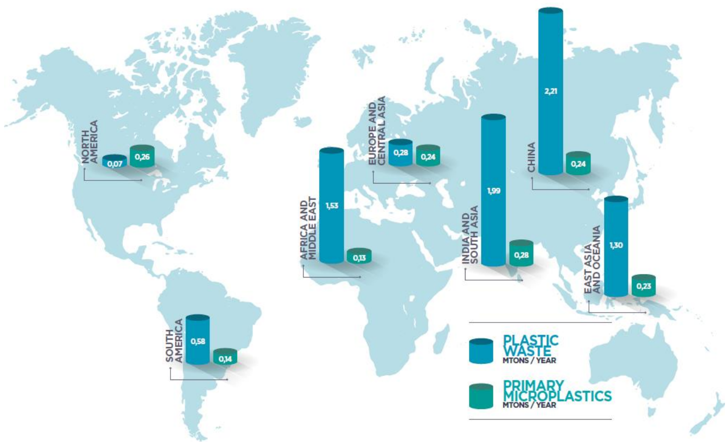
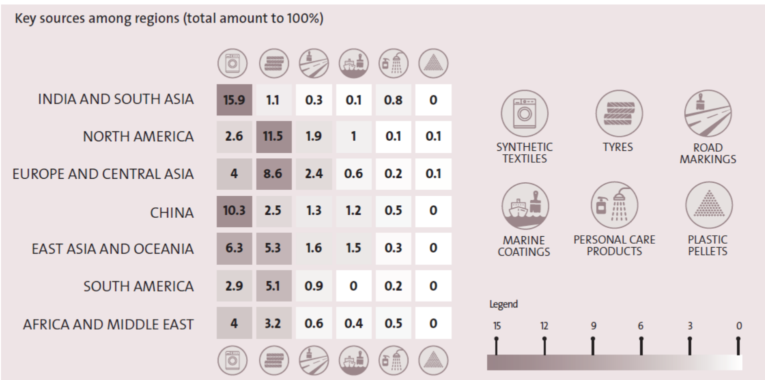


Ilustración 2: Vertidos globales de microplásticos primarios y residuos plásticos en el océano mundial. Fuente: Boucher and Friot, 2017.



Key sources among regions (total amount to 100%)

	Synthetic textiles	Tyres	Road markings	Marine coatings	Personal care products	Plastic pellets
INDIA AND SOUTH ASIA	15.9	1.1	0.3	0.1	0.8	0
NORTH AMERICA	2.6	11.5	1.9	1	0.1	0.1
EUROPE AND CENTRAL ASIA	4	8.6	2.4	0.6	0.2	0.1
CHINA	10.3	2.5	1.3	1.2	0.5	0
EAST ASIA AND OCEANIA	6.3	5.3	1.6	1.5	0.3	0
SOUTH AMERICA	2.9	5.1	0.9	0	0.2	0
AFRICA AND MIDDLE EAST	4	3.2	0.6	0.4	0.5	0

Ilustración 3: Vertidos globales de microplásticos (%) en los océanos del mundo por zona geográfica y fuentes. Fuente: Boucher and Friot, 2017.

Por lo tanto, se puede deducir que un análisis exhaustivo de las fugas hacia los océanos de microplásticos en Europa es de relevante en relación con el problema.

Además, se ha estudiado la situación de la gestión de los residuos plásticos en Alemania, el país europeo que más plástico consume. Debido a las restricciones existentes sobre los vertederos, apenas se contabilizan residuos mal gestionados en el país (PlasticsEurope, 2020), por lo que sus fugas de plástico se deben principalmente a los microplásticos. Para poder desarrollar políticas adecuadas, su cuantificación debería ser el mayor reto.

Por otro lado, Indonesia es uno de los 10 países con más fugas de plástico del mundo. La mala gestión de los residuos es el problema más desafiante en esta nación (Circular GA, 2019).

Para orientar el diseño sostenible y las estrategias de gestión de residuos, se necesitan metodologías eficaces que tengan en cuenta la contaminación por plástico. Con este fin, se ha desarrollado recientemente el informe *Plastic Leak Project (PLP)* (Peano et al., 2020), que proporciona directrices claras para el cálculo de las fugas de micro- y macro plásticos en cada etapa del ciclo de vida, tanto a nivel de empresa como de producto. Considera cuatro sectores específicos, cada uno con su metodología de cálculo correspondiente:

- Productos y envases de plástico (debido a la mala gestión de los residuos)
- Textiles (debido al lavado de textiles sintéticos)
- Transporte (debido a la abrasión de los neumáticos durante la conducción)
- Producción y reciclaje de pellets

Las fugas se consideran el resultado tanto de la pérdida (*loss*) como de la liberación (*release*) de plásticos, que, a través de vías de transferencia y redistribución, terminan en los diferentes compartimentos ambientales, como se muestra en la *Ilustración 4* (Peano et al., 2020).

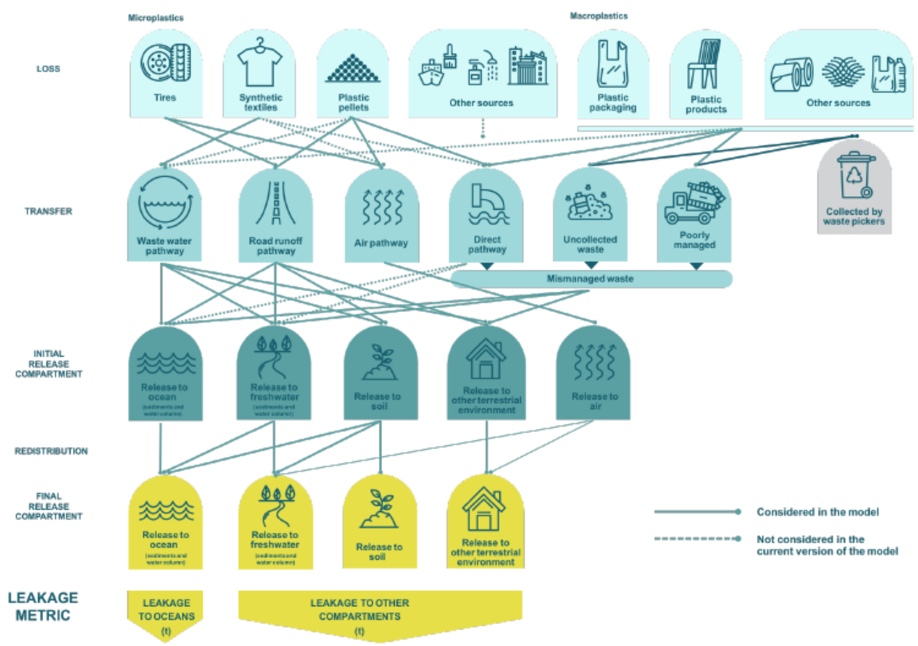


Ilustración 4: Principales etapas del modelado de fugas. Vista detallada. Fuente: Peano et al., 2020.

2. Metodología

Se lleva a cabo el cálculo de las fugas anuales de plástico de las botellas de Tereftalato de polietileno (PET), un artículo de uso diario conocido por ser contribuyente a la contaminación plástica. Para ello, se estudian datos de 2018. El elemento estudiado es una botella de PET de 1 L sin tapón con un peso de 20 g.

Según *OpenLCA* (Winter, 2014), la cadena de producción de las botellas de PET presenta los siguientes pasos:

- Extracción de materia prima y producción de granulado, que tiene lugar en la industria petrolera.
- Producción de componentes plásticos o pellets, que tiene lugar en la industria química.
- Producción y llenado de botellas.
- Punto de venta.
- Reciclaje, que se considera que tiene lugar en la fase de llenado de las botellas.

Para el estudio de caso en Alemania, se aplican las directrices del PLP. Para la obtención de datos, se utilizan *Statista, PlasticsEurope* y *UE statistics*. Además, se han estudiado y comparado varios estudios de Análisis de Ciclo de Vida (ACV) de botellas de PET. De las directrices PLP sólo se consideran en el presente estudio los microplásticos procedentes de la producción de pellets y del transporte, ya que Alemania apenas cuenta con macro plásticos mal gestionados y los microplásticos debidos al lavado de textiles no tienen relación con el producto.

Para ello, se ha explorado la tasa de producción y reciclaje de botellas de PET en Alemania, mostrando que en el país se producen alrededor de 1 millón de toneladas de botellas de PET al año, de las cuales se recicla el 94%. Además, se ha estudiado el método de transporte y las distancias en Alemania. Eligiendo un camión de 13 toneladas como el más usado y basándose en el ciclo de vida de las botellas, se ha calculado la distancia total recorrida por el elemento estudiado, siendo de aproximadamente 286 millones de km al año.

Para estudiar el caso de Indonesia se ha adoptado un enfoque diferente. A partir del análisis y la comparación de varios estudios anteriores sobre la situación de las botellas de PET en este país, se extraen los datos pertinentes sobre las fugas de plástico.

La literatura muestra que el consumo anual de botellas de PET en Indonesia es de 350 mil toneladas, y su tasa de fuga al medio ambiente es del 53% (GA Circular, 2019).

3. Resultados

Tras aplicar la metodología correspondiente a cada caso, se obtienen los resultados pertinentes.

En el caso de Alemania, donde sólo se han considerado los microplásticos, se obtienen los siguientes resultados, presentados en las diferentes perspectivas, tal y como exigen las directrices del PLP.

La *Ilustración 5* muestra la fuga total en Alemania bajo la perspectiva de *resultados clave*, que responde a la pregunta: *¿Cuál es la fuga total a lo largo de mi cadena de valor?*

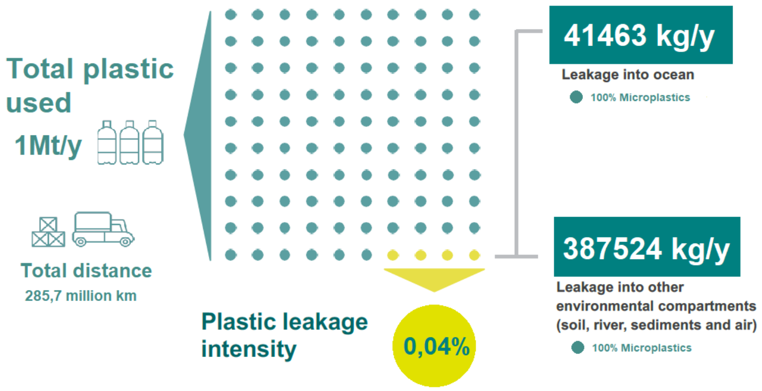


Ilustración 5: Fugas totales en Alemania bajo la perspectiva de resultados clave.

La *Ilustración 6* representa las fugas en Alemania bajo la perspectiva de *cadena de suministro*, respondiendo a las preguntas: *¿Dónde se producen las fugas a lo largo de mi cadena de valor? ¿En qué compartimentos medioambientales?*

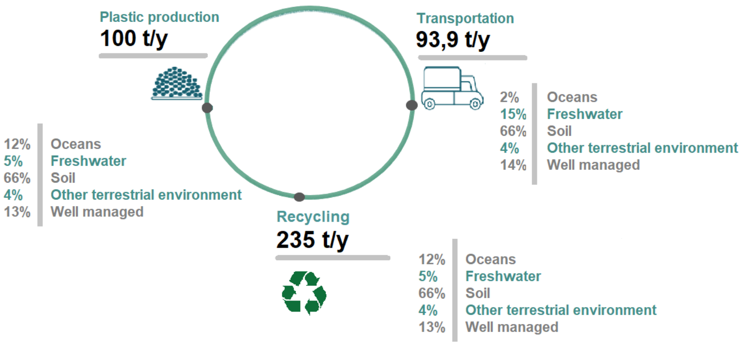


Ilustración 6: Fugas en Alemania bajo la perspectiva de cadena de suministro.

En la *Ilustración 7* se muestran las fugas bajo la perspectiva *nacional*, respondiendo a la pregunta: *¿En qué país se produce la fuga?*

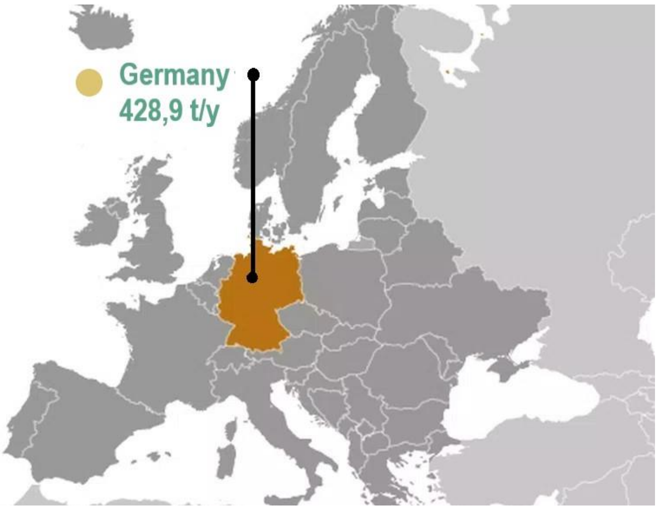


Ilustración 7: Fugas en Alemania bajo la perspectiva nacional.

De las botellas de PET en Alemania, el total de fugas al medio ambiente es de 430 toneladas de microplásticos al año, y al océano unas 42 toneladas. Dado que la producción de PET asciende a 1 millón de toneladas de plástico al año, esto puede traducirse en una intensidad de fuga de plástico del 0,04%.

La contribución de la producción y el transporte a las fugas de plástico es de un rango equivalente, y la del proceso de reciclaje es aproximadamente el doble.

Los resultados de Indonesia revelan datos muy diferentes, dado que se trata de un país en desarrollo en el que la gestión de los residuos sigue siendo uno de los principales retos. Cada año se vierten al medio ambiente unas 190 mil toneladas de macro plásticos, de las que aproximadamente 47000 se vierten al océano.

Además, se han estudiado diferentes alternativas para la reutilización de la basura plástica marina, ya que, si bien la minimización de las fugas es necesaria, la cantidad actual de residuos plásticos en los océanos y otros compartimentos ambientales es de tales dimensiones que su gestión se vuelve extremadamente relevante. La *Ilustración 8* (Idumah and Nwuzor, 2019) muestra las diferentes categorías de gestión de los residuos plásticos.

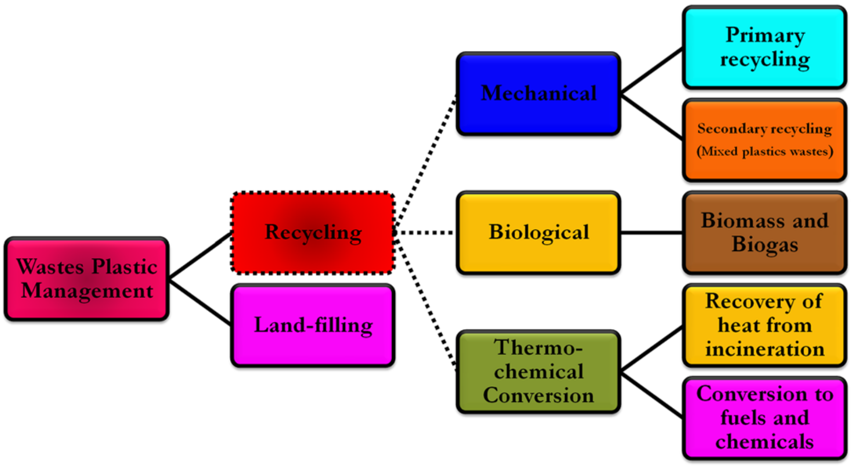


Ilustración 8: Diferentes categorías de gestión de residuos plásticos. Fuente: Idumah and Nwuzor, 2019.

Se ha observado que, aunque las metodologías tradicionales para tratar los residuos plásticos, como el reciclaje, siempre se han considerado como las opciones preferidas, otros métodos innovadores, como la pirólisis, que convierte los residuos plásticos en combustible, ofrecen soluciones eficientes cuando el reciclaje mecánico no es viable. Además, el proceso de incineración con recuperación de energía con técnicas como la gasificación, que reducen las emisiones de CO_2, es otra manera eficaz de deshacerse de los residuos plásticos y convertir el valor calorífico interno de los plásticos en electricidad utilizable. Se has observado las diferentes ventajas e inconvenientes de cada técnica, deduciendo que un sistema integrado con todas estas tecnologías sería la solución óptima.

4. Conclusiones

Al ser la primera vez que se aplican las directrices del PLP a un producto como las botellas de PET y en Alemania, el objetivo de esta tesis es tanto proporcionar resultados tangibles que puedan orientar a los responsables políticos y a la comunidad científica en la lucha contra la contaminación por plásticos como presentar una vía de cálculo que pueda extenderse a otros productos de plástico y a otros países.

En cuanto en dónde deberían centrarse las políticas, en Alemania se ha descubierto que los microplásticos son los principales responsables de las fugas, y en particular debido al proceso de reciclaje. Por lo tanto, se necesitarían métodos de gestión de residuos más eficientes. Además, la reducción de las distancias de transporte y la gestión de los microplásticos durante la cadena de producción de las botellas minimizarían más las fugas.

En Indonesia, en cambio, el principal contribuyente de las fugas plásticas son los macro plásticos debido a la mala gestión de los residuos. Dado que Indonesia es uno de los principales contribuyentes de plásticos marinos en el mundo, esto no sólo debería considerarse un problema nacional, sino también una preocupación global.

5. Referencias

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ABSTRACT

The goal of this project is to identify the current gaps and research needs to a quantitative assessment of impacts related to marine plastic litter.

To this end, the concrete scenario of Germany, the European country with the highest plastic consumption and a scarcity of quantitative data on its plastic leakage into the oceans is examined. In addition, the results are compared to those of Indonesia.

Keywords: Plastics, Microplastics, Germany, Indonesia, Leakage, Oceans.

1. Introduction

The growing production of plastic worldwide is a critical aspect of the 21st century. Due to its low price, convenience, and good properties, it is suitable for all types of applications. However, most of these plastics are not properly managed both during their production and use and at their end-of-life stage, thus they end up entering in the environment (Boucher et al., 2019).

"Plastic leakage is defined as the plastic leaving the technosphere and accumulating in the natural environment" (Peano et al., 2020). Marine plastic leakage is estimated to be three percent of all the worldwide plastic production, which means approximately 12 million tons per year, as displayed in *Illustration 1* (Boucher et al., 2020).

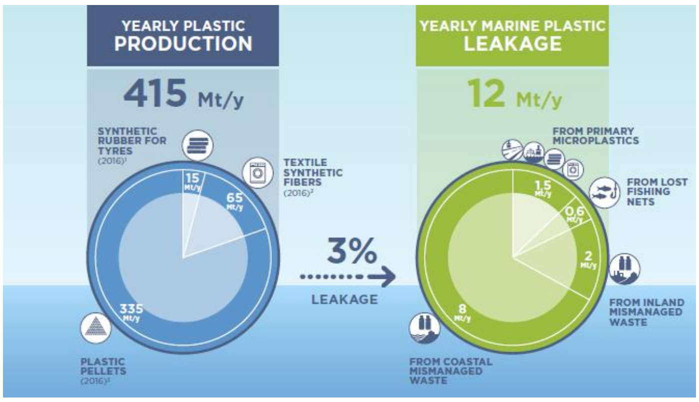


Illustration 1: Plastic production and marine plastic leakage by source: Current best guesses at the global scale. Source: Boucher et al., 2020.

The two main streams for plastic to enter the environment are:

- Visible macroplastics coming from mismanaged waste, defined as plastic fragments with a diameter larger than 5mm (Peano *et al.*, 2020).
- Invisible microplastics, plastic fragments with a diameter of less than 5 mm. They have more discrete ways of reaching the environment, producing potentially harmful

effects on ecosystems and human health. They can come from voluntary additives in several products, such as shower gel or cleaning agents, or result from the unintentional abrasion of plastic objects throughout their life cycle, such as tires when driving or synthetic clothing during washing (Boucher and Friot, 2017).

Marine plastic litter is dominant in coastal countries, and particularly in those with lack of waste management facilities, as displayed in *Illustration 2* (Boucher and Friot, 2017). Regarding the microplastic releases to the world's oceans, the main contributors are Asia, Africa, and the Middle East due to synthetic textiles washing and America, Europe, and Central Asia due to tire abrasion while driving, as it can be further observed in *Illustration 3* (Boucher and Friot, 2017).

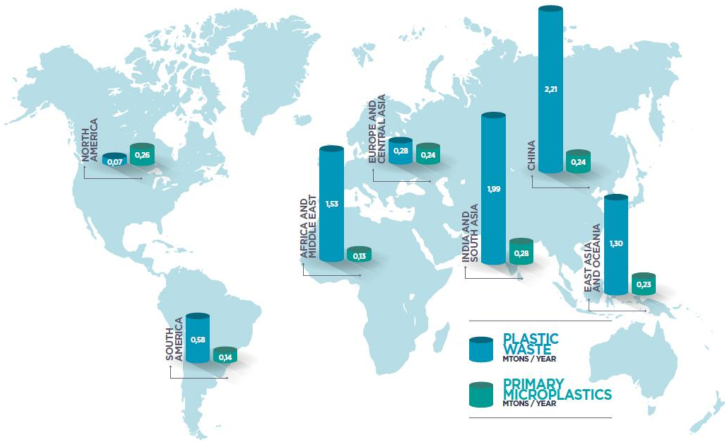
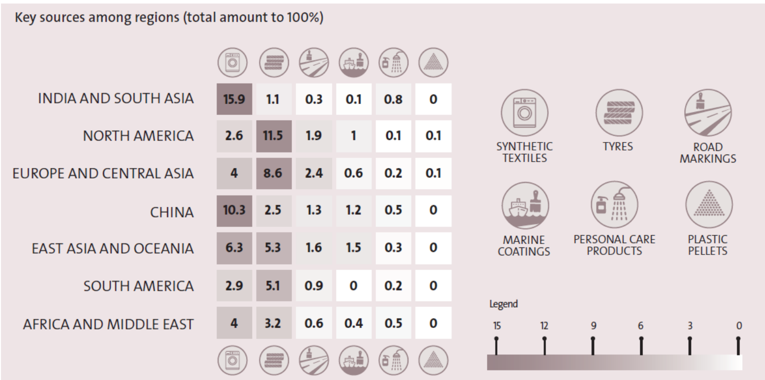


Illustration 2: Global releases of primary microplastics and plastic waste into the world ocean. Source: Boucher and Friot, 2017.



	Synthetic textiles	Tyres	Road markings	Marine coatings	Personal care products	Plastic pellets
INDIA AND SOUTH ASIA	15.9	1.1	0.3	0.1	0.8	0
NORTH AMERICA	2.6	11.5	1.9	1	0.1	0.1
EUROPE AND CENTRAL ASIA	4	8.6	2.4	0.6	0.2	0.1
CHINA	10.3	2.5	1.3	1.2	0.5	0
EAST ASIA AND OCEANIA	6.3	5.3	1.6	1.5	0.3	0
SOUTH AMERICA	2.9	5.1	0.9	0	0.2	0
AFRICA AND MIDDLE EAST	4	3.2	0.6	0.4	0.5	0

Illustration 3: Global microplastic releases (%) to the world oceans by geographical area and sources. Source: Boucher and Friot, 2017.

It can be therefore derived that a comprehensive analysis of the European microplastic leakage to the oceans is relevant in the topic.

In addition, the plastic waste management situation in Germany, as the top plastic consuming country in Europe has been explored. Due to landfilling restrictions, almost no mismanaged waste in the country is accounted (PlasticsEurope, 2020), and therefore its plastic leakage is mainly due to microplastics. In order to be able to develop proper policies, quantifying them should be the biggest challenge.

Indonesia, on the other hand, is one of the top 10 leaking plastic countries worldwide. Mismanaged waste is the most challenging issue in this nation (GA Circular, 2019).

To guide sustainable design and waste management strategies, effective metrics that consider plastic pollution are needed. To this end, the *Plastic Leak Project (PLP)* report (Peano *et al.*, 2020) has been recently developed as for providing clear guidelines for the calculation of micro and macroplastics leakage at each stage of the life cycle at both company and product level. It considers four specific sectors, each with its particular calculation methodology:

- Plastic products and packaging (due to mismanaged waste)
- Textiles (due to synthetic textile washing)
- Transport (due to abrasion of tires while driving)
- Pellet production and recycling

Leakage is considered a result of both loss and release which through transfer and redistribution routes finishes in the different environmental compartments, as illustrated in *Illustration 4* (Peano *et al.*, 2020).

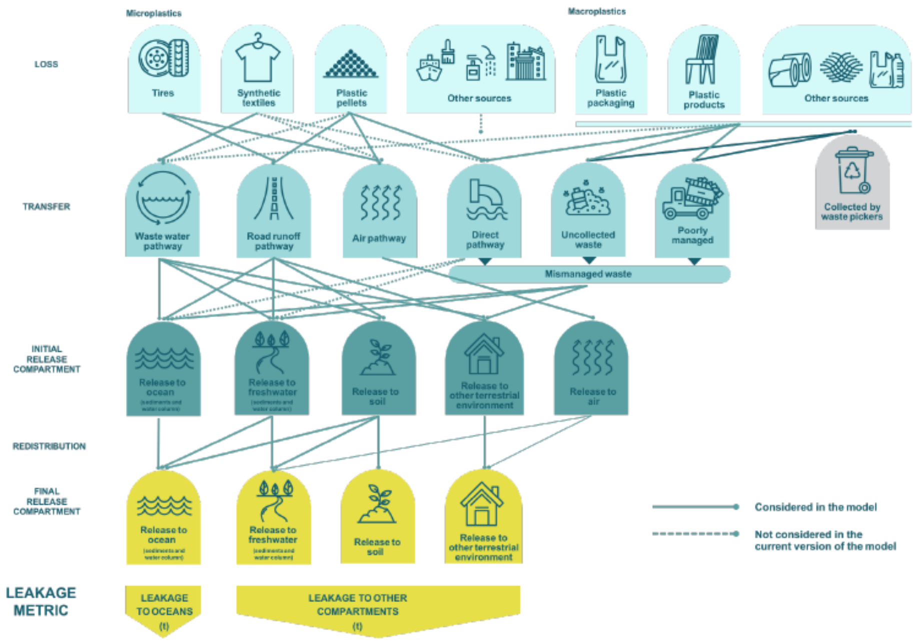


Illustration 4. Key stages of the leakage modelling. Detailed view. Source: Peano et al., 2020.

