



ADVANCING TOWARDS LITTER - FREE
ATLANTIC COASTAL COMMUNITIES
BY PREVENTING AND REDUCING
MACRO AND MICRO LITTER

D2.2.8. Developing methods for microplastic characterisation and monitoring microplastic contamination in marine matrices along French Atlantic coastlines

WORK PACKAGE 2: ASSESSING AND MONITORING MICRO AND MACRO LITTER
CONTAMINATION, ACTIVITY 2: IMPROVED MICROPLASTICS MONITORING, TASK
4: MICROPLASTIC QUANTIFICATION AND ANALYSIS



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Context: The Free LitterAT project

The Free LitterAT project, whose full name is “Advancing towards litter-free Atlantic coastal communities by preventing and reducing macro and microlitter”, is funded by the European Interreg Atlantic program 2021-2027. Lasting 3 years, the project aims to protect biodiversity by implementing innovative approaches to prevent and reduce marine litter pollution. This project, led by CETMAR (Spain), involves 14 partners and 9 associated partners from 4 countries: Ireland, France, Spain and Portugal.

More specifically, the project aims to advance towards litter-free coastal communities by developing, testing and implementing innovative approaches for the prevention, localisation and reduction of marine litter, with a special emphasis on abandoned, lost or discarded fishing gear (also known as ALDFG) and microplastics. The main objectives of the project are:

1. Preventing marine litter by improving waste management and recycling and facilitating the implementation of SUP and PRF Directives;
2. Understanding the origin and location of litter accumulation by identifying major sources, pathways and hotspots of marine litter;
3. Reducing and removing marine litter and associated risks;
4. Promoting litter-free local communities by developing pilot actions and awareness raising activities.

The work is divided into 4 work packages (WP):

WP 1. Prevention by improving waste management and recycling: Prevent marine litter by improving waste collection, recycling and increasing awareness in Atlantic ports and coastal cities, with a specific focus on fisheries related waste, for the preservation of the oceans and marine biodiversity.

WP 2. Assessing and Monitoring micro and macrolitter contamination: Develop and optimise current tools and methods for monitoring macro and microlitter and to enhance processing and analysis solutions that can facilitate and generate harmonised data that can be integrated into actionable outputs.

WP 3. Modelling approaches from micro and macrolitter: from modelling outputs to sources and hotspots: Improve our understanding of the location of accumulation areas of ALDFG, macro and microplastics and their sources, supporting the environmental agencies in charge of marine litter management with powerful modelling tools.

WP 4. Reducing marine litter and associated risks: Contribute to reducing marine litter by developing and demonstrating procedures, systems and manuals to remove different types of marine litter (ALDFG, hotspots, microplastics) in different environments.



WP 2 is divided into 4 Activities:

- A1: Advancing new methods and tools to survey and monitor macro marine litter.
- A2: Improved microplastics monitoring.
- A3: Identification of activity and geographical sources of marine litter.
- A4: Comprehensive assessment of macro and microlitter pollution in the Atlantic Area.

This work was carried out as part of WP2/A2, which generated data using the harmonised protocols for microplastics assessment produced under WP2/A2 and enabled the consortium to provide this additional deliverable.





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Summary

MicroPlastic (MP, < 5 mm) pollution has emerged as a global issue affecting all marine ecosystems. These particles, originating from the fragmentation of larger plastics or manufactured as micro-sized materials, are now detected in all marine compartments — the water column, sediments, and marine organisms. Marine sediments are considered a major sink for these particles, while mussels (*Mytilus* spp.), due to their filter-feeding behaviour, are recognized as valuable bioindicators of biological exposure.

During the project, analyses were conducted to develop harmonized protocols for MP assessment to ensure data reliability and comparability. Moreover, to limit the costs of monitoring and assessing MP pollution, a MP characterization method based on fluorescence-with Artificial Intelligence (AI) system has been developed. The results provided by the fluorescence characterization method appear consistent with the values found in the literature, and are also corroborated by the results obtained from Raman spectroscopy analyses on samples taken from the same stations. After a training phase carried out using fluorescence analysis, the AI success rate was 21% MPs successfully detected and 99% accurately associated to their typology. Even though the AI success rate was low, the analysis performed by AI took half the time required by fluorescence analysis. The AI-assisted workflow demonstrated promising potential for reducing analysis time and supporting image interpretation. However, considering the current detection performance, the system should presently be regarded as a proof-of-concept approach that requires further optimisation before being considered for operational implementation in regulatory monitoring frameworks such as European Marine Strategy Framework Directive (MSFD) or OSPAR programmes.

In parallel, a method was also developed to identify MPs polymers by combining epifluorescence and Raman microscopy. Particles in filters (obtained after collected samples processing) were stained with Nile Red, then analysed with Raman microscopy, without moving them. This approach resulted in a fivefold reduction in the number of particles requiring analysis, while maintaining the total number of plastic particles present on the filter. Thus, automated and integrated analytical workflows could become feasible, with a substantial reduction in the analysis time required by reference techniques.

The Interreg Free LitterAT project provides the first large-scale assessment of MPs contamination in both sediment and biota (mussel (blue mussel (*Mytilus edulis*) and oyster (Pacific oyster (*Crassostrea gigas*) along the French coastlines, revealing the widespread presence of MPs across these matrices. All sediment and oysters' stations were contaminated by MPs (100%), but only 14 out of the 16 stations for mussels sampling were contaminated by MPs (87.5%). For the sediment matrix, the values range from 15 to 773 items/kg dry weight (d.w.), with a mean of 226 items/kg d.w. (standard deviation: 179 items/kg d.w.) and a median of 170 items/kg d.w. For mussels' stations, the values range from 0 to 0.982 item/g wet weight (w.w.), with a mean of 0.305 item/g



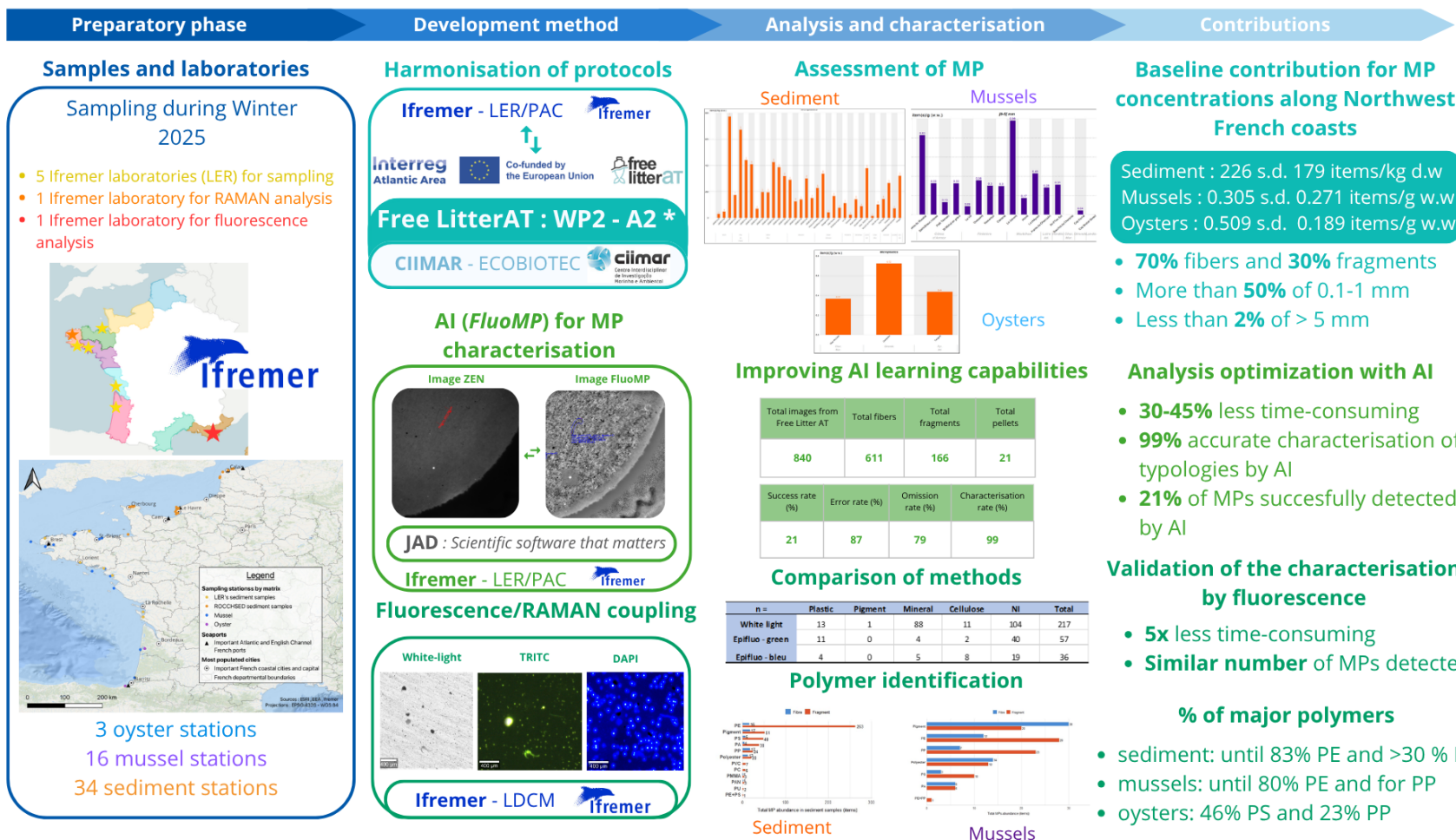
w.w. (standard deviation: 0.271 item/g w.w.) and a median of 0.300 item/g w.w. Concerning oysters' contamination, the values range from 0.367 to 0.723 item/g w.w. with a mean of 0.509 item/g w.w. (standard deviation: 0.189 item/g w.w.) and a median of 0.437 item/g w.w. The French coasts are mainly impacted by fibers (>70%) and fragments (<30%), the particles found in all matrices. The results offer a spatial overview of contamination patterns and contribute to the implementation of the MSFD. These data form a foundation to assess environmental risks associated with MPs and inform public policies to mitigate plastic pollution.

