Policy Brief

Plastic pollution and the plastisphere: findings and recommendations

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Abstract

Plastic pollution is an environmental concern due to the magnitude of mismanaged plastics reaching the environment and affecting it in different ways. Their physicochemical properties, including their light weight, resistance to corrosion and low degradation rates, allow plastics to travel great distances in the environment. Plastics undergo weathering, degradation, and fragmentation processes through exposure to ultraviolet radiation, abrasion, and interactions with biota. The JPI Oceans funded 'MicroplastiX' project explored the interaction between plastics, microorganisms, and the biofilm layer at the surface, which is a less studied scientific area. Moreover, the project also focussed on the organic and inorganic pollutants in this surface biofilm layer, commonly known as 'plastisphere'.

This brief highlights the main project findings resulting from case-studies carried out in the Atlantic Ocean and Mediterranean Sea. These aimed to assess the (1) environmental microplastic (MP) concentrations, (2) genetic diversity and accumulation of persistent organic pollutants (POPs) and trace metals in the plastisphere and the (3) polymer type spectral changes from *in situ* experiments. The aim of this international collaborative and interdisciplinary project was to improve the understanding of how degradation mechanisms affect plastics in natural environments. The team included a network of scientists from diverse research fields (chemistry, biology, microbiology, physics and mathematical modelling), and countries (Sweden, Germany, France, Italy, Spain, Ireland, and Brazil), working in synergy to address gaps on the pathways and fate of plastics in coastal and open ocean waters.

Shifting focus from sources and pathways to fate and degradation

Once a promising material, plastic has gradually become a global environmental threat with ubiquitous distribution and unpredictable socio-economic impacts. Plastic marine debris has been **studied since the early 1970s** and focus on **microplastics** (MPs) began in the **early 2000s**. Considering that **mass production** only started in the **1950s**, it took little to no time until plastic was **widespread** in terrestrial and marine environments. Over the last two decades, **research efforts** on **plastic pollution** have collected significant volumes of data to assess environmental concentrations of this novel pollutant. This information has contributed towards identifying **sources, pathways, fate, and impacts** of plastics. A considerable amount of time and resources were allocated to identify sources and pathways, particularly **accumulation zones in the open ocean** and **assessing the distribution patterns** (e.g. North Pacific Garbage Patch; Lebreton *et al.,* 2018) and assessing the **terrestrial and aquatic pathways of microplastics** (Kumar *et al.*, 2023). Data collection and modelling efforts in the ocean have helped to target accumulation areas. In juxtaposition, **weathering, degradation, and fragmentation** of plastics and microplastics, which relate to **fate and impacts**, are processes where there is **limited**

research available. One of the pioneering projects to explore how these processes affect MP **transport, fate, and toxicity** in the marine environment in the Baltic Sea, was the 'WEATHER-MIC' project (Jahnke *et al.*, 2017). The project provided new insights into **how plastic additives leach to the surrounding environment and organisms** (Rummel *et al.,* 2019) and what are the **impacts of biofilm formation** on the fate of microplastics (Rummel *et al.,* 2017). This has opened the way for other projects to further explore this topic, and to fill the knowledge gaps that remain, just like 'MicroplastiX'.

Understanding the interactions between plastisphere and plastics

The concept of **plastisphere**, introduced by Zettler et al., (2013), describes the **microbial communities associated with plastic marine debris**. The biofilm layer growing on the top of plastics produces a **rich substrate** that attracts organisms and can adsorb POPs. Given that plastic **can travel great distances** and be found far away from its origin, there is a **potential risk** that **invasive** and **potentially harmful species** will be associated with plastic debris. In fact, our research team identified ***Vibrio spp.*** and other **potentially pathogenic bacteria** associated with **microfibers** in the **Mediterranean Sea** (Figure 1, Pedrotti *et al*., 2022).

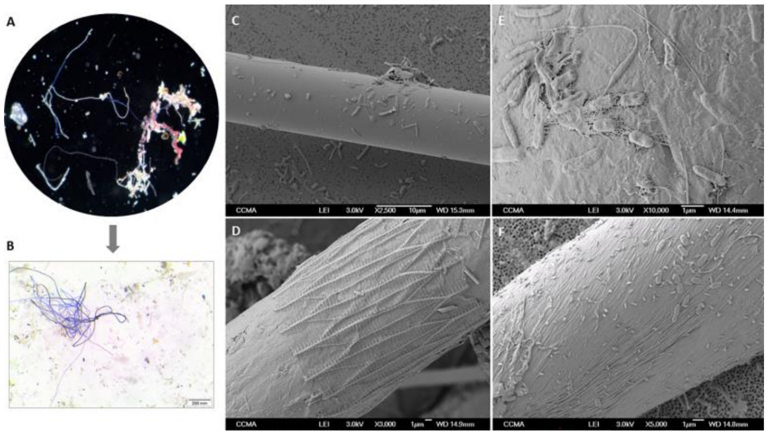

Figure 1 – Floating fibres (A, B) processed under optical microscopy and Scanning Electron Microscopy (SEM) of attached bacteria. Open access figure available in Pedrotti et al., (2022) https://doi.org/10.1371/journal.pone.0275284

