Blue Point

MARINE PLASTIC POLLUTION AND PATHWAYS TO OCEAN SUSTAINABILITY

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CONTENTS

TABLES

FIGURES

ABBREVIATIONS

ALDFG - Abandoned, Lost or Discarded Fishing Gear;

CBs - Cigarette Butts;

DDT - Dichloro-diphenyl-trichloroethane;

GPGP - Great Pacific Garbage Patch;

HDPE - High-density Polyethylene;

LDPE - Low-density Polyethylene;

MPs - Microplastics;

Mt - Million Tons**;**

NPSG - North Pacific Subtropical Gyre;

OCPs - Organochlorine Pesticides;

PA - Polyamide;

PAHs - Polycyclic Aromatic Hydrocarbons;

PCBs - Polychlorinated Biphenyls;

PE - Polyethylene;

PET - Polyethylene Terephthalate;

POPs - Persistent Organic Pollutants;

PP - Polypropylene;

PS - Polystyrene;

PUR - Polyurethane;

PVC - Polyvinyl Chloride;

UNEP - United Nations Environment Programme;

WP1 - Work Package 1;

WWTPs - Wastewater Treatment Plants.

PREFACE

The oceans, the bedrock of life and prosperity for millennia, now face an unprecedented crisis: plastic pollution. It is estimated that 80% of the waste found in the seas consists of plastic – a staggering reality transforming marine ecosystems into vast reservoirs of debris[1]. Alarmingly, projections suggest that without decisive action, by 2050 the oceans could hold more plastic than fish, presenting a catastrophic scenario that underscores the profound impact of human activities on the planet's delicate equilibrium[1].

Regions such as the Atlantic coasts of Portugal, Spain, France, and Ireland are among the most severely affected. In the Bay of Biscay alone, over 55,000 tons of marine plastic have accumulated, posing significant threats not only to biodiversity but also to public health and the economic activities dependent on marine resources.

This global crisis is brought into sharp focus by striking imagery of marine life ensnared in plastic and by alarming data estimating that 50 - 75 trillion pieces of macroplastics (plastics larger than 5 mm) and microplastics (1 mm to 5 mm) currently contaminate our oceans. Every year, approximately 8 to 10 million metric tons of plastic enter the seas[1]. In light of this sobering reality, immediate action is imperative. This pressing challenge must be reframed as an opportunity for change. Recovering and repurposing marine plastic as raw material can mitigate environmental damage while fostering the creation of a sustainable and innovative value chain.

The BluePoint Project, co-funded by the European Union through the INTERREG Atlantic Area Cooperation Program (EAPA_0035/2022), presents a transformative approach to tackling marine plastic pollution. By addressing all stages of the plastic lifecycle – from detection and collection to recycling and product innovation – the project promotes sustainable and circular solutions.

BluePoint aims to establish a multi-stakeholder ecosystem that fosters cooperation, innovation, and entrepreneurship, while leveraging the marine plastics value chain to unlock new business opportunities. This replicable circular economy model seeks to reduce environmental impacts, advance the maritime sector, and drive the transition to a blue circular economy in the Atlantic region. This report, developed under Work Package 1 (**WP1**) as part of Action 1.1, explores the impact of plastics on marine ecosystems, tracing their effects from rivers and estuaries to coastal and open-sea environments. By consolidating scientific knowledge, it enhances understanding of the issue and supports the development of effective, sustainable solutions within the project's broader objectives.

May this report serve as a call to action. Through collective effort, we can restore the vitality of our oceans and build a sustainable future for current and future generations. The time to act is now. Every step, no matter how small, makes a difference.

1 Ocean Literacy Portal: https://oceanliteracy.unesco.org

CHAPTER 1

Plastic Pollution Crisis in Aquatic Ecosystems: a Call for Research and Action

Introduction

In the early 20th century, the condensation reaction of phenol and formaldehyde led to the invention of Bakelite, the first fully synthetic polymer (Thompson *et al.*, 2009; Chamas *et al.*, 2020). This breakthrough marked the beginning of the widespread use of plastics, one of the most transformative materials of modern life. Plastics, synthetic organic polymers (Cole *et al.*, 2011; Mathalon & Hill, 2014) can be moulded into diverse shapes and tailored to achieve specific properties, including strength, permeability, porosity, opacity, and color (Chamas *et al.*, 2020). Their unique combination of low density, flexibility, durability, resilience to deterioration, ease of manufacture, and cost-effectiveness has driven their mass production since the 1950s (Thompson *et al.*, 2009; GESAMP, 2019; Chamas *et al.*, 2020; Manfra *et al.*, 2021; Arat, 2024).

This versatility has enabled plastics to dominate numerous sectors, including the domestic use, food packaging, medicine, industry, and construction (**Figure 1**) (Chamas *et al.*, 2020; Manfra *et al.*, 2021). Consequently, global production reached an estimated 400.3 million tons (**Mt**) by 2022 (Plastics Europe, 2024). The categorisation of plastics is typically undertaken on the basis of the chemical composition of their primary polymer and any side chains (Winiarska *et al.*, 2024), and while numerous polymer types and blends exist, a relatively small number dominate the market. The seven most prevalent types are high-density polyethylene (**HDPE**), low-density polyethylene (**LDPE**), polypropylene (**PP**), polyvinyl chloride (**PVC**), polyurethane (**PUR**), polystyrene (**PS**), and polyethylene terephthalate (**PET**) (**Figure 1**) (GESAMP, 2019). Most plastics are currently derived from non-renewable sources such as oil, natural gas, and coal (Cole *et al.*, 2011; Chamas *et al.*, 2020; Arat, 2024).

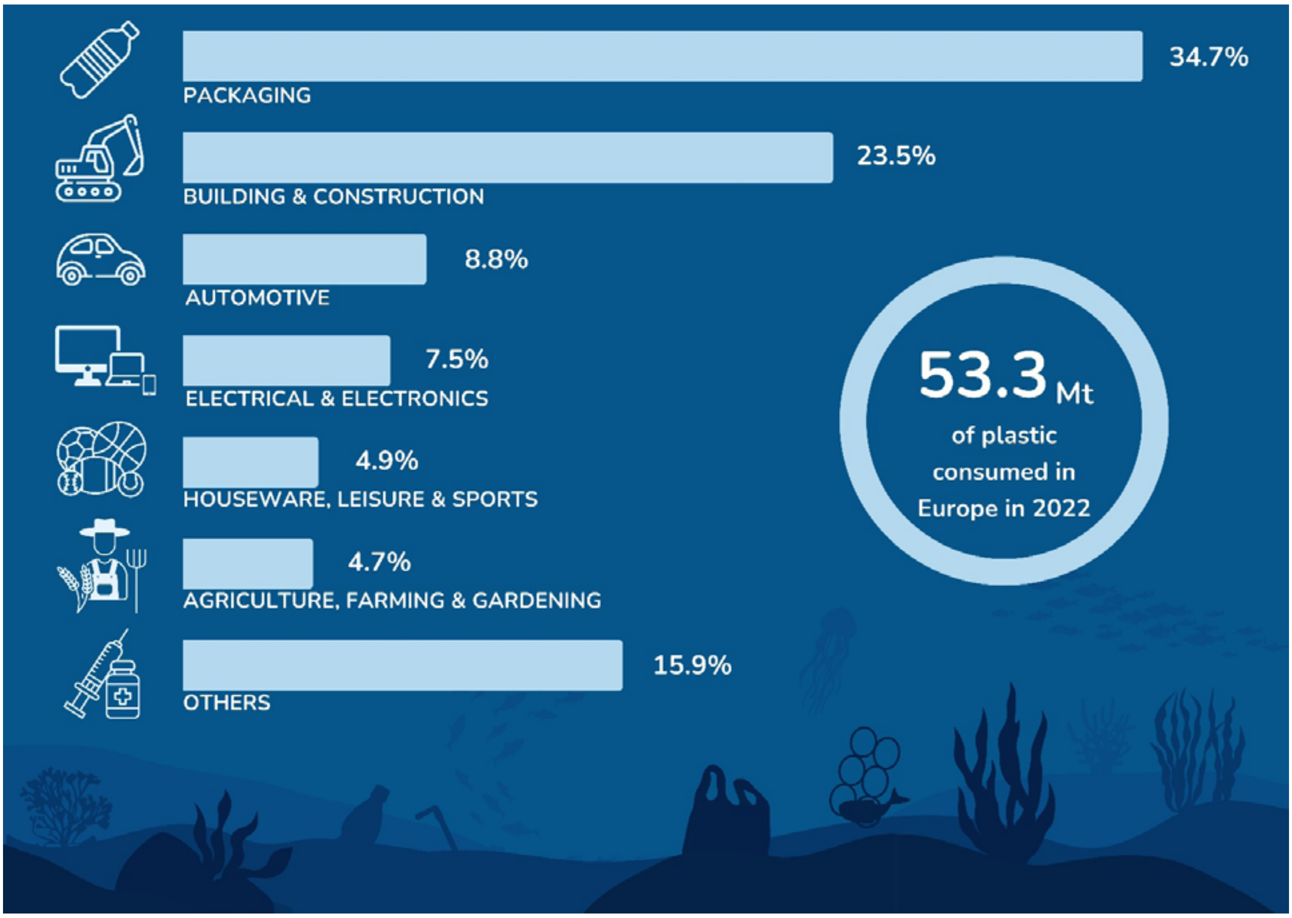


Figure 1. Plastic consumption in Europe by sector (2022) and the most common polymer types on the market (adapted from Plastics Europe, 2024; @CANVA).

While initially celebrated for their beneficial properties, plastics now pose a significant environmental threat (Thompson *et al*., 2009; Chamas *et al*., 2020). Uncontrolled production and consumption, coupled with inadequate waste management, low recycling rates, and limited environmental awareness, have led to vast amounts of plastic accumulating in landfills and natural ecosystems (Manfra *et al*., 2021; Bottari *et al*, 2024). This has resulted in a global plastic pollution crisis affecting both terrestrial and aquatic environments (Manfra *et al*., 2021).

Plastic pollution represents one of the most severe anthropogenic threats to marine ecosystems. In Europe alone, it is estimated that 32.3 million tons of post-consumer plastic waste were collected in 2022. Of this, 26.9% was recycled, 49.6% was utilized for energy recovery, and 23.5% ended up in landfills (**Figure 2**) (Plastics Europe, 2024). Despite the relatively small proportion of plastic entering landfills or the environment, Chamas *et al.* (2020) estimate that this quantity is sufficient to rebuild the Great Wall of China.

The durability of plastics is well-documented, with these materials capable of persisting in the environment for centuries without significant degradation. As a result, plastics constitute a pervasive and substantial problem for marine ecosystems, with profound implications for biodiversity (Arat, 2024; Bottari *et al.*, 2024). The accumulation of plastic waste in these ecosystems adversely affects marine organisms by impairing their mobility, stunting growth, and interfering with reproduction. These impacts often lead to severe outcomes such as ingestion, suffocation, entanglement, and ultimately death (Egbeocha *et al.*, 2018; Silva, 2021; Arat, 2024). Additionally, ingested plastics can ascend through the food chain from lower to higher trophic levels, eventually reaching humans. This demonstrates events of bioaccumulation and biomagnification across food webs (Miller *et al.*, 2020; Arat, 2024). Such processes pose significant risks to human health, including disrupted food security and quality, restricted livelihoods, and the creation of habitats that facilitate the emergence of zoonotic diseases (Silva, 2021).

Plastics, particularly microplastics (plastic particles smaller than 5 mm) and nanoplastics (plastic particles between 1 and 1000 nm) (Eriksen *et al.*, 2014; GESAMP, 2019) have been shown to act as vectors for harmful pollutants and chemicals (Arat, 2024). This amplifies the already substantial challenges posed by plastic pollution. Moreover, the economic costs associated with this issue are escalating, with potential losses in revenue from industries such as tourism, fisheries, and coastal habitat management (Silva, 2021).

Over the past two decades, plastic pollution has garnered increasing attention after a period of relative neglect (GESAMP, 2019; Bertolazzi *et al.*, 2024). Today, marine plastic pollution is a growing focus for researchers, industry leaders, and policymakers (Bertolazzi *et al.*, 2024). However, despite the rising awareness, the rapid accumulation of plastics in the environment continues to outpace our understanding of their fate, persistence, and full impact on all environmental compartments, including shorelines, the sea surface, the water column, and the deep sea. While the scientific community has only recently undertaken in-depth investigations into this issue, the scale and urgency of the problem demand a more rapid and comprehensive research effort (Chamas *et al.*, 2020).

Given these challenges, there is an urgent need for research and intervention strategies that can respond swiftly and effectively to the complex issues posed by plastic pollution (Díaz-Mendoza *et al.*, 2023).