The dataset generated represents the first harmonised multi-matrix national-scale baseline of MPs contamination along the French coastline and provides a crucial reference for future monitoring efforts. These baseline data are essential for long-term trend assessments and threshold development within national and international regulatory frameworks, including OSPAR and MSFD.





Graphic abstract





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List of abbreviations

ABS – Acrylonitrile-Butadiene-Styrene
AI – Artificial Intelligence
CNN – Convolution Neural Network
EIR – Error Identification Rate
ESM – Epifluorescence Stereo Microscope
LDCM – Laboratoire Détection, Capteurs et Mesures
LER – Laboratoire Environnement Ressources
LOD – Limit Of Detection
MSFD – Marine Strategy Framework Directive
MPs – MicroPlastics
NaI – Sodium Iodide
OIR – Omission Identification Rate
PA-6 – PolyAmide-6
PA-12 – PolyAmide-12
PE – Polyethylene
PEHD – PolyEthylene High Density
PELD – PolyEthylene Low Density
PET - Polyethylene Terephthalate
PMMA – PolyMethylMethAcrylate
PP – Polypropylene
PS – Polystyrene
PTFE – PolyTetraFluoroEthylene
PU – Polyurethane
PUR – PolyURethane
PVC - Polyvinyl Chloride
SIR – Success Identification Rate
TCR – Typology Characterisation Rate
WWTP – Waste-Water Treatment Plant

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REPORT

1. Introduction

Plastic pollution has become a major global environmental concern over the past decades, estimated at 368 million tons in 2019 (PlasticsEurope, 2020) and continues to increase, with 79% of plastic waste ending up in the environment (UNEP, 2020).

Once plastic enters the environment, it can undergo physical, mechanical, chemical, and biological degradation processes, leading to the formation of new debris (Ter Halle et al., 2017; Chubarenko et al., 2016). Consequently, plastic pollution is characterized by the presence of macro-, meso-, and micro-sized debris (Alimba and Faggio, 2019). Around 90% of this marine plastic pollution is made up of microplastics (MPs) (Xanthos and Walker, 2017; Eriksen et al., 2014). These particles, smaller than 5 mm (Arthur et al., 2009), are considered one of the most widespread and persistent consequences of the marine plastic pollution (GESAMP, 2015; UNEP, 2023). These particles derive from both primary sources (microbeads, synthetic fibers) and secondary sources (degradation of larger items) (Pirsaheb et al., 2020; Kumar et al., 2022).

Due to their ubiquity and capacity to interact with biota and chemical contaminants, MPs are now recognized as a globally emerging pollutant of concern (Cole et al., 2011), and detected in all marine compartments — from surface waters to deep-sea sediments (Thompson et al., 2004; Andrady, 2011; De Haan et al., 2019; He et al., 2021). Therefore, it is essential to assess contamination levels in the oceans as the last destination of MPs (Chen et al., 2021).

Marine sediments represent a major sink for MPs, where they can accumulate and persist over long timescales. Sediment provides an overall picture of environmental quality and are considered as a stable matrix (Plantec et al., 2025; Woodall et al., 2014). On the other hand, filter-feeding organisms such as mussels (*Mytilus* spp.) are widely used as bioindicators of MP pollution due to their sessile nature, high filtration rates and broad geographical distribution (Li et al., 2016; Bråte et al., 2018). Oysters are also considered as general environmental sentinel organisms (Multisanti et al., 2025; Shumway et al., 2023).

MPs exert multiple effects on marine ecosystems. They can alter sediment properties (porosity, permeability and particle dynamics) and influence the bioavailability of other contaminants (Bakir et al., 2016). Their role as chemical vectors is well established: they can adsorb persistent organic pollutants and heavy metals, facilitating their transfer through food webs and organisms (Koelmans et al., 2016).

At the organism level, numerous studies have reported MP ingestion by benthic and filter-feeding species, leading to physiological disturbances such as reduced filtration



rates, inflammation, oxidative stress and tissue damage (Browne et al., 2008; von Moos et al., 2012).

Determining the current status of distribution and quantity of MPs in the ocean is an urgent task (Yutaka et al., 2020). One of the main challenges in MP research lies in the lack of reference or baseline levels across different marine compartments (Čerkasova et al., 2023; Sharma et Sharma, 2024; Hidalgo-Ruz et al., 2012). As interest in ocean MPs grows, institutions worldwide conduct monitoring through diverse sampling and analysis methods, gradually accumulating data and highlight the need for harmonized and comparable results (Čerkasova et al., 2023). Indeed, methodological inconsistencies (in sampling and analytical protocols), as well as geographical heterogeneity among studies, hinders reliable spatial and temporal comparisons (Rezania et al., 2025). For this reason, a previous task prior to the one presented in this report was initiated in order to propose harmonised protocols for the sampling and extraction of MP in different marine matrices.

Defining baseline contamination levels for sediments and mussels/oysters is therefore essential to, first, provide a robust foundation for comparative studies; second, monitor contamination trends over time; then, evaluate the effectiveness of environmental policies; and finally, contribute to regional and European monitoring frameworks such as the Marine Strategy Framework Directive (MSFD; Galgani et al., 2023) or International Marine Convention (OSPAR, Barcelone; Yang et al., 2024).

Within this context, the present work represents the first study to quantify MP contamination levels in both sediments and biota along the French coastline. It will address key knowledge gaps by:

- characterizing the spatial variability of MP contamination across the French façades;
- contributing to provide national baseline values that can serve as a reference for future monitoring and research efforts.

The objective of this deliverable Activity 2 of Free LitterAT work package 2 is to provide a contribution to baselines at the French national level for marine contamination by MP in sediment and biota matrices, with analyses based on the harmonization of sampling and extraction protocols provided by Free LitterAT's partners in Activity 2.



2. Material and methods

2.1. Study area

Ifremer “Coastal Environment Laboratories” (Laboratoire Environnement Ressources – LER) contributed in sampling 24 locations (Figure 1) from January 30th to March 4th 2025 (Supplementary Materials – Table 8). This study was conducted in the North-Western Atlantic Ocean and allowed the monitoring along the French Atlantic coasts. Three environmental marine matrices have been sampled to evaluate the MP contamination and/or to support the harmonization of protocols: sediment, mussel (blue mussel (*Mytilus edulis*) and oyster (Pacific oyster (*Crassostrea gigas*)). Along the Atlantic French coast, 16 stations were sampled for sediment, 16 stations for mussels and 3 stations for oysters. Alongside, 18 additional sediment stations were sampled along the English Channel French coast, during the oceanographic campaigns of the French Chemical Contaminant Monitoring Network (ROCCHSED), from April 8th to 17th 2025 (Supplementary Materials – Table 9).

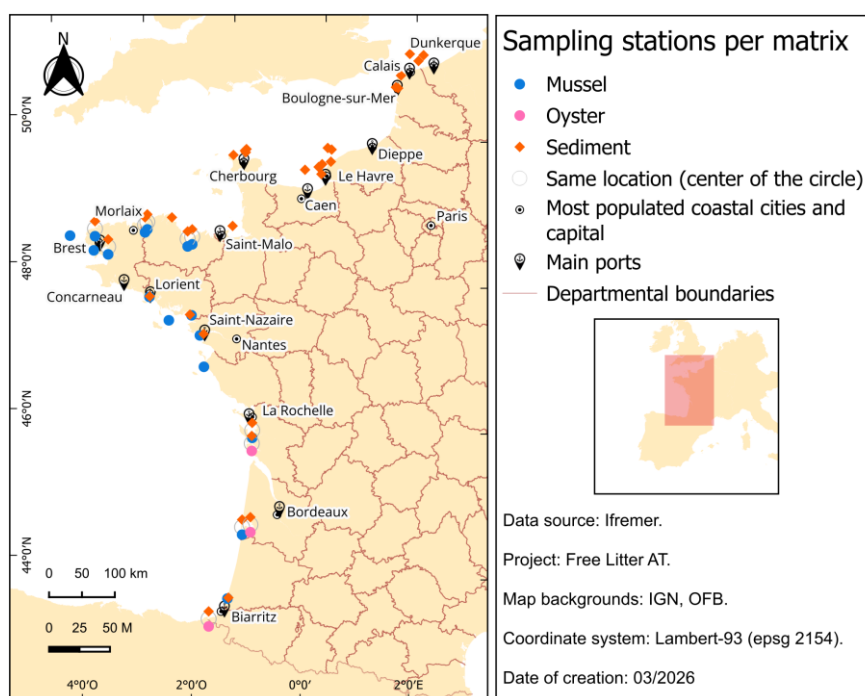


Figure 1: Map of the sampling locations in France



2.2. Specimen/Matrix collection and laboratory process

2.2.1. Sediment samplings and analyses Sediment samples were collected using a box-corer from a boat or by hand using a stainless-steel spatula at low tide, on three 50 cm length squares randomly selected but distanced by at least 20 m. All samples, corresponding to a total of 1 kg of sediment, were collected from the uppermost 5 cm and pooled in glass-boxes before being conducted to the laboratory for processing.

For each station, three or four replicates containing around 50 g of wet weight sediment were prepared for MP analyses. To calculate the percentage of dry matter for the station and then to normalize MP data according to the replicate weight on a dry basis, an additional replicate of 100 g wet weight sediment was covered in an aluminium container and dried during one week at 50°C in an oven.

MPs were extracted from sediment with a density separation step using a sodium iodide (NaI) solution ($d > 1.6 \text{ g/cm}^3$) and placed in an ultrasonic bath for 15 minutes. Once the sediment and organic matter sedimented (Figure 2), the floating particles were recovered with an overflow separation. Then the remaining organic matter was dissolved using KOH solution (10%), at 40°C for 24 h. After full digestion, the solution was vacuum-filtered through a GF/A glass fiber filter (Whatman $\varnothing$ 47 mm, 1.6 μm pore), the filters were transferred to a Petri dish and covered until visual examination under an Epifluorescence Stereo Microscope (ESM) Discovery V12.