Given that larger species such as **barnacles can also colonise plastic debris** (Gill and Pfaller, 2016), and that the **holes and fissures** resulting from **plastic degradation** can increase the **surface-to-area ratio** (Zheng *et al*., 2023), there is a possibility that more species will be identified associated with the plastisphere. **Genetic analysis** of our *in situ* experiments showed a **huge diversity of taxa** in the marine plastisphere. The research team explored the 16S (to identify Bacteria and Archaea) and 18S (for Eukaryotes) genes. In total, **28 phyla of prokaryotes**, and **49 groups of eukaryotes**, were identified. These included **microalgae, invertebrates, and fungi**. Our results highlight the capacity that plastics have to harbor diverse communities, with numerous ecological relationships. This analysis was able to find important taxa such as **bacteria** (*Vibrio spp*.), **invasive worms** (*Hydroides elegans*), and **dinoflagellates** (*Alexandrium spp.*), whose presence can represent a potential ecosystem and human health threat. **Further investigation into these species in the plastisphere of the Mediterranean Sea needs to be conducted.**

MicroplastiX also identified for the first-time water bears (tardigrades) in the plastisphere (Lacerda, Frias and Pedrotti, 2023). **From all the sites tested, water bears were only found in Galway, Ireland, during Summer.**

The genetic diversity assessment showed that the plastisphere is **diverse** and **site dependent**. Moreover, **polymer type** did **not** seem to **influence species richness** but had influence on the community composition in some locations. The Mediterranean sites (two sites in France and one in Italy) shared more common prokaryotes and eukaryotes groups than the Atlantic sites (Ireland, Spain and Brazil, each with one site). In fact, Rio Grande (**Brazil**) and A Coruña (**Spain**) presented the **highest number of prokaryotic phyla**, whereas Toulon (**France**) and Naples (**Italy**) showed the **lowest number of prokaryotic phyla**. This scenario changed for eukaryotes, where Galway (**Ireland**) and Naples (**Italy**) showed higher diversity when compared to the other sites.

Identification challenges: how FTIR spectra change over time under environmental conditions

As plastics undergo weathering and degradation processes, it has been hypothesized that **chemical identification might be hindered** by changes at the plastic surface, which would also result in **spectral changes**. These are thought to occur due to physical (e.g. abrasion), chemical (adsorption of organic and inorganic pollutants) and biological (e.g. development of biofilm layers) degradation processes. To assess the extent of spectral changes, an ***in-situ* experiment** was devised across the consortium. **Eight polymers** were enclosed in containers with holes to facilitate water circulation, and placed in stainless steel cages. These cages were deployed at sea for **one year** and were **sampled seasonally.** The retrieved samples were analysed using **FTIR and RAMAN spectroscopy**. Moreover, POPs and trace metals were assessed, alongside the previously mentioned genetic diversity. The Leibniz Institute of Polymer Research in Germany, and A Coruña University in Spain managed the laboratory analysis of **FTIR and RAMAN spectra**. Our project partners oversaw the **development of MP isolation and characterisation protocols** in biota and sediments (López-Rosales et al., 2022a-b).

The initial hypothesis suggested that slight spectral changes would occur over time, since the plastics were exposed to different **salinity, temperature, pH, and UV radiation** ranges across all sites. However, results showed **significant spectral changes occurred after 60 days of exposure to environmental conditions**. A visualisation tool (Figure 2) was created to assess those changes over time, and the link can be accessed from the provided reference list (Lenz *et al.*, 2023a-d). Results suggest that comparing match percentages between weathered plastics and reference databases might contribute to mismatch identification. This misidentification was specifically observed for **Polyvinyl Chloride (PVC)** by our research team (Fernández-González *et al*., 2022).