Purpose of this Report

Given the urgency of addressing plastic pollution and its associated challenges, the collection of data on its impacts in both marine and freshwater ecosystems serves as a crucial resource. Such data not only enhances our understanding of the issue but also supports the development and implementation of strategies aimed at mitigating its harmful effects on ecosystems. Additionally, these studies can play a vital role in raising public awareness, potentially driving behavioral changes to reduce the release of plastics into the environment. In this context, the primary objectives of this report are to:

1. Review the impact of plastic pollution on marine ecosystems: exploring the extent, nature, and consequences of plastic debris.
2. Review the impact of plastic pollution on freshwater ecosystems: understanding pollution dynamics in rivers, lakes, and other freshwater habitats.

Both objectives are achieved through an in-depth analysis and synthesis of numerous research studies sourced from academic institutions, scientific journals, technical reports, and supplementary datasets.

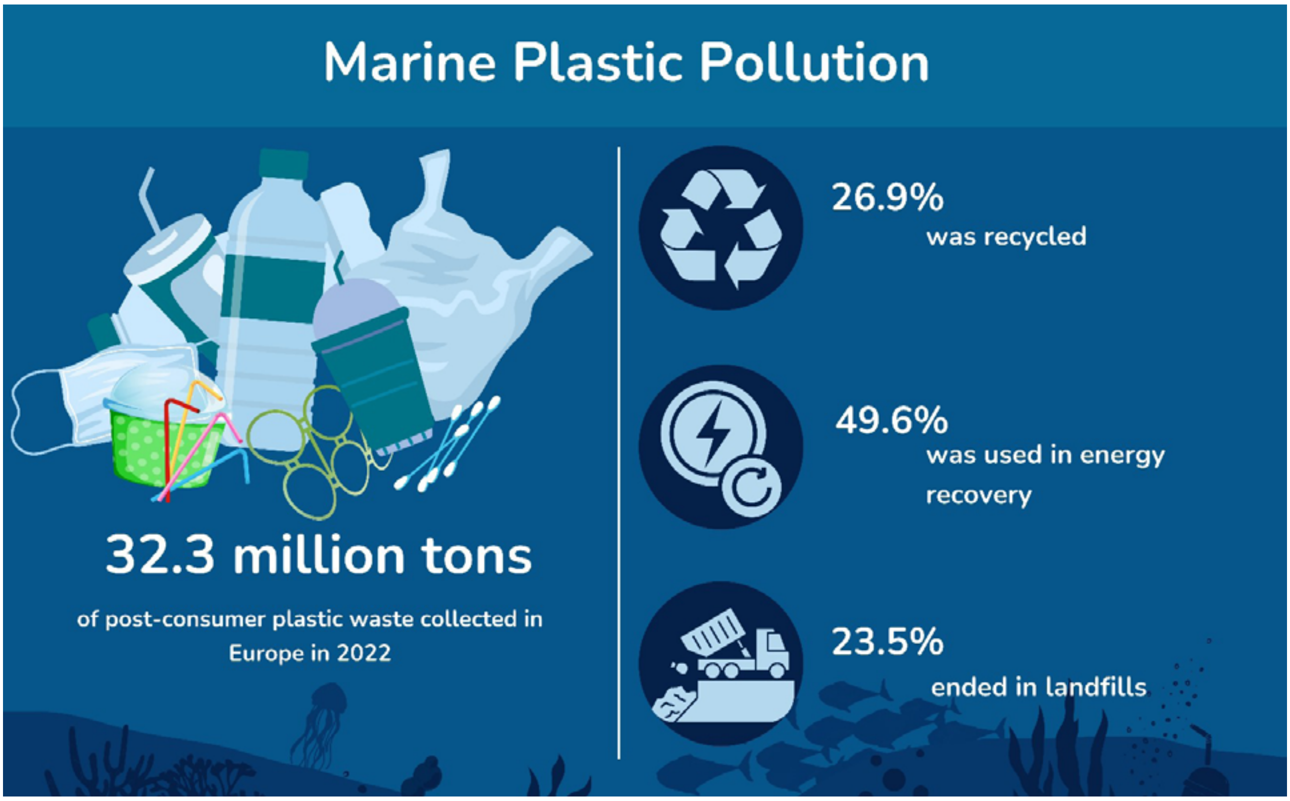


Figure 2. Post-consumer plastic waste collected and its treatment in the European Union, Switzerland, Norway and the United Kingdom in 2022 (adapted from Plastics Europe, 2024; @CANVA).

CHAPTER 2

Plastic Pollution in Marine Ecosystems – a Review

Introduction

The disposal of waste into the ocean has been a long-standing practice among humans, stemming from the misconception that the ocean is an inexhaustible resource (GESAMP, 2019). Moreover, nearly half of the global population resides within 50 miles of the coast, further contributing to this issue (Arat, 2024). However, societal perspectives are evolving, and oceanic plastic pollution has become a critical global concern (Chamas *et al.*, 2020).

Marine litter, as defined by the United Nations Environment Programme (**UNEP**) in 1995, encompasses "any persistent, manufactured or processed solid material discarded, disposed of, or abandoned in the marine and coastal environment" (UNEP, 2021). Plastics, as highlighted in Chapter 1, are synthetic polymers that exhibit thermoplastic, thermosetting, or elastomeric properties, and are commonly used in materials such as fibers, monofilament lines, and coatings (GESAMP, 2019). Thus, marine plastic litter refers to synthetic polymer-based materials discarded in marine or coastal areas. When exposed to environmental factors, these polymers undergo abrasion and fragmentation, producing smaller plastic particles (**Figure 3**) (Law *et al.*, 2014; Chamas *et al.*, 2020). Consequently, plastic litter spans a wide range of sizes, from large objects like vessels to tiny nanoparticles (GESAMP, 2019).

Standardized terminology for the size categories of plastic litter remains absent, complicating comparisons across studies. This review adopts the categorization proposed by GESAMP (2019) (**Table 1; Figure 4**).

Figure 3. Presence of plastic litter on the shoreline, and microplastics particles laid upon a person's hand (@gettyimages).

Table 1. Categories of plastic litter by size, definitions, and measurement units (GESAMP, 2019).

Size Category	Size Divisions	Common Definition	Measurement Units
Megaplastic	> 1 m	Very Large	Meters
Macroplastic	25 – 1000 mm	Large	Meters, Centimeters, Millimeters
Mesoplastic	5 – 25 mm	Medium	Centimeters, Millimeters
Microplastic	1000 nm – 5 mm	Small	Millimeters, Microns
Nanoplastic	1 – 1000 nm (< 1 µm)	Very Small	Nanometers

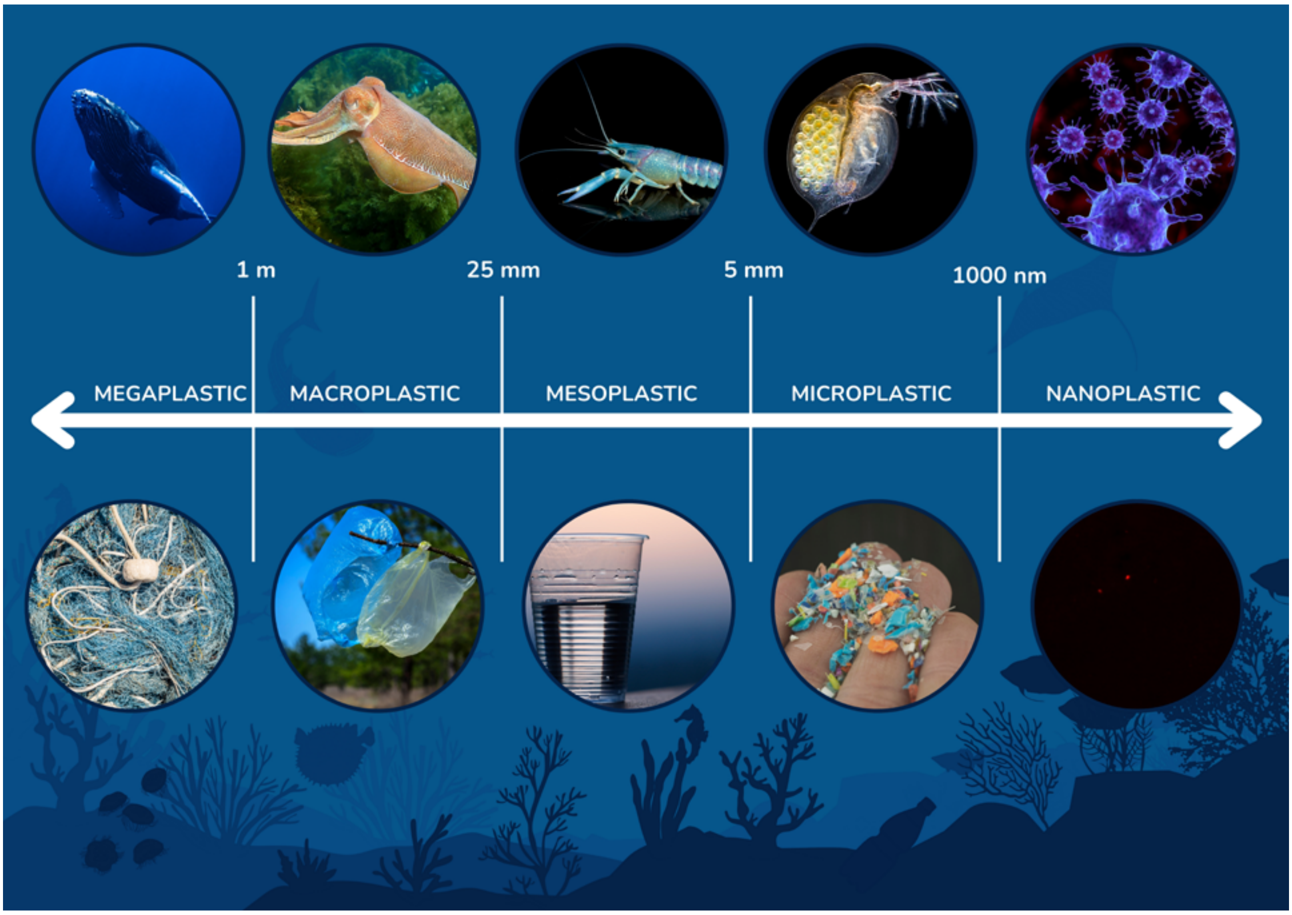


Figure 4. Plastic litter size categories and its comparison to common plastic products and to living organisms (adapted from GESAMP, 2019; Images by @CANVA & @Landscape Laboratory).

Although plastic debris accumulates most noticeably along shorelines – driven by natural forces such as currents, waves, winds, and river flows – its presence extends far beyond these areas. Plastic pollution is found on the ocean surface, within the water column, on deep seabeds, and even within marine organisms (GESAMP, 2019).

Recent studies estimate that the ocean contains between 74 and 199 million metric tons of plastic waste (UNEP, 2021). This includes 7,000 – 35,500 million tons of microplastics in the upper ocean layers, amounting to at least 5.25 trillion particles (Eriksen *et al.*, 2014; Godoy *et al.*, 2023). Research into the top 200 meters of the Atlantic Ocean estimates 11.6 – 21.1 million tons of microplastics, averaging 990 – 6,999 particles per cubic meter (Pabortsava & Lampitt, 2020). Significantly, eight rivers – primarily in middle-income Asian countries – contribute the majority of this plastic waste (Schmidt *et al.*, 2017). Maritime activities account for only approximately 20% of oceanic plastic pollution, with the remainder originating from land-based sources (Arat, 2024).

Sources of Plastic Pollution

Plastic pollution in marine ecosystems originates primarily from two key sources: marine-based and land-based activities (**Figure 5**).

Marine-based plastic pollution is driven by activities such as fishing, aquaculture, shipping, and shoreline tourism (GESAMP, 2019; Arat, 2024). Among these, the fishing and aquaculture industries are the largest contributors, largely due to the extensive use of plastic polymers like polyethylene (**PE**), polypropylene (**PP**), and polyamide (**PA**) in their gear and equipment (UNEP, 2021; Syversen & Lilleng, 2022). Items such as nets, floats, bait boxes, ropes, and other tools often enter marine environments through accidents, adverse weather, gear conflicts, or intentional abandonment (GESAMP, 2019). Abandoned, lost, or discarded fishing gear (**ALDFG**) represents a particularly significant concern, accounting for up to 20% of equipment in certain regions and contributing over 45,000 tons of plastic pollution annually (**Figure 6**) (GESAMP, 2019; Syversen & Lilleng, 2022). Factors such as limited material lifespan, poor waste management practices, inadequate facilities for waste handling at sea, and insufficient incentives for recycling exacerbate this issue (UNEP, 2021). While fishing operations often intentionally abandon gear, aquaculture operators tend to prioritize loss prevention. Nonetheless, losses in aquaculture are frequently attributed to wear and tear, catastrophic weather events, and poor maintenance or installation practices (UNEP, 2021).