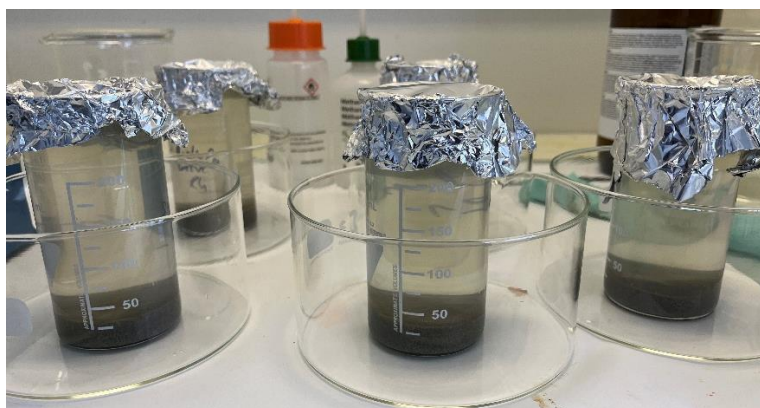


Figure 2 : Density separation step with NaI solution

2.2.2. Mussels and Oysters samplings and analyses

Biota samples were either collected manually for wild organisms or caged and submerged for 6 weeks for farmed organisms. Then, samples were frozen on board, transported to the laboratory and stored at - 20°C until further laboratory analysis.

The bivalves were defrosted for 1 hour. Then, their shells were cleaned with ultrapure milliQ water and, for mussels, the byssus were removed. For each individual, the length,



width and total weight (with the shells) were determined, and the shells were removed to determine the soft tissues wet weight (w.w.).

For each mussel station, individuals were pooled to obtain replicates containing approximately 20g w.w of flesh. Depending on the amount of flesh available, two or three replicates were analysed, with between 2 and 13 mussels per pool. For oyster stations, one individual represents one replicate, with 14 or 15 replicates per station.

For mussels and oysters, another replicate was covered in an aluminium container and dried during one night at 50°C in an oven, to calculate the percentage of dry matter for each station and then to normalize MP data according to the replicate weight on the desired basis

The mussels used for analyses had a mean length of 49.51 mm (standard deviation: 12.41 mm) and a mean width of 24.65 mm (standard deviation: 5.58 mm), whereas the oysters had a mean length of 85.77 mm (standard deviation: 10.25 mm) and a mean width of 43.46 mm (standard deviation: 3.97 mm).

The MPs were extracted by chemical digestion, sedimentation and filtration according to the method of (Phuong et al., 2018c). Bivalves' soft tissues were digested with 10% KOH solution, with magnetic stirring and heated at 40°C for 24 h. Microplastic were obtained after two decantations (Figure 3), the second one with a density separation solution (NaI; $d > 1.6 \text{ g/cm}^3$). Then, the supernatants were filtered on glass fiber filters and covered until visualisation under an ESM Discovery V12.



Figure 3: Decantation of mussels' samples after digestion step



2.3. Microplastic characterisation processing

2.3.1. Visualization analysis with fluorescence

The identification and characterization of MPs was directly performed under an ESM (Zeiss – Discovery. V12.), with an Axiocam 506 mono camera with X0.63 zoom and exposed to an HXP 200c UV lamp with a Rhodamine spectral filter. The images were analysed and processed using Zen 2.5 software (Zeiss). Once the Nile red solution is sprayed on the filter, fluorescent particles (considered as plastic) were counted, categorised (fragments, fibers, pellets, films, etc) and measured (particles > 100 µm).

2.3.2. Development of artificial intelligence for the characterization of microplastics

Following the standard laboratory processing of samples, a visual characterization was performed using fluorescence stereomicroscopy. To automate the counting and typology identification of MPs, tool *FluoMP* was developed. The imaging protocol involves dividing each filter into four quadrants. Each quadrant is photographed, recorded, and subsequently analysed by the Artificial Intelligence (AI) – *FluoMP* -, which enhances image contrast to facilitate detection and show detected MPs.

2.3.3. Characterisation of AI system and JAD company

JAD company (Jäm, Analysis and Development of scientific software that matters) trained a state-of-the-art instance segmentation Convolution Neural Network (CNN) that can process a quadrant image (2208 x 2752 pixels) in less than 2 seconds on a 9-year-old CPU (i3-7100T) with less than 4GB of free RAM. This CNN is characterized by:

- Backbone: A CSPNeXt architecture, which optimizes the trade-off between computational depth and inference speed, essential for processing high-resolution laboratory images.
- Neck: A Path Aggregation Network (PAFPN) that enhances multi-scale feature fusion, essential for simultaneously detecting large fragments and microscopic fibers within the same field of view.
- Head: A dynamic mask head that predicts segmentation masks using dynamic convolution kernels, ensuring precise delineation of MP contours.

While the selected architecture offers robust performance, the instance segmentation field is witnessing the emergence of Transformer-based models that utilize self-attention mechanisms to capture global context, potentially improving the distinction between MPs and similarly shaped organic matter. Additionally, End-to-End detection



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frameworks are removing the reliance on Non-Maximum Suppression, offering a simplified pipeline for dense object scenarios to fasten the detection while avoiding double-detection.

Despite these architectural advancements, the primary limiting factor for AI quality is not the model topology but the quality and consistency of the annotated training data. The variability in human labelling, particularly for ambiguous particles like non-fluorescent MP, introduces noise that no degree of architectural complexity can fully mitigate. Consequently, future efforts shall prioritize annotation quality, ideally via "active learning" cycles, to refine the trainset rather than scaling model parameters or complexifying the model architecture.

2.3.4. Training phases of AI system and JAD company

An initial training phase using annotated images—identifying the MPs present—provided the AI with its first learning stage for detecting and identifying them. The Free LitterAT samples enabled the start of the second AI training phase, aimed at evaluating and analysing the detections made by the system. In this phase, a scientific expert works as an observer alongside the AI to validate, correct, or supplement the AI's analyses. Therefore, the observer is considered as the reference.

To quantify the effectiveness of the AI during this second phase, several parameters are considered:

- (1) Reported analysis time per quadrant with and without AI assistance
- (2) Typology characterisation of the AI for each MP identified
- (3) True positive: MPs identified by the AI and validated as MPs by the observer (in green square on Figure 4)
- (4) False negative: MPs identified by the observer but not detected by the AI (in red square on Figure 4)
- (5) False positive: particles detected by the AI, but not validated as a MP by the observer (in red square on Figure 4)

Based on the three possible cases, success, error, and omission rates were calculated along the Free LitterAT samples.

The **Success Identification Rate** (SIR) corresponds to the percentage of successful identification by the AI and calculates as MPs identified by the AI and validated as MPs by the observer (true positives) relative to the total number identified by the observer.

$$SIR = \frac{\text{True positives}}{\text{Total MPs identified by observer}} \times 100$$



The **Error Identification Rate** (EIR) corresponds to the percentage of error identification by the AI and calculates as MPs detected by the AI but not validated as plastic particles by the observer (false positives) relative to the total number of MPs recorded by the AI.

$$EIR = \frac{\text{False positives}}{\text{Total MPs identified by IA}} \times 100$$

Note: the SIR is not the inverse of the EIR.

The **Omission Identification Rate** (OIR) corresponds to the percentage of failure identification by the AI and calculates as MPs identified by the observer but not detected by the AI (false negatives) relative to the total number of MPs identified by the observer.

$$OIR = \frac{\text{False negatives}}{\text{Total MPs identified by observer}} \times 100$$

Note: the SIR added to the OIR corresponds to the entirety of the actual sample (particle identified as plastic by the observer).

The **Typology Characterisation Rate** (TCR) corresponds to the AI's ability to accurately characterise the typology of MPs when they are detected.

$$TCR = \frac{\text{Identification of true typologies by AI}}{\text{True positives}} \times 100$$



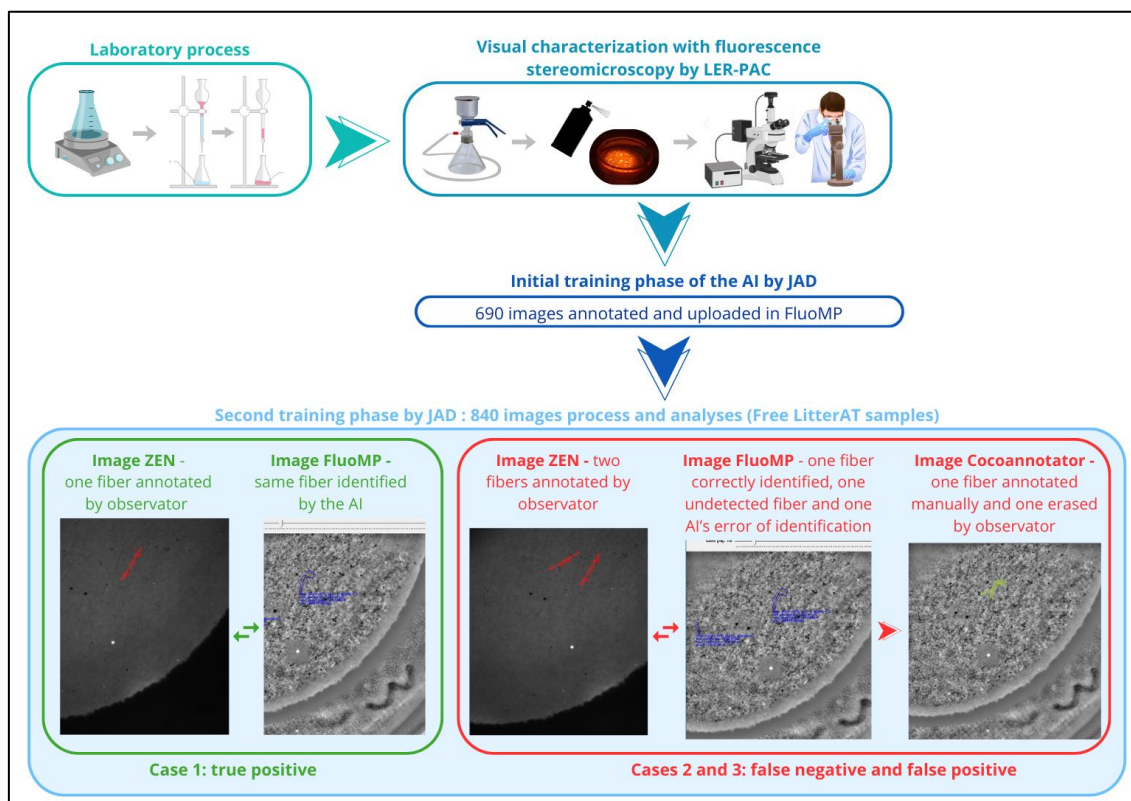


Figure 4. Training phase protocol of AI (FluMP, development by JAD) using annotated images from LER-PAC laboratory

2.4. Polymer identification by RAMAN

2.4.1. Method development: Evaluation of epifluorescence/Raman correlative microscopy for identification of microplastics in marine matrices.