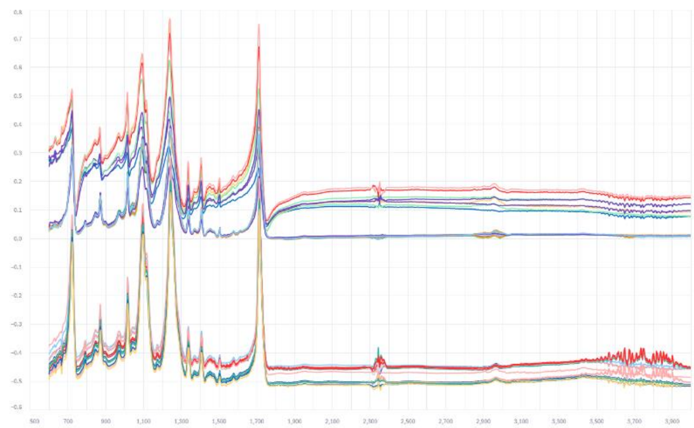

Figure 2 -Spectral changes for Polyethylene terephthalate (PET), in Villefranche, in each season at 7, 60 and 90 days. Figure retrieved from Lenz et al., 2023b.

Exploring microplastic concentrations in new habitats and species

Microplastics are commonly found in marine biota species, however, due to the lack of data in the Central and South Atlantic Ocean, MicroplastiX assessed sites along the coast of Brazil and the West African continent.

Environmental concentrations of MP have been assessed in zooplankton species within estuaries in Brazil (Lima *et al.,* 2023); in juvenile sea bream in a coastal lagoon in Portugal (Müller *et al.,* 2023), as well as in pelagic, mesopelagic, and deep-sea species (Justino *et al.*, 2023a-b, Justino *et al.*, 2022, Ferreira *et al.*, 2022, 2023, Pereira *et al.*, 2023) in the Tropical South Atlantic Ocean. Müller et al. (2023) confirmed that **juvenile white sea bream** feed on a variety of different prey items, yet individuals had **distinct feeding preferences,** making them **more susceptible to plastic ingestion**, particularly fragments. Yet, they may still be prone to ingesting fibers and other small particles, along with the ingestion of natural vegetal prey or detritus.

Two studies were conducted on molluscs, one exploring the **environmental concentrations of MP** (Bruzaca *et al.,* 2022) and the other carried out to **assess how long it would take for oysters to expel all potentially ingested microplastics** (Paul *et al.,* 2023). In the first study, a relatively low MP concentration (**average of 3.6 MPs per gram**) was identified in **clams** (*Anomalocardia flexuosa*) from an estuary in the South Atlantic Ocean. In the second study, it was shown that under laboratory conditions, **two oyster species** (*Magallana gigas* and *Ostrea edulis*), are able to **significantly reduce the concentrations of microplastics after 72 hours**. It is thought that under flowing water conditions, in adequate depuration facilities, the same results would be possible **after 48 hours**.

In the Tropical South Atlantic region, we have explored the **estuarine, coastal, and oceanic environments** using marine species as bioindicators to comprehend the MP contamination gradient. Estuarine fish, especially opportunistic predators, showcase elevated contamination rates, primarily ingesting fibre particles linked to effluent discharge in these areas (Justino *et al*., 2021). On the other hand, **coastal species, primarily feeding on mobile invertebrates**, display lower MP contamination compared to their estuarine counterparts (Figure 3, Justino *et al*., 2023b).

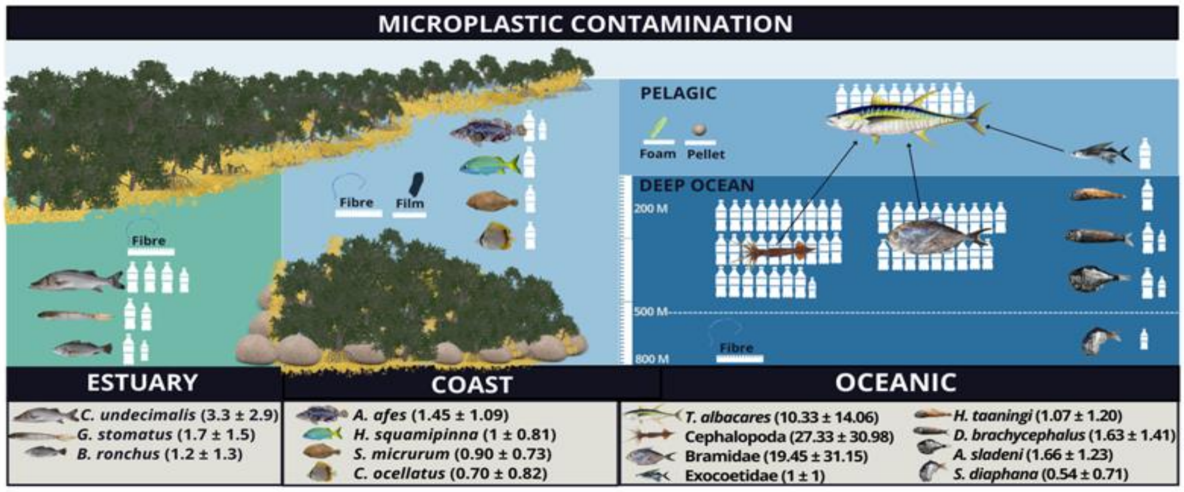

Figure 3- Integrated results of microplastics contamination in an estuary, coastal and oceanic sampling in Brazil