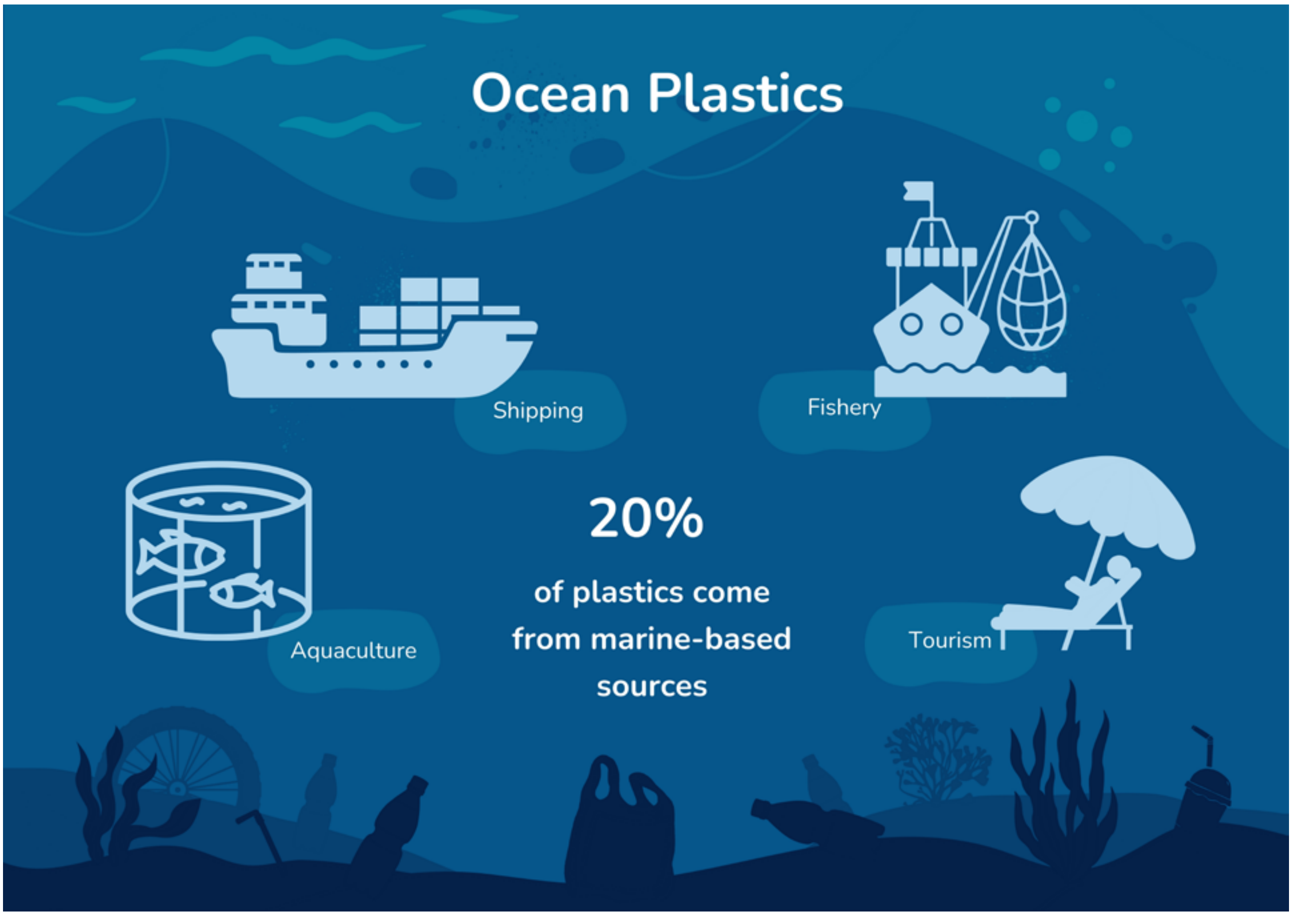
In Europe, fisheries and aquaculture contribute 39% and 14%, respectively, to marine plastic debris (UNEP, 2021). This is particularly concerning given that countries along the Atlantic, including Spain, France, Ireland, and Portugal, rank among Europe's top fishery and aquaculture producers (EUMOFA, 2024).

Shipping activities are another major source of marine-based plastic pollution. Plastics are released through abrasives used during hull cleaning, the degradation of paints and coatings, shipbreaking, and the accidental loss of goods or plastic pellets (GESAMP, 2019; UNEP, 2021; Arat, 2024). Additionally, illegal waste dumping by ships to evade landfill or incineration taxes is a well-documented contributor to marine debris. Ship-based tourism also adds to this problem through the improper disposal of packaging, personal items, and wastewater produced during tours (UNEP, 2021).

Regarding marine-based plastic pollution, tourism – particularly mass tourism – represents a significant source of marine plastic contamination (Chouchene *et al.*, 2021; Díaz-Mendoza *et al.*, 2023). During peak seasons, the volume of waste generated can increase by up to one-third in some countries (UNEP, 2021). This surge often overwhelms local waste management systems, leading to increased plastic debris on beaches (Díaz-Mendoza *et al.*, 2023; Godoy *et al.*, 2023). Restaurants near beaches are also major contributors to this issue. The widespread use of single-use plastics for food packaging exacerbates plastic waste accumulation in coastal areas (Godoy *et al.*, 2023). In regions experiencing high tourist volumes, these combined factors significantly amplify plastic pollution in marine ecosystems.

Despite the significant role of marine-based sources in contributing to plastic pollution in marine ecosystems, they account for only about 20% of the total plastic present in the oceans (Andrady, 2011; Arat, 2024). In contrast, land-based sources represent a far greater input of plastic into marine environments. Estimates suggest that between 1.15 and 2.41 million tons of plastic waste are introduced to the oceans annually via rivers (**Figure 7**) (Lebreton *et al.*, 2017).

Land-based plastics originate from various activities, including agriculture, construction, transportation, urbanization, inadequate waste management, landfilling, and effluents from wastewater treatment plants (**WWTPs**) (UNEP, 2021).



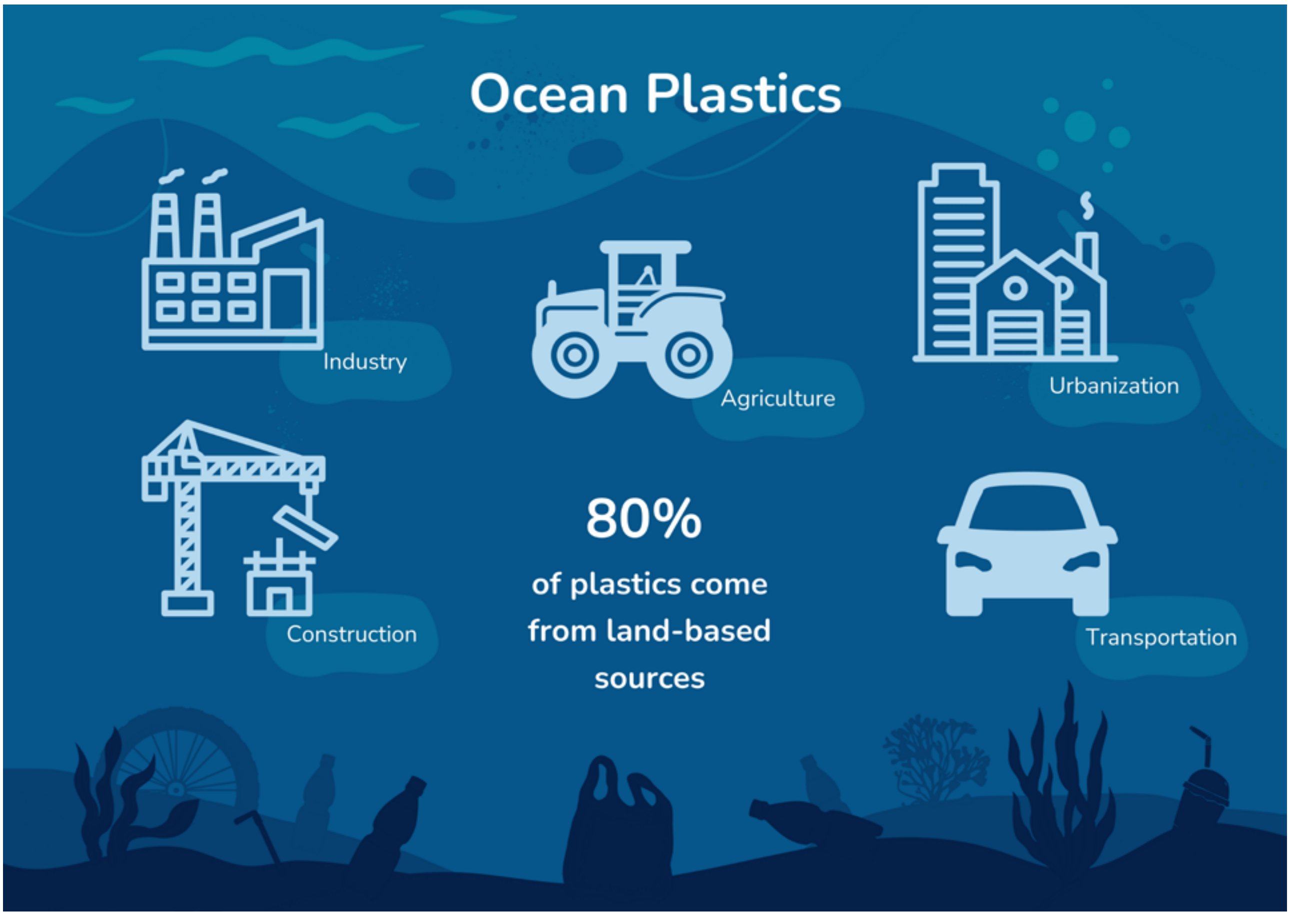


Figure 5. Sources of marine plastic pollution (@CANVA).

Figure 6. Contribution of abandoned, lost, or discarded fishing gear (ALDFG) to marine plastic pollution (@gettyimages).

Agriculture is a major user of plastics, and its soils have become recognized as reservoirs for microplastics. Annually, the agricultural industry utilizes 8 to 10 million tons of plastic, contributing significantly to the proliferation of marine plastics and broader plastic pollution (UNEP, 2021). Plastics in agriculture are used deliberately in applications such as wind tunnels, greenhouses, silage films, and mulch films for covering soil and crops. After serving their purpose, these materials are often discarded, left to degrade, or burned, releasing pollutants into the environment. Additionally, the use of microplastic-based fertilizers, pesticide additives, and soil conditioners further adds to the intentional deposition of plastics in agricultural soils (Zhang *et al.*, 2022).

The industrial sector is another significant contributor to environmental plastic pollution. Industries such as food production, construction, and plastic manufacturing heavily rely on plastic materials.

Figure 7. Coastal deposition of litter, exemplifying rivers as key pathways transporting land-based plastic waste to the ocean (@Landscape Laboratory).

In the food industry, plastic pollution arises from the widespread use of plastic packaging. Approximately 36% of all plastic produced is dedicated to packaging, including single-use items like food and beverage containers. Alarmingly, about 85% of this packaging ends up in landfills or as unregulated waste (Andrades *et al.*, 2016).

In construction, plastics are used in pipes, paints, flooring, roofing, insulation, and sealants for building and road infrastructure (UNEP, 2021). Similarly, the plastic production industry uses virgin pellets – small, disc-shaped or cylindrical granules made from various polymers – as the raw material for manufacturing plastic products **(Figure 8**). These pellets contribute to pollution through accidental losses during transportation or improper disposal of products at the end of their lifecycle, such as single-use containers or old pipes (Ogata *et al.*, 2009; França *et al.*, 2022).

Urbanization significantly exacerbates plastic pollution due to the high intensity of anthropogenic activities. Sources include road markings, pharmaceutical and healthcare products (e.g., personal protective equipment used during the COVID-19 pandemic), and daily-use items such as toothpaste, shampoos, cosmetics, cleaning agents, plastic bags, bottles, caps, and cigarette butts. Improper disposal of these items often leads to their eventual introduction into marine ecosystems (**Figure 9**) (Cole *et al.*, 2011; Anderson *et al.*, 2016; Sun *et al.*, 2020; Silva *et al.*, 2021a; Arat, 2024). Even properly disposed plastics, such as those placed in sanitary landfills, degrade over time into smaller particles that can leach into surrounding environments. These smaller particles, often referred to as microplastics, are especially prone to infiltrating soil and aquatic ecosystems (Arat, 2024).

Figure 8. Nurdles used in plastic production (@gettyimages).

Figure 9. Improper disposal of plastic waste in the environment (@gettyimages).