Existing reference techniques for characterising MPs remain laborious and time-consuming, mainly due to the lack of automated and integrated analytical workflows. The objective of this method development was to evaluate the potential of correlative epifluorescence/Raman microscopy as an approach for identifying MPs in various marine matrices (Figure 5). To achieve this, sediment and mussel/oyster samples from the project (one replicate per station) underwent an innovative procedure that enabled the combination of Raman spectroscopic analysis and Nile Red staining without requiring any movement of the sample.

A replicate of each sampling site was selected for polymer analysis, carried out at Ifremer's Détection, Capteurs et Mesures laboratory (LDCM). As various Nile Red (NR) staining protocols have been reported in the literature, the first step consisted of optimizing the staining procedure. This optimization involved varying several parameters, including the concentration of the Nile Red solution, solvent composition, and staining duration. The efficiency of each condition was assessed based on the



fluorescence signal of microplastics relative to the background, taking into account the choice of analytical membrane and compatibility with Raman analysis. To achieve this, single or mixed polyethylene (PE) and polypropylene (PP) micro-fragments were used as model particles. Different staining approaches were evaluated, including direct spray and bath staining methods, various solvents (acetone, water, ethanol), and different analytical membranes (glass fiber filters, DVPP, and Anodisc membranes).

The selected protocol is as follows: a replicate of the digestate from each sampling site is first filtered through a stainless-steel filter (mesh size: 25 μm) to remove small particles, prevent collapse of the analytical membrane, and eliminate residual digestion solvent (KOH). The retained particles are then immersed for 30 minutes in 100 mL of a filtered Nile Red solution (1 $\mu\text{g/mL}$ in ethanol) under agitation. Subsequently, the particles are carefully recovered from the filter using ultrasonic treatment combined with ethanol rinsing. Finally, the suspension containing the particles is filtered onto the analytical membrane (Anodisc) for further analysis. The filters were stored in the dark to prevent photobleaching.

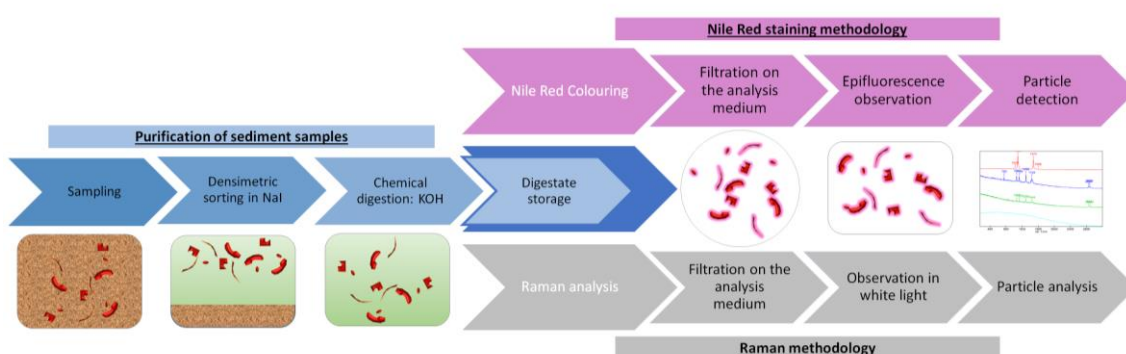


Figure 5 : Schematic illustration of the correlative epifluorescence–Raman microscopy workflow applied to the detection and identification of microplastics in environmental samples, including sediments and marine biota (mussels and oysters).

Images and spectra were acquired using a WITec confocal Raman microscope (alpha300 R, Ulm, Germany), equipped with white-light imaging, Raman spectral acquisition, and epifluorescence modules. The Raman spectroscopy module was fitted with a 785 nm excitation laser, a UHTS 300 spectrograph (300 grooves- mm^{-1} grating), and a CCD detector (DU401A-BV-352, Andor, UK). Epifluorescence imaging was performed using a dedicated filter set (excitation: 520–560 nm; emission: 580–660 nm, TRITC), and complementary transmission brightfield images were systematically recorded. Each analytical filter was imaged under transmitted white light, as well as under fluorescence using both TRITC (optimized for Nile Red visualization) and DAPI filter sets. Large-area images were acquired using a Zeiss EC Epiplan-Neofluar® 5 $\times$ objective (numerical aperture 0.13) with FocusStacking correction. To improve particle detection, images were contrast-enhanced prior to processing with the ParticleScout module. A threshold was applied to generate particle masks, and size-based filtering was used to retain only



particles larger than 100 μm . Raman analyses were subsequently performed using a Zeiss EC Epiplan-Neofluar® 20 $\times$ objective (numerical aperture 0.5), with an integration time of 20 s and three accumulations per spectrum. Autofocus was employed to ensure optimal focusing during spectral acquisition.

For polymer identification, acquired spectra were compared against a reference database comprising Raman signatures of environmentally relevant materials, including synthetic polymers, pigments, and mineral particles. Prior to spectral matching, baseline correction and normalization were applied to minimize instrumental noise and improve peak alignment. Identification was based on the Pearson correlation coefficient, with matches accepted when the Hit Quality Index (HQI) exceeded 0.6. Procedural blanks were systematically analysed to evaluate background contamination. Contamination was considered negligible when blank levels represented less than 5% of the total particle count. Overall, this methodology improves the accuracy, efficiency, and reproducibility of polymer identification in complex environmental matrices.

2.4.2. Samples analysed with Raman

In addition to visual inspection of the filters, on 14 sediment stations (without ROCCHSED monitoring stations) and for each mussel and oyster stations, a replicate per site was selected for polymer analysis, carried out at Ifremer's Détection, Capteurs et Mesures laboratory (LDCM). The filters were passed through an AlphaR 300 Raman micro-spectrometer (μRaman).

2.5. Quality control

All experiments were carefully performed with the aim of preventing MPs contamination. Ethanol solution was always used to clean the work area and material. Most equipment and containers used for experiments were made of glass and metal, the lab coat was cotton only and nitriles gloves were used. All of the containers and beakers were rinsed with ethanol and three times with ultrapure milliQ water before use. In addition, analyses were carried out under a clean chemical hood.

Several blanks ($n=3$) were done to control contamination, one throughout the sample treatment process, one during visualisation and one during fluorescence treatment. After fluorescence analysis, the contamination of the blanks was recorded. During a two-week period of analyses, the dishwasher malfunctioned, and no additional precautions were taken during this time. This resulted in increased contamination of the blanks for five sediment stations (St Brieuc, Bretagne Nord, Petit Taureau, Villes Martin and Pointe du Roselier) and one mussel station (Houat). Taking this into account, the mean for the sediment blanks was 0.6 ± 1.4 fibers/blank, while mussel blanks showed 0.3 ± 1.0 fiber/blank. After excluding these contaminated stations, the mean contamination level for the remaining samples was 0.5 ± 1.2 fibers/blank for sediment



(n=28), 0.2 ± 0.8 fibers/blank for mussels (n=15), and 0.2 ± 0.4 fibers/blank for oysters (n=3). Following Free LitterAT and OSPAR guidelines (Galgani et al., 2023), the limit of detection (LOD) was also calculated for all the blanks. For sediment blanks, the LOD was 4.8 and 3.2 for the mussel blanks. After excluding the contaminated stations during the two-week period, the LOD for the remaining samples was 4.2 for sediment (n=28), 2.7 for mussels (n=15), and 1.5 for oysters (n=3).

For correlative microscopy measure, method blank runs were rigorously conducted prior to sample filtration. Coloration blanks were performed in parallel with the preparation of a batch of around six samples (n=6) (Table 1). Filtered ethanol (mesh: 0.2 μm) was used to simulate a sample. To assess potential airborne contamination, depositional controls were implemented for each sample using a GF/F filter (pore size: 0.7 μm ; Whatman), which was placed near the sample throughout all handling steps until image acquisition. Prior to use, GF/F filters were pre-combusted at 450°C for 4 hours to eliminate any potential organic contamination. All sample handling was performed in a clean environment, with glassware rinsed three times with filtered ultrapure water the filtered ethanol and working surfaces thoroughly cleaned before processing. Particles found in blanks were identified by spectroscopy following the same procedure as the associated sample to evaluate potential contamination and apply necessary corrections to the sample data.

Table 1. Summary of particles found in staining blanks obtained during correlative microscopy analysis.

	Cellulose	PP	PE	PTFE	PS	Samples
Blank n°1	1	3	2	2	1	<u>Sediment</u> : Estuaire de la Vilaine, Saint-Brieuc, Petit Taureau, Bretagne Nord; <u>Mussels</u> : Ouessant, Camare
Blank n°2	4	–	1	–	1	<u>Sediment</u> : Pointe de Roselier, Villes Martin, Kersanton, Hossegor, Cap Ferret, Levill, Comprian, Twingudi; <u>Mussels</u> : Cap Breton, Pointe Chemoulin
Blank n°3	1	10	–	–	–	<u>Sediment</u> : Mus du Loup, Saint-Michel en Grève, Rade de Loreint, Bouchot de Charentes
Blank n°4	4	2	–	–	–	<u>Mussels</u> : Ile d'Yeu, Kersanton, Le Halyven, Levill
Blank n°5	8	1	1	–	–	<u>Mussels</u> : Cap Ferret, Saint-Brieuc, Bouchot de Charentes, Pointe de Roselier, Houat
Blank n°6	5	5	1	–	–	<u>Oysters</u> : Charente-Maritime, Gironde, Pyrénée Atlantique



2.6. Data analysis

In order to be able to compare the results presented in this study, but also with those of other studies, MP data were normalised according to each replicate weight. The reference unit used for sediment is the number of items per kilogram of dry weight (items/kg d.w.). For mussels and oysters, the results are presented according to the three following units: the number of items per gram of wet weight (items/g w.w.), the number of items per gram of dry weight (items/g d.w.) and the number of items per individual (items/ind.). The concentrations and percentages (for replicates with MPs) per size class and per MP typology were first calculated for each replicate, and then averaged for each station. To obtain an overall view by matrix, the values per station were also averaged for each matrix.