In the deep ocean, mesopelagic fish, crucial for **energy transfer in the ocean,** display varied contamination rates and polymer types at different depths, with individuals from the lower mesopelagic zone (500–1,000 m depth) showing lower exposure than those in the upper mesopelagic layer (200–500 m) (Justino *et al*., 2022, Ferreira *et al*., 2023). Lanternfishes, which feed on fish larvae, are particularly susceptible to MP intake, especially the tiniest MP size fraction (Ferreira *et al*., 2023). Additionally, deep-sea cephalopods like the **Vampire squid showed high MP contamination levels**, as their feeding habits involve ingesting faecal pellets and marine snow, and they can accidentally capture the MP particles. These deep-sea organisms, especially mesopelagic species, could act as vectors during vertical migrations and could potentially transfer MPs from shallow to deeper ocean layers, acting like a plastic pump (Ferreira *et al*., 2022, 2023; Justino *et al*., 2022). At the top of the food chain, oceanic predators like **tuna** reveal clear evidence of MPs transfer from contaminated prey to predators. Despite a low occurrence of macroplastics (> 5 mm), the stomachs of tunas exhibited **a substantial presence of MPs, suggesting potential trophic pathways.** The scarcity of macroplastics is attributed to these species' rapid egestion and regurgitation tendencies. Conversely, the high MP contamination is linked to the opportunistic behaviour of predatory species, which ingest large quantities of contaminated prey, accumulating MPs in their stomachs (Justino *et al*., 2023a).

Our findings demonstrate that, **while all marine species and ecosystems assessed** in the Tropical South Atlantic **are contaminated with MPs**, **the ecological patterns of organisms,** particularly predators, which are more susceptible to MP contamination, **are intricately linked to the characteristics of MPs**, including their types, quantities, and MP intake frequency. **Assessing fish communities as biological indicators for plastic pollution in coastal ecosystems is essential, because plastic pollution knows no boundaries. Species- and life-stage-specific feeding modes are important to consider as they might influence uptake and ingestion of different plastic shapes, colours and sizes. The potential contamination risk remains unclear, particularly for deep-sea species, for commercially relevant species such as tuna or sea bream, and eventually for human health.**

Organic and inorganic pollution associated with the plastisphere

Plastics can accumulate POPs and trace metals with unknown consequences to wildlife and humans (Frias, 2020). As such, 'MicroplastiX' assessed **trace and heavy metal pollution adhered to the plastisphere** in the *in situ* experiments, to understand whether there was a relationship between water temperature and site in terms of metal accumulation over time (Lenoble *et al.,* submitted). **Sites with more anthropogenic activities** (e.g. intensive fishing, coastal industries, etc.) **had higher metal bioaccumulation over time.** Curiously, **Polylactic Acid (PLA)**, a biopolymer often used to replace fossil-fuel based polymers, **behaved similarly to the other polymers,** and **occasionally** represented the **polymer with higher trace metal concentrations**. **Villefranche Bay,** in France, exhibited the **lowest metals bioaccumulation**, whereas **Naples,** in Italy, emerged as the site with the **highest metal bioaccumulation**. From our results, we can suggest **Villefranche as a reference site for trace metal bioaccumulation**. The trace metal assessment also included calculated **environmental risk** that would estimate effects across marine food webs.

An assessment of leaching of chemical compounds in tyres was conducted in Spain, where leaching was identified at least in three compounds, **after 90 days of exposure to environmental conditions** Figure 4)**.** Approximately 50 plastic additives, including **flame retardants, UV filters, antioxidants, herbicides, plasticizers, and antimicrobials were assessed,** some being identified as very high concern substances by the European Chemicals Agency (ECHA), where again **Villefranche** emerged as the reference site, with lowest plastic additives leached. The preliminary results show that plastics act as **accumulators** of chemicals, either adsorbed to the polymer itself or to the biofouling, **increasing their capacity to transport contaminants to other areas**. These studies in environmental chemicals showed that **polymers behave as a source of pollutants to the marine environment**, releasing compounds such as **plasticizers**, or in the case of **tyres, benzothiazoles**. Polycyclic aromatic hydrocarbons (PAH), UV filters and synthetic musks were the pollutants that were detected more frequently.