2. Methodology

The annual plastic leakage from Polyethylene terephthalate (PET) bottles, a daily used item which is a well-known contributor to plastic pollution is calculated. To this end, data from 2018 is applied. The studied element is a 1 L PET bottle without cap with a weight of 20g.

According to *OpenLCA* (Winter, 2014), the production chain of PET bottles presents the following steps:

- Raw material extraction and granulate production, taking place at the oil industry.
- Plastic component or pellet production, taking place at the chemical industry.
- Bottle production and filling.
- Point of selling (POS).
- Recycling, considered to take place at the bottle filling stage.

For the German case study, the PLP guidelines are applied. For data sourcing, *Statista*, *PlasticsEurope*, and *EU statistics* are used. In addition, several Life Cycle Analysis (LCA) studies from PET bottles have been studied and compared. From the guidelines only microplastics from pellet production and from transportation apply for the present study since Germany does not account for mismanaged macroplastics and microplastics due to textile washing are not related to the product.

To this end, the production and recycling rates of PET bottles in Germany have been explored, showing that about 1 million ton of PET bottles are produced annually in the country, from which 94% are recycled. Moreover, the transportation method and distances within Germany have been studied. By choosing a 13 Tons truck as an average and based on the life cycle of the bottles, the total travelled distance due to the studied element has been calculated, being approximately 286 million km per year.

A different approach is adopted to study the case of Indonesia. Based on the analysis and comparison of several previous studies on the PET bottle situation in this country, relevant evidence on plastic leakage is then extracted.

Literature shows that the annual PET bottle consumption in Indonesia is 350 thousand tons, and its leakage to the environment rate is 53% (GA Circular, 2019).

3. Results

After applying the corresponding methodology for each case, the pertinent results are obtained.

For Germany, where only microplastics have been considered, the following results are obtained, given in the different perspectives, as required by the PLP guidelines.

Illustration 5 shows the total leakage in Germany under the *key results* perspective, which answers the question: *What is the total leakage along my value chain?*

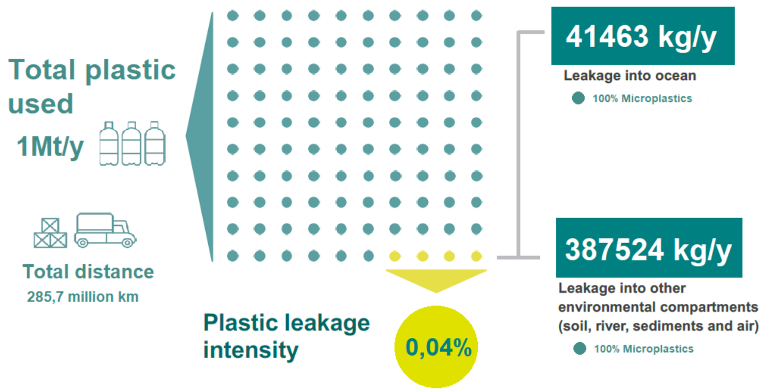


Illustration 5: Total leakage in Germany under the key results perspective.

Illustration 6 displays the leakage in Germany under the *supply chain* perspective, by answering the questions: *Where does the leakage occur along my value chain? In which environmental compartments?*

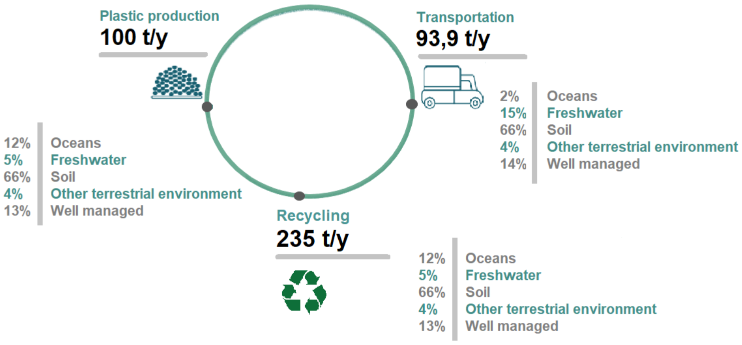


Illustration 6: Leakage in Germany under the supply chain perspective.

In *Illustration 7* the leakage under the *country* perspective is shown, answering the question: *In which country does the leakage occur?*

Illustration 7: Leakage in Germany under the country perspective.

From PET bottles in Germany, the total leakage into the environment is 430 tons of microplastics per year, and into the ocean about 42 tons. Given that PET production amounts to 1 million tons of plastic per year, this can be translated into a 0,04% plastic leakage intensity.

The contribution of plastic production and transportation is roughly the equivalent, and that of the recycling process is about twice as high.

Results from Indonesia reveal very different data, given that it is a developing country in which waste management remains one of the main challenges. About 190 thousand Tons of macroplastics are leaked every year into the environment, from which approximately 47000 tones are released to the ocean.

Furthermore, different alternatives to reuse marine plastic litter have been studied, since although the minimization of leaks is necessary, the current amount of plastic waste in the oceans and other environmental compartments is of such dimensions that its management becomes extremely relevant. *Illustration 8* (Idumah and Nwuzor, 2019) further displays the different plastic waste management strategies.

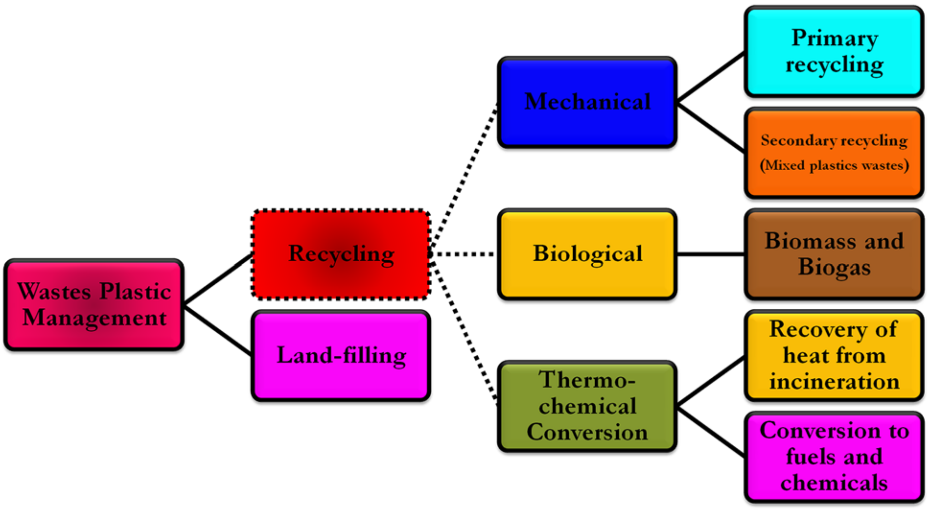


Illustration 8: Waste Plastic Management categories. Source: Idumah and Nwuzor, 2019.

It has been observed that although traditional methodologies to treat plastic debris such as recycling have always been considered as the preferred options, innovative methods such as pyrolysis, which convert plastic waste in fuel, provide good solutions when mechanical recycling is not feasible. Moreover, incineration process with energy recovery with techniques such as gasification, that reduce the CO_2 emissions, is another efficient way to get rid of plastic waste and convert the inner calorific value of plastics into usable electricity. It has been seen that each of these techniques has its benefits and cons, and therefore, an integrated system with all these technologies would be the optimal solution.

4. Conclusions

Being the first time that the PLP guidelines are implemented to a product such as PET bottles and in Germany, the purpose of this thesis is both to provide tangible results that can guide policy makers and the scientific community in tackling plastic pollution and to present a calculation pathway that can be extended to other plastic products and other countries.

In terms of where policies should be focused, in Germany microplastics have been found to be mainly responsible for leakage, and in particular due to the recycling process. Therefore, more efficient waste management methods would be needed. In addition, reducing transport distances and managing microplastics during the bottle production chain would further minimize leakage.

In Indonesia, on the other hand, the main contributor to plastic leakage is macroplastics due to poor waste management. Since Indonesia is a major contributor of marine plastics in the world, this should not only be considered a national problem, but also a global concern.

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List of abbreviations

CO	Carbon monoxide
CO_2	Carbon dioxide
$D_{TRUCK\text{-}VHC}$	Distance travelled by the truck [vhc*km]
EU	European Union
ESCAP	Social Commission for Asia and the Pacific for the South Asian Region
$FinalRelR_{COMPARTMENT}$	Final Release rate of the compartment
g	Gram (10^{-3} Kg)
GES	Good environmental status
IUCN	International Union for Conservation of Nature
IWM	Integrated Waste Management
Kg	Kilogram
Km	Kilometer
L	Liter (10^{-3} m^3)
LCA	Life Cycle Assessment
$Leak_{MICRO\text{-}COMPARTMENT}$	Leakage of microplastics to compartment [kg microplastics]
$Loss_{TRUCK\text{-}TIRES}$	Tire tread loss per km travelled by the vehicle [(kg tread)/(vhc*km)]
M	Million (10^6)
mg	Milligram (10^{-6} kg)
m^3	Cubic meter
mm	Millimeter (10^{-3} m)
MiPL	Microplastics [Kg]
MPP	Marine Plastic Pollution
MSFD	Marine Strategy Framework Directive
MSW	Municipal Solid Waste
Mt	Million ton (10^6 T)
NAFTA	North America Free Trade Agreement

µm	Micrometer (10^{-6} m)
PET	Polyethylene terephthalate
PLP	Plastic Leak Project
POS	Point of selling
$RedR_{COMPARTMENT}$	Redistribution rate of the compartment
$RelR_{COMPARTMENT}$	Release rate of the compartment
$R_{FRESHED}$	Sedimentation rate
r-PET	Recycled PET
SAR	South Asian Region
SDGs	Sustainable Development Goals
$ShPolymer_{TRUCK-TIRES}$	Share of polymer [kg (microplastics)/ kg (tread)]
T	Ton (10^3 Kg)
$TireLoss_{VEHICLE}$	Tire tread losses from vehicle
$TotTireLoss_{TRUCK}$	Losses of microplastics related to tire tread abrasion on road surfaces for transport of goods by truck [kg (microplastics)]
TRWP	Tire and road wear particles
Vhc	Vehicle
WFD	Waste Framework Direction

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1. INTRODUCTION

The growing production of plastic worldwide is a critical aspect of the 21st century. Due to its low price, convenience, and good properties, it is suitable for all types of applications: from food packaging to transport structures. It is estimated that from its first uses in the 1950s to the present moment, 8300 million tons have been generated (Boucher *et al.*, 2019). However, most of these plastics are not properly managed both during their production and use and at their end-of-life stage, thus they end up entering in the environment.

"Plastic leakage is defined as the plastic leaving the technosphere and accumulating in the natural environment" (Peano *et al.*, 2020). As 10 Mt of plastics leak into the ocean annually from various sources, it is expected that by 2050 there will be more plastics than fish in the ocean (Boucher and Friot, 2017). Plastics can perdure in the environment for hundreds of years, polluting soils, air, and water. Toxic substances settle in waterways where they eventually enter the food chain and hence the body system. These particles act as carcinogens and mutagens, posing a threat to vegetation, human and animal health and environment as a whole (Verma *et al.*, 2016). In addition, related economic activities are also negatively affected, potentially leading to considerable losses. Hence, drastic measures must be taken to improve the current situation.

To deal with the marine plastic pollution problem, different national strategies have been developed. At the European level, the Marine Strategy Framework Directive (MSFD) has been adopted, which aims to protect the marine environment across Europe. It comprises criteria and guidelines to be followed, such as the restriction of single-use plastics and the regulation of fishing practices (European Commission, 2020). Furthermore, several European countries, including Germany, have implemented landfilling restrictions in an attempt to reduce plastic waste and contribute to a circular economy, resulting in higher recycling rates (PlasticsEurope, 2020).

However, in order to take appropriate action, it is necessary to quantify the magnitude of the problem, which requires measuring the actual amount of plastic that ends up in the oceans.

Among the various methodologies that exist, the *Plastic Leak Project (PLP): Methodological guidelines* (Peano *et al.*, 2020), which measures in terms of inventory, the quantity of micro- and macroplastics that ends up in the marine environment, is used in this project as a reference. Previous implementations of this method have been made at industrial level in two different sectors, a product plastic leakage assessment on a textile garment and a corporate plastic leakage assessment for a multinational dairy company, providing for each case the most relevant leakage hotspots, as a decision-making support for plastic reduction actions.

According to Boucher and Friot in 2017 in *Primary Microplastics in the Oceans*, Europe is a significant contributor to microplastics in the ocean, largely resulting from tire abrasion while driving. Being Germany the largest plastic consuming country in Europe (PlasticsEurope, 2020) and with a lack of data on the actual amount of leakage in this country, the need to address the issue at national level from an inventory perspective becomes crucial to take further action.

For this purpose, the present project aims to estimate plastic leakage during the production, use and waste management of PET bottles in Germany, a product selected because of its daily use and for being a well-known source of plastic pollution. The PLP methodological guidelines are carefully applied to obtain results in terms of inventory. Literature reports several prior studies on the environmental impacts of this product, as for example *LCA comparison of PET water bottles sold in Germany deriving from different production locations* (Winter, 2014), *Carbon Footprint and Life Cycle Assessment of PET Bottle Manufacturing Process* (Alfarisi and Primadasa, 2019), or *Comparative life cycle assessment of fossil and bio-based polyethylene terephthalate (PET) bottles* (Chen, Pelton and Smith, 2016). Nevertheless, these analyses have been carried out with tools such as Life Cycle Assessment (LCA), this is, in terms of impact, and do not consider plastic as a pollutant. The current report thus represents a novelty in this field.

Being Asia the largest contributor to marine leakage, this project also explores the plastic waste situation in Indonesia, the fourth most populated country in the world, and one of the six South East Asian countries which contribute to the 29% of global marine plastic leakage

(GA Circular, 2019). The aim hereby is to achieve a meaningful comparison to provide an overall perspective of the problem.
Moreover, different ways to reuse marine plastic waste are presented.

The purpose of this thesis is thus to enhance the European plastics strategy at sectoral level by providing tangible results that can guide policy makers and the scientific community in tackling plastic pollution.

To this end, the structure of the work is divided into the following chapters. Chapter 2 or *Theoretical Background* documents the different ways to measure the marine plastics problem, particularly the PLP Guidelines, as well as the literature research of the situation in Indonesia. The various technologies for reusing marine plastics are also mentioned in this section. Next, chapter 3, *Methodology*, covers the calculation methods. For Germany, the PLP Methodological Guidelines are implemented based on national data. On the other hand, for the case of Indonesia, an estimate of plastic leakage based on other methodologies is made. The following is chapter 4, *Results*, which presents the outcomes of both the applied methodology and the investigation on the different technologies for marine plastics reuse. Next is chapter 5, *Discussion*, in which the analysis and interpretation of the results is included. Lastly, chapter 6 or *Conclusion* links the initial targets with the outputs.

2. THEORETICAL BACKGROUND

Plastics are an integral part of everyday life around the globe. From single-use plastic bags to high-end equipment, they are used in a wide range of applications. They appeared in middle of the 20th century and since them, due to their enormous potential and amount of favorable properties, such as low density, durability, resistance to corrosion, flexibility, etc., they have shaped the world and have been preferred over other materials (PlasticsEurope, 2020). For this reason, global plastic production has steadily increased since its first uses in 1950, reaching 368 million tones (Mt) in 2019 (PlasticsEurope, 2020). Plastics are mostly produced in the following formats: resins, powders, pellets, synthetic fibers for textiles and synthetic rubber for tires (Boucher *et al.*, 2019).
Nevertheless, plastic is not always properly managed during its use and end-of life stage. Only 7% of the whole plastic that has been produced up to now has been recycled (Boucher *et al.*, 2019). The rising production of plastic and the poor circularity of its economy cause an increasing amount of filtration into the environment and particularly, into the offshore area every year. “The quantity of plastic flowing into waterways and, ultimately, into the oceans is called marine plastic leakage” (Boucher *et al.*, 2019). It is estimated that three percent of all the world’s plastic production leaks into the ocean per year (Boucher *et al.*, 2020). Consequently, plastic pollution has become one of the biggest problems of the 21st century, and drastic measures need to be taken to face it.

2.1. MARINE LITTER

In multiple studies, diverse sources of plastic leakage have been catalogued and measured. Marine plastic leakage is estimated to be three percent of all the worldwide plastic production (Boucher *et al.*, 2020), which could be translated to approximately 10 million metric tons (Mt)/year (IUCN, 2018).

The two main streams for plastic to enter the environment are the visible macroplastics from mismanaged waste and invisible microplastics from several sources, such as the tire abrasion while driving (Peano *et al.*, 2020). The below definitions are relevant regarding this topic.

- Macroplastics are defined as plastic fragments larger than 5 millimeters (mm), usually from single-use durable plastics, such as straws and plastic bags. They enter the marine and terrestrial environment through a non-efficient waste treatment infrastructure (Peano *et al.*, 2020).

- Microplastics are defined as plastic fragments with a diameter of less than 5 mm and over 1 micrometer (µm) (GESAMP, 2019). These small particles are much more penetrating than macroplastics and have more discrete ways of reaching the environment, producing potentially harmful effects on ecosystems and human health.

- Primary microplastics are defined as microplastics lost from the technosphere and leaked into different environmental compartments as tiny pieces. They can come from voluntary additives in several products, such as shower gel or cleaning agents, or result from the unintentional abrasion of plastic objects throughout their life cycle, such as tires when driving or synthetic clothing during washing. When discharged through domestic wastewater or road runoff, primary microplastics can pass through treatment systems and accumulate in rivers and oceans (Boucher and Friot, 2017). In *Figure 1* (Boucher and Friot, 2017) the main sources of primary microplastics can be observed.

Figure 1: Main sources of primary microplastics. Source: Boucher and Friot, 2017.

- Secondary microplastics are micro particles of plastic formed from the fragmentation and weathering of larger plastic. It can either happen before entering the marine environment, or once offshore, due to the degradation from ocean waves, UV exposure, etc. (IUCN, 2018).

Figure 2 (Boucher *et al.*, 2020) shows the various sources of plastic production and leakage. As it can be seen, macroplastics from mismanaged waste are the main path to the marine environment. From this mismanaged waste, coastal (8Mt/year) plays a more important role than inland (2 Mt/ year). Also, primary microplastics (1,5Mt/year) and from lost fishing nets

(0,6Mt/year) are relevant sources of leakage.

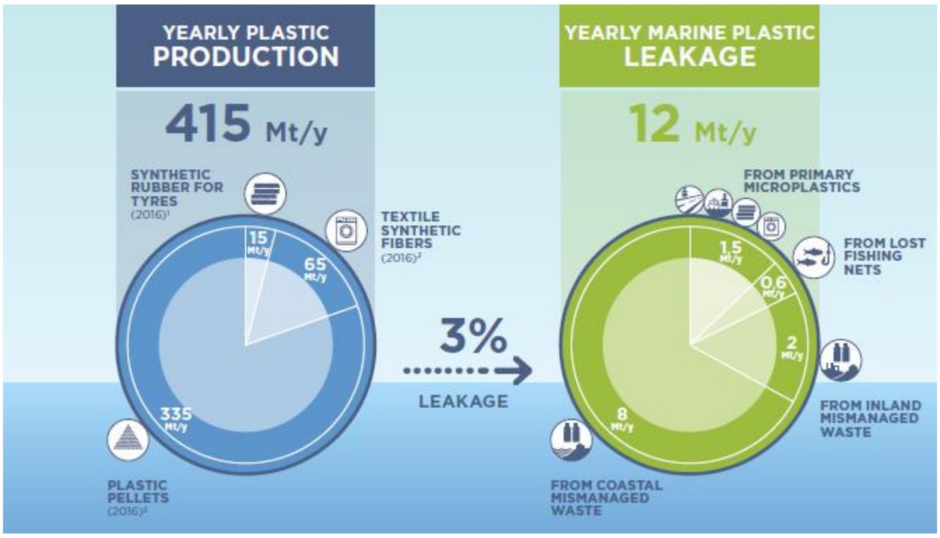

Figure 2: Plastic production and marine plastic leakage by source: Current best guesses at the global scale. Source: Boucher et al., 2020.

Among the various primary microplastics that are released into the ocean, *Figure 3* (Boucher and Friot, 2017) shows the proportion of each one. As displayed, the main source is due to the laundry of synthetic textiles (35%), and second to the erosion of tires while driving (28%). The third important contribution (24%) is due to city dust. Personal care products account for 2% of the global release of primary microplastics to the world ocean (Boucher and Friot, 2017).

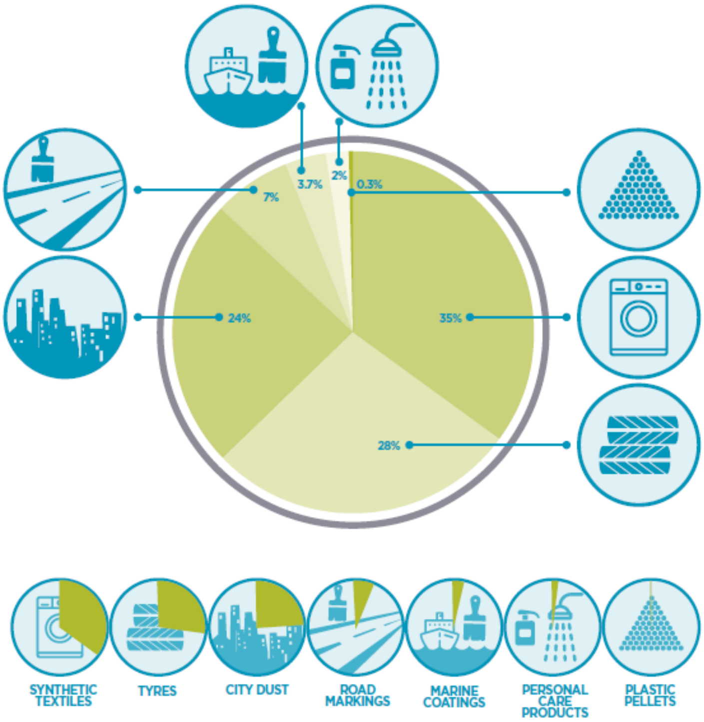

Figure 3: Global releases of primary microplastics to the world oceans. Source: Boucher and Friot, 2017.

2.1.1. DISTRIBUTION OF MARINE PLASTICS

To have a better understanding of the global plastic leakage into the ocean, the worldwide plastic production has been studied first.

In 2018, the total plastic production around the world almost reached 360 million tons, being this value in Europe of almost 62 million tons (PlasticsEurope, 2019). *Figure 4* (PlasticsEurope, 2019) illustrates the different contribution of each area. As it can be observed, Asia is responsible of more than a half (51%) of the worldwide plastic production, being China its main source (30%). North America Free Trade Agreement (NAFTA) (18%) and Europe (17%) are next relevant contributors.

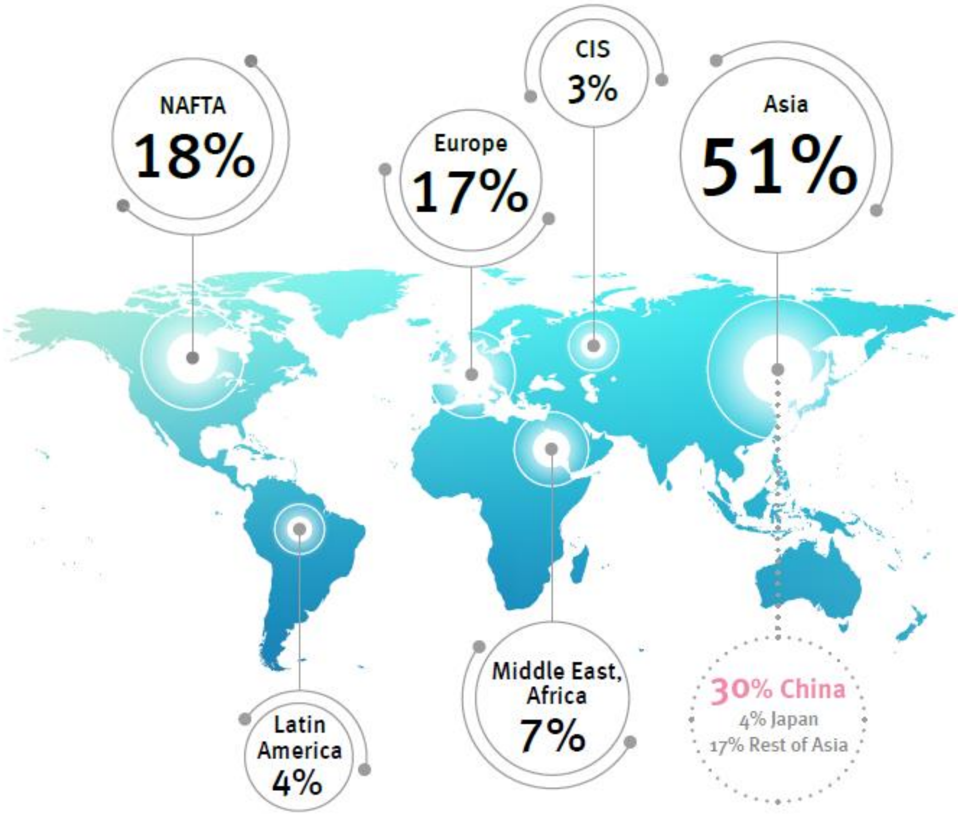

Figure 4: Distribution of global plastics production in 2018. Source: PlasticsEurope, 2019.

To study marine plastic leakage from the different regions, seven areas have been differentiated, as seen in *Figure 5* (Boucher and Friot, 2017): Africa and Middle East, South America, Europe and Central Asia, East Asia and Oceania, North America, China and India and South Asia (Boucher and Friot, 2017).