Data analysis and graphics were performed using R (V.4.5.1). The maps of results were created using QGis (V.3.40.10-Bratislava). Kruskal-Wallis (`kruskal.test{stats}` V.4.5.1) and Dunn post-hoc (`dunn.test{dunn.test}` V1.3.6) tests were carried out to identify potential differences between the stations. Non-parametric tests were chosen due to the non-Gaussian distribution of the data. When significant differences were found according to the Kruskal-Wallis test ($p\text{-value} < 0.05$), the pairwise comparisons with the Dunn test were performed using Holm method to adjust the $p\text{-value}$ for multiple comparisons.





3. Results of methodological developments

3.1. Results provided by the AI during the second training phase

Following an initial AI training phase based on the integration of 690 images from previous projects, a second training phase was initiated using images from the Free LitterAT project.

Thereby, 840 images (each corresponding to one quadrant of the filter under analysis) have been provided by Free LitterAT project for three different matrices, with 280 images from sediment matrix, 290 from mussel matrix and 270 from oyster matrix. These images were uploaded and analysed by the AI, alongside a visual observation by a scientific expert (Table 2). Across all of these images, 376 images presented one or several fibers (for a total of 611 fibers identified), 155 images had one or several fragments (for a total of 166 fragments identified) and 13 images recorded one or several pellets (for a total of 21 pellets identified). Considering the number of fibers and fragments in the filters, the AI will better perform for these two typologies (fiber and fragment). In contrast, pellets were rarely observed, and films were absent from the samples

Table 2. Numbers of total images and total MPs by typologies observed from Free LitterAT Project and used for AI's training

Total images from Free LitterAT samples analysed by AI	Total fibers recorded	Total fragments recorded	Total pellets recorded
840	611 (on 376 images)	166 (on 115 images)	21 (on 13 images)

To assess the AI's effectiveness the success (SIR), error (EIR), and omission (OIR) identification rates were calculated. The AI successfully detected 21% (SIR) of the MPs identified by the observer, corresponding to its detection capability during the second training phase. However, 79% (OIR) of MPs identified by the observer were not detected by the AI (Table 3). Alongside, 87% of the particles detected by the AI were not validated by the observer as MPs, consequently the reliability of AI's positive predictions was of 13%. Moreover, the AI associated at 99% (TCR) the accurate typologies to the MPs when detected by AI and validated by the observer (true positives). Although the AI system showed a very high Typology Characterisation Rate (99%) for correctly detected particles, its detection performance remains limited at the current stage of development (SIR = 21%) and a high omission rate was observed (OIR = 79%). Therefore, the present version of FluMP should be considered as a proof-of-concept tool rather than an



operational monitoring solution. Additional training datasets and algorithm refinement are required before implementation within routine monitoring programmes.

Table 3. Efficiency rate of the AI (%)			
↑ Success identification rate	↓ Error identification rate	↓ Omission identification rate	↑ Typology Characterisation Rate
21	87	79	99

Finally, for both the sediment and mussel matrices, the analyses are less time-consuming with AI identification alongside visual characterisation by the observer, than with visual characterisation only (Figure 6). For mussels' samples, the time is almost divided by 2 with the AI (45% less time by quadrant with AI characterization). The contrast of the image potentially helps to rapidly target the areas that need to be checked. However, for oysters' samples, no difference in time analyses was observed by quadrant with or without AI.

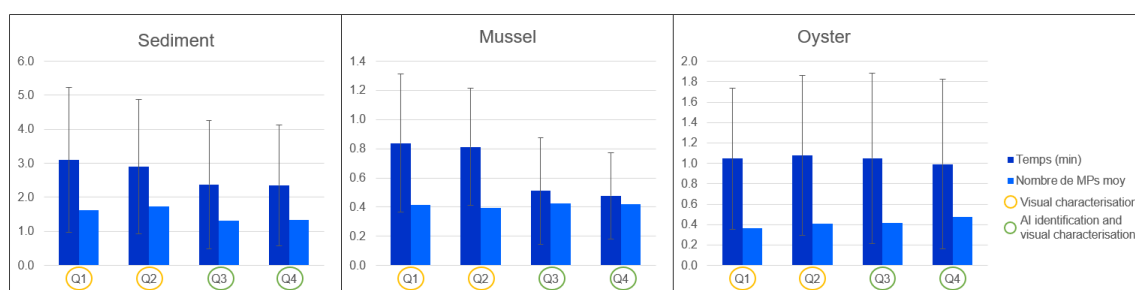


Figure 6. Time analyses by quadrant-filter of sediment, mussels' and oysters' samples, with mean number of MPs detected

3.2. Evaluation of epifluorescence/Raman correlative microscopy for identification of microplastics in marine matrices

The objectives of this part of the project were threefold: (i) to quantify MPs contamination using μ -Raman spectroscopy; (ii) to evaluate the efficiency of Nile Red staining based on Raman-confirmed particles; and (iii) to assess Nile Red staining as a subsampling strategy to accelerate MP analysis. The primary focus was on objective (i), and the corresponding results are presented and discussed in the section "Results of microplastic contamination assessment." Objectives (ii) and (iii) are still under evaluation; therefore, the results presented below are preliminary and not yet complete.

A specific protocol was developed to compare:

- particle detection on bright-field transmission images combined with Raman spectroscopy analysis;



- particle detection on epifluorescence images using a TRITC filter cube adapted to Nile Red emission.

Briefly, particles are first localized on transmission images through binarization and mask-processing steps, after which Raman spectra are acquired for each detected particle. This workflow enables the determination of both particle morphology and chemical composition. Particles are subsequently classified into the following material categories: plastics (e.g., PE, PP, PS), carbon, cellulosic-derived materials, organic matter (OM), inorganic matter (IM), filter (when spectra correspond to the PVDF signal of the analytical membrane), spectra (when a signal is obtained but cannot be identified using the reference database), and non-identified (NI) when no signal is obtained. As the NI category remains uncertain, it is excluded from statistical comparisons.

TRITC epifluorescence images are processed using the same binarization and mask-generation approach as for transmission images, and are then overlaid with the transmission/Raman results to evaluate detection performance. Four outcomes are defined:

- **True positive:** plastic particles correctly detected by Nile Red staining;
- **True negative:** non-plastic particles correctly not detected by Nile Red staining;
- **False positive:** non-plastic particles incorrectly detected by Nile Red staining;
- **False negative:** plastic particles not detected by Nile Red staining.

The statistical analysis performed on mussel biota was based on a pooled dataset of 10 samples collected from different sites. This approach minimizes potential “individual” and “site” effects, allowing a more robust assessment of Nile Red staining efficiency. The evaluation of Nile Red staining performance in mussel samples, using Raman microspectroscopy as a reference method, reveals contrasted detection efficiencies across material categories (Figure 7). Plastic particles were the most reliably identified, with 166 true positives and no false positives, indicating high specificity toward hydrophobic polymeric materials. However, a substantial number of false negatives ($n = 199$) was observed, highlighting an under-detection of plastics and suggesting that a significant fraction of polymer particles was not stained or detected under the applied conditions. In contrast, pigment particles showed limited detection efficiency, with only 13 true positives compared to 34 false negatives.

Non-plastic materials were, in some cases, correctly discriminated but also prone to misclassification. Carbon was almost exclusively classified as true negatives ($n = 24$), with negligible false detection. In contrast, Organic Matter (OM) was systematically misclassified as false positives ($n = 17$). Cellulosic materials exhibited a nearly balanced distribution between true negatives ($n = 84$) and false positives ($n = 81$), indicating limited selectivity and possible staining of non-plastic, organic-derived particles. Inorganic Materials (IM) were particularly affected, with a very high number of false positives ($n = 733$), suggesting strong interference from mineral-associated signals or background fluorescence.



Overall, these results demonstrate that while Nile Red staining is highly specific for plastics when detection occurs, its sensitivity remains limited and its selectivity is compromised by certain non-plastic matrices, particularly inorganic and cellulosic materials. When considering only plastic particles, approximately 16% of detected items are correctly identified as plastics, corresponding to an error rate of ~84%. When extending the analysis to all anthropogenic particles (plastics, pigments, and cellulosic materials), the proportion of correctly detected particles increases to ~26%, with an associated error rate of 74% in mussel samples.

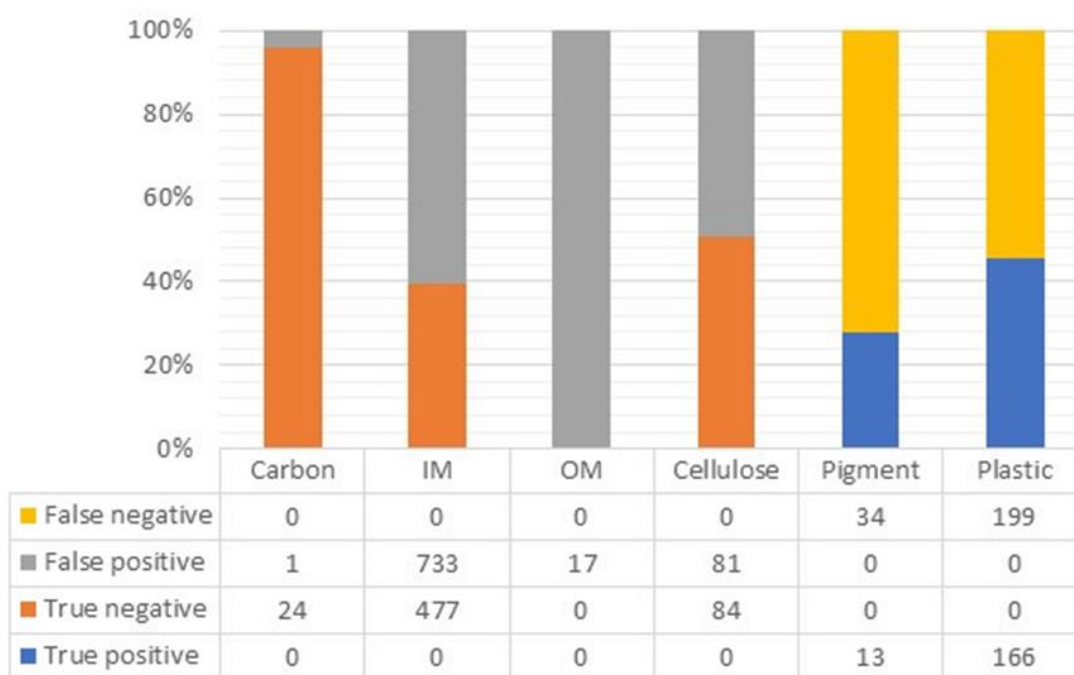


Figure 7: Evaluation of Nile Red staining performance for microplastic detection in mussel samples using Raman microspectroscopy as reference method (where, Inorganic Materials (IM), Organic Matter (OM)).