Microplastic pollution predominantly originates from land-based sources rather than marine sources (**Figure 10**). This is because microplastics (**MPs**) are not solely the result of the degradation of inadequately managed plastic waste but also stem from other common sources such as tyre wear, paint degradation, washing of synthetic textiles, or pre-manufactured microplastics (e.g., virgin pellets) (Godoy *et al.*, 2023). Microplastics can be classified into two primary categories: primary microplastics and secondary microplastics.

Primary microplastics are intentionally manufactured at a microscopic scale for specific purposes. This category includes virgin pellets and microplastics used in products such as cosmetics, detergents, hand cleaners, abrasive powders, and air-blast cleaning media. Conversely, secondary microplastics result from the degradation of larger plastic objects during their use or after they are released into the environment. Common sources of secondary microplastics include textile and rope fibers, fragmentation of larger plastic debris, vehicle tire abrasion, and paint flakes (Cole *et al.*, 2011; GESAMP, 2019; UNEP, 2021).

Microplastics and nanoplastics are also released into the environment through wastewater effluents (Anderson *et al.*, 2016; Xu *et al.*, 2019). Wastewater Treatment Plants (**WWTPs**), which process wastewater from industrial, domestic, and agricultural activities, often discharge effluents containing significant amounts of plastic. Synthetic fibers from laundering synthetic textiles (Xu *et al.*, 2019) and microplastics from personal care products (Sun *et al.*, 2020) are particularly prevalent. It is estimated that approximately 1,500 metric tons of microplastics from personal care products escape WWTPs annually, entering aquatic environments globally (Sun *et al.*, 2020).

To mitigate this issue, it is essential that WWTPs are equipped to efficiently remove microfibers and microplastics from effluents before discharge. However, the effectiveness of these systems depends on the specific treatment methods employed and the local environmental context in which they operate (Manfra *et al.*, 2021). Despite these efforts, studies suggest that approximately two-thirds of microplastics in the ocean originate from the washing of synthetic fabrics and the abrasion of rubber tires, underscoring the predominance of secondary microplastics over primary microplastics in the environment (Chamas *et al.*, 2020; UNEP, 2021).

The distribution of plastic waste from land-based sources is uneven globally. According to Jambeck *et al.* (2015), the amount of land-based plastic waste entering the ocean is influenced by three key factors: population density, the quality of waste management systems, and economic status. As a result, the majority of plastic waste inputs originate from middle-income countries in Asia, Africa, and South and Central America – regions characterized by rapid economic development and inadequate waste management infrastructure (Jambeck *et al.*, 2015; Lebreton *et al.*, 2017). Therefore, targeted monitoring and mitigation efforts in these regions are critical.

While land-based sources of marine plastic pollution are well-documented, the impacts of marine-based sources remain less thoroughly investigated (Arat, 2024). Whether

Figure 10. Microplastic pollution in marine ecosystem (@gettyimages).

deliberate or accidental, the problem of plastic pollution – be it marine-based or land-based – depends significantly on how it is conceptualized and perceived by individuals and societies. In this context, a "third source" can be proposed, framing marine litter and plastic pollution as a cultural issue. This perspective highlights the importance of disseminating scientific knowledge to the general public, raising awareness, and inspiring proactive behavior, especially among younger generations (**Figure 11**) (Bertolazzi *et al.*, 2024).

Dynamic Behavior and Transport Process

The distribution and fate of plastic particles within marine ecosystems are inherently complex, making them challenging to quantify (Godoy *et al.*, 2023). While anthropogenic activities and land-based sources significantly influence the total abundance of plastic debris, environmental factors and the characteristics of plastic items (e.g., size, shape, and composition) exert a greater impact on their transport, distribution, and eventual fate (GESAMP, 2019; Chouchene *et al.*, 2021).

The transport of plastics from land-based sources into marine environments is predominantly driven by precipitation, wind, tides, and floods, with riverine systems serving as the primary pathways (Jambeck *et al.*, 2015; Schmidt *et al.*, 2017). Jambeck *et al.* (2015), estimated that 4.8 to 12.7 million metric tons of mismanaged solid waste enter the oceans annually via rivers. Furthermore, Schmidt *et al.* (2017) estimated that 88% to 95% of global marine plastic debris originates from just 10 rivers.

The intensification of extreme weather events due to climate change exacerbates this issue, facilitating the dispersion of mismanaged waste across terrestrial, freshwater, and marine ecosystems (Wang *et al.*, 2019; Lo *et al.*, 2020). For instance, tropical storms, such as the typhoon that struck Sanggou Bay, China, in 2017, increased the abundance of microplastics (**MPs**) in sediments and seawater by up to 40% (Wang *et al.*, 2019). Stronger winds and heavier rainfall can release buried plastics from sediments and increase flooding in rivers worldwide, leading to heightened plastic mobilization (Roebroek *et al.*, 2021). Monsoon-associated rainfall further intensifies the volume of plastics entering oceans through riverine systems. Additionally, catastrophic events such as storms and tsunamis contribute significantly to plastic debris influx, introducing waste from urban stormwater systems and damaged coastal infrastructure (Eriksen *et al.*, 2016; GESAMP, 2019).

In marine ecosystems, the transport and spatial distribution of plastic debris are dictated by ocean currents, waves, and

Figure 11. Inspiring proactive behavior among the general public as a mean of combating river and marine plastic pollution (@Landscape Laboratory).

winds (Chouchene *et al.*, 2021; UNEP, 2021). In coastal areas, tides and rainfall interact with shoreline features – such as morphology, vegetation, bioturbation, surface ice, terrain, and slope – to influence the movement and accumulation of plastic debris on and off beaches (**Figure 12**) (Prata *et al.*, 2020; Chouchene *et al.*, 2021; UNEP, 2021).

The behavior of plastic particles in the water column is shaped by their composition, density, and shape. These factors determine whether a particle will float, remain neutrally buoyant, or sink (Cole *et al.*, 2011). Plastics with a density lower than seawater tend to float, concentrating in the sea-surface microlayer (Arat, 2024). However, in estuarine habitats, such particles can submerge when encountering water fronts, causing their vertical position in the water column to vary (Cole *et al.*, 2011).

Although plastics initially float upon entering the marine environment, microbial biofilms often form on their surfaces, allowing algae and invertebrates to colonize the particles (**Figure 13**). This biofouling process increases the plastics' density, causing them to sink. Conversely, high-density plastics can appear at the surface in areas with turbulent or wavy conditions (Cole *et al.*, 2011; Arat, 2024).

In the open ocean, large-scale currents interact with eddies and winds, driving the horizontal movement of floating plastics (**Figure 14**) and forming accumulation zones within ocean gyres – wind-driven systems that rotate clockwise in the Northern Hemisphere and counter clockwise in the Southern Hemisphere (Eriksen *et al.*, 2016; UNEP, 2021; Rynek *et al.*, 2024). The most well-known accumulation zone is the "Great Pacific Garbage Patch" (**GPGP**), located within the North Pacific Subtropical Gyre (**NPSG**) (Rynek *et al.*, 2024). Other significant zones include the South Pacific Subtropical Gyre, the Eastern Pacific Ocean Gyre, and the gyres in both the North and South Atlantic Oceans (Eriksen *et al.*, 2014; Law *et al.*, 2014).

Plastic fragmentation through photodegradation and other weathering processes produces smaller particles that are more likely to disperse vertically and sink into the deep sea. This occurs through mixing, diffusion, or reduced buoyancy caused by biofouling. Smaller particles undergo biofouling more rapidly due to their high surface-to-volume ratio, further facilitating vertical transport (Eriksen *et al.*, 2016; Pabortsava & Lampitt, 2020). This highlights that plastic dispersion occurs throughout the entire water column (Cole *et al.*, 2011).

Figure 12. Accumulation of plastic debris on beaches (@Landscape Laboratory).

Figure 13. Float fragment colonized by goose barnacles (*Lepas sp.*) and other biofouling organisms, found on the beach (@Landscape Laboratory).

Figure 14. Plastic waste floating in the open sea, creating an "island" made of plastic (@gettyimages).

Monitoring, Assessment and Abundance of Plastics

Monitoring the presence of plastic litter in the marine environment is a critical step in evaluating the extent and potential impacts of plastic pollution.

Monitoring can be defined as the "repeated measurement of a characteristic of the environment or a process, with the objective of detecting trends in space or time" while adhering to specific conditions. These conditions include accounting for factors that might influence the results, thereby ensuring the measurements are representative. Conversely, assessment can be understood in two primary ways: (i) as an initial study aimed at providing a comprehensive overview of environmental conditions to design and guide a more effective monitoring program, or (ii) as an integral part of the monitoring process, where the findings are analyzed and used to inform decision-making. In summary, monitoring is an ongoing, long-term process involving repeated measurements to establish baseline conditions and detect temporal changes, whereas assessment involves critically contextualizing this information to inform the design and evaluation of public policies and mitigation measures (GESAMP, 2019).

Both assessment and monitoring are indispensable for addressing the multifaceted challenges posed by plastic pollution (**Figure 15**). They are essential for determining the scale and impacts of the problem, providing objective data to guide the development of mitigation strategies, evaluating the effectiveness of these strategies, and fostering adaptive management practices (GESAMP, 2019).

Figure 15. Assessment and monitoring of plastic and microplastic pollution in the environment (@Landscape Laboratory).

The tables provided in the annex, summarize the assessment and monitoring efforts regarding the presence and abundance of plastics across all compartments of the marine environment (**Tables A1, A2, and A3**).

Despite growing attention on assessing plastic pollution in marine environments and an increasing number of studies in recent years, direct comparisons between findings must be approached with caution. The lack of standardized protocols for analyzing plastic, particularly microplastic abundance, poses a significant barrier to meaningful comparisons. This challenge is further compounded by inconsistencies in sampling, extraction, and analytical methods employed across different studies.

Firstly, differences in the units used to report plastic abundance (e.g., particles/L, particles/m³, particles/m², particles/kg) often render comparisons impossible, as these units are not directly comparable. Secondly, discrepancies in the size classification of plastic particles introduce additional challenges when attempting to harmonize findings across studies (Arat, 2024). Lastly, variations in methodology – ranging from sampling techniques to counting protocols – can result in either overestimation or underestimation of plastic abundance and distribution (Godoy *et al.*, 2023; Arat, 2024). According to Prata *et al.* (2024), the lack of standardized procedures represents the most significant barrier to the effective analysis of microplastics.

It is therefore critical to develop a universal standardized protocol for the assessment of different plastic size categories and environmental compartments. Such a protocol should include validated techniques for sampling, contamination control, specialized equipment, and plastic identification. This standardization is especially important given that plastic pollution surveys are often resource-intensive and time-consuming processes (Chiba *et al.*, 2018; Prata *et al.*, 2024).

Risks and Implications of Marine Plastic Pollution

Plastic pollution represents a significant threat to marine ecosystems, posing complex challenges that extend across environmental, economic, and social dimensions. The pervasive presence of plastic debris in marine environments compromises the integrity of natural ecosystems and diminishes the socio-economic benefits they provide (Beaumont *et al.*, 2019). This section explores the multifaceted impacts of marine plastic pollution on the environment, marine life, public health, and socio-economic activities.

• Environmental Impacts of Plastic Pollution

Plastic polymers often contain numerous additives, such as plasticizers, biocides, and flame retardants. Once introduced into marine environments, plastic debris not only acts as a substrate for pathogenic microbes (Bowley *et al.*, 2021) but also absorbs toxic persistent organic pollutants (**POPs**), including dichloro-diphenyl-trichloroethane (**DDT**), polychlorinated biphenyls (**PCBs**), and polycyclic aromatic hydrocarbons (**PAHs**) (Rios *et al.*, 2007; Rios *et al.*, 2010). For instance, cigarette butts (**CBs**) – one of the most commonly found types of litter on beaches (**Figure 16**) – release harmful substances such as nicotine, tar, heavy metals (e.g., cadmium, lead, arsenic), and carcinogenic chemicals into the environment as they degrade (Qamar *et al.*, 2020; Lucia *et al.*, 2023).

These pollutants pose ecotoxicological risks to marine organisms, resulting in inhibited growth, abnormal embryo

Figure 16. Single-use plastic litter partially buried in beach sand, a plastic drinking straw and a small plastic cap fragment, illustrating common plastic debris found on shorelines (@Landscape Laboratory).

development, heavy metal bioaccumulation, and alterations in sediment microbial communities (Quéméneur *et al.*, 2020; Lucia *et al.*, 2023). Furthermore, plastic debris of various sizes serves as a vector for contaminants, transporting hazardous substances to remote and pristine areas (Hong *et al.*, 2018).

The issue is exacerbated by microplastics (**MPs**). Due to their small size, larger surface area, and high affinity for hydrophobic contaminants (GESAMP, 2019), MPs readily bind to pollutants such as PCBs, PAHs, organochlorine pesticide (**OCPs**), brominated flame retardants, and phthalates (Hong *et al.*, 2018). As plastic particles degrade, their surface area increases, intensifying their environmental impact (Shaniv *et al.*, 2021). Marine organisms that ingest contaminated microplastics experience digestive blockages, false satiation, starvation, and a deterioration of physical condition. Moreover, the ingestion of microplastics facilitates the transfer of pollutants through the food chain, posing additional risks to marine ecosystems (Hong *et al.*, 2018).