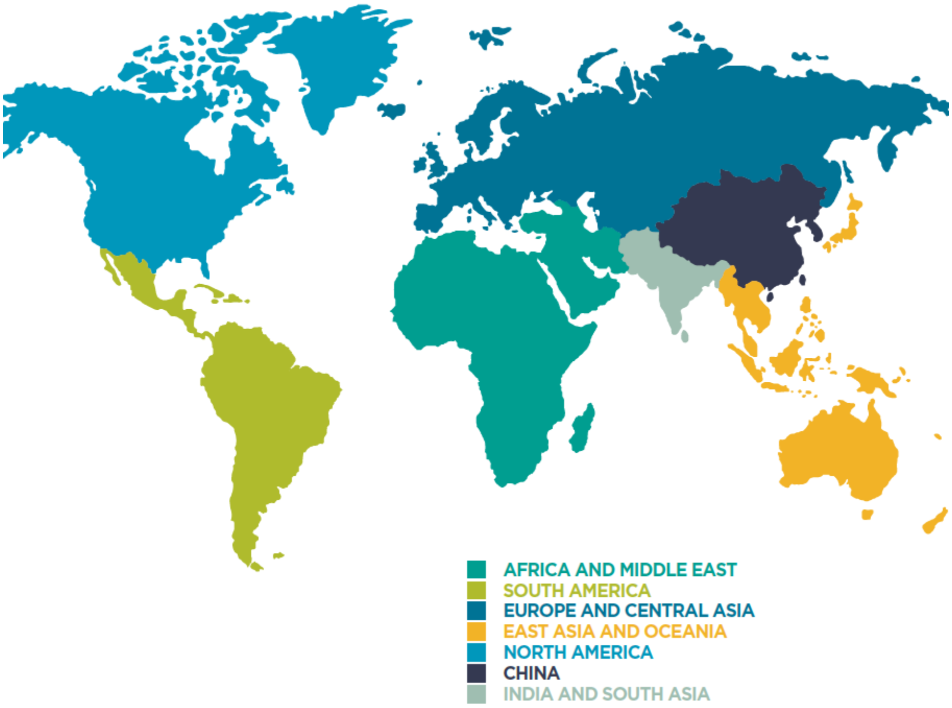

Figure 5: Considered regions. Source: Boucher and Friot, 2017.

Plastic leakage due to mismanaged waste has been identified dominant in coastal countries, particularly those with lack of waste management facilities. *Figure 6* (Boucher and Friot, 2017) shows the global releases of both primary microplastics and plastic waste into the world's oceans. The regional differences can be explained as a result of various patterns that depend on local characteristics, such as population densities, gross domestic product, cultural habits and the effectiveness of local infrastructure to retain waste (Billard and Boucher, 2019). These sectoral differences are further displayed in *Figure 7* (Boucher and Friot, 2017) for the different microplastic sources.

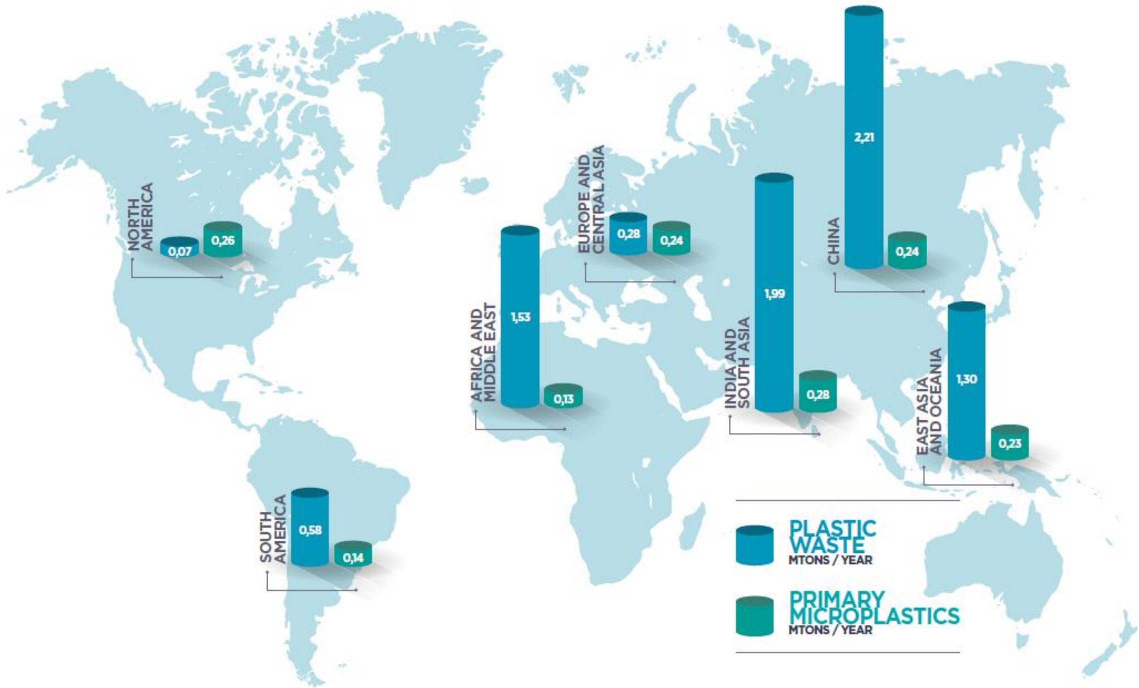

Figure 6: Global releases of primary microplastics and plastic waste into the world ocean. Source: Boucher and Friot, 2017.

Key sources among regions (total amount to 100%)

	Synthetic textiles	Tyres	Road markings	Marine coatings	Personal care products	Plastic pellets
INDIA AND SOUTH ASIA	15.9	1.1	0.3	0.1	0.8	0
NORTH AMERICA	2.6	11.5	1.9	1	0.1	0.1
EUROPE AND CENTRAL ASIA	4	8.6	2.4	0.6	0.2	0.1
CHINA	10.3	2.5	1.3	1.2	0.5	0
EAST ASIA AND OCEANIA	6.3	5.3	1.6	1.5	0.3	0
SOUTH AMERICA	2.9	5.1	0.9	0	0.2	0
AFRICA AND MIDDLE EAST	4	3.2	0.6	0.4	0.5	0

SYNTHETIC TEXTILES
TYRES
ROAD MARKINGS
MARINE COATINGS
PERSONAL CARE PRODUCTS
PLASTIC PELLETS

Legend: 15 12 9 6 3 0

Figure 7: Global microplastic releases (%) to the world oceans by geographical area and sources. Source: Boucher and Friot, 2017.

The global microplastic contribution from each region is illustrated in *Figure 7* (Boucher and Friot, 2017). Synthetic textiles are the main source in Asia, Africa, and the Middle East. In America, Europe and Central Asia, the tires dominate, as the travelled distances are higher than the rest of the world. The main global issues are, by order of relevance (in % of total releases): textiles in India and South East Asia, tires in North America (11,5%), textiles in China (10,3%) and tires in Europe and Central Asia (10,3%) (Boucher and Friot, 2017).

From the above data, it can be inferred that a comprehensive analysis of the German plastic situation as the most plastic consuming country in Europe, and with lack of information at national level, is essential for an overall understanding of the problem.

2.1.2. WORLDWIDE STRATEGIES TO FACE THE PROBLEM

Regarding the different strategies that have been carried out to face this global issue, the Marine Strategy Framework Directive (MSFD) for the European Union (EU) and the Economic and Social Commission for Asia and the Pacific (ESCAP) for the South Asian Region (SAR) have been considered.

<u>The Marine Strategy Framework Directive</u>

The EU's Marine Strategy Framework Directive was adopted in June 2008, with the aim to protect the marine environment across Europe. The Commission established detailed criteria and methodological standards to help Member States implement the MSFD.

The EU adopted a report on the first implementation cycle of the Marine Strategy Framework Directive in June 2020. This report is one of the most comprehensive globally, aiming to address prevailing pressures such as overfishing and unsustainable fishing practices, plastic litter, excess nutrients, underwater noise, and other types of pollution. In order to achieve its goal, the Directive establishes European marine regions and sub-regions on the basis of geographical and environmental criteria. It lists four marine regions: the Baltic Sea, the North-east Atlantic Ocean, the Mediterranean Sea, and the Black Sea, located within the geographical boundaries of the existing Regional Sea Conventions. *Figure 8* (European Commission, 2020) illustrates the MSFD Factsheet.

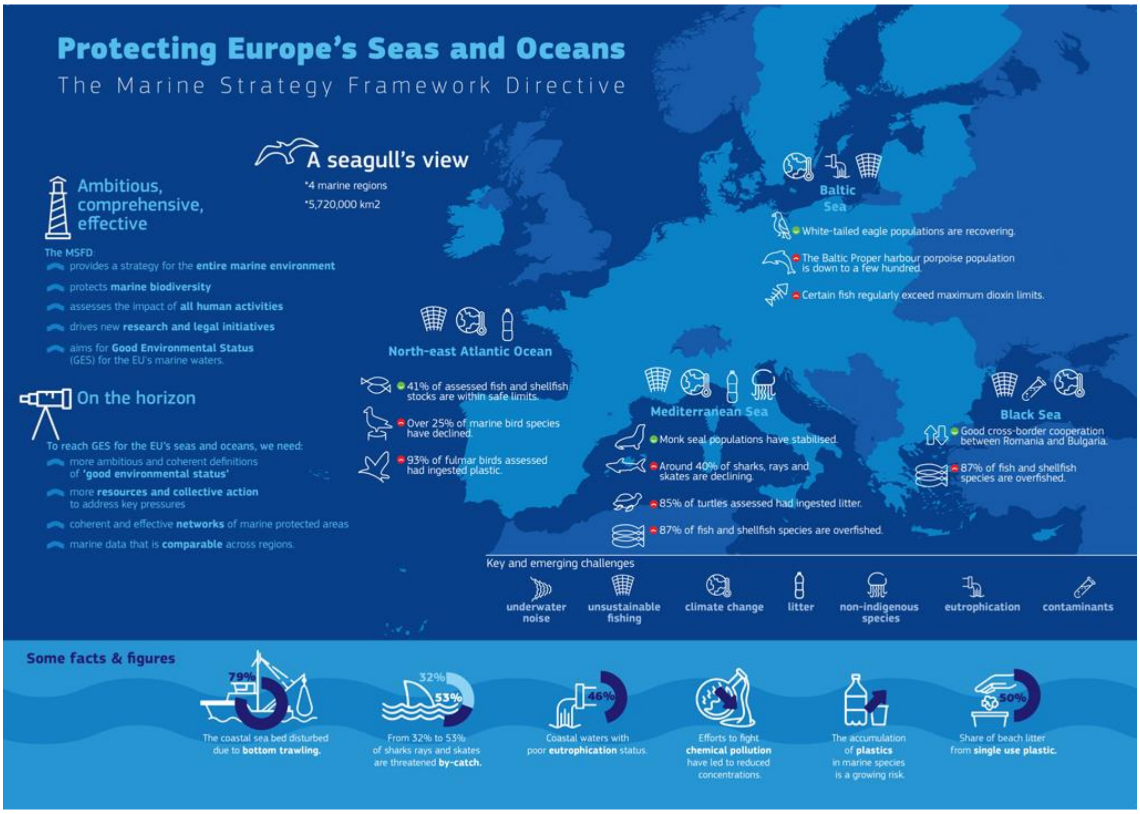

Figure 8: MSFD Factsheet. Source: European Commission, 2020.

The quality status of European waters presents a mixed picture. For instance, some marine species exhibit recovery signs (e.g., white-tailed eagles in the Baltic Sea), whereas others show a strong degradation (40% of elasmobranchs in the Mediterranean). Even though fishing effort has been reduced in the North-East Atlantic, some 79% of Europe's coastal sea floor and 43% of the surface area of the shelves/slope are physically altered, mainly due to bottom trawling. Forty-six percent of Europe's coastal waters remain heavily eutrophicated. While EU rules regulating chemicals have led to a decline in contaminants, there is an increased accumulation of plastics and plastic chemical debris in most marine ecosystems.

The Directive has promoted a clearer understanding of the pressures and impacts of human activities at sea, and their consequences for marine ecosystems. The learnings from the implementation of this Directive were, for example, a motivating factor leading to the adoption of the Single Use Plastics Directive.

The new EU Biodiversity Strategy 2030 was adopted in May 2020 and aims to strengthen the marine ecosystem protection and restore them to achieve “good environmental status” (GES), including the broadening of protected areas and the establishment of strict protected zones for the recovery of habitats and fish stocks. It emphasizes the importance of an ecosystem-based approach to the management of human activities at sea, with the objective of protecting marine species, especially those that are endangered or in poor condition; and of tackling practices that damage the seabed.

(European Commission, 2020)

<u>ESCAP</u>

The Economic and Social Commission for Asia and the Pacific (ESCAP) is the United Nations regional center that fosters cooperation among countries to achieve inclusive and sustainable development. It is the largest regional intergovernmental platform, with 53 member states and 9 associate members, and has become a powerful regional think tank that provides countries with solid analytical products that provide insight into the evolving economic, social, and environmental dynamics of the region.

The overall objective of ESCAP is to enhance inclusive and sustainable economic and social development in the Asia-Pacific region, prioritizing the fulfilment of the 2030 Agenda for Sustainable Development and the achievement of the Sustainable Development Goals (SDGs). ESCAP focuses on strengthening institutional capacities to serve the rights of the people of the region and tackle their aspirations and needs.

There is need for institutional change at all levels to guarantee an effective provision of essential services to the region's growing population, which is increasing the demand for adequate food, clothing, shelter, housing, water, energy, and transport infrastructure, along with other basic needs.

(ESCAP, 2021)

ESCAP members have recently ratified their commitment to address the Marine Plastic Pollution (MPP) concern, as it is one of the most pressing environmental challenges for Asia and the Pacific. The South Asian Region (SAR) has two of the most contaminated rivers in the world (the Ganges and the Indus). The transboundary nature of marine plastic pollution demands early recognition by all countries to control the extent of marine pollution before it gets out of control. Therefore, *UNESCAP SSWA POLICY BRIEFS - Marine Plastic Pollution in South Asia* (Kapinga and Chung, 2020) has been developed to provide policy recommendations for decision-makers and stakeholders.

The seriousness of MPP in South Asia is largely due to poor waste management systems and an inadequate plastics recycling sector. Its consequences have a negative impact on wildlife, community health and economic losses.

Attempts to impose plastic bans in the SAR in the previous decade were unsuccessful due to weak enforcement by the authorities. Plastic bans in the SAR range from banning the circulation of certain types of materials or thicknesses on the market to total bans on plastic-related activities. However, even with plastics ban legislation, many SAR countries have had a record of failing to implement these regulations consistently due to insufficient resources at the local level.

In addition, laws regulate macroplastic products such as plastic bags, but there is no microplastics consideration, being microplastics yet known as hazardous for the environment.

In this situation, the policy priority for tackling marine plastic pollution in SAR is stated as follows:

- Develop the baseline data on marine plastic pollution and waste management at city, national and regional levels and facilitate knowledge exchange.
- Support structures that help improve the waste management system.
- Better enforcement of plastic ban and utilization of economic instruments.
- Engaging all stakeholders, including non-governmental organizations, private sector, regional and international organizations.

(Kapinga and Chung, 2020)

2.1.3. CURRENT PLASTIC WASTE SITUATION IN GERMANY

The current situation of plastic waste in Germany is presented below. However, the focus of this report is on plastic leakage due to PET bottles. Therefore, among all plastics, packaging waste is presented in the subsequent sections.

At European level, it has been observed that nations with landfill restrictions present higher recycling rates, as seen in *Figure 9* (PlasticsEurope, 2020). Therefore, to achieve circularity of plastics, zero landfilling is needed.

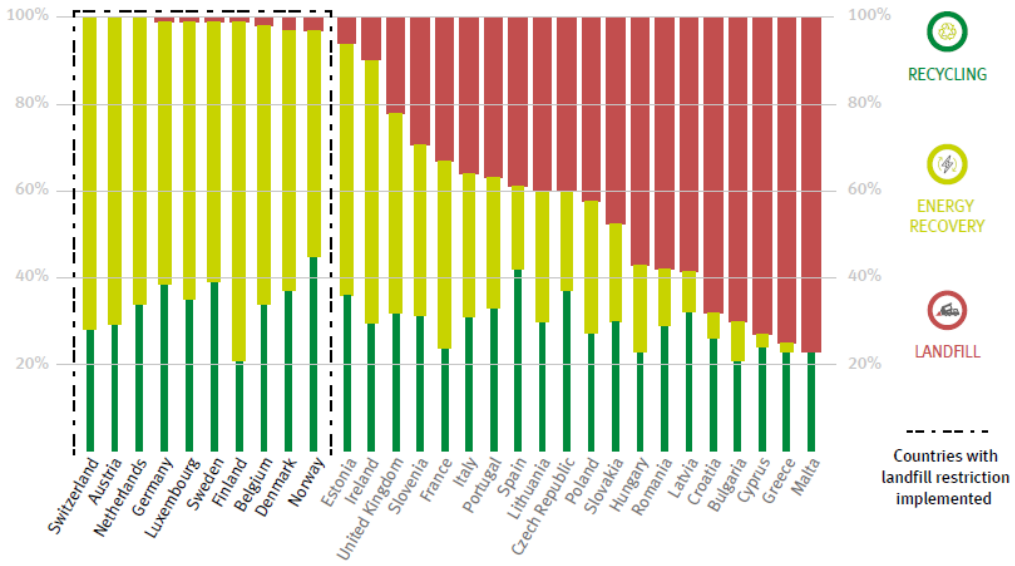

Figure 9: Plastic post-consumer waste rates of recycling, energy recovery and landfill per European country in 2018. Source: PlasticsEurope, 2020.

Among the countries with landfill restrictions stands Germany, which as previously mentioned, is the European top plastic-consuming nation (PlasticsEurope, 2020).

In Germany, 3,1 million tons of plastic post-consumer packaging waste were collected in 2018 with the goal to be treated. As it can be observed in *Figure 10* (PlasticsEurope, 2020), it presents almost zero landfilling, and recycling and energy recovery processes are equally applied. From 2006 to 2018, the volume of plastic packaging waste collected for recycling increased by 75%, energy recovery increased by 75% and landfill decreased by 95%.

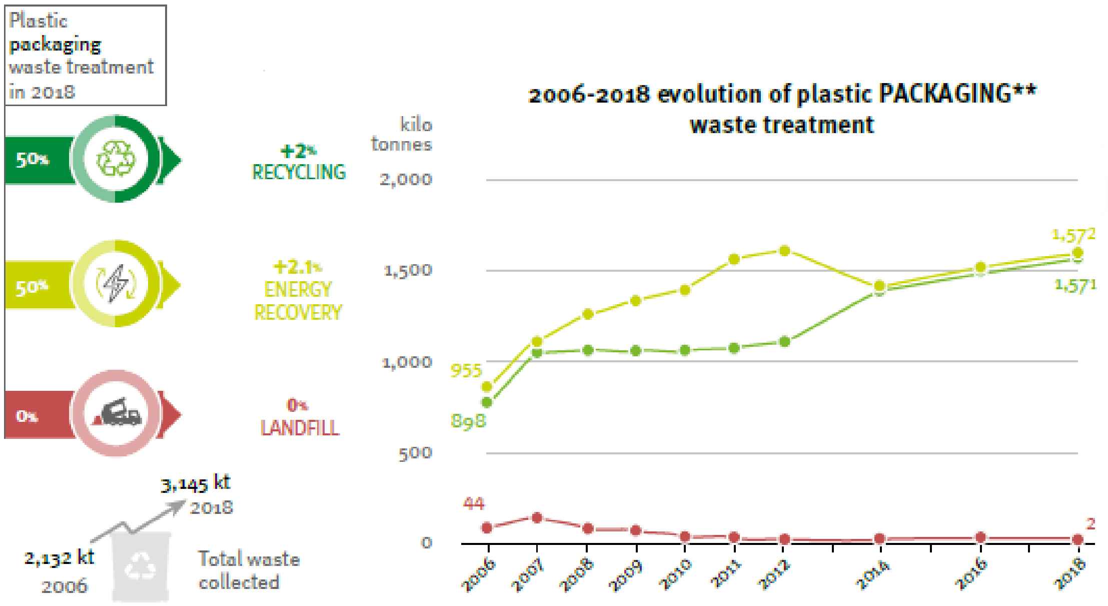

Figure 10: Plastic packaging waste treatment in Germany from 2006 to 2018. Source: PlasticsEurope, 2020.

From the previous information, it can be derived that the plastic leakage to the environment in Germany is mostly due to microplastics. The biggest challenge should be to identify and quantify them to be able to measure the size of the problem. This way, corresponding policies and solutions could be developed.

2.1.4. CURRENT PLASTIC WASTE SITUATION IN INDONESIA

According to *Full Circle* report (GA Circular, 2019), Indonesia is one of the top 10 leaking plastic countries worldwide. Being Asia the greatest consumer of plastics in the world and the largest contributor to marine leakage, studying its plastic waste situation is representative.

To that purpose, the *Full Circle* report, from GA Circular in 2019, has provided a systematic and comparative baseline of the stream of plastic packaging from production to end states by examining PET bottles in six South East Asian nations. To this end, 9 key cities among these countries have been studied. These six countries are Indonesia, the Philippines, Vietnam, Thailand, Myanmar, and Malaysia, which together account for a total population of over 600 million people, higher than the combined population of all 28 European Union countries.

Key findings from this study reveal the following:

- The countries studied account for 3,8% of global PET bottle consumption but are the source of 29% of global plastic leakage into the world's oceans.

- At a city level, the average PET collected-for-recycling rate across the nine key Southeast Asian cities studied is 54%, while 36% stays in landfills and 10% leaks into the environment. *Figure 11* (GA Circular, 2019) shows the average plastic flow in these countries.

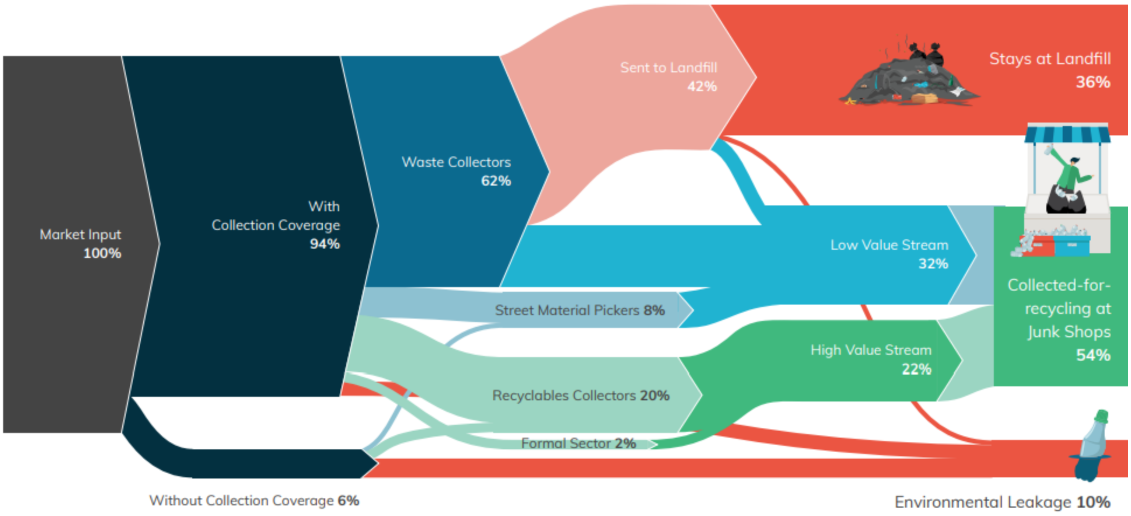

Figure 11: Key Flows and end destination of post-consumer PET bottles in 9 Southeast Asian cities. Source: GA Circular, 2019.

From *Carbon Footprint and Life Cycle Assessment of PET Bottle Manufacturing Process* (Alfarisi and Primadasa, 2019), it can be extracted that Indonesia, as the fourth most populated nation worldwide, has a high demand for plastics and is responsible for 10% of the world's mismanaged waste (Jambeck *et al.*, 2015). As it can be seen in *Figure 12* (British Plastics Federation, 2015), the plastics demand in Indonesia is predominated by the packaging sector (55%), being bottle-grade PET, one of the most important plastic packaging materials.

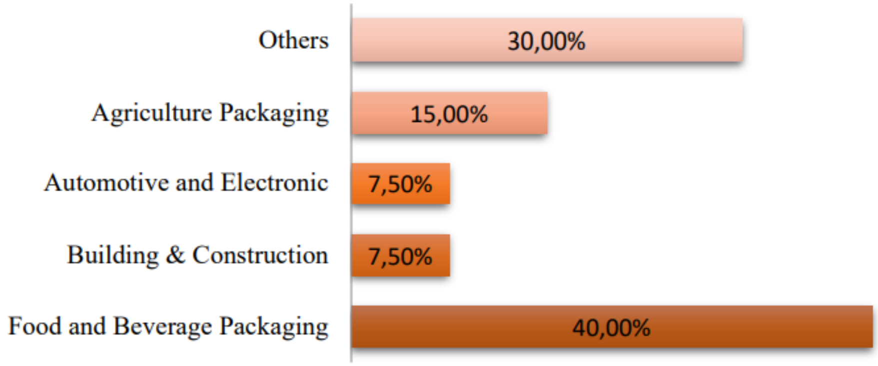

Figure 12: Distribution of Indonesian Demand by Segment in 2015. Source British Plastic Federation, 2015.

As it has been explained, the main contributor to plastic leakage in the six South East Asian nations are macroplastics due to the poor waste management infrastructure. A proper waste management system is thus the biggest challenge in developing countries. For accomplishing that, measuring the amount of macroplastic leakage is required to identify the dimension of the problem and be able to develop the best solution.

2.2. METHODOLOGIES TO MEASURE MARINE LITTER

This complex and global problem does not have a simple solution. Industries and policy makers are taking decisions in a situation of great uncertainties. The principle "We can only manage what we can measure", implies that effective metrics that consider plastics pollution and that take into account the complex trade-offs of environmental impact are needed to guide sustainable design and waste management strategies (Billard and Boucher, 2019). In the following sections the development history and the description of existing approaches and methodologies to provide suitable metrics in plastic leakage accounting are presented

The International Union for Conservation of Nature (IUCN) is currently developing in collaboration with the scientific community a top-of-the-line plastic hot spot calculator that can assist key stakeholders in government, the private sector, civil society and academia with the required data and analysis to inform their decision-making on mitigating plastic leakage (Boucher *et al.*, 2019). To that end, Boucher et al. presented in 2019 the *Review of plastic footprint methodologies: laying the foundation for the development of a standardised plastic footprint measurement tool*, a report that provides an examination of existing and emerging methodologies. It covers nineteen approaches that had been identified in early 2019. Two groups of methodologies are presented: the first comprises those that map plastic waste flows and recycling rates; the second encompasses those that focus on the modelling of pathways to measure plastic leakage into waterways and oceans, from both poorly managed waste and microplastics. According to the IUCN report, the plastic footprint can include the following three dimensions, also illustrated in *Figure 13* (Boucher *et al.*, 2019).

1. The quantity of plastic used in a system (often named as "source"). In this case, the plastic footprint is measured in kilograms of plastic per year.