Focusing on plastic particles only, the performance of Nile Red staining shows strong variability depending on polymer type (Figure 8). Detection efficiency, expressed as the proportion of true positives relative to the total number of plastic particles identified by Raman microspectroscopy, is highest for polystyrene (PS), with 11 true positives out of 13 particles (~85%), indicating a good affinity of Nile Red for this polymer. Similarly, polyethylene (PE) and polyester exhibit relatively good detection rates, with ~67% (22/33) and ~63% (17/27) of particles correctly identified, respectively.

Intermediate performance is observed for polyamide (PA), with a detection rate of ~58% (7/12), and polypropylene (PP), for which only 50% of particles were detected (22 true positives vs. 22 false negatives). In contrast, polytetrafluoroethylene (PTFE) shows markedly lower detection efficiency, with only ~37% of particles correctly detected (86 true positives vs. 149 false negatives), highlighting the poor affinity of Nile Red for this highly hydrophobic and chemically inert polymer. The PE+PP category, although



represented by a limited number of particles, shows complete detection (1/1), which should however be interpreted cautiously given the low sample size.

Overall, these results indicate that Nile Red staining efficiency is polymer-dependent, with better performance for polymers such as PS and PE, and significantly reduced sensitivity for others, particularly PTFE and, to a lesser extent, PP.

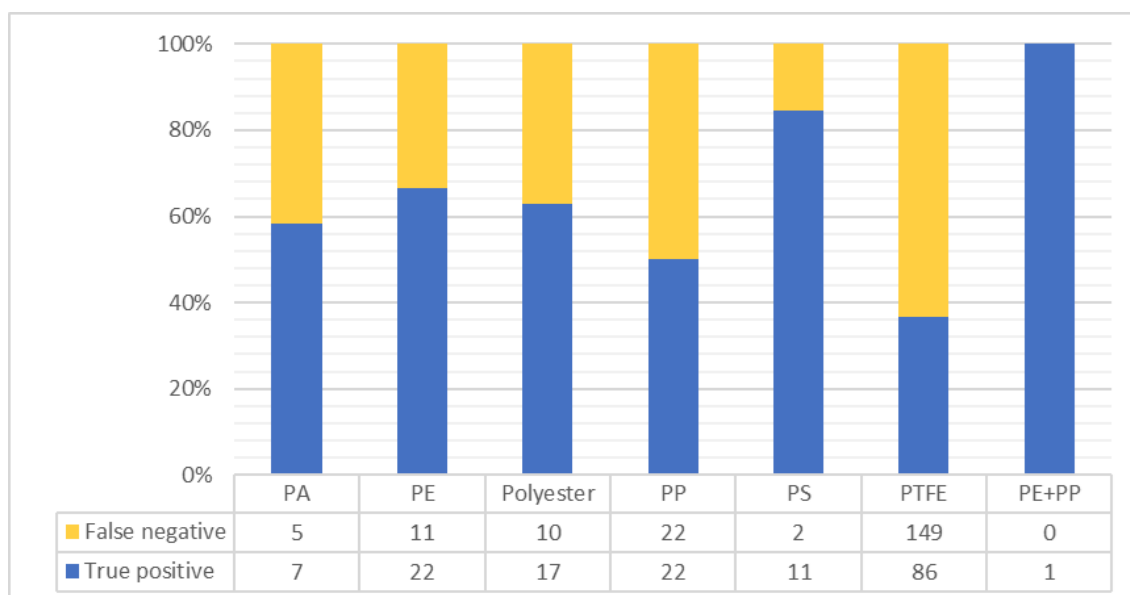


Figure 8: Evaluation of Nile Red staining performance for microplastic detection only in mussel samples using Raman microspectroscopy as reference method.

These preliminary results will be further complemented by applying the same analytical workflow to additional environmental matrices, namely sediments and oyster samples, in order to assess the robustness and reproducibility of the observations across contrasting sample types. In parallel, a more detailed characterization of the mineral particles detected under Nile Red staining will be conducted. This will aim to determine whether the observed signals originate from intrinsic autofluorescence of certain minerals or from actual Nile Red adsorption, thereby clarifying the mechanisms underlying the high rate of false positives observed for inorganic materials.

Altogether, this extended investigation will provide a more comprehensive evaluation of the method's performance in complex environmental matrices and will be consolidated and disseminated through a dedicated scientific publication.



4. Results of microplastic contamination assessment in marine matrices along the French Coastline

4.1. Plastic concentrations in sediment

4.1.1. Total concentrations

All 34 stations were contaminated, with total plastic concentrations, including mesoplastics (>5mm) and MPs (<5mm), ranging from 15 to 773 items/kg of dry weight (d.w.). The mean total plastic concentration was 227 items/kg d.w. (standard deviation (s.d.): 180 items/kg d.w.), with a median of 171 items/kg d.w.

Mesoplastics were only observed in two stations: “Saint-Brieuc coques”, with around 27 items/kg d.w., and “Villes - Martin (c)”, with around 15 items/kg d.w., resulting in an average of 1.24 item/kg d.w. (s.d.: 5.27 items/kg d.w.). In these two stations, the proportion of mesoplastics represents respectively 7.69% and 2.78% of total plastics. Mesoplastics (particles >5 mm) accounted for, on average, 0.3% of the total number of plastic particles identified across all sediment stations.

The mean MP concentration was 226 items/kg d.w. (s.d.: 179 items/kg d.w.), with a median of 171 items/kg d.w. The lowest plastic contamination was at “Bouchot de Charente” with 15 items/kg d.w. (Figure 9). Eight other stations presented concentrations under 100 items/kg d.w. Eleven of the 34 stations presented concentrations between 100 and 200 items/kg d.w., three stations had concentrations between 200 and 300 items/kg d.w., another six stations between 300 and 400 items/kg d.w. and three stations between 400 and 500 items/kg d.w. Finally, the highest concentrations in sediment were observed at “GRAB 25-06” station (ROCCHSED campaign, with 773 items/kg d.w.) and “GRAB 25-11” station (ROCCHSED campaign, with 672 items/kg d.w.). The Kruskal-Wallis test shows a statistical difference between the stations according to MP concentrations (p-value < 0.001).



Free LitterAT deliverable D.2.2.6 (WP2-A2-Task2)

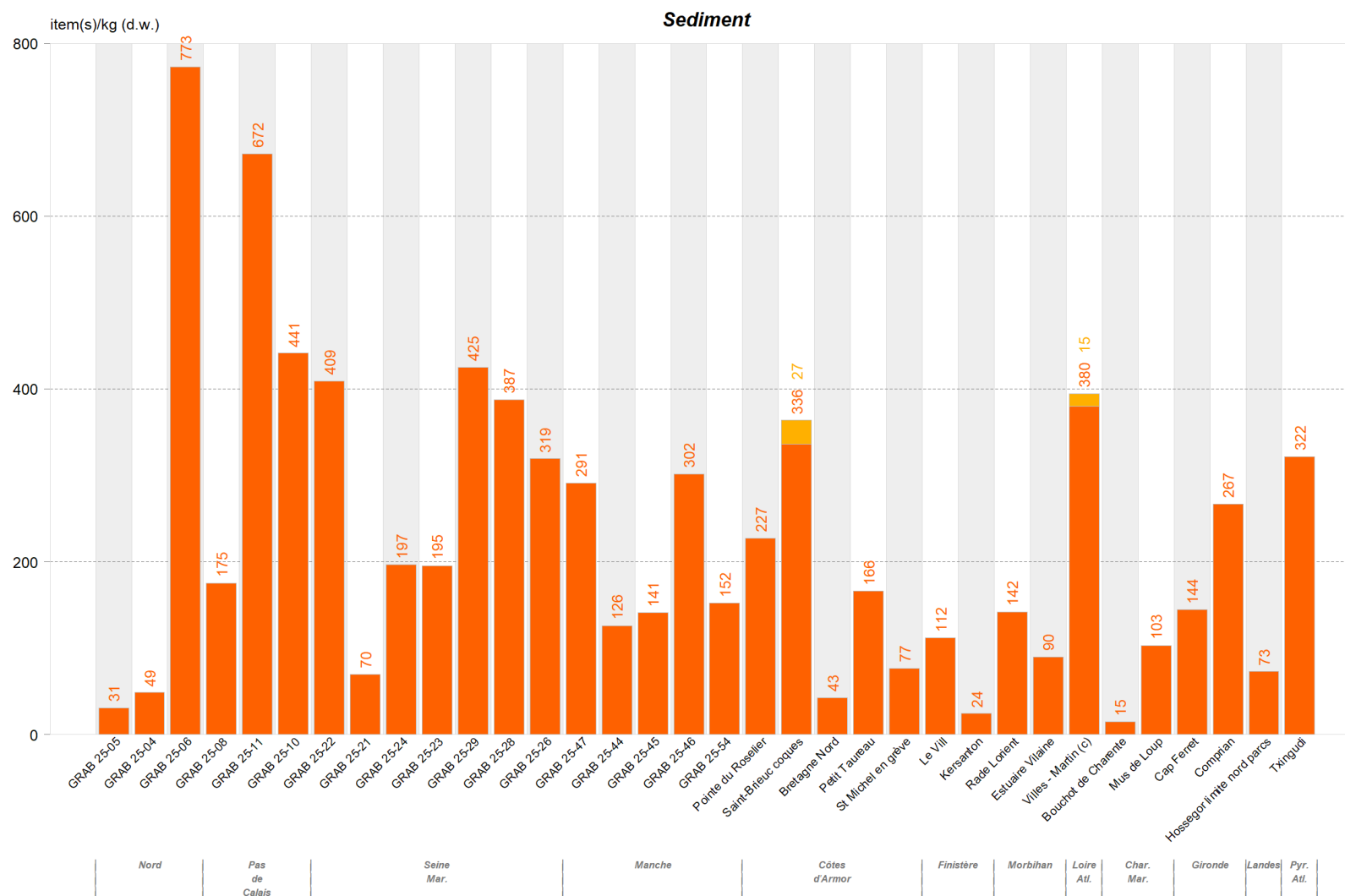


Figure 9. Concentrations of microplastics (dark orange) and mesoplastics (light orange) in sediment along the French coast.