• Impacts of Plastic Pollution on Marine Life

Plastic pollution poses a significant threat to marine wildlife, impacting species across the spectrum, from microscopic zooplankton to large fish, seabirds, marine reptiles, and mammals. Interactions between marine organisms and plastic debris have been documented in over 690 species, including those classified as endangered or vulnerable. Among these interactions, ingestion and entanglement are the most frequently reported (**Figure 17**) (Gall & Thompson, 2015; Bottari *et al.*, 2024). For instance, a study along the Italian coast revealed that 61% of cases involved entanglement, while 39% were instances of ingestion (Bottari *et al.*, 2024).

Entanglement occurs when marine organisms become trapped or immobilized by plastic debris, such as fishing nets, lines, plastic floats, bottles, sheets, and rings. These interactions are particularly common with abandoned, lost, or otherwise discarded fishing gear (**ALDFG**), which significantly contributes to the problem (GESAMP, 2019). This issue is especially concerning in the Atlantic Region, home to several of Europe's major fishing nations. Countries in this region maintain substantial fishing fleets, often using gear like gillnets, hooks, and traps, which collectively accounted for more than 60% of the total fishing fleet gear in 2022 (Ireland: 65%; France: 76%; Spain: 83%; Portugal: 92%) (EUMOFA, 2024). This widespread use of fishing gear makes the region a potential hotspot for marine plastic pollution, particularly from ghost nets, hooks, and fishing lines.

Plastic debris can entangle marine animals, leading to severe consequences such as injuries (e.g., lacerations, mutilations, infections), physical deformities (especially in juveniles subjected to prolonged entanglement), suffocation, drowning, and impaired ability to hunt or evade predators. These outcomes frequently result in the death of the affected animals (Gall & Thompson, 2015; Law, 2017). Although entanglements are the most frequently reported type of interaction (Gall & Thompson, 2015; Bottari *et al.*, 2024), this does not necessarily mean they are more harmful than ingestion. Their impacts are simply more visible, easier to document, and more likely to capture public attention (Gall & Thompson, 2015; GESAMP, 2019).

In recent years, studies on the ingestion of plastic debris by marine species have gained momentum in the academic community, with over 200 species now reported to ingest plastic (Law, 2017). Marine animals often mistake plastic fragments, such as fishing net remnants, cups, bottles, filters, food packaging, balloons, and balloon strings, for prey (GESAMP, 2019; Prarat & Hongsawat, 2022). While some species can regurgitate indigestible plastic, others cannot, leading to accumulation in the gut. This can cause blockages, gastrointestinal perforations, reduced stomach capacity, false satiation, growth retardation, and, ultimately, death (Gall & Thompson, 2015; Law, 2017; Hong *et al.*, 2018; Bottari *et al.*, 2024). As larger plastic debris fragments into smaller pieces in the environment, the risks to marine organisms intensify. Microplastics, in particular, pose unique dangers. Their small size, increased surface area, and high affinity for hydrophobic contaminants enable them to carry pollutants such as PCBs, PAHs, and pesticides into marine food webs (Hong *et al.*, 2018). The adverse effects of microplastic ingestion include intestinal blockages, altered feeding behaviors, tissue abrasion, stunted growth, gene and protein expression disruptions, and inflammation (UNEP, 2021; Prarat & Hongsawat, 2022).

Unlike entanglement, the ingestion of plastic debris is more closely linked to the feeding behaviors of specific species and the size of both the organism and the debris ingested (Law, 2017; GESAMP, 2019). As plastic pollution continues to grow, its impacts on marine biota demand urgent attention to mitigate the cascading effects on marine ecosystems.

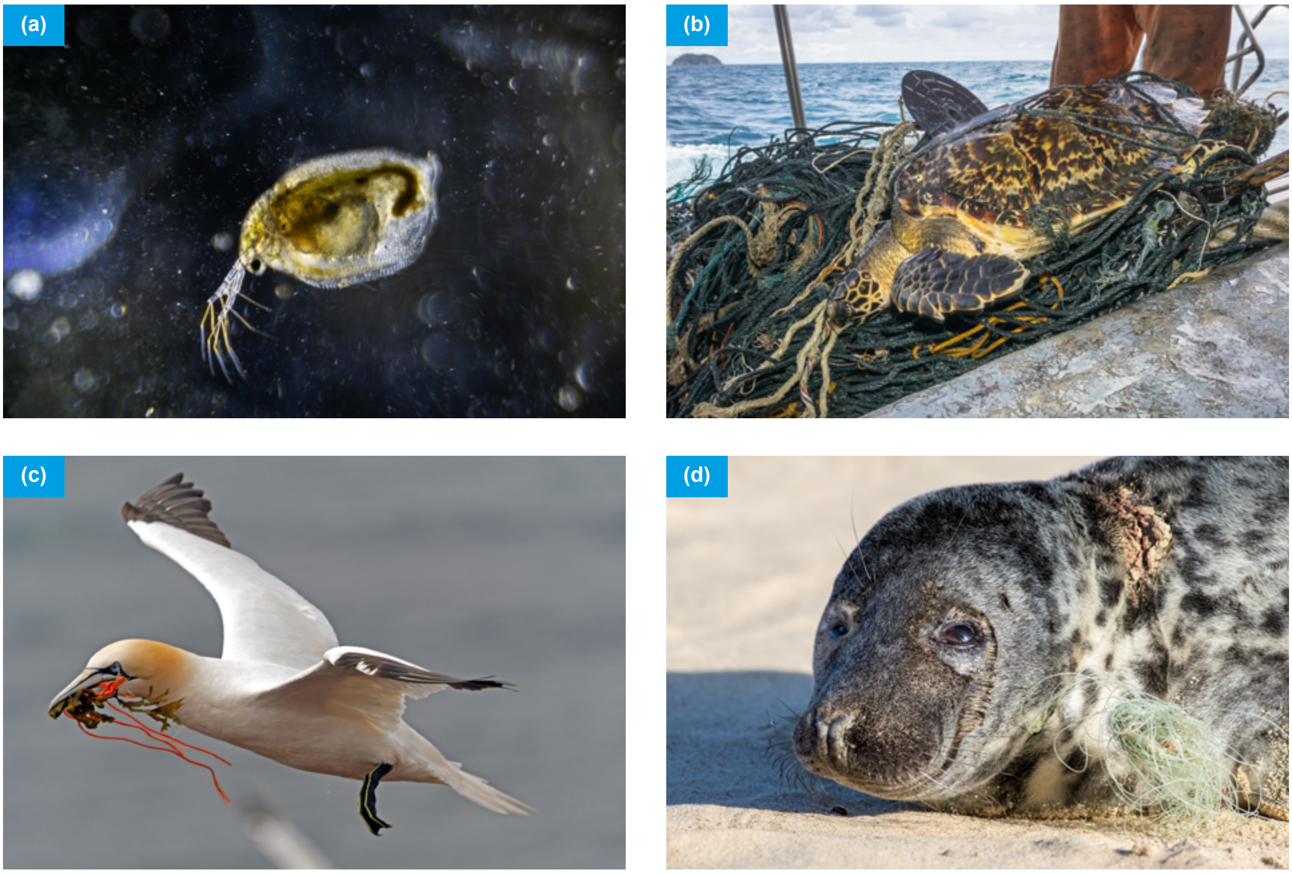


Figure 17. Examples of plastic pollution impacts across marine trophic levels: **(a)** zooplankton exposed/associated with microplastic particles; **(b)** sea turtle entangled in abandoned/lost fishing gear **(ALDFG)**; **(c)** seabird carrying plastic debris; **(d)** marine mammal showing evidence of entanglement by net/line. Together, the panels illustrate the two dominant interaction pathways - ingestion and entanglement from micro- to megafauna (@gettyimages).

• Marine Plastic Debris as a Vector for Invasive Species

With the growing prevalence of plastic debris in the marine environment, its potential to act as a vector for the spread and establishment of non-indigenous species as invasive organisms is increasing (Barnes, 2002; García-Gómez *et al.*, 2021). Many species naturally use floating materials such as wood and volcanic rocks as rafts for dispersal (Barnes, 2002). However, the widespread availability and superior characteristics of plastic debris compared to natural substrates have made it a preferred medium for colonization by alien species with invasive potential, as well as by pathogens (García-Gómez *et al.*, 2021; Silva *et al.*, 2021a).

The intrinsic properties of plastic debris – such as its persistence, buoyancy, chemical diversity, durability, surface roughness, and ubiquitous presence in all compartments of the marine environment – facilitate colonization by both macro- and microbiota. These properties enable the transport of various species across geographical regions and ecosystems (GESAMP, 2019; García-Gómez *et al.*, 2021). Biological traits of organisms, such as being sessile, filter-feeding, or having the ability to settle on low-energy surfaces, further enhance their attachment to plastic debris (Rech *et al.*, 2018). Additionally, many organisms can survive extended periods on these floating artificial substrates, even reproducing while adhered to them, which increases opportunities for the dispersal of invasive species (Holmes *et al.*, 2015).

Over the past 15 years, the role of plastic debris as a vector for species dispersal has been extensively studied. The rafting and dispersion of non-indigenous species with invasive potential have been documented worldwide (Barnes, 2002; Holmes *et al.*, 2015; Rech *et al.*, 2018; García-Gómez *et al.*, 2021; González-Ortegón *et al.*, 2024). For instance, Holmes *et al.* (2015) reported species from the southeastern USA and the Caribbean – typical of warm, southern waters – appearing on the coasts of England and Ireland. These organisms were attached to macro-debris washed ashore following westerly storms.

González-Ortegón *et al.* (2024) demonstrated that adult colonies of *Didemnum vexillum*, a species native to Japan and a successful invader in Europe, could expand their range in the Irish Sea by using plastic debris substrates such as HDPE, PP, and PS. Similarly, a study in two major European aquaculture regions (Venice Lagoon, Italy, and the Algarve, Portugal) identified eight invasive species colonizing anthropogenic debris, much of which was linked to aquaculture activities (Rech *et al.*, 2018).

Aquaculture has been identified as a significant vector for invasive species dispersal, either through deliberate introductions or accidental detachment of gear with colonized surfaces (Rech *et al.*, 2018). Abandoned, lost, or discarded fishing gear (**ALDFG**), including aquaculture equipment, poses a high risk of introducing non-indigenous species into new habitats. Numerous invasive species have been found associated with this type of material (Holmes *et al.*, 2015). Additionally, organisms can migrate by attaching to ship hulls, being transported to new locations during voyages (Barnes, 2002).

The introduction of invasive species via marine plastic pollution has significant socio-economic and ecological consequences. From a socio-economic perspective, the establishment of non-indigenous species in aquaculture areas disrupts farming operations, affecting native species and causing substantial financial losses. As aquaculture provides one-third of the global seafood supply, such impacts are particularly concerning (Barnes, 2002; Rech *et al.*, 2018). Ecologically, the introduction of invasive species alters local ecosystems by competing with and threatening native species, leading to cascading effects throughout the ecosystem (González-Ortegón *et al.*, 2024). Furthermore, floating debris can carry microorganisms, including those with virulent and antibiotic-resistant genes, spreading new diseases to other regions and threatening both ecosystem integrity and public health (Lamb *et al.*, 2018; García-Gómez *et al.*, 2021).

Given the broad impacts of invasive species transported by plastic debris, it is critical to prioritize research addressing this issue. Enhanced understanding will enable the development of strategies to mitigate the socio-economic and ecological consequences of this growing threat (Rech *et al.*, 2018).

• The Socioeconomic Impacts of Marine Plastic Pollution

Marine ecosystems provide a wide array of essential services and benefits to human societies, underpinning various socioeconomic activities. However, the increasing prevalence of marine plastic litter poses serious threats to coastal social and economic activities, as well as to the well-being of human communities (Aretoulaki *et al.*, 2021; UNEP, 2021). These impacts can broadly be categorized into two main areas: economic impacts, affecting industries such as fishing, aquaculture, tourism, and shipping, and social impacts, which primarily concern human physical and mental health and well-being (Aretoulaki *et al.*, 2021).

From an economic perspective, the value of marine ecosystem services is closely tied to the performance of key sectors such as seafood production (fishing and aquaculture), tourism, and maritime trade (Aretoulaki *et al.*, 2021). Seafood is one of the most consumed foods worldwide, with 19% of the global population depending on it as a fundamental source of animal protein (Golden *et al.*, 2016; Beaumont *et al.*, 2019). Aquaculture, responsible for one-third of global seafood production, plays a critical role in the economic growth of many countries (Rech *et al.*, 2018; Aretoulaki *et al.*, 2021). However, the health and productivity of both fishing and aquaculture industries are directly dependent on the sustainability of marine ecosystems (Aretoulaki *et al.*, 2021).