2. The amount of plastic released into the environment during production, transport, use or end-of-life of a plastic product (often referred to as "plastic leakage"). Here the plastic footprint represents an inventory, in unit of mass, of plastic leakage into the environment. The quantification of resource consumption as well as resource emitted into the environment throughout the life cycle is called "the inventory" by the Life Cycle Assessment (LCA) community.

3. The impact caused directly or indirectly by the emitted pollutants (or the spilled plastic) on human health or the environment. It is a feature of the more advanced LCA methodologies.

(Boucher *et al.*, 2019)

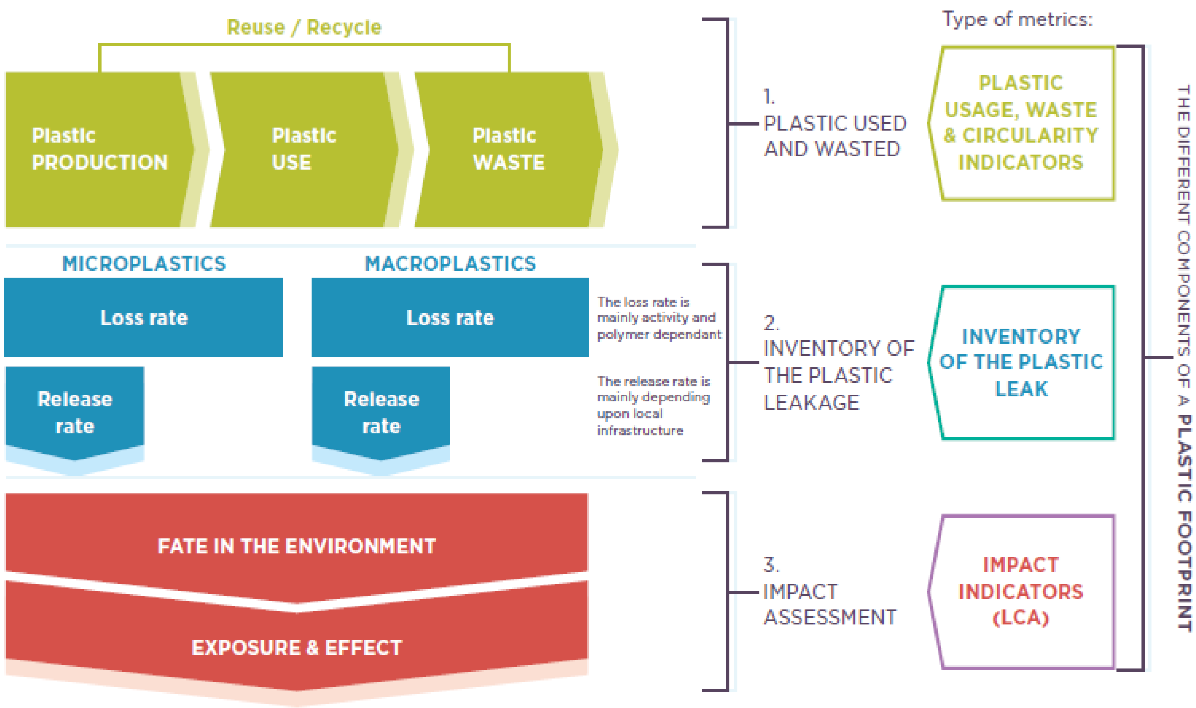

Figure 13: What is included in a plastic footprint? 3 main modeling stages lead to 3 types of metrics: 1) plastic used and waste, 2) inventory of plastic leakage, and 3) impact assessment. Source: Boucher et al., 2019

LCA (Life Cycle Assessment) is an environmental assessment methodology based on an inventory of potential flows of pollutants entering different compartments of the environment (e.g. air, water, soil) and the assessment of associated environmental impacts (ISO, 2006). Current LCAs do not consider plastic itself a pollutant, instead they assume that 100% of the waste flows go to landfill, incineration or recycling (Boucher *et al.*, 2019). Literature reports several prior studies on the environmental impacts of PET bottles, as for example *LCA comparison of PET water bottles sold in Germany deriving from different production locations* (Winter, 2014), *Carbon Footprint and Life Cycle Assessment of PET Bottle Manufacturing Process* (Alfarisi and Primadasa, 2019), or *Comparative life cycle assessment of fossil and bio-based polyethylene terephthalate (PET) bottles* (Chen, Pelton and Smith, 2016).

As a result of research activities, methodologies that assess plastic waste in developing countries, have been developed. Some examples that are mainly used in the present work are *Carbon Footprint and Life Cycle Assessment of PET Bottle Manufacturing Process* (Alfarisi and Primadasa, 2019) and *Full Circle: Accelerating the Circular Economy for Post-Consumer* (GA Circular, 2019).

In order to consider plastic as a pollutant, the PLP guideline has recently been developed as an inventory methodology, which comprehensively quantifies the amount of plastic that ends up in the marine environment. As considered one of the most complete existing methodologies, it is carefully applied in this project. More details are provided in the subsequent section.

2.2.1. PLASTIC LEAK PROJECT

The Plastic Leak Project (PLP) report (Peano *et al.*, 2020) was developed by a joint team of Quantis and EA. Quantis is a consultancy with focus on guiding top companies toward most environmentally sustainable solutions. EA is an eco-design center which models sources and pathways of micro- and macroplastics.

The PLP is a multi-stakeholder initiative designed to build better metrics to help shape operational solutions and effective actions to address the plastics pollution crisis. Its objective is to provide clear guidelines for calculating the quantity of micro and macroplastics leakage at each level of the life cycle at both company and product level. It considers four specific sectors, each with its particular calculation methodology:

- Plastic products and packaging: It accounts the macroplastic losses during a product life cycle or various value stages of corporate activities. These losses can occur at the production stage (e.g., agricultural plastic lost on field or plastic scrap lost at the manufacturing facility), during the use stage of a plastic product (e.g., fishing devices lost during fishing activities), or at plastic packaging or product end-of-life (e.g., a plastic bag littered in the street).
- Textiles: This is, the leakage of microplastics stemming from the abrasion of synthetic textiles during laundering. Namely, these leakages are synthetic microfibers from textiles, and are considered microplastics that can be aggregated with other leakages of micro- and macroplastics.
- Transport: The microplastics leakage related to tire abrasion on road/strip surfaces for road transport and air transport.
- Pellet production and recycling: Pellets are a form of microplastics defined as “small mass of preformed molding material, having relatively uniform dimensions in a given lot used as feedstock in molding and extrusion operations” (ISO, 2013). The PLP report

focus on the pellet entering drains at or near plastics facilities at the manufacturing and recycling stages.

Defining leakage as "The quantity (in grams) of plastic leaving the technosphere and ending up in the natural environment", it is considered to be a result of both loss and release, through transfer and redistribution routes.

- Loss is "The quantity of plastic that leaves a managed product or waste management system". It is represented by the fraction of plastic materials that is separated from the product during its manufacture, use or transport (for microplastics), or by poorly managed waste (for macroplastics), that is, the portion that escapes the technosphere.

  Various types of transfer routes lead from loss to release. Transfer pathways are the main ways in which plastics are released from the technosphere into a compartment of nature. Six transfer pathways are identified in the PLP: wastewater (e.g., washing synthetic textiles), road runoff (e.g., abrasion of tires), air (e.g., microplastics released from synthetic textiles), uncollected waste (e.g., garbage, fly ashes), mismanaged waste (e.g., unsanitary landfills, illegal dumping), and the direct pathway.

- The initial release compartment is the medium into which the plastic is released by a single or a combination of multiple channels. The subsequent initial release compartments are taken into consideration: ocean, fresh water (rivers or lakes), soils (e.g., via spreading of sewage sludge on agricultural soils), terrestrial environment (plastic deposited in dumpsites, macroplastic deposited on buildings and trees, littered macroplastic packaging) and air (plastic dust from abrasion or washing).

- The redistribution of the plastic from an initial compartment to its final compartment involves various kinds of transfers, such as leaching, transport in freshwater bodies or wind blowing. The PLP considers two redistribution mechanisms: the transport of plastic by rivers and the redistribution of microplastic emitted by air onto freshwater and soil.

- The final release compartment is the last medium to which the plastic is sent after the redistribution phase. The PLP models the following: ocean, freshwater, soil, and terrestrial environment.

Figure 14 and *Figure 15* (Peano *et al.*, 2020) show these stages graphically.

Figure 14: Key stages of the plastic leakage modelling: Overview. Source: Peano et al., 2020.

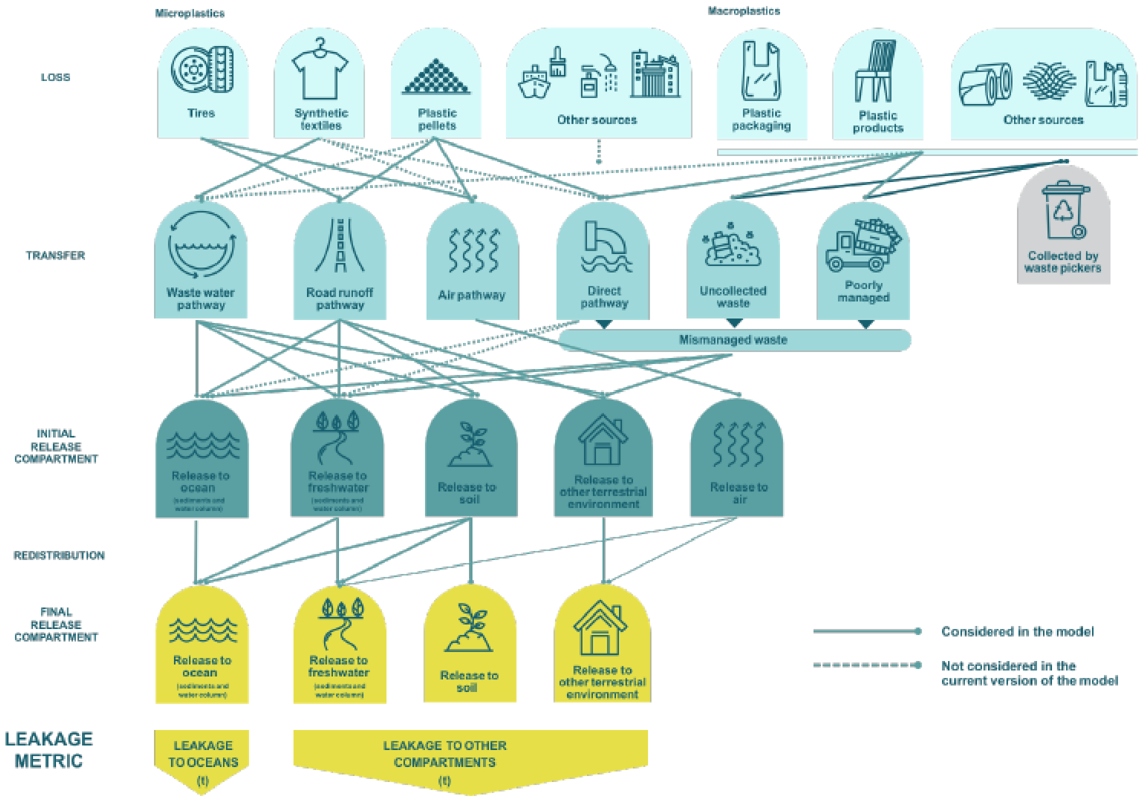

Figure 15: Key stages of the leakage modelling. Detailed view. Source: Peano et al., 2020.

Plastic leakage metrics can be examined from different approaches, which provide various viewpoints to understand leakage hotspots. Hotspots are defined as a country, a product, a polymer, or a stage in the value chain that contributes significantly, either in a direct or indirect way, to leakage.

In *Figure 16* (Peano *et al.*, 2020) mandatory and optional perspectives for reporting a product or corporate footprint are displayed, each of which addresses a particular question.

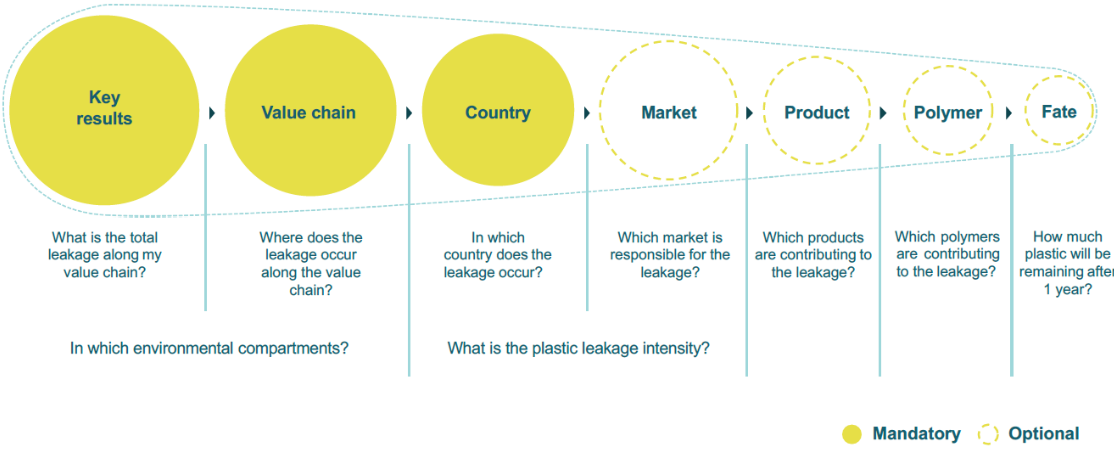

Figure 16: Different perspectives of plastic leakage. Source: Peano et al., 2020.

The mandatory perspectives are listed below.

- The *key results* perspective answers the questions: *What is the leakage along my value chain? In which environmental compartments? Figure 17* (Peano *et al.*, 2020) shows a plastic leakage assessment key results.

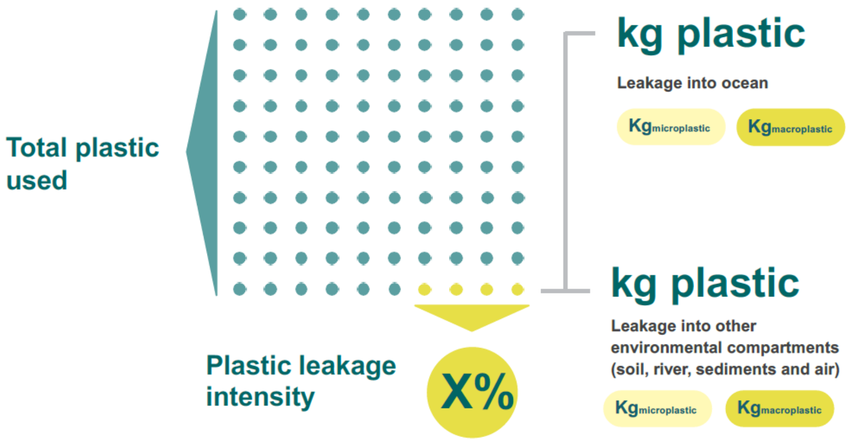

Figure 17: Example of display for a plastic leakage assessment key results Source: Peano et al., 2020.

- The *value chain* perspective answers the questions: *Where does the leakage occur along the value chain? In which environmental compartments?* In *Figure 18* (Peano *et al.*, 2020): the life cycle stages to be included in a plastic leak assessment are displayed.

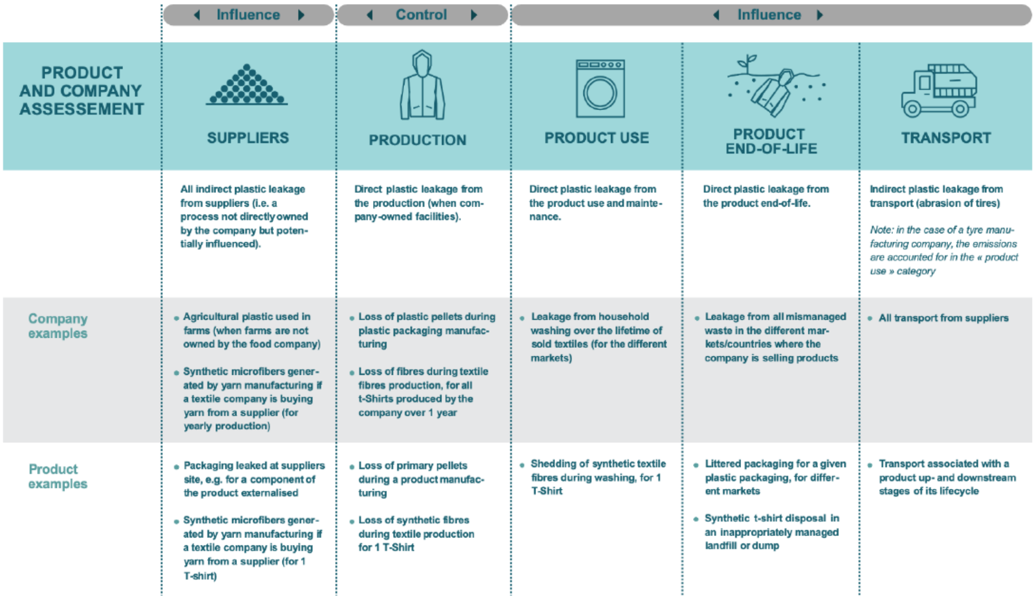

Figure 18: Life cycle stages to be included in the system boundaries of a plastic leak assessment. Source: Peano et al., 2020.

- The *country* perspective answers the questions: *In which country does the leakage occur? What is the plastic leakage intensity? Figure 19* (Peano *et al.*, 2020) shows an example of a country perspective within a plastic leakage assessment for a multinational dairy company, studied in the PLP.

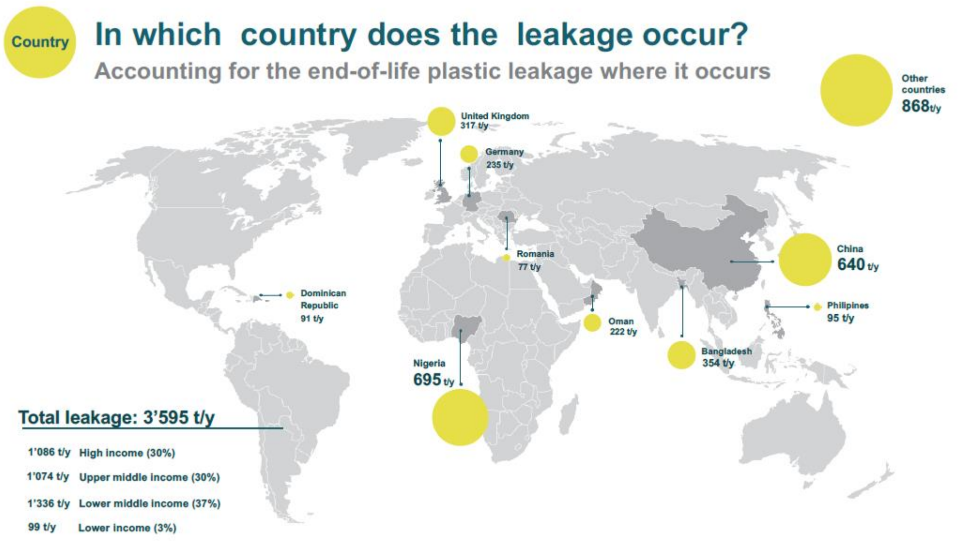

Figure 19: Example of a country perspective within a plastic leakage assessment. Source: Peano et al., 2020.

Optional perspectives may be analyzed if they add value based on the type of study. The following optional perspectives can be explored:

- The *market* perspective answers the questions: *Which market is responsible for the leakage? What is the plastic leakage intensity?*
- The *product* perspective answers the question: *Which products are contributing to the leakage?*
- The *polymer* perspective answers the question: *Which polymers contribute to the leakage?*
- The *fate* perspective answers the question: *How much plastic will remain after 1 year?*

In order to carry out a proper assessment of plastic leakage, an appropriate process has to be followed. The general framework of a plastic leakage assessment relation with the LCA framework as described in the ISO 14040/44 standards is displayed in *Figure 20* (Peano *et al.*, 2020).

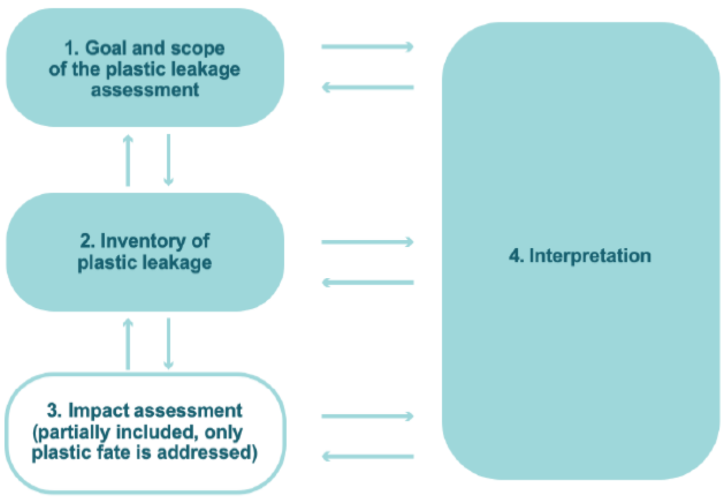

Figure 20: General framework of the plastic leak assessment. Source: Peano et al., 2020.

As illustrated, the first step is to define the goal and scope of the assessment. For that purpose, whether a general or a more specific analysis is going to be carried out must be stated, in order to determine the level of precision of the data collected. The system boundaries, functional unit, and data sources to be used should also be defined.

Second step is to calculate the inventory of plastic leakage. It involves two steps:

1. To map macro- and microplastic leakages: identification of the origin of leaks and the location where they occur.
2. To collect data: Both primary data, including amount of plastic, travelled distance of

the vehicles, etc., and secondary data, average values which are available in the PLP guidelines.

The calculation routes of the inventory are given in detail in *Chapter 3*.

Third step is impact assessment, which is only included when plastic fate is addressed. The environmental fate of a chemical describes the proportion of chemical that is transferred to the environment, and the length of time the chemical remains in various environmental media. Addressing plastic fate, hence, involves studying the situation in a period of time.

As shown above, interpretation is essential throughout every stage.

An example of the leakage for a water bottle assessment is given in the report, which can serve as a starting point for the present study. See *Table 1* (Peano *et al.*, 2020).

Table 1: Macro and microplastic leakage for a 100 ml water bottle assessment. Source: Peano et al., 2020.

Life cycle stages	Nature of plastic leakage
SUPPLIERS	Microplastics from pellets
PRODUCTION	Macroplastics from packaging production
PRODUCT USE	Not applicable
PRODUCT END-OF-LIFE	Microplastics from landfills
	Macroplastics from packaging end-of-life
TRANSPORT	Microplastics from tire abrasion
	Microplastics from road markings

In addition, the PLP report includes two industrial applications of this methodology. The first case study is an assessment of plastic leakage from a product in a textile garment and the second is an assessment of plastic leakage from a multinational dairy company. For each scenario, the most relevant leakage hotspots are provided, as a decision-making support for plastic reduction actions.

The previous information has been extracted from the *PLP: Methodological Guidelines* document (Peano *et al.*, 2020).

2.3. ALTERNATIVES TO REUSE MARINE PLASTIC LITTER

Multiple studies address the various alternatives for treating plastics after disposal. Among them, the following ones have been applied as main source of information: *Novel trends in plastic waste management* (Idumah and Nwuzor, 2019), *Plastic solid waste utilization technologies: A Review* (Awasthi, Shivashankar and Majumder, 2017), and *Pyrolysis of plastic waste for liquid fuel production as prospective energy resource* (Sharuddin *et al.*, 2018).

To assess the methodologies' impacts, *Environmental and Economic Life Cycle Analysis of Plastic Waste Management Options. A Review* (Bernardo, Simões and Pinto, 2016), *Plastic waste as a fuel - CO2-neutral or not?* (Eriksson and Finnveden, 2009), and *Toxic pollutants from plastic waste-a review* (Verma *et al.*, 2016) have been used.

Plastics recycling is defined as the recovery of scrap or waste plastics and the further reprocessing of the material into feasible forms that differ entirely from their initial state. The final product resulting from the different technologies has led to the distinction between the various plastics waste processing alternatives (Idumah and Nwuzor, 2019). *Figure 21* (Idumah and Nwuzor, 2019) shows the following Plastic Solid Waste (PSW), this means, from macroplastics, utilization technologies.

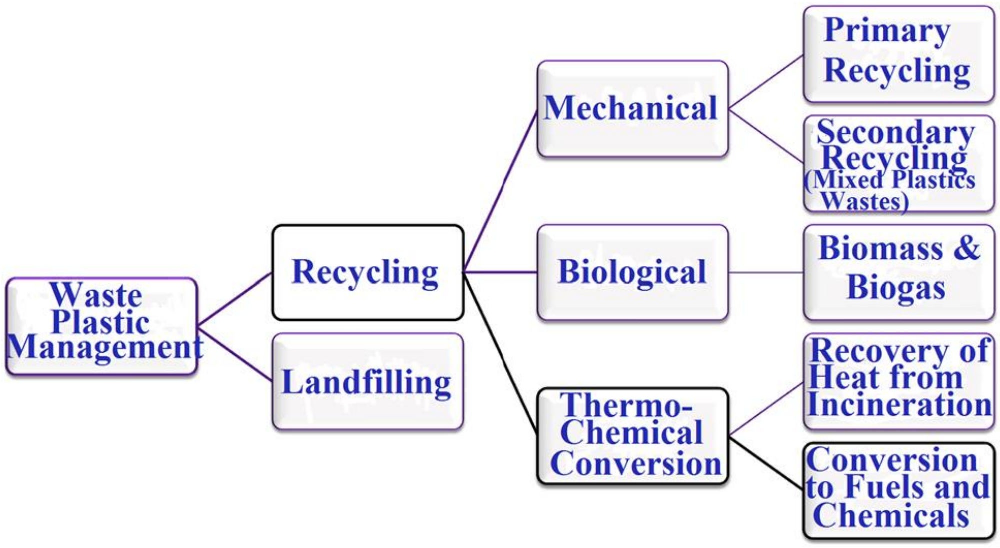

Figure 21: Plastic solid waste utilization technologies. Source: Idumah and Nwuzor, 2019

As it can be observed, plastic recycling could be classified into four main categories including re extrusion (Primary), mechanical (Secondary), chemical (Tertiary) and energy recovery (Quaternary). Each methodology offers peculiar benefits placing it at advantage for specific requirements, needs or applications. Primary recycling involves the manufacturing of products whose performance attributes are equivalent to those fabricated utilizing the pristine plastics. In secondary recycling, the plastic derived is used in products requiring fewer pressing attributes, in comparison with original material usage (Idumah and Nwuzor, 2019). Chemical recycling produces chemicals and fuels for the chemical industry, and energy recovery involves the oxidation of the material, producing heat, energy and gaseous fuels and oils. The conversion of waste materials to energy could also be achieved through biological processes such as anaerobic digestion. Landfilling, the traditional approach, involves waste dumping into the environment. It pollutes soil, underground water and air, and no material is recovered again, hence it is not a recycling method (Awasthi, Shivashankar and Majumder, 2017).