4.1.2. Sizes of plastic particles

On average, most of plastic particles were between 100 and 1,000 μm in size (60%), of which 14% were between 100 and 300 μm , 14% between 300 and 500 μm and 32% between 500 μm and 1 mm in size (Figure 10). Then, particles between 1 and 2 mm in size represented 32%, followed by particles between 2 and 5 mm with a mean of 8%. Particles over 5 mm (mesoplastics) represented on average 0.3% of plastic particles found in sediment French samples. Geographical repartition of size particles is presented in Figure 11. No clear geographical pattern is observed. Particles between 100 and 1,000 μm in size represented a majority of particles for the 26 stations, whereas particles between 1 and 2 mm in size were in majority for 7 stations and both size ranges are of equal importance for one of the seven stations. Among the 7 stations with a majority of particles between 1 and 2 mm, two were located in the North of the Bay of Biscay and seven along the English Channel. In most cases for particles between 100 and 1000 μm in size, there was a predominance of particles from 500 to 1000 μm .

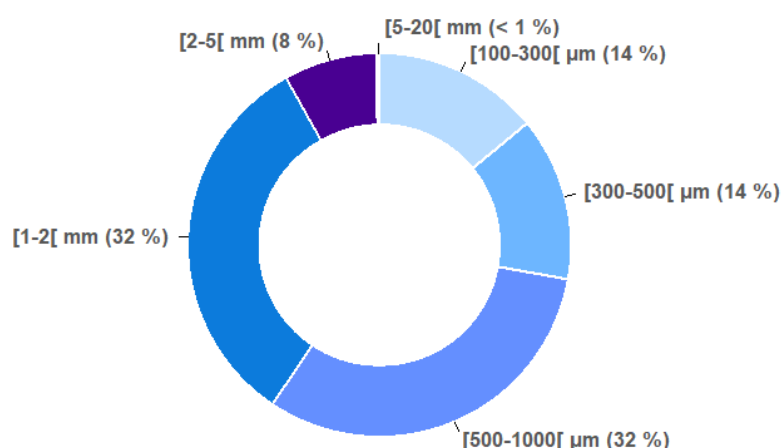


Figure 10. Average percentage of total plastic particles across all stations, per size range, for the French sediment samples

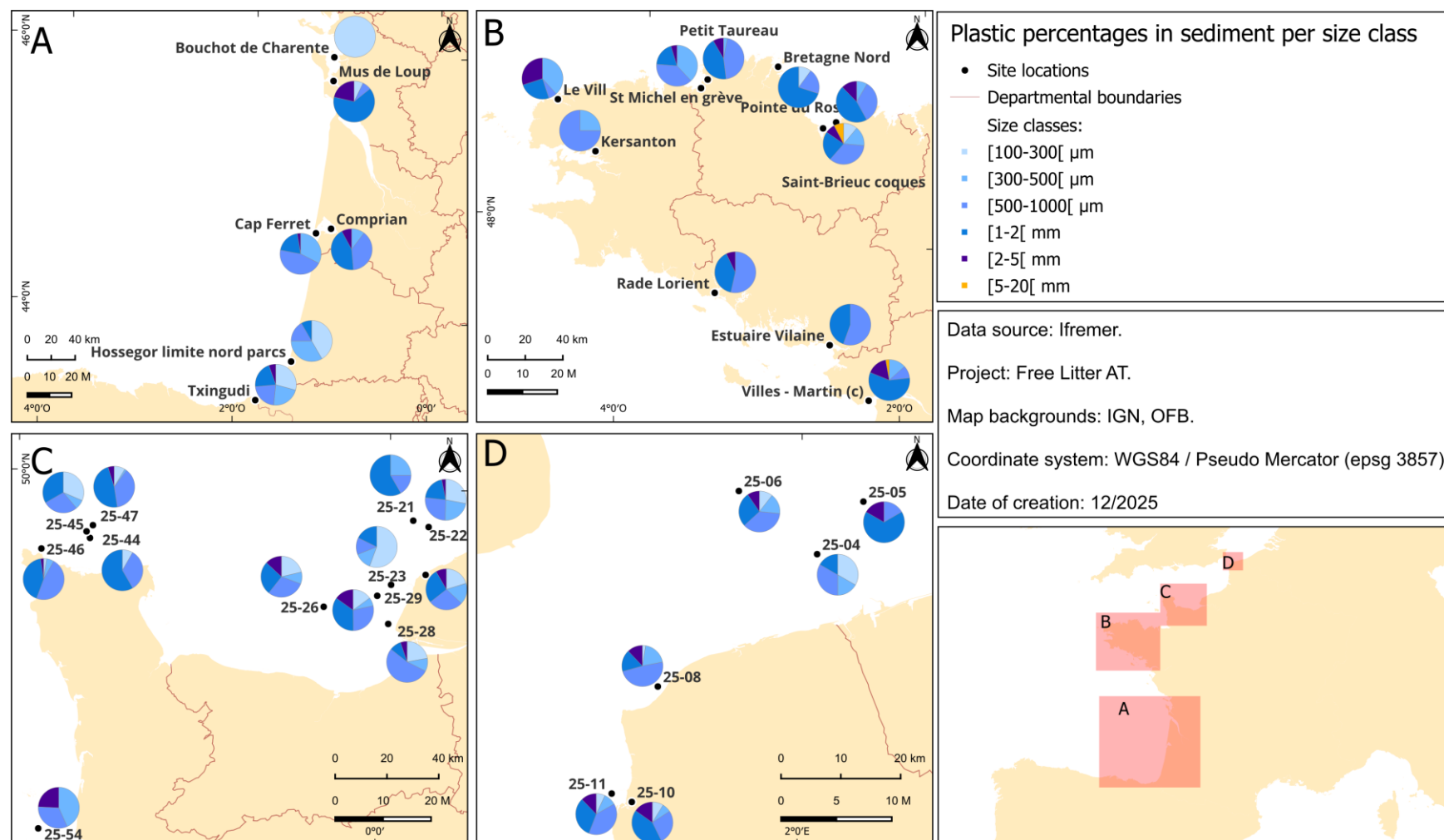


Figure 11. Average percentages across all replicates of total plastic particles (mesoplastics and MPs), per size range, in sediment for each station along the French coast.



4.1.3. Typologies of microplastic particles

Given the low level of mesoplastics observed, only the typologies of MPs were considered. A majority of MPs were fibers (83%), followed by fragments (9%) and pellets (8%, Figure 12).

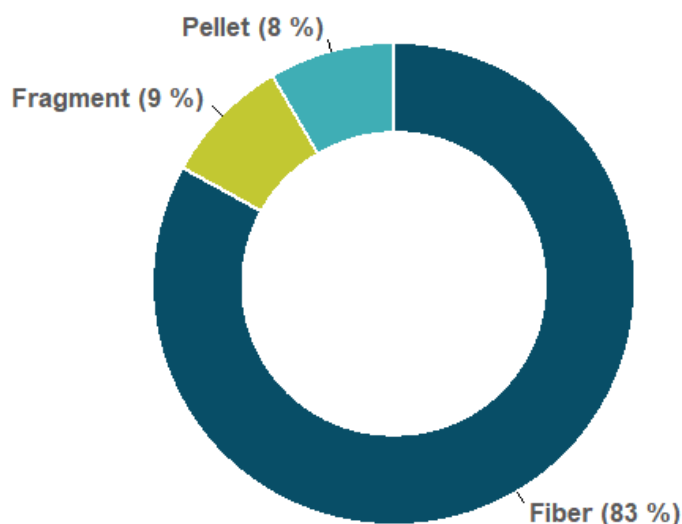


Figure 12. Average percentages across all stations of MP typologies for the French sediment samples

Twelve stations presented only fibers (between 24 and 364 items/kg d.w.) and one station (*i.e.* “Bouchot de Charente”) had only pellets (15 items/kg d.w.; Figure 13 & Figure 14). Thirteen stations presented both fibers and fragments, with a predominance of fibers for twelve stations (between 61 and 98% of fibers) and a majority of fragments for “Le Vill” (53%). The station “GRAB 25-22” presented also two typologies, with fibers (338 items/kg d.w.) and pellets (71 items/kg d.w.). Finally, seven stations had fibers, fragments and pellets. Six of them had a majority of fibers (between 58 and 94%) whereas “GRAB 25-23” had a majority of pellets (59%).

Fiber concentrations ranged from 0 (“Bouchot de Charente”) to 751 items/kg d.w. (“GRAB 25-06”). Fragment concentrations ranged from 0 (14 stations) to 126 items/kg d.w. (“Txingudi”). Finally, pellet concentrations ranged from 0 (25 stations) to 114 items/kg d.w. (“GRAB 25-23”).

The geographical repartition of MP typologies is presented in Figure 13. Fibers were observed along the entire French Atlantic coast, whereas fragments were essentially detected in the Northwestern of Brittany and in the south of the Bay of Biscay. Pellets were mainly detected around the Seine estuary and also in two stations of the Bay of Biscay.