Plastic pollution significantly threatens these industries by compromising the productivity, viability, and safety of their outputs (Beaumont *et al.*, 2019). Fish stocks are directly impacted through entanglement in abandoned, lost, or discarded fishing gear (**ALDFG**) (Parton *et al.*, 2019; Bottari *et al.*, 2024) or ingestion of plastic particles (Egbeocha *et al.*, 2018; Macieira *et al.*, 2021), leading to fish mortality and population declines (Beaumont *et al.*, 2019; Aretoulaki *et al.*, 2021). Such declines, particularly in economically valuable species, create significant economic repercussions (Arat, 2024). Industries may struggle to meet growing seafood demand, resulting in reduced profits (Aretoulaki *et al.*, 2021). The consequences for the global economy are especially pronounced in regions with high aquaculture and fishery production, such as the Atlantic region (EUMOFA, 2024). Moreover, reduced fish stocks exacerbate challenges for low-income countries where access to high-nutritional-value seafood is vital. In these regions, diminished availability could lead to severe health crises (Golden *et al.*, 2016). Consumer perception of seafood quality also plays a pivotal role. Concerns about contamination, such as microplastics in seafood, can deter consumption, prompting a shift to alternative food sources and hindering the development of fishing and aquaculture industries (Aretoulaki *et al.*, 2021).

The shipping industry also faces economic challenges due to marine plastic pollution. Accumulated plastic debris increases the risk of ship collisions, potentially damaging hulls, causing engine shutdowns, and creating navigational hazards. These issues may jeopardize human safety and impose substantial costs for ship repairs, lost cargo, operational delays, and reputational damage, further hindering the sector's development (Aretoulaki *et al.*, 2021).

Marine tourism, another vital economic driver for coastal communities, relies heavily on the aesthetic and environmental quality of beaches and coastal waters (Aretoulaki *et al.*, 2021; Díaz-Mendoza *et al.*, 2023). Plastic pollution, such as cigarette butts and single-use plastics on beaches, undermines the recreational value of these destinations, discouraging tourists and resulting in economic losses for local communities (Beaumont *et al.*, 2019; Aretoulaki *et al.*, 2021; Díaz-Mendoza *et al.*, 2023). To mitigate these impacts, many coastal regions organize cleanup campaigns. However, these initiatives are costly, time-intensive, and require significant human and mechanical resources, including heavy machinery and skilled labor (Silva, 2021).

Globally, the economic losses caused by marine plastic litter in the fishing, aquaculture, and tourism sectors were estimated to range from $6 billion to $19 billion annually by 2018 (UNEP, 2021). Additionally, the environmental costs of marine plastic, based on ecosystem service values from 2011, were estimated at $3,300 to $33,000 per tonne annually (Beaumont *et al.*, 2019). With the continued influx of plastic into marine environments, these costs could escalate to a staggering $100 billion in annual financial risks for businesses (UNEP, 2021).

The deterioration of marine environments due to plastic pollution has far-reaching social consequences, including significant impacts on human health and well-being. These effects arise from various factors, such as the ingestion of contaminated seafood, exposure to pathogenic organisms and toxic pollutants attached to plastic particles, and injuries caused by contact with plastic debris (Aretoulaki *et al.*, 2021; UNEP, 2021).

Coastal areas are popular destinations due to their recreational and social opportunities, such as bathing, diving, sports, and social interactions (UNEP, 2021). However, the presence of plastic litter on beaches poses serious risks to public health. Unsanitary plastic debris, such as cigarette butts, can release chemicals with endocrine-disrupting properties or harbor pathogenic microorganisms, leading to skin exposure risks. These hazards are particularly concerning for children, who may inadvertently ingest small items like cigarette butts while playing, driven by curiosity and oral exploration behaviors (Díaz-Mendoza *et al.*, 2023; Vanapalli *et al.*, 2023). Nicotine poisoning from ingesting cigarette butts has been reported to cause nausea and vomiting in children, with potentially lethal outcomes at doses as low as 1.0 mg/kg of body weight (Vanapalli *et al.*, 2023).

Recreational activities in coastal areas also expose individuals to physical injuries from sharp debris or entanglement in discarded fishing nets. Such incidents can range from minor cuts to life-threatening situations. For instance, divers entangled in nets may struggle to free themselves, potentially leading to drowning (Beaumont *et al.*, 2019; Aretoulaki *et al.*, 2021). These risks discourage people from visiting coastal areas and participating in recreational activities, which can negatively affect their mental health and emotional well-being (Beaumont *et al.*, 2019).

Another critical health concern linked to plastic pollution is the presence of microplastics (**MPs**) in the human body. Microplastics can enter the body through contaminated food, inhalation, or skin absorption (Aretoulaki *et al.*, 2021; UNEP, 2021; Huang *et al.*, 2022; Ragusa *et al.*, 2022; Winiarska *et al.*, 2024). Accumulation of MPs has been documented in various human tissues and organs, including colonic tissue (Ibrahim *et al.*, 2021), sputum (Huang *et al.*, 2022), cirrhotic liver tissue (Horvatits *et al.*, 2022), breast milk (Ragusa *et al.*, 2022), the placenta (Ragusa *et al.*, 2021), and even human blood (Leslie *et al.*, 2022).

The potential health impacts of MPs are concerning. Studies have linked MPs to enzymatic disruption, fetal growth restriction, and adverse effects on children's motor, cognitive, and behavioral development (Gibson *et al.*, 2018; Ragusa *et al.*, 2021). Despite these findings, further research is urgently needed to comprehensively assess the full extent of microplastics' effects on human health (Aretoulaki *et al*., 2021).

The decline in mental health and well-being can also be attributed to the emotional toll of witnessing the harm caused by plastic pollution to iconic and culturally significant species, such as sea turtles, seabirds, and cetaceans. Images and reports of these animals injured or killed by plastic debris evoke strong emotional responses, which can have a widespread negative impact on public mental health. The rapid dissemination of such distressing information via social and mainstream media amplifies these effects (Beaumont *et al*., 2019; Aretoulaki *et al*., 2021; UNEP, 2021).

In light of the numerous adverse effects of marine plastic pollution on public health and socio-economic activities, urgent measures are needed to mitigate further damage. Public concern about marine plastic pollution is significant, as highlighted by Davison *et al.* (2021), who surveyed individuals across 14 countries in Europe and Australia. The study found widespread awareness of the potential human health risks and strong support for increased funding for research to better understand and address these impacts.

CHAPTER 3

Plastic Pollution in Freshwater Ecosystems

Introduction

Plastic pollution in marine ecosystems has garnered significant global attention due to its widespread impacts on ecosystems, biodiversity, and socio-economic activities (Mansfield *et al.*, 2024). However, approximately 80% of all plastic litter found in oceans originates from land-based sources, with rivers serving as the primary transport pathways (**Figure 18**) (Andrady, 2011; Arat, 2024). Recent studies estimate that rivers introduce more than 60 billion microplastic particles into the oceans every day (GESAMP, 2016).

Despite their critical role in the global plastic cycle, freshwater ecosystems remain comparatively under-researched compared to their marine counterparts (Mansfield *et al.*, 2024). A literature search conducted in December 2024 on ScienceDirect for the period between 1980 and 2024 highlights this disparity: of the 169,727 studies retrieved with the term "plastic pollution," only 27,625 publications (16.3%) addressed freshwater systems, compared to 49,074 studies (29.4%) focusing on marine ecosystems. This lack of data limits our understanding of the accumulation, abundance, transport, and ecological impacts of plastic particles in freshwater environments. However, in recent years, this knowledge gap has begun to close due to the increasing scientific and public focus on the issue (Blair *et al.*, 2019).

Figure 18. River with plastic debris, serving as the main pathway of plastic litter from terrestrial to marine environments (@Landscape Laboratory).

Assessment and Abundance of Plastic Particles in Freshwater Ecosystems

The effective monitoring of plastic pollution in freshwater ecosystems is essential for quantifying its presence, understanding its transport mechanisms, assessing its ecological impacts, and evaluating mitigation strategies (van Emmerik *et al*., 2023).

Recent studies confirm that plastic particles are pervasive across freshwater and terrestrial environments worldwide, highlighting their abundance in rivers, sediments, and surface waters (**Figure 19**) (Lin *et al*., 2018; Blair *et al*., 2019; Schell *et al*., 2021; Ribeiro *et al*., 2022; Mansfield *et al*., 2024). **Table A4** (in annex) summarizes key monitoring efforts aimed at assessing the concentration and distribution of plastic particles across freshwater environments globally. Data include environmental compartments (e.g., surface water, sediment), particle size categories, and plastic concentrations.

The results indicate that plastic pollution is widespread across freshwater ecosystems globally. Analysis of sediment samples presented in **Table A4** revealed that the Pearl River in Asia exhibited the highest concentration of plastic items per kilogram among all studies reviewed. Even when considering the mean value (1669 items/kg), Lin *et al.* (2018) reported plastic particle abundances in the Pearl River sediments that were two orders of magnitude greater than those observed in another Asian river (3.03 particles/100 g, equivalent to 30.3 particles/kg) by Alam *et al.* (2019). Comparable levels of plastic particle abundance were identified in sediment samples from two European countries within the Atlantic Region: Portugal (Ribeiro *et al*., 2022) and Spain (Schell *et al*., 2021). Conversely, lower abundances – one order of magnitude less – were reported in river sediments from other European countries, such as Poland (Sekudewicz *et al*., 2021), Ireland (Murphy *et al*., 2022), and the United Kingdom (Tibbetts *et al*., 2018; Blair *et al*., 2019) as well as in South Africa (Nel *et al*., 2018).

When evaluating the concentration of plastics in river water (measured in items/m³, as presented in **Table A4**), another Asian river reported the highest abundance (maximum of 7924 items/m³) (Lin *et al*., 2018). Even the mean concentration (2724 items/m³) observed in the Pearl River exceeded levels recorded in rivers in Portugal (Rodrigues *et al*., 2018) and Poland (Sekudewicz *et al*., 2021). In studies reporting results in items/L, rivers in the Iberian Peninsula displayed the highest abundance of plastic particles in surface water (Prata *et al*., 2021; Schell *et al*., 2021) compared to all other case studies summarized in **Table A4**. These levels were one order of magnitude higher than those found in a U.S. river (Said & Heard, 2020) and two orders of magnitude higher than those in an Indonesian river (Alam *et al*., 2019).

Figure 19. Presence of plastic litter in the surface water of a freshwater system (@gettyimages).

However, as highlighted in **Chapter 2**, direct comparisons between studies must be approached cautiously. Beyond differences in geographic and environmental conditions, this caution stems from the lack of standardized protocols for assessing plastic litter abundance in freshwater environments. For example, even within a single study, results can vary depending on the unit used to report plastic particle abundance (Rodrigues *et al.*, 2018). The need for standardized methodologies, consistent data collection protocols, and improved model validation is therefore pressing (Rodrigues *et al.*, 2018; Castro-Jiménez *et al.*, 2019; Schell *et al.*, 2021).

Seasonal variations also significantly influence the abundance of plastic litter in freshwater ecosystems. For instance, Schell *et al.* (2021) observed higher concentrations of microplastics in river water during periods of high flow but noted lower concentrations in the sediments during these times. Conversely, Nel *et al.* (2018), reported greater microplastic abundance in sediments during periods of reduced flow. Similarly, Hurley *et al.* (2018) found that flood events could efficiently transport significant quantities of microplastics downstream. Consequently, the timing of sampling is a critical factor to consider in studies assessing plastic litter in freshwater systems.

In addition to hydrodynamic and ecological conditions, land use around river environments strongly influences plastic litter concentrations (Schell *et al.*, 2021). Proximity to urban settlements is a primary driver of freshwater plastic pollution (Rodrigues *et al.*, 2018; Tibbetts *et al.*, 2018; Ribeiro *et al.*, 2022). In the study by Alam *et al.* (2019) observed that microplastic fibers were the predominant shape in water and sediment samples from the Ciwalengke River, attributing this to domestic activities, such as laundry, and the nearby textile industry. Furthermore, the presence of wastewater treatment plants (**WWTPs**) in river catchments can significantly impact microplastic concentrations. Said & Heard (2020) hypothesised that the existence of a WWTP is a critical factor to the presence of microfibers in the surface water, as they found higher concentrations downstream of WWTPs installations compared to upstream. Also, Schell *et al.* (2021) estimated that approximately 1.0 x 10^{10} microplastic particles are released annually into the Henares River via wastewater, contributing 15 – 50% of the river's total microplastic contamination. However, Lin *et al.* (2018) suggested that while WWTPs can mitigate microplastic release, they are not entirely effective, and residual plastics still enter the environment.