Determining the best way to manage plastic waste is of crucial significance. Such tools as LCA and economic analysis have successfully been used to assist in that decision. Current literature on LCA of the management of plastic waste is extensive and results are generally consistent, proving that mechanical recycling causes the lowest environmental impacts (Bernardo, Simões and Pinto, 2016). Nevertheless, this process presents some limitations relative to the high costs during the separation process, which also produces contamination of water, minimizing the sustainability of the technology (Idumah and Nwuzor, 2019). In addition, not all plastics are feasible to recycle, either for technical reasons or for their poor quality (Eriksson and Finnveden, 2009). Thus, other techniques such as waste plastics conversion to energy are required.

Furthermore, innovative alternatives for the treatment of plastic waste, in particular PET bottles, have been explored, among which the following three options have been considered:

- The recycling of plastic waste as concrete. It seems to be a promising solution for the alternative use of plastic waste (Kamaruddin *et al.*, 2017). The use of plastic litter in asphalt pavement application is a proper approach to prevent pavement degradation and will help to eliminate waste in an environmentally friendly way (Awasthi, Shivashankar and Majumder, 2017).
- The obtention of ecological products such as textile fibers from recycling PET. Literature shows multiple advantages of using the textile fiber from recycled PET bottles (r-PET) to produce a ring made of cotton and compact yarns (Sarioğlu and Kaynak, 2018). The house construction based on PET bottle brick in developing countries. They present a strong, low cost and ecofriendly housing solution, which can be an effective alternative for the reduction of PET plastic from the environment (IRP India, 2013).

2.4. RESEARCH QUESTION

As described above, marine plastic pollution is a critical challenge of the 21st century, affecting the environment, health of living beings and related economic activities. To face this problem, decisive measures must be taken. As shaping action requires the identification of emission hotspots (Billard and Boucher, 2019), measurement constitutes the first step towards change.

Being Europe a significant contributor to microplastics in the ocean (Boucher and Friot, 2017) and Germany the largest plastic consuming country in Europe (PlasticsEurope, 2020) with a lack of data at national level, the need to address the marine plastics problem in this country becomes of relevant importance to take further action.

Literature reveals multiple research studies on the impacts of plastics in Germany, carried out with tools such as LCA. Although the effectiveness of these tools has been demonstrated, a research gap has been identified, as plastics are not considered as pollutants in this form of assessment. Furthermore, as the results are given in the form of impacts, such studies do not consider the amount of plastic that ends up in the oceans. Therefore, a research approach for Germany in terms of inventory, i.e., measuring the quantity of micro- and macroplastics that end up in marine environments, is particularly relevant to reach an accurate understanding of the scale of the problem and develop proper policies.

As a result, the current work aims to address the problem at national level from an inventory perspective, by applying the PLP guidelines, a recently developed methodology which stands out for its accuracy, for the first time to the German context. A PET bottle has been chosen as the unit of study, and the micro- and macroplastics leakage is comprehensively calculated, providing robust results which constitute a novelty in the field.

In parallel, leakage due to PET bottles in Indonesia is examined, as being one of the top 10 leaking countries in the world. A different approach, based on the comparison of previous related studies, is used for the evaluation. The results are also contrasted with those of Germany, with the aim of achieving a meaningful comparison that provides a global perspective of the problem.

In addition, the different ways to reuse marine plastic are presented, since although the minimization of leaks is a necessity, the magnitude of the current amount of plastic waste in the oceans and other environmental compartments is of huge dimensions and its management is extremely relevant.

The purpose of this thesis is thus both to provide tangible results that can guide policy makers and the scientific community in tackling plastic pollution and to present a calculation pathway that can be extended to other plastic products and other countries.

3. METHODOLOGY

The working methodology is detailed throughout this chapter. As described above, the plastic leakage in Germany and Indonesia are examined, each case approached with a different method.

The plastic leakage due to PET bottles in Germany is calculated. This product has been chosen because of its everyday use and for being a well-known contributor to plastic pollution. Furthermore, plastic leakage from PET bottles in Indonesia is calculated. To that end, the outputs from previous literature are used to carry out an estimation. These results are finally compared with those from Germany.

For the German case study, the PLP guidelines are applied. For data sourcing, *Statista, PlasticsEurope*, and *EU statistics* are used. In addition, several LCA studies from PET bottles such as *Comparative life cycle assessment of fossil and bio-based polyethylene terephthalate (PET) bottles* (Chen, Pelton and Smith, 2016), *Comparison of Life Cycle Assessment of PET Bottle and Glass Bottle* (Odabasi and Buyukgungor, 2016) and *Carbon Footprint and Life Cycle Assessment of PET Bottle Manufacturing Process* (Alfarisi and Primadasa, 2019) have been studied and compared. *The OpenLCA 1.4 case study: LCA comparison of PET water bottles sold in Germany deriving from different production locations* (Winter 2014), stands out due to its data accuracy, as its source is the well-known ecoinvent database. The mentioned paper examines the life cycle of PET water bottles from the raw material extraction to the point of sale in Germany. It presents and compares three different scenarios, each of which with a different production location, and therefore, different transportation distances. The first case represents one-liter bottles produced and consumed in Germany. *Cases 2* and *3* represent one-liter bottles produced and filled in China/Turkey and consumed in Germany. To apply the outcomes of this research to the present work, *Case 1,* which considers every step is carried out in Germany, is considered.

A different approach is adopted to study the case of Indonesia. Based on the analysis and comparison of several previous studies on the PET bottle situation in this country, relevant evidence on plastic leakage is then extracted. The principal papers employed are *Carbon Footprint and Life Cycle Assessment of PET Bottle Manufacturing Process* (Alfarisi and

Primadasa, 2019) and *Full Circle: Accelerating the Circular Economy for Post-Consumer* (GA Circular, 2019). The latter examines the plastic waste stream due to PET bottles in six South East Asian countries, including Indonesia, and results are provided at national and city level.

The studied element is a 1 Liter (L) PET bottle with a weight of 20 grams (g) (American Samoa Power Authority, 2013). It is considered without cap, as seen in the *Figure 22.*

Figure 22: PET bottle to be studied.

The research for the two countries is conducted on an annual scale, both with data from 2018.

According to *OpenLCA* (Winter, 2014), the production chain of PET bottles presents the following steps, also displayed in *Figure 23* (Winter, 2014):

- Granulate production (including raw material extraction)
- Plastic component production
- Bottle filling
- Point of selling (POS)

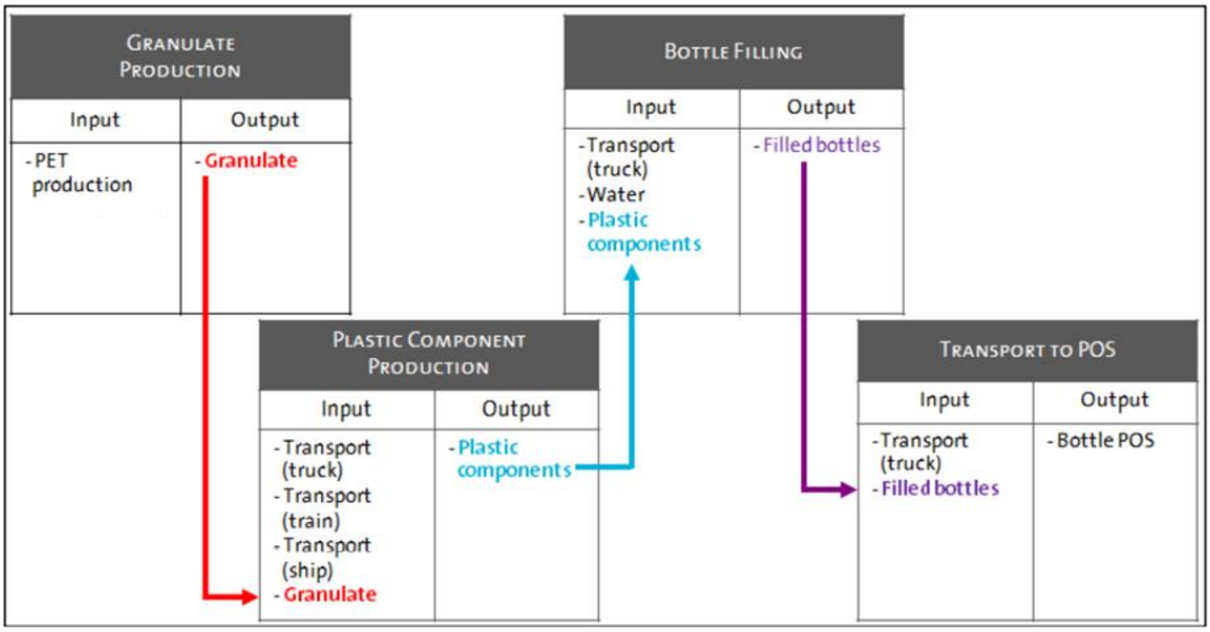

Figure 23: Production chain of PET bottles. Source: Winter, 2014.

It can be observed that the process begins with the extraction of crude oil, and its refining into PET granulate, a process denominated *Granulate production* and which takes place in the oil industry. The granulates are subsequently transported to the chemical industry, where they are converted into plastic pellets in the so-called *Plastic component production* stage. These pellets are further delivered to a manufacturing plant to be converted into bottles and are then filled with the corresponding re-fill, which is assumed to be water for calculation simplicity. Finally, the filled bottles are transported to the point of sale.

The present study aims to cover the whole life cycle of the bottle, this means, from material extraction, until it is taken to the recycling station. Thus, the recycling of the bottles, is considered, assumed to also take place at the bottle filling center. *Figure 24* shows thus the complete assessment to be used in this project.

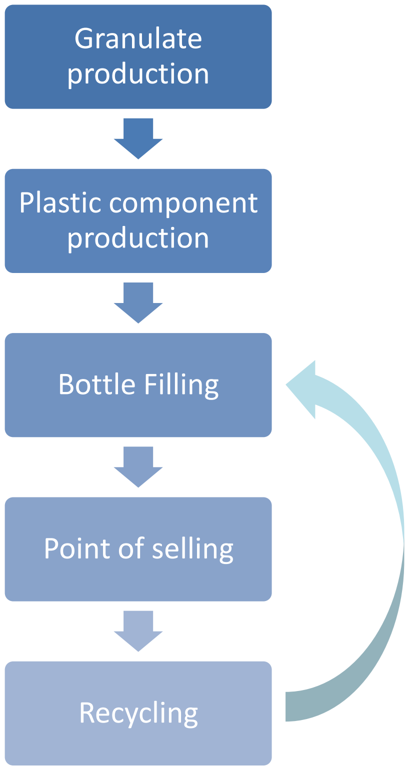

Figure 24: Life cycle of PET bottles.

Having *Figure 24* as a reference for the project, it can be inferred that for the plastic leakage calculation in Germany, microplastics from pellet production and from transportation apply for the present study. Nevertheless, this is further detailed in the subsequent section.

The following sub-chapters describe in detail the calculations to be carried out for each case, and the corresponding assumptions made.

3.1. MARINE PLASTICS IN GERMANY

In the first place, in order to be able to calculate the plastic leakage due to the selected product in Germany, it is necessary to study its demand and performance (i.e., recycling rate, etc.) in the country. It is important to note that the following will be analyzed on an annual scale with data from 2018, currently the most up-to-date data available from the reputable information source *PlasticsEurope*.

From the PlasticsEurope report of 2020, it can be extracted that the annual plastics demand in Europe in 2018 was 51,2 Mt, from which 24,6% takes place in Germany. This is, a yearly plastics demand in Germany of 12,5952Mt. From the overall plastics, 7,7% is from PET bottles, which result in an annual 0,9698 Mt of PET bottles in the studied country. To apply a conservative methodology, it is rounded up to 1Mt.

Assuming a 1L bottle with a weight of 20g as an average one (American Samoa Power Authority, 2013), it makes 50000 million PET bottles per year. As for a German population of 83 million people (Statista, 2021a), it would mean an average consumption of 602,4 bottles per person per year. *Table 2* summarizes these results.

Table 2: PET bottles in Germany.

Annual plastic demand Europe	**Annual plastic demand Germany (24,6%)**	**Annual PET bottles demand Germany (7,7%)**	**Annual amount of PET bottles in Germany (20g/bottle)**	**Annual amount of PET bottles per person (83 M. people)**
51,2 Mt	12,5952Mt	0,9698 Mt≈1Mt	50000 M. bottles	602,4 bot/ per.

Regarding the recycling rate in Germany, 94% of the PET bottles are being recycled (2015), from which:

- 34% goes into new PET bottles,
- 27% to the film industry,
- 23% into textile and
- 16% to other applications

(IK, 2018)

Table 3 displays the amount of recycled PET bottles in Germany.

Table 3: Recycled PET bottles in Germany.

Annual recycled PET bottles Germany (94% of total)	Annual amount of recycled PET bottles in Germany (20g/bottle)	Annual amount of recycled PET bottles per person (83 M. people)
0,94 Mt	47000 M. bottles	566,3 bot/ per.

In Germany, non-recycled waste is incinerated as a means towards elimination (Nelles, Gruenes and Morscheck, 2016), hence it is presumed that this is also true for the specific case of PET bottles. Therefore, the remaining 6% of non-recycled bottles are assumed to be incinerated and to not generate mismanaged waste.

From these findings and by taking *Figure 24* for the life cycle of PET bottles as a reference, it can be determined that the calculations required with the PLP guidelines are microplastics due to transport and pellet production and recycling. Microplastics due to textiles do not apply here, and macroplastics generated by mismanaged waste plastics are not taken into account, as mentioned above.

In addition, regarding the incineration process, several studies such as *Is incineration the terminator of plastics and microplastics?* (Yang *et al.*, 2021), provide empirical evidence that incineration is a potential source of microplastics released into the environment. Nevertheless, as the available data to carry out such calculations is scarce, it has been decided not to compute them to avoid unprecise results, being aware that they exist and that it is a limitation of this project.

Under the assumptions outlined above, it is consequently relevant to emphasize that PET bottles in Germany do not cause macroplastic leakage, but rather all leakage consists of microplastics.

3.1.1. MICROPLASTICS FROM TRANSPORTATION

3.1.1.1. Assumptions

To calculate the microplastic leakage from transportation in Germany, it is required to obtain the transportation distances and means.

As stated above, several studies have been considered and compared. Among them, the *Open LCA: Case Study* (Winter, 2014) is used as a baseline to extract various pieces of information, as its data source is the recognized *ecoinvent* database. The mentioned paper distinguishes three trips in the PET bottles production chain (A, B and C), and it provides their correspondent distances and transportation. The given journeys, expressed as destination points, are:

- A: Plastic component production
- B: Bottle filling
- C: Transport to POS

An additional step (D) is considered in the present project:

- D: Transport to the recycling point.

This trip is assumed to be from the POS, as this is where deposit machines are located in Germany, to the bottle filling center, so the travelled distance in D is the same as in C. *Table 4* shows the average transportation distances, expressed in kilometers (km), and means within Germany.

Table 4: Transportation distances and means in the PET bottle life cycle in Germany.

Transport	Process	Transportation distance	Transportation means
A	Plastic component production	200Km	Lorry
B	Bottle filling	200 Km	Lorry
C	Transport to POS	50 Km	Lorry
D	Transport to recycling point	50 Km	Lorry

As it can be seen in *Table 4*, the most frequent vehicle is the lorry (Winter, 2014). To estimate the number of trips needed to reach the annual demand, and therefore, the total travelled distance, its characteristics (payload and usable volume) are required.

The most used truck in Germany for transportation of beverages is the MAN TGM (MAN, 2021). See *Figure 25* (BBS, 2021).

Figure 25: MAN TGM truck. Source: BBS, 2021.

An average 13 Tons (T) truck is chosen, with its specifications in *Table 5*. A maximum capacity of 75% of its volume is considered.

Table 5: Truck specifications.

Payload	**Measures**	**Volume**	**Capacity (75% Volume)**
13T	9,8x2,5x2,2m	53,47m3=53470L	40000L

To calculate the total distance, the number of trips per step are required. To obtain that, it is necessary to check how much load fits per truck. It is relevant the fact that the transported material differs in each trip: in A PET granulate, in B PET pellets, in C filled bottles and in D empty bottles. The densities from PET granulate and PET pellets are 480 and 560 Kilogram (kg)/cubic meter (m^3) respectively (BPS, 2019). For the bottle filling, density of water, this is 1000 Kg/m^3 (BPS, 2019), is taken, to simplify calculations. Since water is not always the content of the bottles, this is a limitation of the project. In addition, the annual transported material is set for each journey. For that, the 1Mt demand of PET bottles in Germany, or 50000 million units are used (from *Table 2*) for trips A, B and C. For journey D, 0,94Mt of bottes or

47000 million units are considered (from *Table 3*), due to the 94% recycling rate of the bottles (IK, 2018). These values are summarized in *Table 6*, where 'unit' corresponds to a 1L bottle with a mass of 0,02 kilograms (kg).

Table 6: Transported material per journey.

Trip	**Transported material**	**Mass per unit Kg/unit**	**Annual amount of transported material**
A	PET Granulate	0,02 Kg/unit	1Mt PET
B	PET pellets	0,02 Kg/unit	1Mt PET
C	Filled bottles	1,02 Kg/unit	50000M. bottles
D	Empty bottles	0,02 Kg/unit	47000M.bottles

Having determined the material per trip, it is checked if the 13T payload fits per volume in the truck. This is fulfilled in trips A, B, and C. In journey D, as the volume corresponding the total distance exceeds the maximum capacity, the capacity of the truck is established as the load. Once the load per trip is set, the total number of trips is calculated.

These calculations are shown in *Table 7*.

Table 7: Calculation of the total distanced travelled in Germany.

	Distance per unit	Transported material	Mass per unit kg/ unit	Density kg/m³	Volume per unit L/unit	Max units due to payload (13T)	Volume of max units (Max. 40000L)	Load per trip	Number of trips	Distance in Km
A	200Km	PET Granulate	0,02 Kg/unit	480	0,0417 L/unit	650000 units	27105 L	13T	76923	15384616
B	200Km	PET pellets	0,02 Kg/unit	560	0,0357 L/unit	650000 units	23207 L	13T	76923	15384616
C	50Km	Filled bottles	1,02 Kg/unit	-	1 L/unit	12745 units	12745 L	12745 bottles	3923107	196155355
D	50km	Empty bottles	0,02 Kg/unit	-	1 L/unit	650000 units	650000 L	40000 bottles	1175000	58750000

By adding the total amount of kilometers, the annual travelled distance in Germany due to PET bottles is obtained, shown in *Table 8*.

Table 8: Annual travelled distance in Germany in the PET bottle life cycle

Total travelled distance in Germany
285674586Km = 2,857x108 Km= 285,7 million km

3.1.1.2. Calculations

This section covers the calculations of the microplastics from tire abrasion due to the transportation of the corresponding product. To that purpose, the PLP guidelines are applied, as of *Section 8*. All the information in this chapter is taken from the mentioned report.

Particles resulting from the abrasion of tire tread on road surfaces are one of the main sources of microplastic losses in the environment (Jan Kole *et al.*, 2017). Tire tread particles are a matrix of synthetic polymers. The tire wear particles are always embedded with pavement particles (Kreider *et al.*, 2010); together they form tire and road wear particles (TRWP), which are then emitted to the environment. An average ratio of 50% tread wear and 50% road wear are used. However, to perform a plastic leakage assessment the road fraction of TRWP is excluded, since this fraction is mainly mineral material (Peano *et al.*, 2020). *Figure 26* (Peano *et al.*, 2020) explains this process.

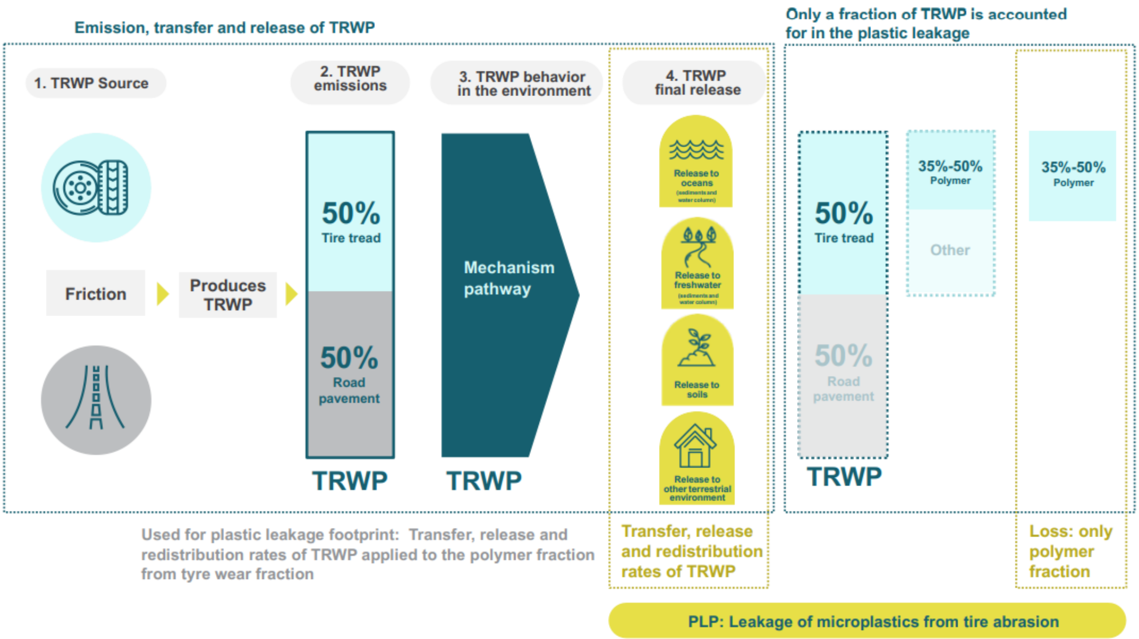

Figure 26: Tire and Road Wear Particles (TRWP) and calculation of leakage of microplastics from tire abrasion. Source: Peano et al., 2020.

Thus, only the polymer fraction from the tire fraction of TRWP is taken into account to quantify tire tread losses, in short $TireLoss_{VEHICLE}$. There are different transfer pathways, depending on the TWRP size.

- The TRWP below 10 µm are emitted into air
- The TRWP above 10 µm deposited near the road are emitted into soil
- The TRWP above 10 µm transported by runoff water are released into soils, surface water or oceans.

Following these various transfer pathways, microplastics from tire tread losses are released in various initial environmental compartments such as air, freshwater, oceans, or soils. The release rate ($RelR_{COMPARTMENT}$) is defined as the fraction of the loss that is released in the different compartments.

Finally, TRWP released in the different initial compartments can be redistributed towards other final environmental compartments. For example, if released TRWP are not captured by a combined sewer system nor at the later stage of wastewater treatment, they might reach freshwater sediments or stay in suspension in waterways and ultimately be redistributed to oceans. The redistribution rate ($RedR_{COMPARTMENT}$) is the fraction of the release that is redistributed in different environmental compartments.

Figure 27 (Peano *et al.*, 2020) represents the main methodological principles to account for plastic leakage to environment applied to microplastics leakages from tire abrasion.

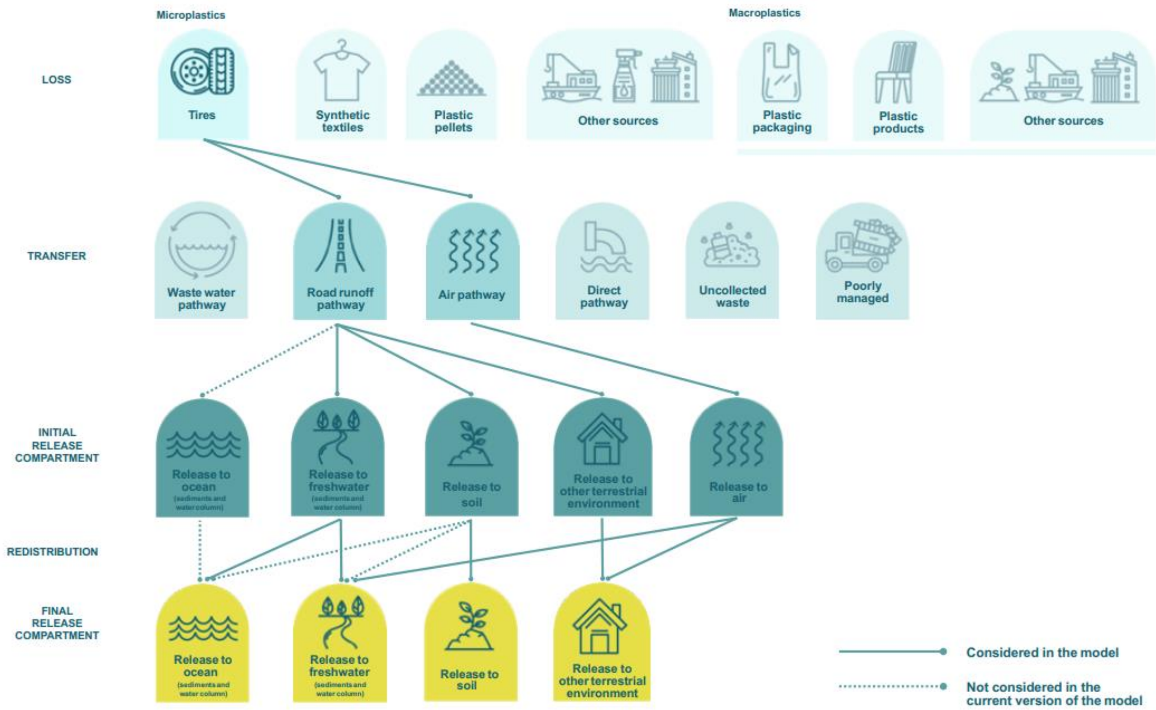

Figure 27: Summary of losses, transfers pathways and plastic release compartments for microplastics from tire abrasion. Source: Peano et al., 2020.