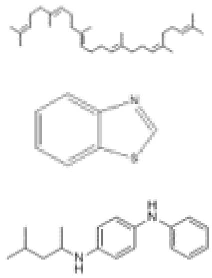

Figure 4 - Examples of leached chemicals from tyres

Combining all efforts into modelling

Results and information inferred from the *in situ* and laboratory experiments, were integrated within a modelling framework, simulating MP dynamics in seawater. This model assessed **the role of turbulence, at microscales, and how those affect the collision and settling rates of MP particles**, of different sizes and densities. These **turbulent effects** were then **included** in a **numerical solver able to track MP dispersion**, using Lagrangian methods, **within the water column**. The code was implemented in Fortran and Matlab, and it can be seamlessly integrated with an oceanic, large-scale circulation model.

Another biophysical process that has been exhaustively investigated with our multi-scale numerical approach is the **influence of biofouling in density**. We coupled an extended version of the **biofouling equation,** originally proposed by Kooi et al. (2017), **into one complementary coastal model**: the Regional Ocean Modelling System (ROMS, Haidvogel *et al*., 2008). The numerical configuration describes the **spatio-temporal behavior of microplastics**, injected from a highly polluting river into the Thyrrenian basin (southwestern Mediterranean Sea). Our findings suggest that **biofouling significantly impacts MP transport** within a limited range of particles' sizes and in two out of the four polymers tested. Understanding the influence that **biofouling has in plastic density is crucial to correctly assess MP distribution models.**

Sharing our knowledge with the local communities

MicroplastiX outreach reached more **than 6,000 people across the entire project duration**, either through our website, where the top 5 of visits were from Brazil (14.3%), France (11%), Ireland (10%), Germany (9%) and United States of America (9%). Social

Figure 5 - MicroplastiX outreach and awareness activities in Brazil

media engagement led to almost **800 people** following us over two platforms. The team participated in several national, European, and international conferences with over 25 posters and 15 oral communications. Project partners also attended, organised, or participated in over 35 webinars, workshops and public engagement informal chats (Figure 5) on each side of the Atlantic Ocean. MicroplastiX produced four newsletters available in our website, and features in more than 20 newspaper interviews and press releases including **Forbes, UnterWasserWelt, Wissenschaftler, Diário de Pernambuco, among others.** Considering that most of the project was developed during the Covid-19 pandemic, being able to conduct simultaneous *in situ* experiments, provide results and attend conferences with a strong online engagement is an achievement.

Perspectives for future work in policy and research

Given the relevance of this research topic in the ongoing policy negotiations at the United Nations (UN), European Commission (EC) and individual country levels, we believe that our findings provide **new insights to associated risks of plastic and microplastic pollution.** These insights **extend not only to plastisphere biodiversity**, but also encompass the implications for **organic and inorganic pollutants**, as well as the leaching of plastic additives.

Many efforts and notably advancements have been carried around the world, particularly in the UN's legally binding instrument on plastic pollution (**Plastics Treaty**; UN, 2022), the EC **Single Use Plastic (SUP) Directive**, the Kenyan plastic bag ban, the French single use plastic packaging ban, and the successful story of the German 'Pfand' (deposit return scheme), among others.

Since plastic pollution is a multi- and transdisciplinary research field, we believe that the next step on MP research will be to assess their environmental and human health risks. This can be done by resorting to **molecular methods**, including **environmental DNA (eDNA),** but also **stable isotope analysis**, spectrophotometric methods to identify and characterise MPs (**FTIR, RAMAN,** or new technologies that might be developed to enhance identification).

The advent of **artificial intelligence** and **machine learning** resources will facilitate the processing of large datasets, particularly in increasingly higher resolution spatio-temporal models. These models have the capacity to assimilate *in situ* observations of MP concentration, enabling more accurate simulations that can be used for assessing convergence and accumulation sites in the open ocean, assess the fate of plastics and MP in the water column. These innovative approaches will also contribute to **finding relevant and causal statistical correlations** that can be used to **promote dialogue and have better informed decisions at a multistakeholder level**.

Investments into **science communication** and **ocean literacy**, especially in translating complex scientific results into accessible language for stakeholders and society is crucial. These efforts are indispensable for **minimizing misinformation** and **promoting evidence-based decision-making processes**. Moreover, recognising the **borderless nature of plastic pollution** and the varying levels of development among nations, it is essential to **involve countries from the Global South** inclusively, to meaningfully change reality and tackle plastic pollution in the Ocean.

Contributors

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