Rivers serve as major conduits of plastic litter to marine environments. For example, Castro-Jiménez *et al.* (2019), reported an average of 37 items/hour of floating plastic in the surface waters of the Rhone River, equating to an annual contribution of approximately 2.23 x 10^5 macroplastic items to the NW Mediterranean Sea. Similarly, van Emmerik *et al.* (2023) observed peak transport rates of 858 items/hour and 1575 items/hour in the Rhine (Europe) and Odaw (Africa) rivers, respectively, emphasizing the role of freshwater systems as pathways for land-derived plastic pollution to the oceans.

Although rivers contribute significantly to plastic pollution, the majority of plastic litter introduced into terrestrial and aquatic riverine compartments does not ultimately reach the seas. Instead, rivers serve as substantial reservoirs for plastic waste, with litter accumulating along riverbanks, vegetation, sediments, and infrastructure near population centers and pollution sources (**Figure 20**) (van Emmerik *et al.*, 2022; Pace *et al.*, 2024). For instance, van Emmerik *et al.* (2023) recorded maximum accumulations of 17 items/m² on riverbanks of the Odaw River. Similar findings were reported by Pace *et al.* (2024) and Ballerini *et al.* (2022) in northern Portuguese rivers and French river-lake systems, respectively, where plastic constituted 86.14% and 56.63% of all macrolitter.

Figure 20. Retention and accumulation of plastic litter in the riverbanks of freshwater systems (@Landscape Laboratory).

Although a substantial proportion of land-sourced plastic litter does not reach the oceans, its presence in river systems still poses significant environmental risks. Plastic in rivers breaks down into smaller particles over time, persisting for decades and exerting detrimental effects on freshwater organisms, akin to the impacts observed in marine ecosystems (van Emmerik *et al.*, 2022).

Assessment, Abundance and Impacts of Plastic Particles in Freshwater Organisms

In recent years, numerous studies have demonstrated that freshwater ecosystems are significantly contaminated with plastic particles of various sizes. These ecosystems also serve as major conduits, transferring large amounts of plastic debris from land-based sources into the seas (Lin *et al.*, 2018; Castro-Jiménez *et al.*, 2019; Ribeiro *et al.*, 2022; van Emmerik *et al.*, 2023). Despite growing interest and research on plastic pollution in freshwater environments, the interactions between plastic litter and freshwater organisms remain poorly understood (**Figure 21**) (Collard *et al.*, 2019).

Evidence has emerged of benthic organisms incorporating plastic particles into their structures (Tibbetts *et al.*, 2018; Ehlers *et al.*, 2020) or ingesting microplastics from their surroundings (Hurley *et al.*, 2017; Ribeiro *et al.*, 2022). This issue is particularly concerning because, as observed in marine environments, plastic particles can bioaccumulate and biomagnify through the food web, reaching higher trophic levels (Hurley *et al.*, 2017; Miller *et al.*, 2020).

The table in annex summarizes key studies that have assessed and monitored the presence and abundance of plastic particles in various freshwater organisms (**Table A5** in annex).

Similar to other studies on plastic pollution in the environment, inconsistencies in sampling methods, methodologies, and data collection create significant challenges in comparing existing findings. In a global review of plastic particle ingestion by freshwater fish, Collard *et al.* (2019) highlighted these difficulties, noting variations in protocols, including small sample sizes, reliance on visual sorting to identify microplastics (**MPs**), and inconsistent reporting units.

Plastic particles have been found in a wide range of freshwater animals, from small benthic invertebrates to larger organisms such as freshwater birds (**Table A5**). Freshwater organisms can actively ingest plastic particles if present in their environment. Microplastics have been detected in various benthic invertebrates, with Ribeiro *et al.* (2022) reporting a maximum of 1069.4 particles/kg in Oligochaeta. Hurley *et al.* (2017) and Nel *et al.* (2018) also documented microplastics in benthic organisms, but their results were reported in different units – particles/kg, particles/g, and particles/mg. When standardized to particles/kg, African river organisms showed the highest abundance of MPs (1.12 x 10^6 particles/kg) (Nel *et al.*, 2018) compared to the English (1.29 x 10^5 particles/kg) (Hurley *et al.*, 2017) and the Portuguese rivers (Ribeiro *et al.*, 2022).

The case studies summarized in **Table A5** reveal that freshwater fish from Asian rivers had a higher average ingestion of plastic particles (Zheng *et al.*, 2019; Kasamesiri & Thaimuangphol, 2020)), aligning with the higher levels of plastic pollution found in sediments and water columns in these rivers (Lin *et al.*, 2018). In contrast, fish from European watercourses exhibited the lowest presence of plastic particles, with an average of less than one particle per fish (Horton *et al.*, 2018; Roch *et al.*, 2019). Among the various shapes of microplastics ingested by fish, fibers were the most commonly reported type (Silva-Cavalcanti *et al.*, 2016; Zheng *et al.*, 2019; Kasamesiri & Thaimuangphol, 2020). Kasamesiri & Thaimuangphol (2020) suggested that these fibers primarily originate from fishing gear and synthetic clothing. Additionally, Silva-Cavalcanti *et al.* (2016) observed higher ingestion rates of MPs in areas with greater urbanization.

Although the effects of plastic ingestion in freshwater environments remain less studied compared to marine ecosystems, some impacts have been documented. The abundance and size of ingested particles significantly influence the severity of adverse effects (Roch *et al.*, 2019). In fish, plastic ingestion has been negatively correlated with the diversity of other food items consumed (Silva-Cavalcanti *et al.*, 2016), indicating potential interference with feeding behaviors (Jovanović, 2017). Ingested plastic particles can physically block digestive organs, cause ulcerations and mechanical damage, and translocate to other organs such as the liver and brain (Mattsson *et al.*, 2017; Collard *et al.*, 2018). Behavioral disorders have also been observed.

These particles may enter the human food chain through the trophic web (Mattsson *et al*., 2017).

Adverse effects have already been reported in organisms other than fish (Ehlers *et al*., 2020; Silva *et al.*, 2021b; Di Lorenzo *et al*., 2023). Silva *et al.* (2021b) demonstrated that microplastic ingestion by *Chironomus riparius* larvae activated an innate immune response, resulting in oxidative stress and increased energy expenditure, making the organisms more vulnerable to pathogens, pollutants, and abiotic stressors (Silva *et al*., 2021b). Additionally, Silva *et al.* (2023), reported delayed regeneration of planarian auricles by at least one day after ingestion of contaminated prey. The ingestion of MPs by macroinvertebrates has also been shown to disrupt aquatic ecosystem functioning by altering predator–prey dynamics and trophic interactions (e.g., Krause *et al*., 2021; Di Lorenzo *et al*., 2023).

Beside ingestion, Ehlers *et al.* (2020) observed that caddisfly larvae used plastic particles to construct emergency cases. However, this practice reduced case stability, increasing vulnerability to predation and displacement by river currents. Moreover, proximity to plastic particles in these cases may expose the larvae to leachates, causing toxic effects through gill absorption (Ehlers *et al*., 2020).

Despite the evident presence of plastic pollution and its documented impacts on freshwater ecosystems, research in this area remains limited. This disparity may be attributed to the higher economic value of marine resources and greater funding for marine studies compared to freshwater systems (Collard *et al*., 2019). Nonetheless, further efforts are essential to understand the plastic burden in freshwater ecosystems, with a particular emphasis on fish species, given their importance as a food source for humans (Roch *et al*., 2019).

Figure 21. Bird nest containing eggs and incorporating anthropogenic plastic debris as nesting material, illustrating an indirect pathway of plastic pollution impacts on wildlife, e.g., entanglement risk and exposure of chicks (@Landscape Laboratory).

CONCLUSION

In conclusion, this report underscores the significant presence and profound impact of plastic pollution on the marine environment. As an emerging global issue, marine plastic pollution poses serious threats to ecosystems, biodiversity, and socioeconomic activities, drawing increasing scientific and public attention. Plastics are pervasive across marine environments, and their surfaces can adsorb hazardous substances, presenting ecotoxicological risks to marine life. Additionally, plastics facilitate the spread of non-indigenous species with invasive potential and microorganisms carrying virulence and antibiotic resistance genes.

Plastic debris also directly affects marine biota through entanglement or ingestion, leading to a wide spectrum of adverse effects, including physical injuries, behavioral changes, deformities, suffocation, drowning, and in severe cases, mortality. These biological impacts ripple through to human systems, adversely affecting socioeconomic activities, public health, and overall well-being.

Freshwater ecosystems are equally affected, serving as critical pathways for the transportation of plastic debris from terrestrial sources to the ocean. Despite this, freshwater systems remain understudied, and research gaps persist. This is concerning, as the ecological and socioeconomic consequences of plastic pollution in freshwater systems are no less severe than those in marine environments.

Given these realities, urgent action is needed to prevent further ecosystem degradation. The establishment of a universal standard protocol that consolidates validated techniques and equipment is essential to enable direct comparisons across studies and enhance our understanding of the issue. Moreover, the perspective on marine plastic pollution must shift – from viewing it solely as a problem to recognizing it as an opportunity. By addressing every stage of the plastic lifecycle and promoting sustainable, circular solutions that repurpose marine plastics as raw materials, we can mitigate environmental harm while unlocking a sustainable and innovative value chain (**Figure 22**). This approach is crucial to driving the transition towards the much-needed blue circular economy.

Figure 22. Transition to a blue circular economy by creating new materials from plastic litter previously removed from the environment (@Landscape Laboratory).

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ANNEX

Table A1. Assessment of plastic pollution and abundance in beach sediments worldwide. It includes details such as the sampling period, location, plastic size categories (as defined in Table 1), concentrations, and study references. Plastic concentrations are presented as total (*), mean (**) or median (***).

Sampling Period	Beach	Location	Plastic Size Category	Concentration	Reference
07 / 2012	McCormack Beach	Nova Scotia, Canada	Microplastic	28 - 51 particles/10g sediment (**)	Mathalon & Hill (2014)
07 / 2012	Rainbow Haven Beach	Nova Scotia, Canada	Microplastic	38 - 74 particles/10g sediment (**)	Mathalon & Hill (2014)
07 / 2017	Sanggou Bay	Shandong Province, China	Microplastic	2178 items/kg (**)	Wang *et al.* (2019)
08 / 2017	Sanggou Bay	Shandong Province, China	Microplastic	3035 items/kg (**)	Wang *et al.* (2019)
03 / 2017 & 08 / 2017	9 Slovenian Beaches	Slovenia	Microplastic	7.2 - 10.9 particles/kg (**)	Korez *et al.* (2019)
02 / 2018	Costa Nova Beach	Aveiro, Portugal	Microplastic	11 particles/kg (*)	Prata *et al.* (2020)
06 / 2018	Costa Nova Beach	Aveiro, Portugal	Microplastic	43 particles/kg (*)	Prata *et al.* (2020)
10 / 2018	Costa Nova Beach	Aveiro, Portugal	Microplastic	20 particles/kg (*)	Prata *et al.* (2020)
10 / 2018	Barra Beach	Aveiro, Portugal	Microplastic	100 particles/kg (***) 15 - 320 particles/kg (*)	Chouchene *et al.* (2021)

11 / 2018	La Herradura Beach	Granada Coast, Spain	Microplastic	45 particles/kg d.w. (***)	Godoy *et al.* (2020)
11 / 2018	Montril Beach	Granada Coast, Spain	Microplastic	31.5 particles/kg d.w. (***)	Godoy *et al.* (2020)
11 / 2018	La Rábita Beach	Granada Coast, Spain	Microplastic	22.0 particles/kg d.w. (***)	Godoy *et al.* (2020)
09 / 2018	4 Chinese Beaches	Hong Kong, China	Microplastic	188 items/kg (**)	Lo *et al.* (2020)
09 / 2018	4 Chinese Beaches	Hong Kong, China	Microplastic	355 items/kg (**)	Lo *et al.* (2020)
09 / 2018	4 Chinese Beaches	Hong Kong, China	Macroplastic	0.047 items/m^2 (**)	Lo *et al.* (2020)
09 / 2018	4 Chinese Beaches	Hong Kong, China	Macroplastic	0.54 items/m^2 (**)	Lo *et al.* (2020)
11 / 2019	8 Vietnamese Beaches	Da Nang, Vietnam	Microplastic	9238 items/kg (**)	Nguyen *et al.* (2020)
08 / 2020 - 09 / 2020	6 Thai Beaches	Rayong Province, Thailand	Microplastic	338.89 particles/kg d.w. (**)	Prarat & Hongsawat (2022)
06 / 2021 - 05 / 2022	Pehuen Co Beach	Province of Buenos Aires, Argentina	Macroplastic (Cigarette butts)	0.005 - 0.396 items/m^2 (**)	Díaz-Mendoza *et al.* (2023)
06 / 2021 - 05 / 2022	Bocagrande Beach	Catargena, Colombia	Macroplastic (Cigarette butts)	0.068 - 0.310 items/m^2 (**)	Díaz-Mendoza *et al.* (2023)
06 / 2021 - 05 / 2022	Peró Beach	Cabo Frio, Rio de Janeiro, Brazil	Macroplastic (Cigarette butts)	0.647 - 0.750 items/m^2 (**)	Díaz-Mendoza *et al.* (2023)

06 / 2021 - 05 / 2022	Malécón Beach	Playas Vilamil, Ecuador	Macroplastic (Cigarette butts)	0.023 - 0.144 items/m^2 (**)	Díaz-Mendoza *et al.* (2023)
06 / 2021 - 05 / 2022	La Audiencia Beach	Manzanillo, Mexico	Macroplastic (Cigarette butts)	0.076 - 0.231 items/m^2 (**)	Díaz-Mendoza *et al.* (2023)

Table A2. Assessment of plastic pollution and abundance in the water column of marine ecosystems worldwide. It includes details such as the sampling period, column component (surface, middle, or deepwater), location, plastic size categories (as defined in Table 1), concentrations, and study references. Plastic concentrations are reported as total (*), mean (**) or median (***).