Calculation rules for tread losses

The equation for calculating tire tread losses of goods transport by truck is the following (1), having as input data the distance travelled by the corresponding amount of vehicles (vhc):

$$TotTireLoss_{TRUCK}[kg\ microplastics] = D_{TRUCK-VHC}[vhc * km] * Loss_{TRUCK-TIRES}\left[\frac{kg\ tread}{vhc*km}\right] * ShPolymer_{TRUCK-TIRES}\left[\frac{kg\ microplastics}{kg\ tread}\right] \quad (1)$$

To carry out this calculation, the parameters in *Table 9* apply, where each of them is described, and the units and their generic values are stated. As it is shown, the total distance travelled by the truck is primary data to be provided. The tire tread loss and the share of polymer vary among vehicles and their values are calculated in the PLP report from existing literature in this topic. Therefore, to determine them, the obtained results from PLP, outlined in the tables below, are used.

Table 9: Parameters to calculate tread losses for transport of goods by truck.

Abbreviation	Description	Unit	Generic value
$D_{TRUCK-VHC}$	Distance travelled by the truck	vhc*km	n/a (primary data to be provided)
$Loss_{TRUCK-TIRES}$	Tire tread loss per km travelled by the vehicle	Kg (tread)/(vhc*km)	*Table 7*
$ShPolymer_{TRUCK-TIRES}$	Share of polymer	Kg (microplastics)/ kg (tread)	*Table 8*
$TotTireLoss_{TRUCK}$	Losses of microplastics related to tire tread abrasion on road surfaces for transport of goods by truck	Kg (microplastics)	n/a (to be calculated)

From the PLP guideline (Peano *et al.*, 2020) , the following *Table 10* and *Table 11* (Peano *et al.*, 2020) have been extracted, which provide the values for $Loss_{TRUCK-TIRES}$ and $ShPolymer_{TRUCK-TIRES}$ respectively. For the chosen vehicle, the values for *medium/heavy truck short haul* apply.

Table 10: Loss of tire per kilometer for different types of vehicles for road transport. Source: Peano et al., 2020

Type of vehicle		$Loss_{vehicle\_tires}$ **Loss of tire tread per kilometer travelled by the vehicle** [mg (tread) / (vhc*km)]
Motorcycle	Motorcycle	45
	Scooter	45
Passenger car/light truck	Passenger car	102
	Light truck	142
Bus/coach	City bus	415
	Long haul coach	326
Medium/heavy truck	Medium/heavy truck long haul	517
	Medium/heavy truck short haul	658

Table 11: Share of polymer (synthetic rubber + natural rubber) in tire tread for different types of vehicles. Source: Peano et al., 2020.

Type of vehicle		$ShPolymer_{vehicle\_tire}$ **Share of polymer fraction (synthetic rubber + natural rubber) in tire tread** [kg (microplastics[14]) / kg (tread)]
Motorcycle	Motorcycle	0.40
	Scooter	0.50
Passenger car / light truck	Passenger car	0.35
	Light truck	0.36
Bus/coach	City bus	0.50
	Long haul coach	0.58
Medium/heavy truck	Medium/heavy truck long haul	0.60
	Medium/heavy truck short haul	0.50
Aircraft	Aircraft	0.53

Calculation rules for initial release rates

The calculations for $RelR_{OCEAN}$, $RelR_{FRW}$, $RelR_{SOIL}$, $RelR_{TERENV}$ and $RelR_{AIR}$ are explained in *Figure 28* (Peano *et al.*, 2020) and the average initial release rates are presented in *Table 12*.

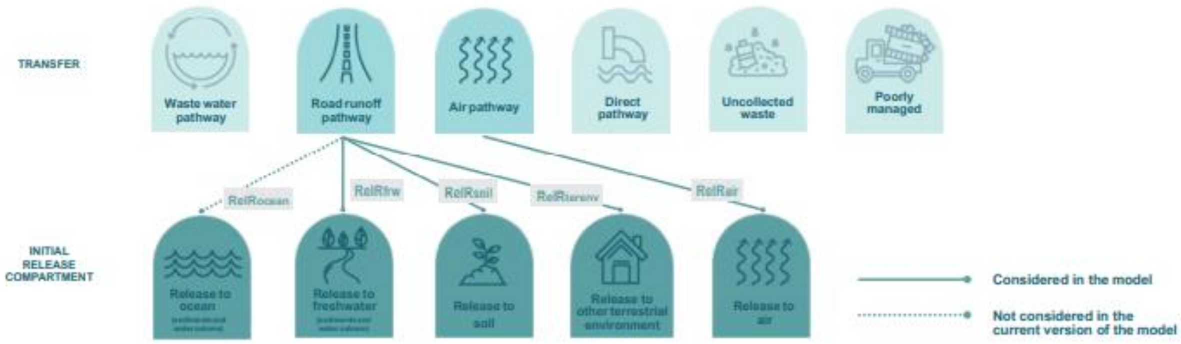

Figure 28: Release rates leading from the road runoff and air pathways to the initial release compartment for TRWP. Source: Peano et al.,2020.

Table 12: Initial release rates. Source: Peano et al., 2020.

ABbreviation	Description	Generic value [% of TRWP emitted], or [% of microplastic from tire abrasion]
$RelR_{oceans}$	Release rate of TRWP in ocean compartment	0%
$RelR_{air}$	Release rate of TRWP in air compartment	2%
$RelR_{frw}$	Release rate of TRWP in freshwater compartment	17%
$RelR_{soil}$	Release rate of TRWP in soil compartment	66%
$RelR_{terenv}$	Release rate of TRWP in other terrestrial compartments	2%
Well managed waste	Part of TRWP that is removed from the environment	14%

<u>Calculation rules for redistribution rates</u>

The equation to calculate the redistribution rate RedR$_{COMPARTMENT}$ is presented in *Figure 29* (Peano *et al.*, 2020) and summarized in the below table (*Table 13*).

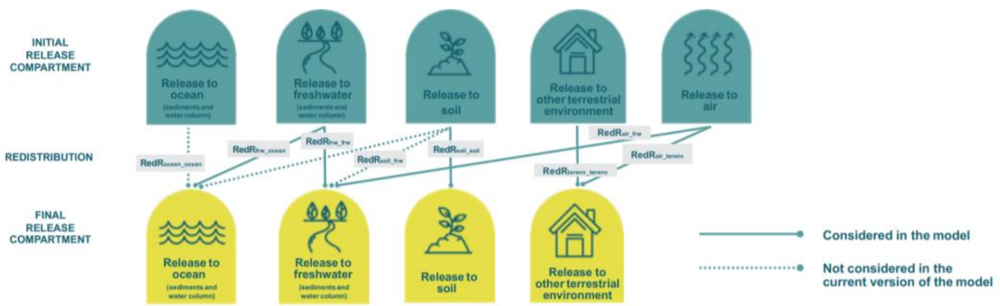

Figure 29: Redistribution rates for microplastics. Source: Peano et al., 2020.

Table 13: Redistribution rates for tire losses.

Abbreviation	Description	Generic value [% of microplastics redistributed]
$RedR_{OCEAN\_OCEAN}$	Redistribution to ocean of TRWP initially released to ocean	100%
$RedR_{FRW\_OCEAN}$	Redistribution to ocean of TRWP initially released to fresh water	1- $R_{FRESHED}$
$R_{FRESHED}$	Sedimentation rate	90%
$RedR_{FRW\_FRW}$	Redistribution to fresh water of TRWP initially released to fresh water	$R_{FRESHED}$
$RedR_{SOIL\_SOIL}$	Redistribution to soil of TRWP initially released to soil	100%
$RedR_{AIR\_TERENV}$	Redistribution to terrestrial environments of TRWP initially released to air	97%
$RedR_{AIR\_FRW}$	Redistribution to fresh water of TRWP initially released to air	3%
$RedR_{TERENV\_TERENV}$	Redistribution to ocean of TRWP initially released to terrestrial environments	100%

<u>Leakage and final release rates</u>

The leakage of microplastics to each compartment Leak $_{MICRO\text{-}COMPARTMENT}$ is ultimately calculated as the sum of the microplastic loss from tire abrasion (TotTireLoss), multiplied by the release rates (RelR) and the redistribution rates (RedR) in each specific environmental compartment, as seen in the following equations (2), (3), (4) and (5).

$$Leak_{MICRO-OCEANS} = \sum TotTireLoss * RelR_{FRW} * RedR_{FRW-OCEANS} \tag{2}$$

$$Leak_{MICRO-FRESH\ WATER} = \sum TotTireLoss * (RelR_{FRW} * RedR_{FRW-FRW} + RelR_{AIR} * RedR_{AIR-FRW}) \tag{3}$$

$$Leak_{MICRO-SOIL} = \sum MiPL * RelR_{SOIL} * RedR_{SOIL-SOIL} \tag{4}$$

$$Leak_{MICRO-TERENV} = \sum MiPL * (RelR_{TERENV} * RedR_{TERENV-TERENV} + RelR_{AIR} * RedR_{AIR-TERENV}) \tag{5}$$

To simplify the approach, the final release rates in the final environmental compartments ($FinalRelR_{COMPARTMENT}$), calculated as initial release rates (RelR) multiplied by the redistribution rates (RedR), can be directly applied to the loss from tire abrasion, and are presented in *Table 14*, data from PLP (Peano *et al.*, 2020). These final release rates are expressed as a percentage of the TRWP emitted.

Table 14: Final release rates.

Abbreviation	**Description**	**Generic value [% of TRWP emitted], or [% of microplastics from tire abrasion]**
$FinalRelR_{OCEAN}$	Final release rate of TRWP in ocean (sediments and water column) compartment	2%
$FinalRelR_{AIR}$	Final release rate of TRWP in air compartment	0%
$FinalRelR_{FRW}$	Final release rate of TRWP in freshwater (sediments and water column) compartment	15%
$FinalRelR_{SOIL}$	Final release rate of TRWP in soil compartment	66%
$FinalRelR_{TERRENV}$	Final release rate of TRWP in other terrestrial compartments	4%
Well managed waste	Part of TRWP that is removed from the environment	13%

3.1.2. MICROPLASTICS FROM PRODUCTION, USE AND RECYCLING

3.1.2.1. Assumptions

This chapter addresses the microplastic leakage due to the production, use and recycling of PET bottles in Germany. As explained above, these calculations are also carried out with the PLP guidelines (Peano *et al.*, 2020), from which *Section 9* applies.

For this purpose, it is necessary to establish the annual quantity of PET bottles in Germany, which, as estimated in *Table 2* from section *3.1*, is 1Mt.

The production chain of the product has been as well determined, as in *Figure 24*.

3.1.2.2. Calculations

Companies that produce plastic products use feedstocks of plastic materials which are melted and formed into plastic goods. These feedstock, or raw material, often consists of small pellets, defined as a "small mass of preformed molding material, having relatively uniform dimensions in a given lot, used as feedstock in molding and extrusion operations". It is recognized that pellets may be spilled and lost at any point in the plastics value chain: at compounders, masterbatch makers, distributors, resellers, storage locations, processors, recyclers, during waste management, at ports and when being transported between each of these points (Peano *et al.*, 2020).

Current research on pellet loss focuses on pellets entering drains at or near plastics facilities. *Figure 30* (Peano *et al.*, 2020) represents the general methodological principles to account for plastic leakage to the environment as applied to pellets.

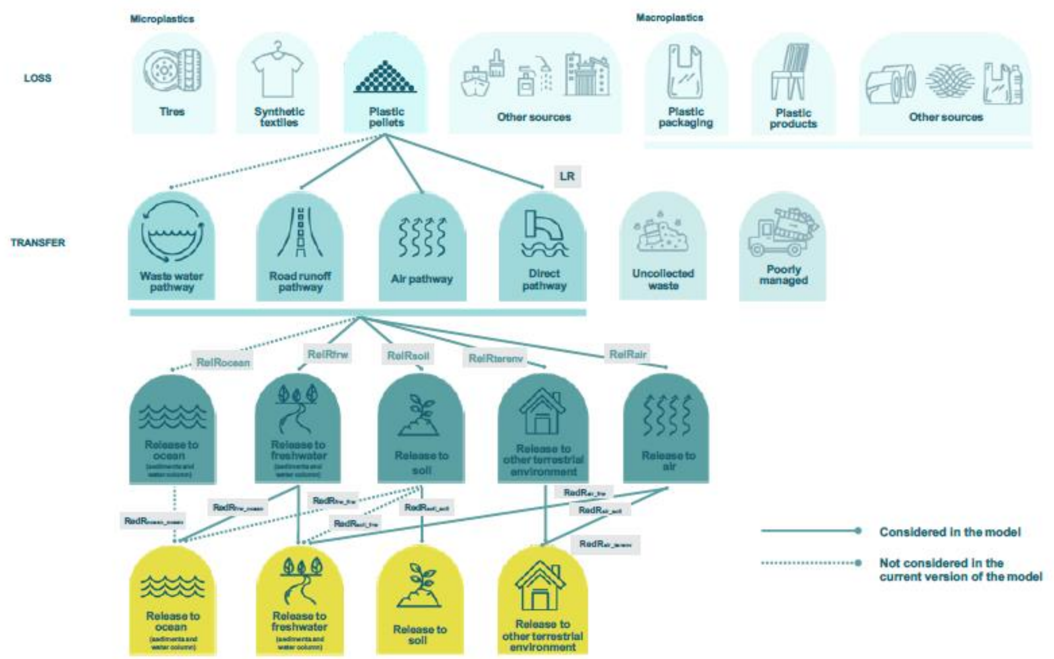

Figure 30: Losses, transfer pathways and plastic release compartments for pellets. Source: Peano et al., 2020.

<u>Calculation rules for loss rates</u>

Based on previous literature in this topic, the PLP report (Peano *et al.*, 2020) has estimated the leakage to the environment for each of the production stage. These values are shown in *Table*

15 (Peano *et al.*, 2020). By summing all the steps, it is derived the order for pellet loss to a range between 0,001% and 0,1%. Due to the high uncertainty, it is recommended to use the average value of 0,01%.

Table 15: Estimates of the losses of pre-production plastics. Source: Peano et al., 2020.

	Description	Loss rate/leakage in the environment	References
Production	Producers create polymers and extrude resin pellets from powders or liquids. Spills occur during handling, loading and unloading, as well as leakage from containers and storage silos.	0.01% - 0.04%	Lassen et al. (2015) Sundt et al. (2014) Cole and Sherrington (2016)
Transportation	Transport includes loading and unloading, accidental loss from railcars, trucks and shipping containers (due to unsuitable packaging, spills and so on) that transfer pellets from producers to processors. This estimate is based on an average transportation distance between the plastic pellets production plant and the plastic processing plant.	0.001%-0.002%	Hann et al. (2018),
Processing	Processors (or converters), which melt and remold plastic pellets (usually compounds) into final plastic products. Spills occur during handling, loading and unloading, as well as leakage from containers and storage silos.	0.01% - 0.04%	Lassen et al. (2015) Sundt et al. (2014) Cole and Sherrington (2016)
Waste management	Management of producers and processors' waste: pellet loss mostly occurs during storage for disposal when pellets are either disposed of with mixed residual waste or blown away from bins stored outside.	0.01% - 0.04%	Lassen et al. (2015) Sundt et al. (2014) Cole and Sherrington (2016)
Recycling	Recyclers, which sort, clean and process waste plastics (predominantly packaging) into recycled plastic pellets and compounds.	0.01% - 0.04%	Lassen et al. (2015) Sundt et al. (2014) Cole and Sherrington (2016)
Suppliers	Logistics suppliers, providing intermediary services to the stakeholders above, aside from transporters i.e., including warehousing, redistribution, packaging etc. These intermediary points are important as they represent additional stages at which pellets are handled and can therefore be lost.	0.01% - 0.04%	Lassen et al. (2015) Sundt et al. (2014) Cole and Sherrington (2016)

Therefore, for the entire production process, a pellet loss rate of 0,01% is used for the total quantity of bottles. In addition, the loss rate from recycling and waste management is applied for the amount of recycled bottles. Since this value ranges from 0,01% to 0,04%, as illustrated in *Table 15*, the average value of 0,025% is set.

<u>Calculation rules for release and redistribution rates</u>

Pellet losses are assumed to follow similar pathways to enter the environment as TRWP, so release and redistribution rates can be taken from the previous chapter, this is *Table 9* and *Table 10*. The only value that differs is the retention rate for freshwater sediments ($R_{FRESHED}$), estimated to be 30%.

The leakage calculation is the same as for TRWP, so the equations from section *3.1.1.2* apply.

3.2. MARINE PLASTICS IN INDONESIA

The present chapter addresses the calculation of plastic leakage due to PET bottles in Indonesia. As indicated earlier, the *Full Circle* report (GA Circular, 2019) is used as principal source of information for this section, as it approaches the topic in a comparable way.

As detailed throughout the section, the PLP guidelines are not implemented for this subject, due to the lack of sufficient information to carry out such a comprehensive assessment of this country. Nevertheless, with the findings of the source reports, an estimation of plastic leakage is made in order to get an overview of the situation and to be able to contrast it with previous results.

The structure to be implemented is as follows. Firstly, the assumptions are presented, drawn largely from information sources, and secondly, the underlying calculations are explained.

3.2.1. ASSUMPTIONS

To conduct this analysis, it is necessary to identify the amount of PET bottles that the country annually consumes, as well as the leakage ratio.

As explained previously, the *Full Circle* report (GA Circular, 2019) examines PET bottle consumption in nine cities belonging to six Southeast Asian countries: Indonesia, the Philippines, Vietnam, Thailand, Myanmar and Malaysia, as although these countries account for 3,8% of global PET bottle consumption, they are the source of 29% of global plastic leakage into the world's oceans. This research was completed in 2018, and predictions were made on how the scenario would develop in the future.

The total PET bottle market within the studied nations and its forecast for the upcoming years can be seen in *Figure 31* (GA Circular, 2019).

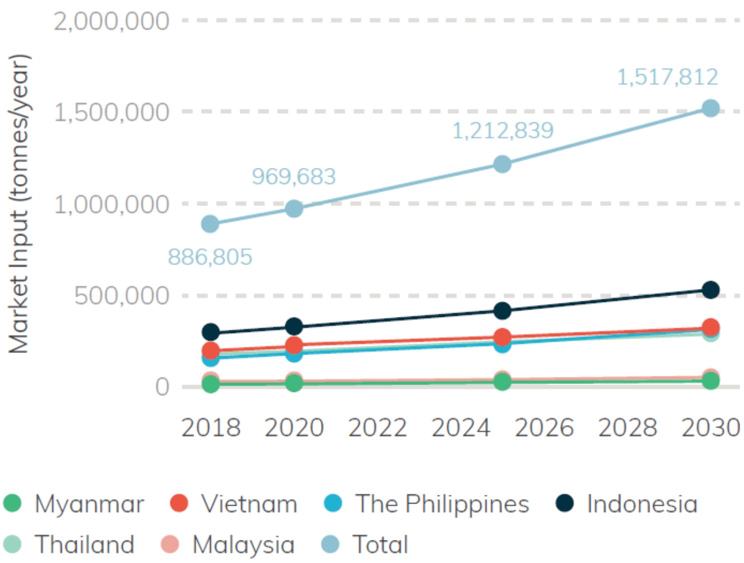

Figure 31: PET bottle market inputs across the six largest southeast Asian countries. Source: GA Circular, 2019.

From the source image, the PET bottle market input in Indonesia can be estimated to be 350000 tons per year (from 2018). Since the current project is considering a one litter 20g bottle as unit, this could be translated to 17500 million bottles. As the population in Indonesia is 264 million people (Statista, 2021b), it can be expressed as 66,3 bottles per person per year. *Table 16* shows these outcomes.

Table 16: Annual PET bottle demand in Indonesia.

Mass of PET bottles in Indonesia per year	Amount of PET bottles in Indonesia per year	Amount of PET bottles in Indonesia per person (264 million) per year
350000 tons	17500 M. bottles	66,3bot/per.

Regarding the leakage to the environment rate in the Southeast Asian countries, the *Full Circle* report (GA Circular, 2019) provides two different findings. The first one is the leakage rate in the studied cities, and the second one is the average rate in the whole countries. Although the second one is the valid one for the calculations, both are presented to show the difference between urban area and the whole nation.

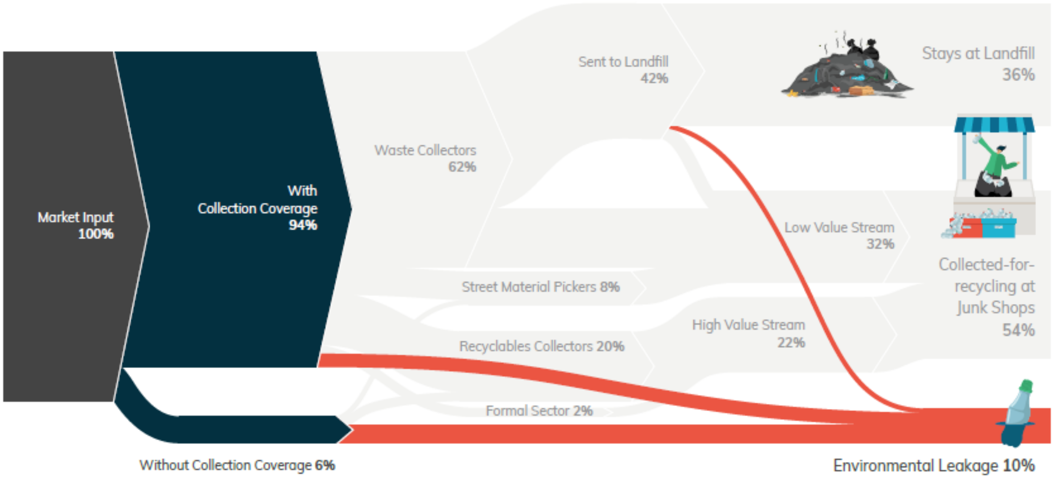

Figure 32: Environmental leakage in the nine Southeast Asian cities. Source: GA Circular, 2019.

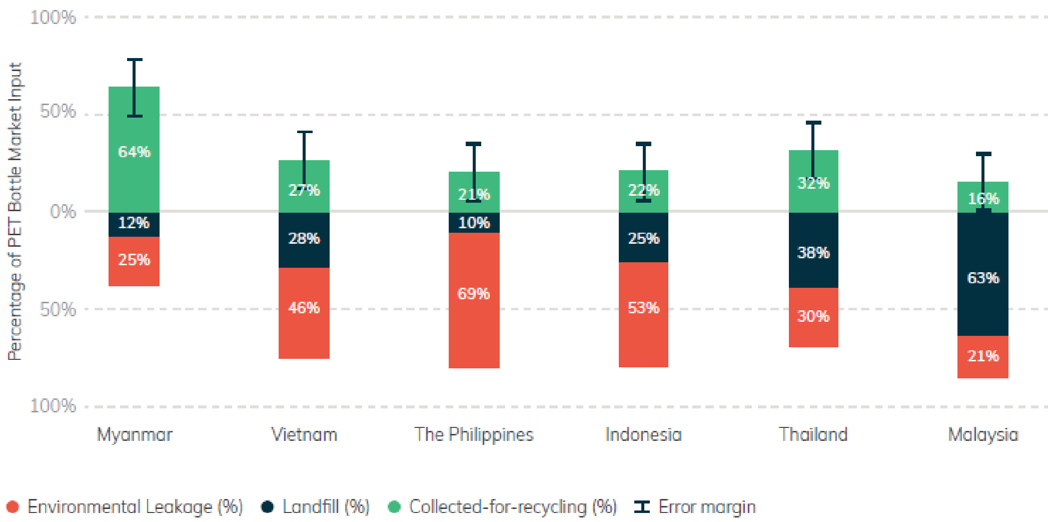

Figure 33: End destination of post-consumer PET bottles in six countries across Asia. Source: GA Circular, 2019.

As shown in *Figure 32* (GA Circular, 2019), the environmental leakage in the cities has a rate of 10%, in contrast with the average value for the whole country, shown in *Figure 33* (GA Circular, 2019), which is 53%, as the collected-for-recycling rate is significantly lower. These outcomes are summarized in *Table 17*.

Table 17: Average leakage rates in the cities and in the whole Indonesia.

Average leakage rate in the 9 studied cities	**Average leakage rate in Indonesia**
10%	53%

According to GA Circular in *Full Circle* report, environmental leakage is defined as "PET that is leaked into the environment, including streets, and waterways. This can happen as a result of littering or open dumping of waste". This means, macroplastics due to mismanaged waste have been considered. Nevertheless, all possible environmental compartments are accounted. To calculate the amount of leakage into the oceans out of the total environmental leakage due to mismanaged waste, the widely accepted value in the literature of 25% (Jambeck *et al.*, 2015) is applied.

Regarding the microplastic leakage due to PET bottles, there is a lack of sufficient data to carry out a complete assessment with tools such as the PLP guidelines. Nevertheless, in order to estimate them, the average global percentage from primary microplastics that end up in the oceans out of the total yearly plastic production has been assumed to apply.

From the global yearly plastic production of 415Mt, about 1,5Mt of primary microplastics end up in oceans (Peano *et al.*, 2020), as *Figure 34* (Peano *et al.*, 2020) shows. This average proportion could be translated to a 0,36% of microplastic leakage out of the total plastic production.

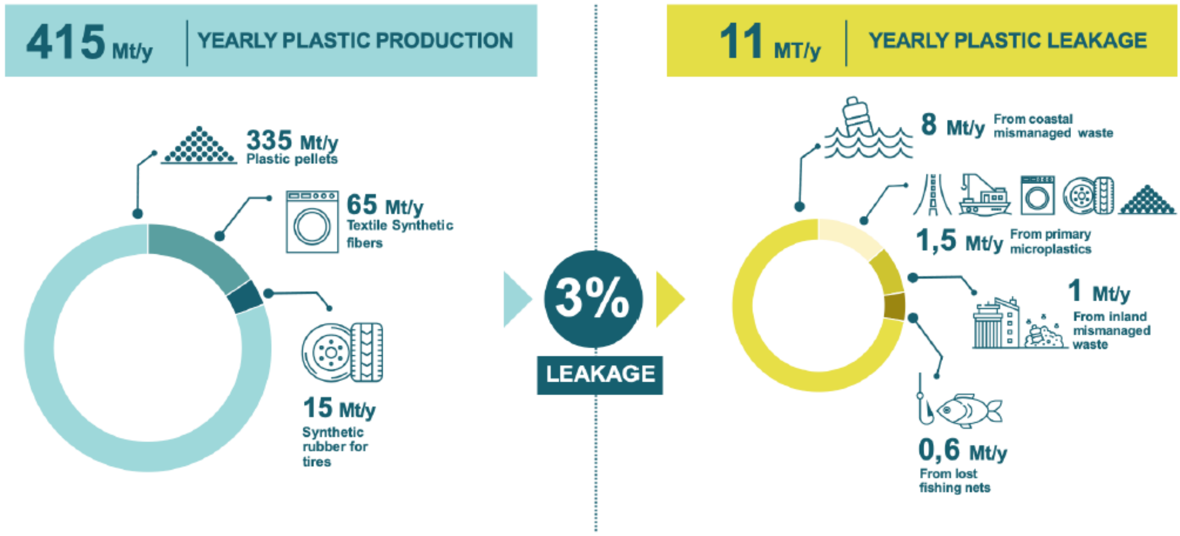

Figure 34: Plastic production and plastic leakage by source. Source: Peano et al., 2020.