Sampling Period	Column Component	Location	Plastic Size Category	Concentration	Reference
07 / 2012	Surface Seawater	Sardinian Sea, Northwest Sardinia	Microplastic	0.00 - 0.44 items/m^3 (*), 0.10 items/m^3 (**)	Panti *et al.* (2015)
07 / 2013	Surface Seawater	Sardinian Sea, Northwest Sardinia	Microplastic	0.00 - 0.69 items/m^3 (*), 0.24 items/m^3 (**)	Panti *et al.* (2015)
10 / 2016 - 11 / 2016	Surface Seawater	Northeastern Levantine Coast of Turkey	Micro- and Mesoplastic	0.376 items/m^2 (**)	Gündoğdu & Çevik (2017)
07 / 2017	Surface Seawater	Sanggou Bay, Shandong Province, China	Microplastic	63.6 items/L (**)	Wang *et al.* (2019)
08 / 2017	Surface Seawater	Sanggou Bay, Shandong Province, China	Microplastic	89.5 items/L (**)	Wang *et al.* (2019)
08 / 2020 - 09 / 2020	Surface Seawater	Rayong Province, Thailand	Microplastic	1781.48 particles/m^3 (**)	Prarat & Hongsawat (2022)
Summers of 2020 & 2021	Surface Seawater	Chukchi Sea, Western Arctic Ocean	Microplastic	0 - 18815 particles/km^2 (*), 5236 particles/km^2 (**)	Ikenoue *et al.* (2023)

10 / 2020	Surface Seawater	Kattegat/ Skagerrak Basin, Denmark	Microplastic	18 - 87 MPs/m³ (*), 41 MPs/m³ (**), 40 MPs/m³ (***)	Gunaalan *et al.* (2024)
10 / 2020	Middlewater	Kattegat/ Skagerrak Basin, Denmark	Microplastic	186 - 157 MPs/m³ (*), 53 MPs/m³ (**), 31 MPs/m³ (***)	Gunaalan *et al.* (2024)
10 / 2020	Deepwater	Kattegat/ Skagerrak Basin, Denmark	Microplastic	13 - 95 MPs/m³ (*), 35 MPs/m³ (**), 47 MPs/m³ (***)	Gunaalan *et al.* (2024)

Table A3. Assessment of plastic pollution and abundance in estuaries worldwide. It includes details such as the sampling period, location, plastic size categories (as defined in Table 1), concentrations, and study references. Plastic concentrations are presented as total (*), mean (**) or median (***).

Sampling Period	Estuary	Location	Plastic Size Category	Concentration	Reference
07 / 2014 - 09 / 2014	Pearl River Estuary	Hong Kong, China	Microplastic	5595 items/m² (**)	Fok & Cheung (2015)
07 / 2014 - 09 / 2014	Mobile Bay Estuary	Gulf of Mexico, USA	Microplastic	5 - 117 pieces/m² (*)	Wessel *et al.* (2016)
02 / 2015	Mira Estuary	Southwest Coast, Portugal	Microplastic	8.0 - 37.1 particles/g d.w. (*)	Duarte *et al.* (2020)
09 / 2016 - 11 / 2016	Río de la Plata Estuary	Southern Coastal Fringe, Argentina	Microplastic	164 MPs/m³ (**)	Pazos *et al.* (2018)
04 / 2017 - 06 / 2017	Río de la Plata Estuary	Southern Coastal Fringe, Argentina	Microplastic	114 MPs/m³ (**)	Pazos *et al.* (2018)
Spring and Autumn 2017	Pas Estuary	Gulf of Biscay, Cantabria, Spain	Meso- and Microplastic	0.18 - 5.05 items/m² (**)	Mazarrasa *et al.* (2019)

Spring and Autumn 2017	Miera Estuary	Gulf of Biscay, Cantabria, Spain	Meso- and Microplastic	0.01 - 3.21 items/ m^2 (**)	Mazarrasa *et al.* (2019)
Spring and Autumn 2017	Asón Estuary	Gulf of Biscay, Cantabria, Spain	Meso- and Microplastic	0.00 - 2.77 items/ m^2 (**)	Mazarrasa *et al.* (2019)
07 / 2018	Yellow River Estuary	Shandong Province, China	Microplastic	654 items/L (**)	Han *et al.* (2019)
08 / 2020	St. Lawrence Estuary	Quebec City, Canada	Microplastic	120.7 MPs/m^3 (**)	Kelly (2024)
10 / 2019 - 05 / 2022	Delaware Bay Estuary	Delaware, USA	Microplastic	0.34 MPs/m^3 (**)	Nitzberg *et al.* (2024)
10 / 2019 - 05 / 2022	Delaware Bay Estuary	Delaware, USA	Macroplastic	8.2 x 10^{-3} MPs/ m^3 (**)	Nitzberg *et al.* (2024)

Table A4. Assessment of plastic pollution and abundance in freshwater ecosystems worldwide. It includes details such as the sampling period, location, freshwater body, environmental compartment (surface water, riverbed sediment, and riverbank), plastic size categories (as defined in Table 1), concentrations, and study references. Plastic concentrations are presented as total (*), mean (**) or median (***).

Sampling Period	Location	Freshwater Body	Environmental Compartment	Plastic Size Category	Concentration	Reference
12 / 2015 & 02 / 2016	Glasgow, Scotland, UK	Kelvin River	Sediment	Microplastic	161 - 432 MPs/kg dry sediment (*)	Blair *et al.* (2019)
02 / 2016 - 07 / 2016	Eastern Cape Province, South Africa	Bloukrans River	Sediment	Microplastic	6.3 - 160.1 particles/kg (**)	Nel *et al.* (2018)
03 / 2016 & 10 / 2016	Aveiro, Portugal	Antuã River	Sediment	Microplastic	18 - 629 items/kg (*)	Rodrigues *et al.* (2018)

06 / 2017 - 07 / 2017	Birmingham, UK	Tame River	Sediment	Microplastic	165 particles/kg (**)	Tibbetts *et al.* (2018)
07 / 2017	Guangzhou, China	Pearl River	Sediment	Microplastic	80 - 9597 items/kg (*) 1669 items/ kg (**)	Lin *et al.* (2018)
07 / 2017 - 08 / 2017, 11 / 2017 & 04 / 2018	Central Spain	Henares River Catchment	Sediment	Microplastic	0 - 2630 MPs/kg dw (**)	Schell *et al.* (2021)
10 / 2017 - 11 / 2017	Majalaya District, Indonesia	Ciwalengke River	Sediment	Microplastic	3.03 particles/100 g dw (**)	Alam *et al.* (2019)
01 / 2018	Poland	Vistula River	Sediment	Microplastic	190 - 580 items/kg (*)	Sekudewicz *et al.* (2021)
08 / 2018 & 07 / 2019	Ireland	Barrow River	Sediment	Microplastic	172.5 MPs/ kg (**)	Murphy *et al.* (2022)
Summer 2020	Guimarães, Portugal	Selho River	Sediment	Microplastic	932.5 - 1593.2 particles/kg dw (*)	Ribeiro *et al.* (2022)
Summer 2020	Guimarães, Portugal	Costa/Couros River	Sediment	Microplastic	2130.3 - 3018.2 particles/kg dw (*)	Ribeiro *et al.* (2022)
03 / 2016 & 10 / 2016	Aveiro, Portugal	Antuã River	Surface Water	Microplastic	58 - 1265 items/m^3 (*)	Rodrigues *et al.* (2018)
09 / 2016 - 09 / 2017	Arles, France	Rhone River	Surface Water	Macroplastic	37 items/hour (**) 26 items/hour (***)	Castro - Jiménez *et al.* (2019)
07 / 2017	Guangzhou, China	Pearl River	Surface Water	Microplastic	379 – 7924 items/m^3 (*) 2724 items/ m^3 (**)	Lin *et al.* (2018)

07 / 2017 - 08 / 2017, 11 / 2017 & 04 / 2018	Central Spain	Henares River Catchment	Water	Microplastic	1 - 227 MPs/ m^3 (*)	Schell *et al.* (2021)
10 / 2017 - 11 / 2017	Majalaya District, Indonesia	Ciwalengke River	Surface Water	Microplastic	5.85 particles/L (**)	Alam *et al.* (2019)
01 / 2018	Poland	Vistula River	Water	Microplastic	1.6 - 2.55 items/L (*)	Sekudewicz *et al.* (2021)
06 / 2018 & 07 / 2018	Nashville, USA	Cumberland River	Surface Water	Microplastic	27.9 microfibers/L (**)	Said & Heard (2020)
11 / 2019	Porto, Portugal	Douro River	Surface Water	Microplastic	231 MPs/L (***)	Prata *et al.* (2021)
12 / 2021 - 01 / 2022	Ghana	Odaw River	Surface Water	Floating Plastic	0 - 1575 items/ hour (*)	van Emmerik *et al.* (2023)
03 / 2022	Switzerland, Germany & Netherlands	Rhine River	Surface Water	Floating Plastic	3 - 858 items/ hour (*)	van Emmerik *et al.* (2023)
12 / 2021 - 01 / 2022	Ghana	Odaw River	Riverbank	-	13 - 17 items/ m^2 (*)	van Emmerik *et al.* (2023)

Table A5. Assessment of plastic pollution and abundance in organisms of freshwater ecosystems. It includes details such as the sampling period, location, freshwater body, organism, plastic size categories (as defined in Table 1), concentrations, and study references. Plastic concentrations are presented as total (*), mean (**) or median (***).

Sampling Period	Location	Freshwater Body	Organism	Plastic Size Category	Concentration	Reference
-	Canada	-	18 Bird Species	Microplastic	0 - 0.33 particle/bird	Holland *et al.* (2016)

07 / 2012 - 11 / 2014	Brazil	Xingu River	16 Serrasalmid Species	Meso- and Microplastic	0 - 42 particles/ species (*)	Andrade *et al.* (2019)
05 / 2013 - 06 / 2013	Serra Talhada, Brazil	Pajeú River	*Hoplosternum littorale*	Microplastic	1 - 24 particles/fish (*) 3.6 particles/ fish (**)	Silva-Cavalcanti *et al.* (2016)
07 / 2013 - 10 / 2013	UK	Thames River	*Rutilus rutilus*	Microplastic	0.69 particles/ fish (**)	Horton *et al.* (2018)
2014 - 2018	Baden - Württemberg, Germany	16 Rivers and 7 Lakes	22 Freshwater Fish Species	Microplastic	0.2 particles/ fish (**)	Roch *et al.* (2019)
-	China	Pearl River Catchment	9 Freshwater Fish Species	Meso- and Microplastic	7.0 items/ individual (**)	Zheng *et al.* (2019)
02 / 2016 & 07 / 2016	Eastern Cape Province, South Africa	Bloukrans River	*Chironomus* spp.	Microplastic	0.37 - 1.12 particles/mg ww (**)	Nel *et al.* (2018)
Spring 2017	Manchester, UK	Waterbody Fed by Irwell River	*Tubifex tubifex*	Microplastic	129 particles/g tissue (**)	Hurley *et al.* (2017)
10 / 2018	Maha Sarakham Province, Thailand	Chi River	8 Freshwater Fish Species	Microplastic	1.76 particles/ fish (**)	Kasamesiri & Thaimuangphol (2020)
Summer 2020	Guimarães, Portugal	Selho River	Oligochaeta	Microplastic	134.0 - 558.6 particles/kg fw (*)	Ribeiro *et al.* (2022)
Summer 2020	Guimarães, Portugal	Costa/Couros River	Oligochaeta	Microplastic	95.3 - 1069.4 particles/kg fw (*)	Ribeiro *et al.* (2022)

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