Although it is recognized that this is not a highly precise way of measuring them, and that it is a limitation of the project, the greater part of plastic leakage in Indonesia is due to macroplastics, so the difference between an accurate and an approximate estimate of microplastics is not representative.

3.2.2. CALCULATIONS

As stated above, the PLP guidelines are not implemented for this section since there is insufficient information to perform accurate calculations. Instead, the previously mentioned percentages extracted from the *Full circle* (GA Circular, 2019) and from the *PLP* (Peano *et al.*, 2020) reports are applied to the total PET production per year in Indonesia, to get an overall picture of the plastic leakage situation in this country.

Regarding the rates that are used, the average leakage rate for Indonesia is applied for macroplastics, this is a 53%. For microplastics, the ratio of marine microplastics out of the total plastic production, which is 0,36%, is taken. Both percentages from section *3.2.1*.

4. RESULTS

The application of the methodology explained in the previous chapter with the corresponding assumptions, provides the plastic leakage from PET bottles in Germany and in Indonesia, presented in this section. The findings are given as the total leakage for each country, as well as the leakage per inhabitant, to allow a further comparison of the results.

4.1. MARINE PLASTICS IN GERMANY

The implementation of the PLP guidelines to the situation in Germany yields the microplastics leakage from transportation and from plastic production, use and recycling. The total plastic leakage is given in form of *Key Results*, of *Value Chain* and of *Country* perspectives, the mandatory approaches to display a plastic leakage assessment according to the PLP report.

4.1.1. MICROPLASTICS FROM TRANSPORTATION

The microplastics leakage due to tire abrasion during transportation from PET bottles in Germany is provided in *Table 18*. As considered environmental compartments include oceans, freshwater, soil, and other terrestrial compartments. In addition, the microplastic leakage per inhabitant, expressed in milligram (mg) per person is presented.

Table 18: Microplastics from transportation of PET bottles in Germany.

	Total microplastics in Germany due to tire losses	**Percentage out of total microplastics due to tire losses in Germany**	**Microplastics due to tire losses per person in Germany (83M.people)**
$TotTireLoss_{TRUCK}$	93987 Kg	100%	1132 mg/per.
Leak $_{MICRO\text{-}OCEANS}$	1598 Kg	1,7%	19 mg/per.
Leak $_{MICRO\text{-}FRESHWATER}$	14446 Kg	15,36%	174 mg/per.
Leak $_{MICRO\text{-}SOIL}$	62031 Kg	66%	747 mg/per.
Leak $_{MICRO\text{-}TERENV}$	3803 Kg	3,94%	46 mg/per.
Well managed	13158 Kg	14%	159 mg/per.

4.1.2. MICROPLASTICS FROM PRODUCTION, USE AND RECYCLING

Table 19 displays the microplastic leakage from the production and use of PET bottles in Germany. The same environmental compartments as for the transportation are considered, namely oceans, freshwater, soil, and other terrestrial compartments. The microplastics per person is also given.

Table 19: Microplastics from production and use of PET bottles in Germany.

	Total microplastics in Germany due to production and use	**Percentage out of total microplastics due to production and use in Germany**	**Microplastics due to production and use per person in Germany (83M.people)**
MiPL PRODUCTION	100000 Kg	100%	1205 mg/per.
Leak MICRO-OCEANS	11900 Kg	11,9%	143 mg/per.
Leak MICRO-FRESHWATER	5160 Kg	5,16%	62 mg/per.
Leak MICRO-SOIL	66000 Kg	66%	795 mg/per.
Leak MICRO-TERENV	3940 Kg	3,94%	47 mg/per.
Well managed	13000 Kg	13%	157 mg/per.

In addition, as also explained in the previous chapter, a pellet loss rate of 0,025% is applied to the 94% of recycled bottles, providing the corresponding microplastic leakage from recycling, as displayed in *Table 20*.

Table 20: Microplastics from recycling of PET bottles in Germany

	Total microplastics in Germany due to recycling	**Percentage out of total microplastics due to recycling in Germany**	**Microplastics due to recycling per person in Germany (83M.people)**
MiPL $_{PRODUCTION}$	235000 Kg	100%	2831 mg/per.
Leak $_{MICRO-OCEANS}$	27965 Kg	11,9%	337 mg/per.
Leak $_{MICRO-FRESHWATER}$	12126 Kg	5,16%	146 mg/per.
Leak $_{MICRO-SOIL}$	155100 Kg	66%	1868 mg/per.
Leak $_{MICRO-TERENV}$	9259 Kg	3,94%	112 mg/per.
Well managed	30550 Kg	13%	368 mg/per.

4.1.3. TOTAL PLASTIC LEAKAGE IN GERMANY

By adding the microplastics leakage due to transportation and due to the production, use and recycling, the total plastic leakage in Germany due to PET bottles is obtained, as it can be observed in *Table 21*. In *Table 22* these results are further presented per person.

Table 21: Total plastic leakage of PET bottles in Germany.

	Total microplastics in Germany	**Percentage due to transportation**	**Percentage due to production and use**	**Percentage due to recycling**
MiPL $_{TOTAL}$	428987 Kg	21,9%	23,3%	54,8%
Leak $_{MICRO-OCEANS}$	41463 Kg	3,9%	28,7%	67,4%
Leak $_{MICRO-FRESHWATER}$	31732 Kg	45,5%	16,3%	38,2%
Leak $_{MICRO-SOIL}$	283131 Kg	21,9%	23,3%	54,8%
Leak $_{MICRO-TERENV}$	17002 Kg	22,4%	23,1%	54,5%
Well managed	56708 Kg	23,2%	22,9%	53,9%

Table 22: Plastic leakage per person of PET bottles in Germany

	Total microplastics per person in Germany (83M.people)	**Percentage due to transportation**	**Percentage due to production and use**	**Percentage due to recycling**
MiPL TOTAL	5169 mg/per.	21,9%	23,3%	54,8%

These outcomes are provided below in the different mandatory perspectives.

Key results perspective

Figure 35 answers the question: *What is the total leakage along my value chain?*

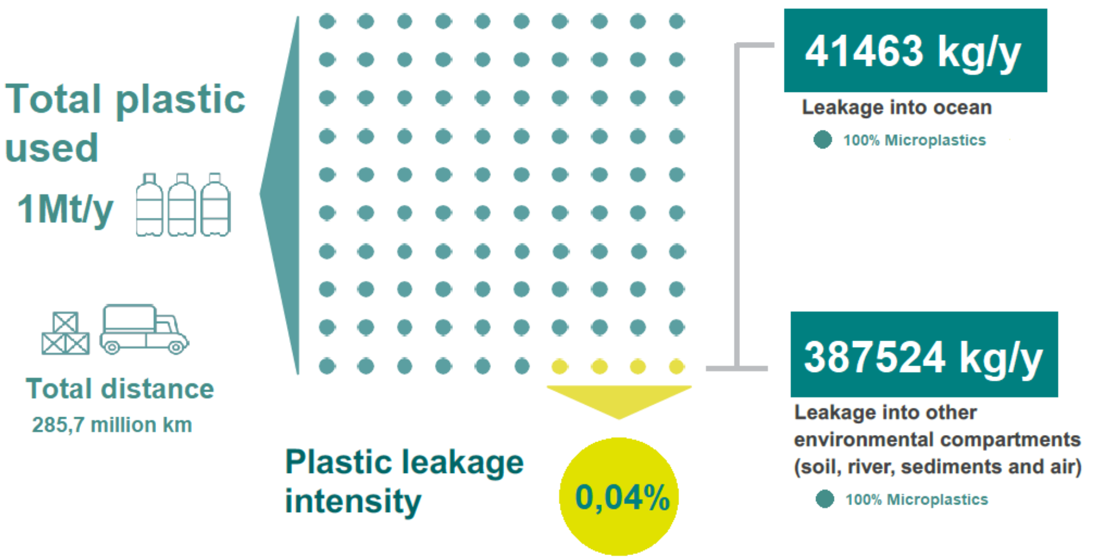

Figure 35: Total leakage in Germany under the key results perspective.

Supply chain perspective

Figure 36 answers the questions: *Where does the leakage occur along my value chain? In which environmental compartments?*

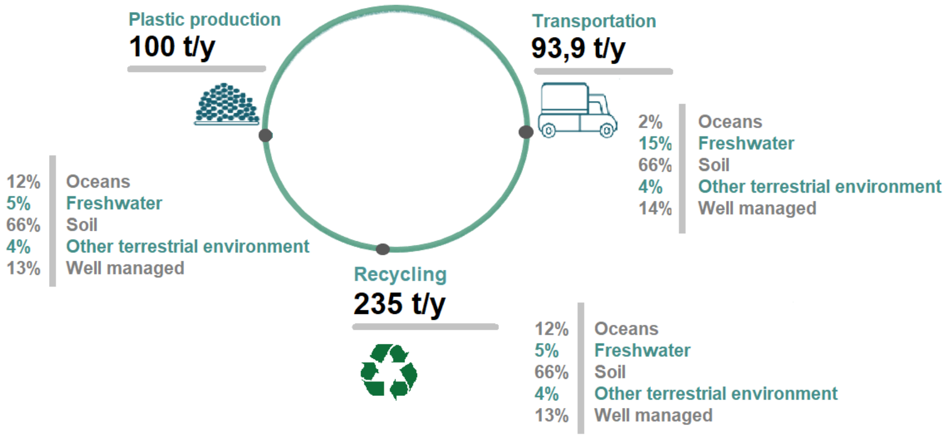

Figure 36: Leakage in Germany under the supply chain perspective.

Country perspective

Figure 37 answers the question: *In which country does the leakage occur?*

Figure 37: Leakage in Germany under the country perspective.

4.2. MARINE PLASTICS IN INDONESIA

The macroplastic leakage due to PET bottles in Indonesia, calculated by extracting the required information from previous related literature, is presented in *Table 23*. Both the total leakage and the leakage per inhabitant are given, as well as the plastic leakage intensity of the country. As environmental compartments, only the ocean is considered, due to the scope of this project. Furthermore, *Table 24* presents the microplastic leakage to the oceans from the analyzed product.

Table 23: Macroplastic leakage due to PET bottles in Indonesia.

	Macroplastic leakage in Indonesia due to mismanaged waste	**Macroplastics due to mismanaged waste per person in Indonesia (264 M. people)**	**Leakage in Indonesia out of the total PET production (Plastic leakage intensity)**
Total leakage	185500 Ton	0,7 kg/per.	53%
Leakage to the ocean	46375 Ton	0,17 Kg/per.	13,25%

Table 24: Microplastic leakage due to PET bottles in Indonesia.

	Microplastic leakage in Indonesia	**Microplastics per person in Indonesia (264 M. people)**
Leakage to the ocean	1260 Ton	4773 mg/per.

4.3. ALTERNATIVES TO REUSE MARINE PLASTIC LITTER

Due to the multiple benefits of plastic, its consumption is increasing day by day, which causes an enormous rise in plastic waste. When incorrectly disposed, plastic can perdure in the environment for hundreds of years, polluting soils, air, and water. Toxic substances settle on the crops and in waterways where they eventually enter the food chain and hence the body system. These released particles act as carcinogens and mutagens, posing a threat to vegetation, human and animal health and environment as a whole (Verma *et al.*, 2016). This toxicity and lack of biodegradability require an effective waste management solution.

Nowadays, there is a global challenge confronting the efficient municipal solid waste (MSW) management. The growing accumulation of these debris' materials, leading to inadequate waste management, has led to a series of environmental concerns, such as the regular emission of greenhouse gases and a scarcity of available space for their disposal. These problems have generated alarming public concern, leading to policy legislation aimed at minimizing the amount of waste entering the environment (Idumah and Nwuzor, 2019).

This chapter aims to explore the different alternatives for the management of plastic waste, as well as their benefits and drawbacks.

Different technologies

Recycling has been defined as waste recovery and material reprocessing into viable products which entirely differ from their original status. The final output obtained from the different techniques has allowed the distinction between the different plastic recycling techniques (Idumah and Nwuzor 2019). As it can be seen in *Figure 38* (Idumah and Nwuzor, 2019), plastic recycling could be classified into four main categories including re extrusion (Primary), mechanical (Secondary), chemical (Tertiary) and energy recovery (Quaternary). Each methodology offers peculiar benefits placing it at advantage for specific requirements, needs or applications.

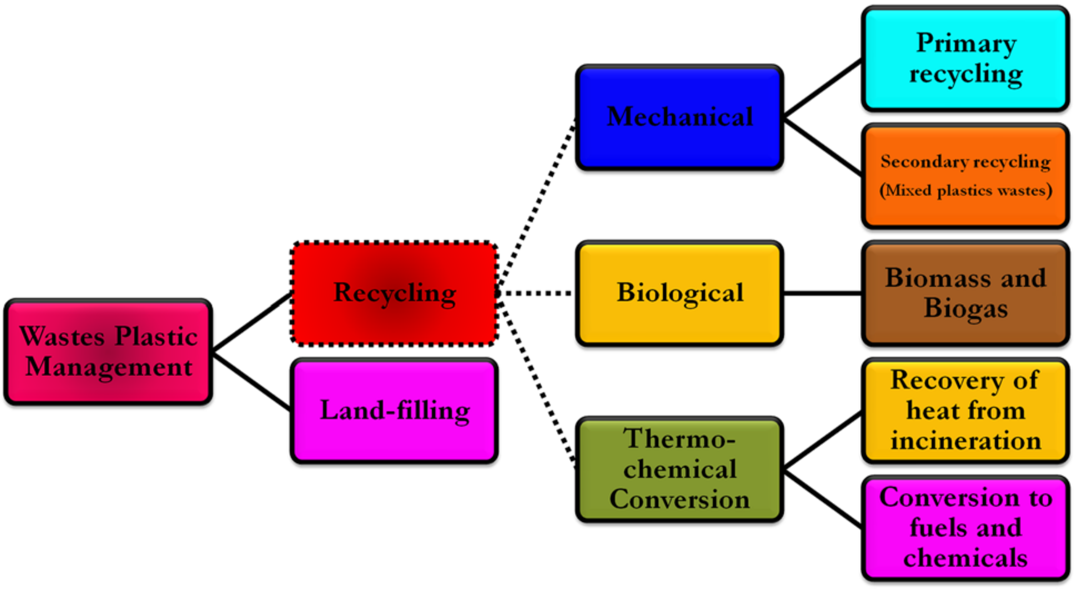

Figure 38: Waste Plastic Management categories. Source: Idumah and Nwuzor, 2019.

Landfilling, the traditional approach, involves waste dumping into the environment. It constitutes a high risk on animal and human health and creates environmental contamination problems, such as groundwater pollution, sanitary issues and so on (Idumah and Nwuzor, 2019). The sustainability aspect is another drawback, as no material is recovered again. The dumping of waste plastic in open areas is however the most commonly used waste disposal method in developing countries (Awasthi, Shivashankar and Majumder, 2017).

Primary recycling involves the manufacturing of products whose performance attributes are equivalent to those fabricated utilizing the pristine plastics. It implies the re-introduction of scrap, industrial or single polymer plastic edges, and parts to extrusion cycle in order to produce goods of similar material and hence, comparable properties of the original (Awasthi, Shivashankar and Majumder, 2017).

In secondary recycling, the plastic derived is used in products requiring fewer pressing attributes, in comparison with original material usage (Idumah and Nwuzor, 2019). This process entails physical modification, as solid plastic debris is recovered and re-used in mechanical means. Mechanical recycling requires separation, washing and preparation of the waste to produce high quality, homogenous and clean products. Separation of plastic waste items has been identified as the most relevant part in this procedure. The identification of the different plastic waste must be done within a short time. It may be manual or automated. As separation techniques, following stand out:

- By different density.
- Triboelectric separator, in which the differentiation between two plastic items is carried out by rubbing them into each other. This way, one material becomes positively and the other becomes negatively charged or neutral.
- High speed accelerator, which delaminates shredded waste and separates the delaminated material by air classification, sieves, and electrostatics.

A big challenge by mechanical recycling is the removal of the paint coating on plastics. To perform it, there are several ways such as grinding, abrasion or solvent stripping. The latter involves the dipping of the coated plastic into solvents, and posterior peeling coatings.

This widely used method, however, presents some limitations relative to the high cost of labor needed during the separation procedure, also resulting in the contamination of water, which in turn minimized the sustainability of the process. Consequently, researchers diverted towards other alternatives of energy recovery to compensate the high degree of energy demand (Awasthi, Shivashankar and Majumder, 2017; Idumah and Nwuzor, 2019).

In chemical or tertiary recycling, the waste plastic is utilized as feedstock in the process generating the chemicals and fuels. Since plastics come from petroleum, the end-product derived from the chemical recycling has been considered to have such high calorific value that could be used as an alternative fuel (Sharuddin *et al.*, 2018). The technology behind is the conversion through polymerization processes plastic items into smaller molecules, typically liquids or gases, providing high product quality and minimum waste. PET and polyamide are two good examples of suitable plastics for this application. These polymers can be depolymerized to reproduce monomers, and then polymerized again to form the new polymer (Awasthi, Shivashankar and Majumder, 2017; Idumah and Nwuzor, 2019).

Three techniques can be used in chemical recycling, as seen in *Figure 39* (Idumah and Nwuzor, 2019).

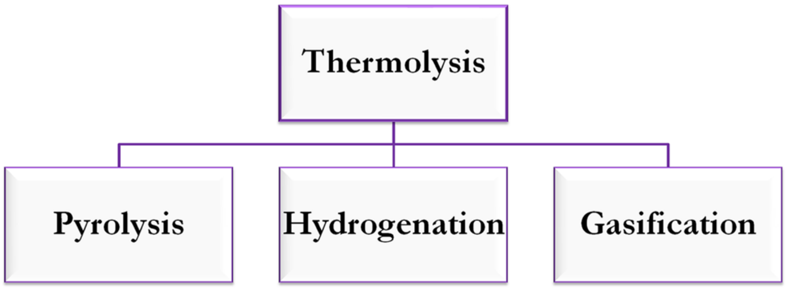

Figure 39: Chemical recycling techniques. Source: Idumah and Nwuzor, 2019.

- Pyrolysis is a thermochemical treatment in which plastic is heated in absence of oxygen until plastic waste decomposes. Due to thermal instability of organic compounds, pyrolysis results in a combination of thermal cracking and condensation reactions which finally produce generation of numerous solid, liquids, and gaseous fractions. Temperatures can range from 400ºC to 650ºC, and whereas at low temperatures more viscous liquids are obtained, at high temperatures small gas molecules result.

  The essential steps of pyrolysis include the following, as *Figure 40* (Patni *et al.*, 2013) shows.

  1. Uniform plastic heating over a limited temperature range avoiding significant temperature fluctuations.
  2. Purging oxygen from pyrolysis chamber.
  3. Dealing with the carbon by-product before it behaves as a thermal insulator and reduces the heat exchange to the plastic.
  4. Careful condensation and fractionation of the pyrolysis steams to obtain a high quality and consistent distillate.

  (Patni *et al.*, 2013)

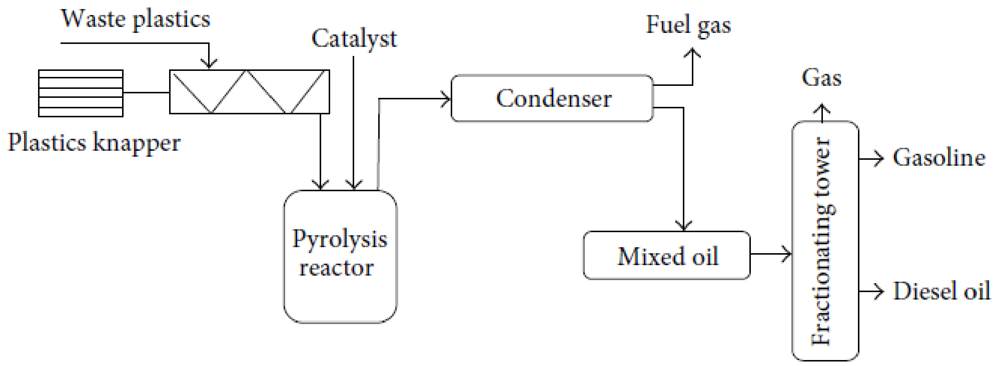

Figure 40: Essential steps of pyrolysis. Source: Patni et al., 2013.

This process is effective in producing valuable hydrocarbons and has achieved visibility for its cumulative benefits in regard to environmental pollution and reduction of carbon footprint of plastics by decreasing carbon monoxide and carbon dioxide emissions (Awasthi, Shivashankar and Majumder, 2017; Idumah and Nwuzor, 2019).

Literature provides evidence that the physical properties of the end products from pyrolysis are very similar to those of the commercial gasoline and diesel. It is also a technique which offers flexibility in terms of product preference by adjusting the parameters involved. With this method, the waste management becomes more efficient, less landfill is required, less contamination and it is more economic. The dependency of fossil fuel as the non-renewable energy can also be decreased, solving the rise in energy demand (Sharuddin *et al.*, 2018).

- Gasification involves the thermochemical treatment of plastic waste through air, converting material into gaseous product which contain carbon di oxide, carbon monoxide, and hydrogen and methane gas. The main advantage of this process is that by using air, it becomes a simpler and more cost-effective alternative. Nevertheless, due to the presence of nitrogen in air, the calorific value of resulting fuels due to dilution of fuel gases could be reduced. This technique has been applied together with biomass, deriving into fuel gases used for heating, lightening and power generation (Awasthi, Shivashankar and Majumder, 2017).
- Hydrogenation consists of the addition of hydrogen by a chemical reaction. Recycling of plastic waste by addition of hydrogen is applied in the liquefaction of coal and converted into naphtha and oil gas. The main end products resulting from plastic waste hydrogenation are hydrochloric acid, halogenated solid residue and gas (Awasthi,

Shivashankar and Majumder, 2017).

Quaternary recycling or energy recovery involves the oxidation of the material, producing electricity, heat, and power. The conversion of waste materials to energy could be also be achieved through biological processes such as anaerobic digestion (Awasthi, Shivashankar and Majumder, 2017).

Traditionally, in order to reduce waste volume, it has been burned inappropriately, causing large amounts of bottom ash and several toxic pollutants. These released components include hazardous halogens for human health with severe consequences such as risk of heart disease, respiratory problems such as asthma, damaging the nervous system, and so on (Verma *et al.*, 2016).

Nevertheless, burning in a properly designed and operation condition via the incineration process can be an efficient route of reducing plastic waste. This combustion must be complete so that approximately 90% of plastic material is reduced to carbonic acid, carbon dioxide (CO_2) and water and issues such as carbon monoxide (CO) emission and smoke are avoided (Verma *et al.*, 2016).

With energy recovery procedures benefits such as the waste volume minimization, less need of landfill, destruction of toxic wastes and electricity generation arise. Carrying out this process through gasification has been determined as the superior process of combustion, as it provides higher amount of electricity at lower cost and fewer CO_2 emissions (Idumah and Nwuzor, 2019).

A further point is the fact that, compared to material recycling and biological treatment, incineration units are robust in regard to the quality of the waste. The installations are equipped to deal with bulky and heterogeneous waste. Although some costs such as cleaning equipment are higher, the revenues from the energy sold are supported by a waste fuel reception rate (Eriksson and Finnveden, 2009).

Figure 41 (PlasticsEurope, 2018) schematically shows the plastic production and waste management cycle.

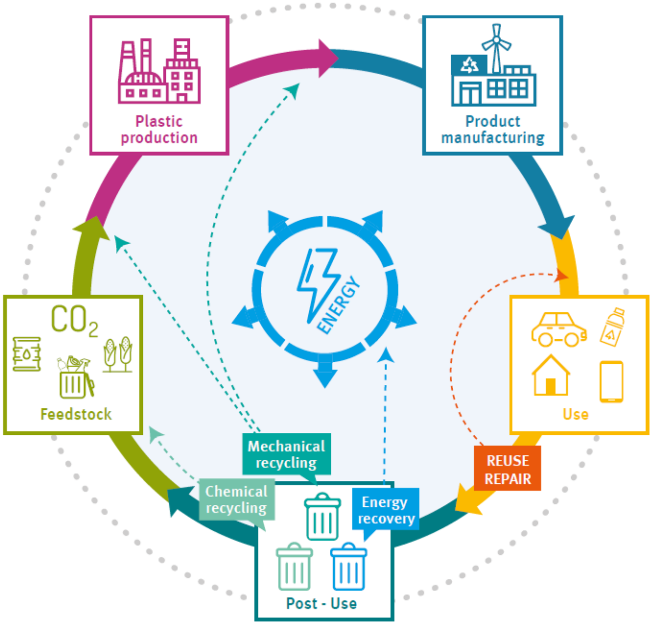

Figure 41: Plastic production and waste management cycle. Source: PlasticsEurope, 2018.

<u>Assessment and selection criteria</u>

The Waste Framework Directive (WFD) has established a waste hierarchy on which waste policies within the European Union as well as in many other countries, are based (Bernardo, Simões and Pinto, 2016). It is the following, as also seen in *Figure 42* (Idumah and Nwuzor, 2019).

1. Waste prevention and reduction
2. Re-use of products
3. Recycling of material (either mechanical or feedstock)
4. Recovery of energy
5. Final disposal

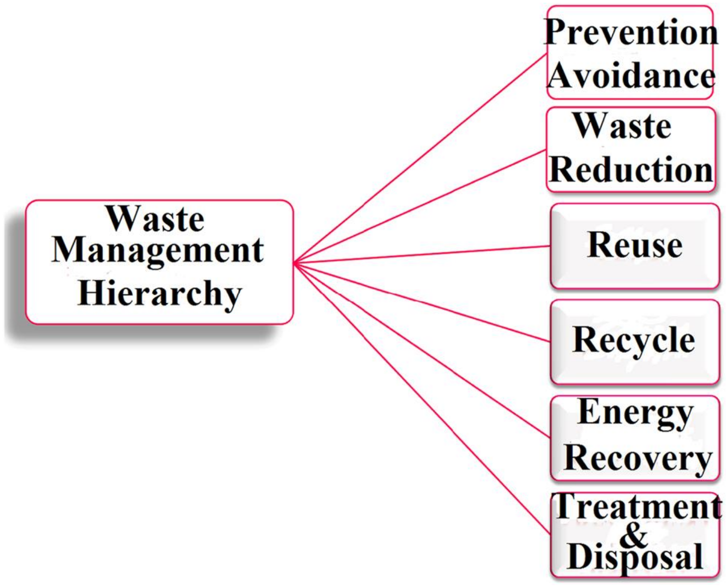

Figure 42: Waste management hierarchy. Source: Idumah and Nwuzor, 2019.

Waste prevention is stated to be best alternative. Through efficient product designing, manufacturing, and packaging, effective waste source minimization is achieved. Product reutilization or primary recycling, when feasible, is preferred to recycling because the product does not require reprocessing. Recycling is determined better to energy recovery processes and landfilling disposal is the least desirable alternative (Idumah and Nwuzor, 2019).

Several LCA have been applied to evaluate the different waste management methodologies, with robust results which show that mechanical recycling has the lowest environmental impacts (Bernardo, Simões and Pinto, 2016).

Nevertheless, as previously mentioned, this procedure has several drawbacks, and it may not be always possible to carry out. Hence, an Integrated Waste Management system (IWM) becomes imperative. This concept incorporates feasible waste management schemes through combination of several techniques. The aim is to attain environmental advantages, economic optimization and social acceptance (Idumah and Nwuzor, 2019). *Figure 43* (Idumah and Nwuzor, 2019) shows the different activities in IWM.

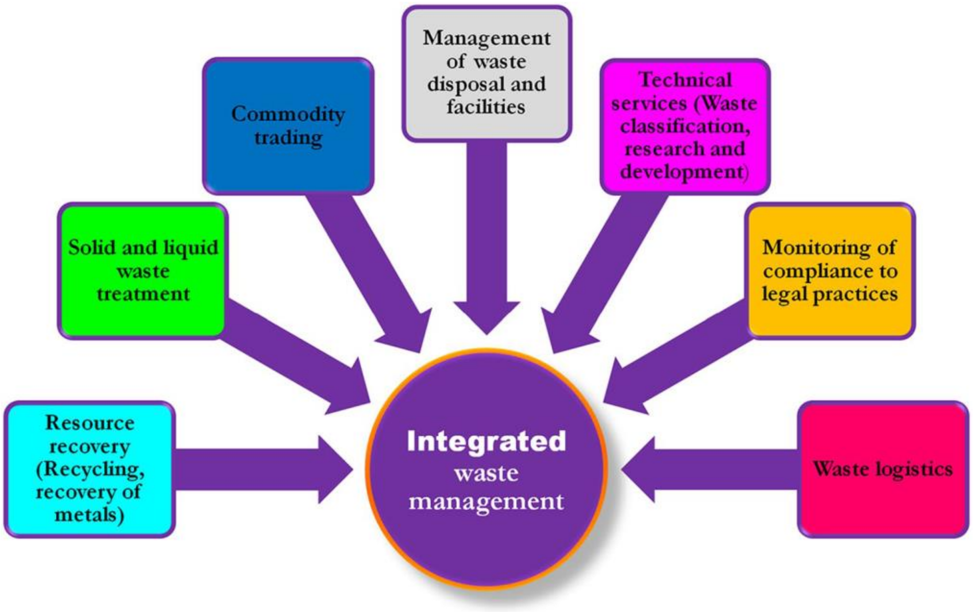

Figure 43: Integrated Waste Management activities. Source: Idumah and Nwuzor, 2019.

Current waste management situation

In 2018, 29,1 million tons of plastic waste were collected in Europe in order to be treated. Plastic waste exports outside the EU have decreased by 39% from 2016 to 2018 (PlasticsEurope, 2020). As it can be seen in *Figure 44* (PlasticsEurope, 2020), from collected plastic in that year, 42,6% was incinerated, 32,5% was recycled and 24,9% disposed to landfill.

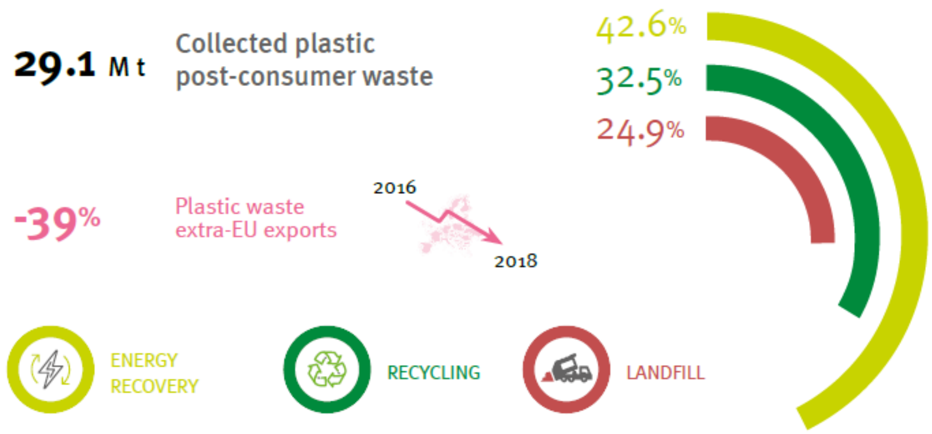

Figure 44: Collected plastic waste management in Europe. Source: PlasticsEurope, 2020.

In 2018, 5,3 million tons of plastic post-consumer waste were officially collected in Germany to be managed (PlasticsEurope, 2020). As *Figure 45* (PlasticsEurope, 2020) shows, 38,6% was recycled (both mechanical and chemical), 60,7% treated by energy and 0,6% landfilled.

The evolution between 2006 and 2018 of plastic waste treatment can also be observed, showing an increase in recycling and incineration and a decrease in landfill disposal.

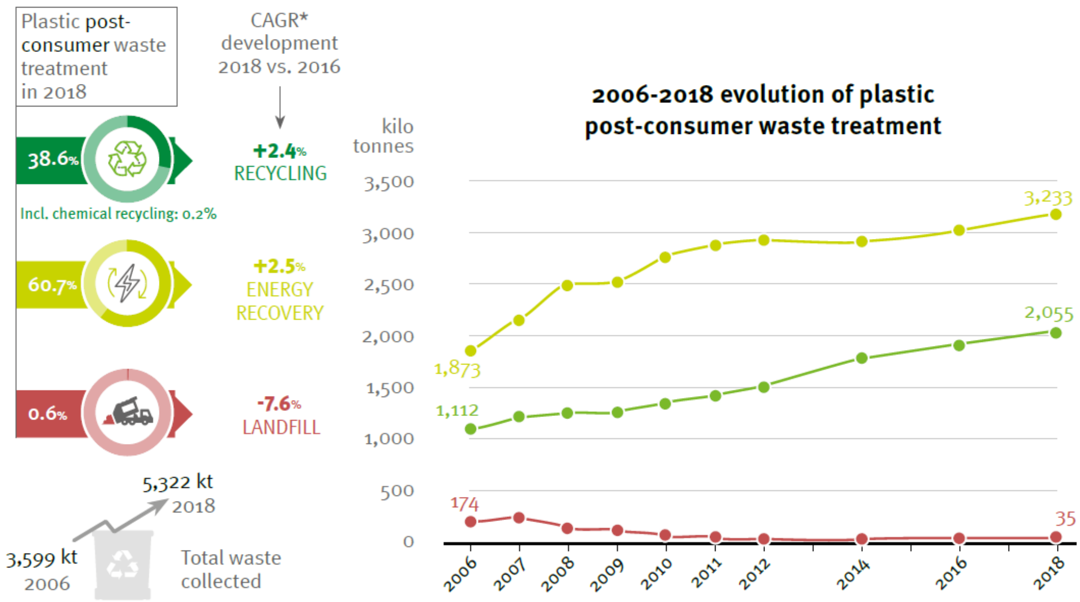

Figure 45: Collected plastic waste management in Germany. Source: PlasticsEurope, 2020.

Regarding the Asian waste management situation, as in section *2.1.4* explained, the following six South East Asian nations: Indonesia, the Philippines, Vietnam, Thailand, Myanmar, and Malaysia, which together account for a total population of over 600 million people (higher than the whole European population), are responsible for the 29% of the global plastic leakage into the oceans. Across these countries, the estimated average collected-for-recycling rate is 26%, with another 26% going to landfills and the remaining 48% leaking into the environment (GA Circular, 2019).

<u>Plastic waste utilization in other applications</u>

Plastic waste formed for high grade resins has been recycled into several products such as automotive parts, home appliances, textiles, and films.

Three innovative options to recycle plastic waste have been explored: application in concrete, in the textile industry and the construction of PET bottle houses.

An innovative alternative which has been studied is the incorporation of recycled plastic resins into concrete. Concrete is made up from coarse and fine aggregates, cement, and water. It is one of the most prevalent construction materials due to the low cost of production.

Traditionally, it presents several weaknesses like crack propagation and low tensile strength if no appropriate preconditioner takes place. Hence, an aggregate mix is required to improve its qualities. It has been studied that by introducing recycled plastic waste as an aggregate, physical properties such as compressive strength, dimensional stability, and durability can be enhanced. Thus, the application of plastic debris in concrete can contribute meaningfully toward a more sustainable and integral construction industry (Kamaruddin *et al.*, 2017).

Among all plastics, PET is the most widely recycled in the world. Eco-friendly goods obtained by PET recycling are mainly used as textile fibers, in which recycled PET (r-PET) is used to generate a cotton blended ring and compact yarns. *Figure 46* (Sarioğlu and Kaynak, 2018) shows the global annual r-PET market volume by end-use in 2016.

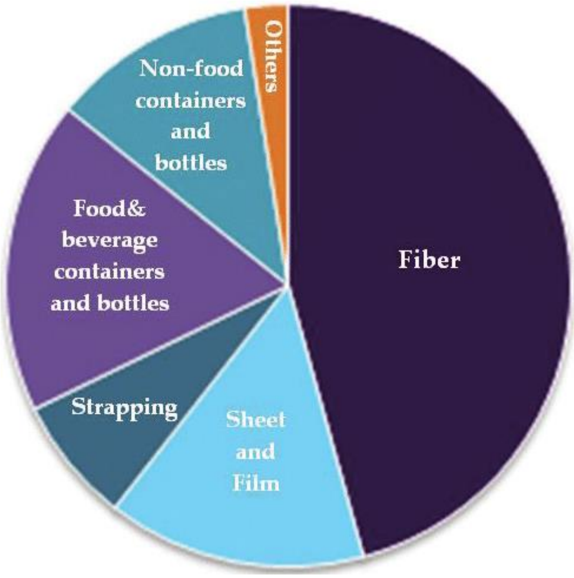

Figure 46: Global annual r-PET market volume in 2016. Source: Sarioğlu and Kaynak, 2018.

There are various attempts of textile brands using r-PET to fulfill their social responsibility in regards with sustainability. Several studies explore the benefits of including these fibers to the clothing, concluding that r-PET has a significant economic advantage and enough potential to be applied in the textile industry Sarioğlu and Kaynak, 2018. Another technology that has been applied is the development of low-cost housing solutions in developing countries. The procedure to follow is the following.

- PET bottles collection from garbage.
- Pack the bottles with sand or mud and cap.
- These sand- or mud-filled bottles work like construction bricks.
- Lay down foundation with bottle bricks and concrete.

- Frame windows and door of wood or iron.
- Position of beams for holding roof and roofing with cemented sheet.
- Fit solar bomb on the roof for light source.
- Level off the floor with brick bottles.
- Plaster inner and outer wall.

Figure 47 (IRP India, 2013) shows a construction out of this technique.

Figure 47: PET Bottle construction. Source: IRP India 2013.

These low-cost houses are equally as strong as brick ones. The numerous benefits of this alternative include environmental protection, low price, job creation, long-lasting, and energy efficiency, among others. Hence, it could be used as an effective solution for the PET reduction in developing countries, where the plastic waste management is a challenging issue as recycling methods are not very present (IRP India, 2013).

5. DISCUSSION

Given that it has been the first time that the PLP guidelines have been applied to a product such as PET bottles and at national level in Germany, the aim of this thesis is both to provide tangible results that can guide policy makers and the scientific community in the tackling of plastic pollution and to present a calculation pathway that can be transferred to further plastic products as well as to other countries.

In order to identify where policies should be focused, the results of the plastic leakage calculation from PET bottles have been analyzed, revealing significantly contrasting results for each country. For Germany, where only microplastics have been accounted, a plastic leakage intensity of 0,04% has been estimated. Although this value would not appear to be particularly high, it implies an annual leakage to the oceans of approximately 42 Ton, and to other environmental compartments of approximately 388 Ton. Expressing the plastic leakage per inhabitant, about 5 grams per person are released to the environment from PET bottles in Germany. Approximately 10% of the plastic leakages to the environment end up in the oceans, as it can be seen in *Figure 48*. Furthermore, the results show that approximately 13% of microplastics are being removed from the environment, which suggests that the management of this waste is already occurring and improving this rate should be a target.

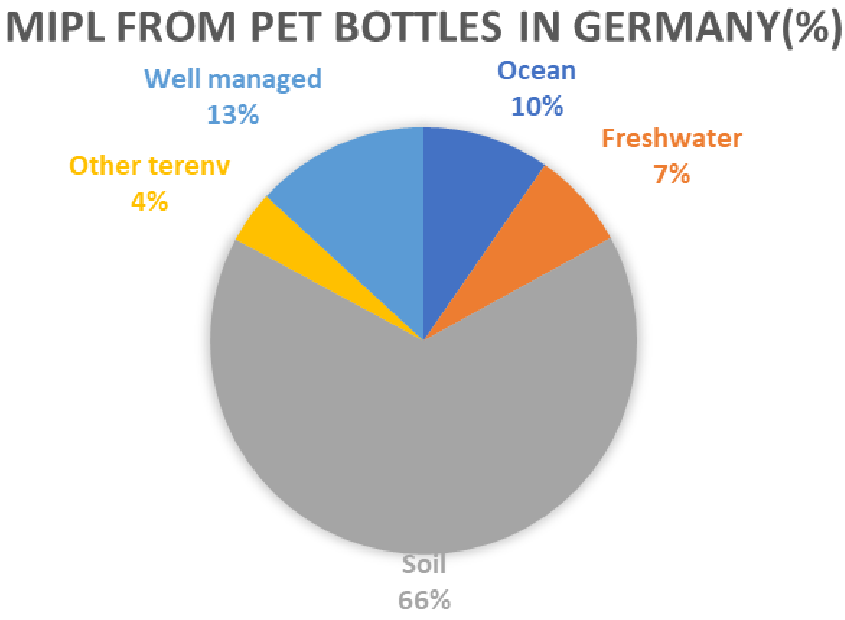

Figure 48: Microplastics from PET bottles in Germany. Environmental compartments.

From these findings it can be inferred that although plastic waste management in Germany performs rather efficiently, as no leakage of macroplastics is reported, measures to reduce the amount of microplastics released into the environment are still required. To consider where these measures should focus, the different leakage contributions have been analyzed. *Figure 49* shows the different microplastics hotspots during the life cycle of the product, showing that the recycling stage is where most leakage occur. Therefore, improving recycling methods should be the priority. Moreover, both the transportation and plastic production stages are responsible for a considerable amount of plastic losses, and therefore both reducing the amount of travelled distance and achieving more efficient plastic production process are relevant measures which should be considered to improve the current situation.

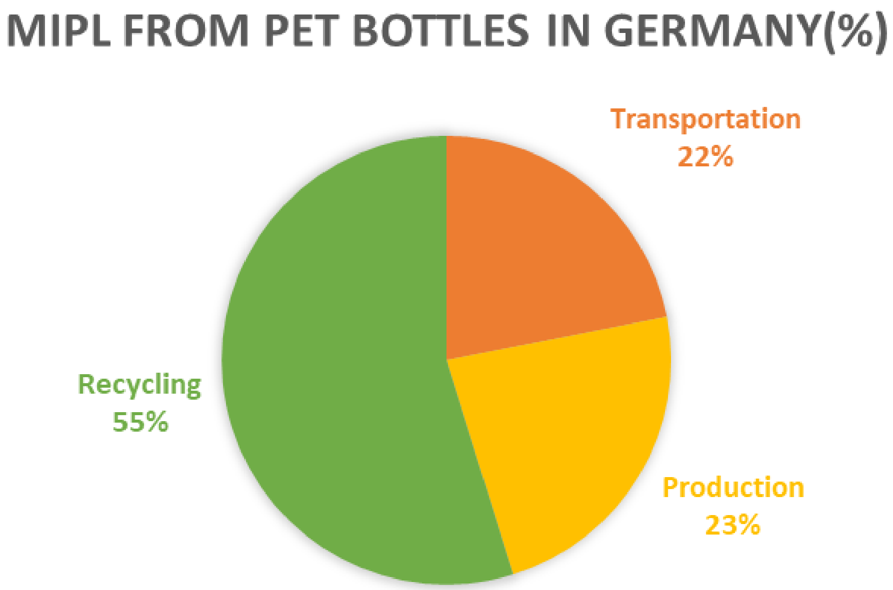

Figure 49: Microplastics from PET bottles in Germany. Different contributions.

Germany has been taken as a reference for the study as it is the major plastic-consuming country in Europe and therefore extrapolating these results to the continental level would be sensible.

In Indonesia, on the other hand, the results of the study reveal very different data. In a developing country where waste management remains one of the biggest challenges, the annual leakage of macroplastics due to PET bottles is 185500 tons into the environment and 46375 tons into the oceans. Regarding microplastics, about 1260 t are estimated to enter the oceans annually. This means, approximately 97% of the whole leakage comes from mismanaged waste, as displayed in *Figure 50*.

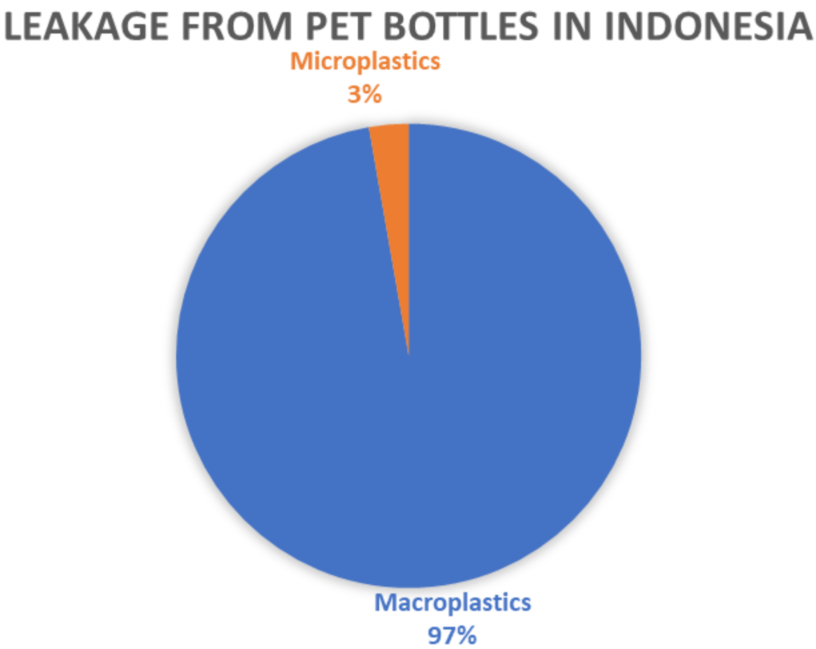

Figure 50: Plastic leakage from PET bottles in Indonesia

The plastic leakage intensity in this country is 53%. Looking at the per capita values, it appears that per person in Indonesia 0,7 kg of macroplastics are released into the environment, 0,17 kg of macroplastics end up in the oceans and about 4 grams of microplastics end up in the oceans.

Therefore, policies in Indonesia which focus on a proper management of plastic debris should be the priority. Nevertheless, given that Indonesia is one of the top 10 contributors to marine plastics in the world, this should be considered not only a national but also a global issue.

Regarding the comparison of the methodologies, the PLP Guidelines provides a much more complete, exhaustive analysis. As results are given in terms of inventory, it is useful to measure the scale of the problem. Nevertheless, data obtention for the case of Indonesia was a challenge and therefore it was decided to compute the leakage in an alternative way.

Furthermore, different alternatives to reuse marine plastic litter have been studied, since although the minimization of leaks is necessary, the current amount of plastic waste in the oceans and other environmental compartments is of such dimensions that its management becomes extremely relevant.

It has been observed that although traditional methodologies to treat plastic debris such as recycling have always been considered as the preferred options, innovative methods such as pyrolysis, which convert plastic waste in fuel, provide good solutions when mechanical recycling is not feasible. Moreover, incineration process with energy recovery with techniques such as gasification, that reduce the CO2 emissions, is another good way to get rid of plastic waste and convert the inner calorific value of plastics into usable electricity. It has been seen that each of these techniques has its benefits and cons, and therefore, an integrated system with all these technologies would be the optimal solution.

In addition, innovative recycling methods, such as the application of recycled PET fibers into clothing or reinforcement of pavements, and the construction of PET bottle houses in developing countries, have been explored.

Nevertheless, the current work presents several limitations due to the scope of the project.

Regarding the implementation of the PLP guidelines to Germany, the following assumptions to simplify the problem have been taken. First, the whole supply chain is considered to take place in this country and no bottle importation is accounted, as the PET bottle demand is assumed to be equal to the production. It is known that it is much more complex, but in order to provide the results at national level, this simplification had to be taken. In addition, no macroplastic from PET bottles is considered. Although evidence shows that plastic waste due to packaging in Germany is very low, other related plastics (such as the films that carry several bottles), have not been accounted and constitute an indirect source of waste due to the bottles. Moreover, the microplastic leakage due to incineration, which is known to contribute to a significant part of leakage, has not been considered for lack of reliable data. In addition, the bottle filling is assumed to be water to facilitate the calculations, knowing that it is not always the case.

Regarding the study of Indonesia, it has been taken in a general level in order to provide an insight of the scale problem, but the accuracy of the results is not as high as the previous analysis. In addition, the microplastics of this country have been accounted with the average global microplastic ratio due to lack of data. A further implementation of the PLP guidelines at this country is therefore recommended.

This project has thus provided an approach to the problem and a roadmap to follow, but due to its scope and limitations, a more in-depth study of the situation is called for.

6. CONCLUSION AND OUTLOOK

The initial aim of the present project was to examine the marine plastic litter scenario in Germany. Gaps and research needs related to the topic were analyzed and it was decided to contribute a new approach to the literature. For this purpose, an inventory analysis was used to calculate the leakage of plastics into the oceans due to PET bottles, a widely used product which is well-known for its potential contribution to plastic pollution. Tangible results were obtained in terms of the amount of plastics discharged into the oceans, which could aid the scientific community researching on plastic pollution in general and specifically marine plastics. For a more complete overview, it was decided to compare it to another country, Indonesia, selected because of its large contribution to ocean littering. This second assessment has been conducted in a less comprehensive manner, providing nonetheless a sense of the scale of the problem. In addition, various alternatives for the management of plastic litter were explored and compared.

It can therefore be concluded that the initial targets have been successfully achieved.

Based on the obtained results, it can be drawn that a considerable amount of microplastics is discharged annually into the oceans in Germany and thus measures need to be established to tackle this problem. While strategies to eliminate marine litter have been implemented at the European level, and in more ambitious countries, measures to get rid of macroplastics are in vigor, microplastics remain a neglected issue in policy making.

Furthermore, the findings indicate a great need for proper waste management in developing countries, both at city and rural levels, as the extent to which they contribute plastic waste to the oceans is on a massive scale. Indonesia, the studied country, has been reported as one of the top 10 contributors to plastic pollution. Therefore, policies in such countries that focus on efficient litter management are urgently required. Since this is a global problem and the resources of such nations are often scarce, international action to jointly assist in dealing with plastic pollution in developing countries has been identified as a matter of need.

Several obstacles with regard to data collection have been identified throughout the study.

For such a broad topic, finding consistent data was a challenge. It was therefore essential to study and compare multiple sources. Moreover, mapping the existing situation of the plastics cycle in Germany was a challenge. The case study of Indonesia has also not been straightforward, as research on the subject is limited for this country. Several assumptions which are mentioned along the project were thus taken.

This work aims to contribute to the scientific community in addressing the plastic pollution problem. However, since there are limitations to the study and the accuracy throughout the project differs, several recommendations for future studies are presented in the continuation of the investigation. Firstly, the study of the situation in Germany as a whole, i.e., taking into account imports and exports of both products and waste, would provide more accurate results. In addition, a more comprehensive study of the situation in Indonesia is proposed, through the application of inventory methodologies such as the PLP guidelines. Furthermore, with regard to the study of PET bottles, it is also suggested to consider them with their packaging, as they constitute a waste that depends indirectly on PET bottles.

Consequently, although this research has provided insights into the problem, there is still a long way to go in the investigation process, and a continuation that continues contributing tangible data useful for policy making is therefore necessary.

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ANNEX I: ALIGNMENT WITH THE SDGS

This work, in line with the achievement of a sustainable development, focuses on the following objectives:

- Clean water and sanitation: with the aim of reducing the micro- and macroplastics of the oceans, this goal is one of the main ones considered in the project.
- Responsible consumption and production: with the results of the project, it is intended to show that the current production and consumption system is not sustainable from the plastic pollution perspective, and that a shift in the process towards responsible production and consumption should be implemented.
- Climate action: the pollution of plastic, a problem that indirectly affects climate change, is addressed with the aim of minimizing it as much as possible.
- Life below water: by achieving clean and plastic-free waters, good living conditions for fish and aquatic creatures can be ensured.
- Life on land: Although this project focuses on marine plastics, a large amount of plastic waste ends up in landfills, affecting the lives of land-based animals and living beings. Through the reduction of all types of plastic waste, a better quality of life on land will be achieved.