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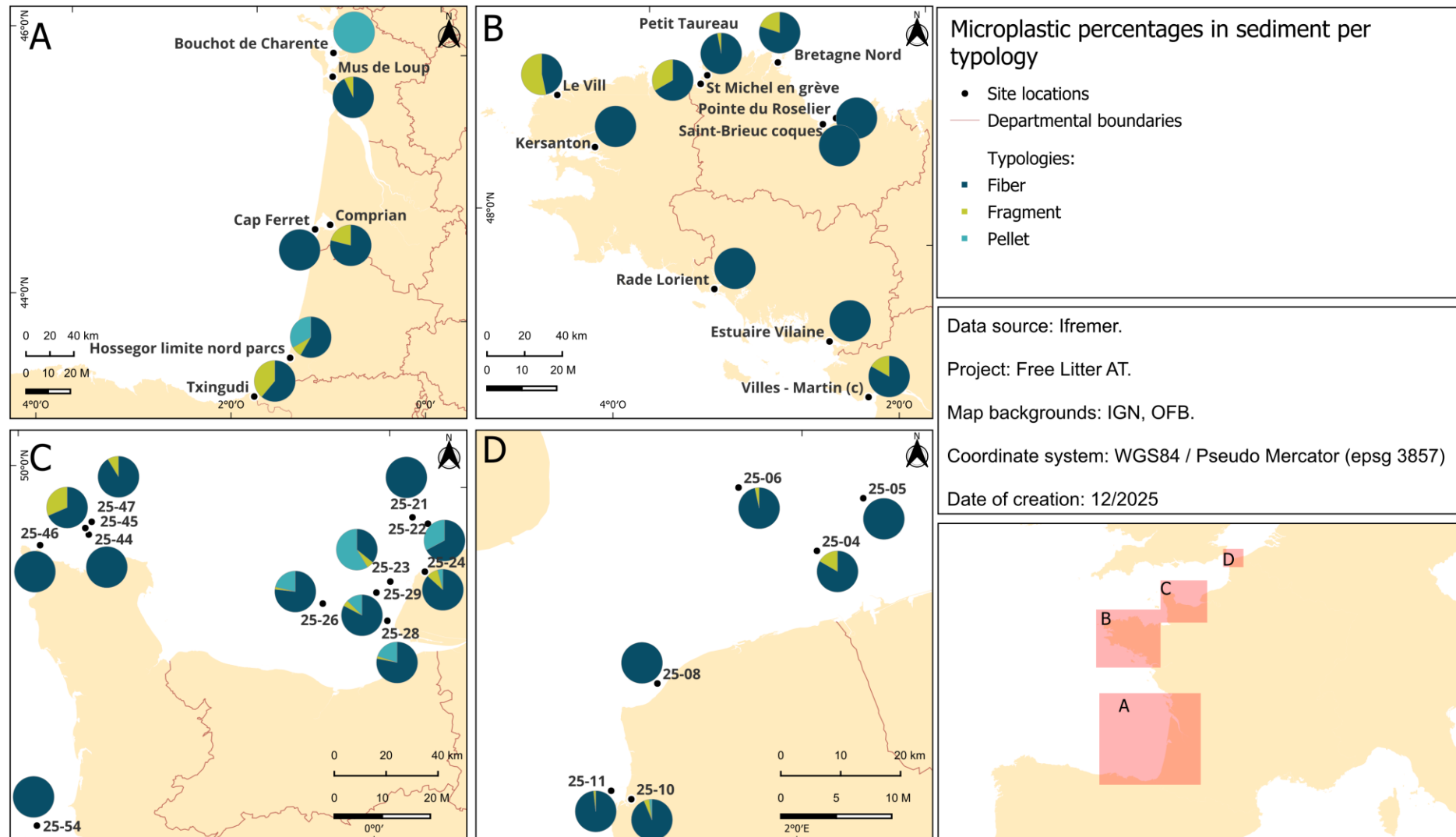
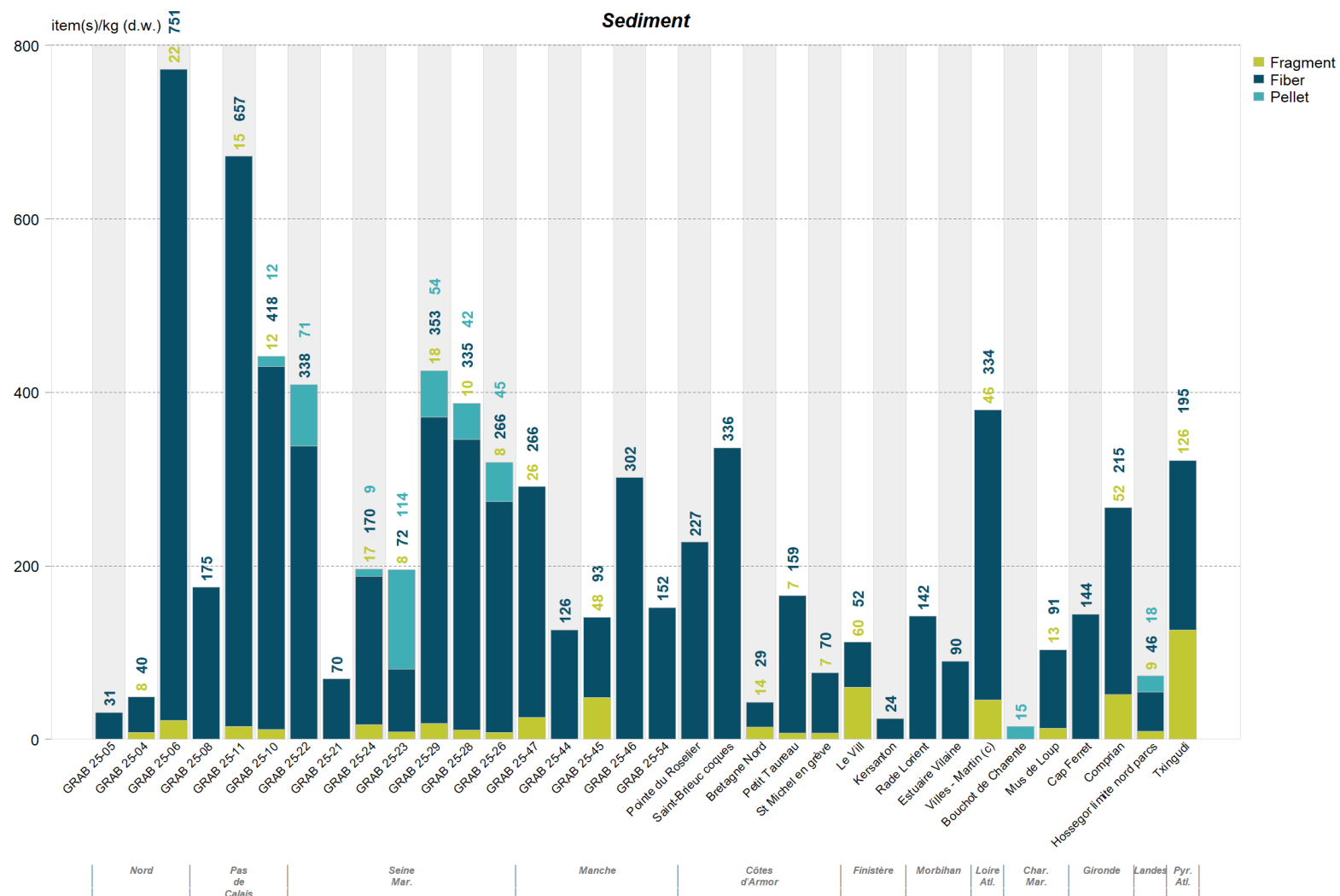


Figure 13. Average percentages of MP particles per typology in sediment for each station along the French coast



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Figure 14. Concentrations of MPs per typology (items/kg d.w.) in sediment along the French coast



4.1.4. Composition of microplastic particles

The distribution of MP polymer types in sediments along the French coastline shows marked spatial variability between sampling sites (Figure 15). Overall, polyethylene (PE) and polypropylene (PP) dominate the polymer composition in most locations, with PE frequently representing the highest proportion, reaching up to ~83.9% at certain sites (e.g., Villes Martin) and remaining above 30% in many others (e.g., Bretagne Nord, Petit Taureau, St Michel en Grève, Le Vill, Mus du Loup, Bouchot de Charente, Hossegor and Txingudi). PP also contributes substantially, particularly in Kersanton and Cap Ferret, where it accounts for up to 45% and 50% of MPs, respectively. Polystyrene (PS) and polyester are locally significant, with PS reaching 45.7% at St Brieuc and polyester (90% correspond to polyethylene terephthalate (PET)) dominating in specific areas such as Rade de Lorient (75%) and Cap Ferret (50%). Secondary polymers including polyamide (PA), polyvinyl chloride (PVC), polycarbonate (PC), polymethyl methacrylate (PMMA), polyurethane (PU), and polyacrylonitrile (PAN) are generally present in lower proportions but can contribute significantly at individual sites (e.g., PA at Petit Taureau and St Michel en Grève).

In some cases, pigments such as phthalocyanine blue (PB15) generated intense Raman signals that masked the underlying polymer signatures. This category was nevertheless included due to its anthropogenic origin, even when the polymer matrix could not be identified. Notably, some sites exhibit a strong prevalence of this category, particularly at Estuaire Vilaine (75%) and Combrit (66.7%).

When considering MPs typologies (Figure 15 & Figure 16), fragments clearly dominate over fibers for most polymer types, particularly for PE, which exhibits by far the highest abundance of fragments ($n = 263$) compared to fibers ($n = 16$). A similar trend is observed for PS (48 vs 6), and PA (38 vs 4), indicating that fragmentation processes likely represent a major pathway for MPs generation in these environments. In contrast, some polymers such as PP and polyester show a more balanced distribution between fibers and fragments, suggesting mixed sources including both textile-derived fibers and degraded plastic debris. Minor polymers (e.g., PVC, PC, PMMA, PAN, PU, PE+PS) are almost exclusively present as fragments, although their overall contribution remains limited.

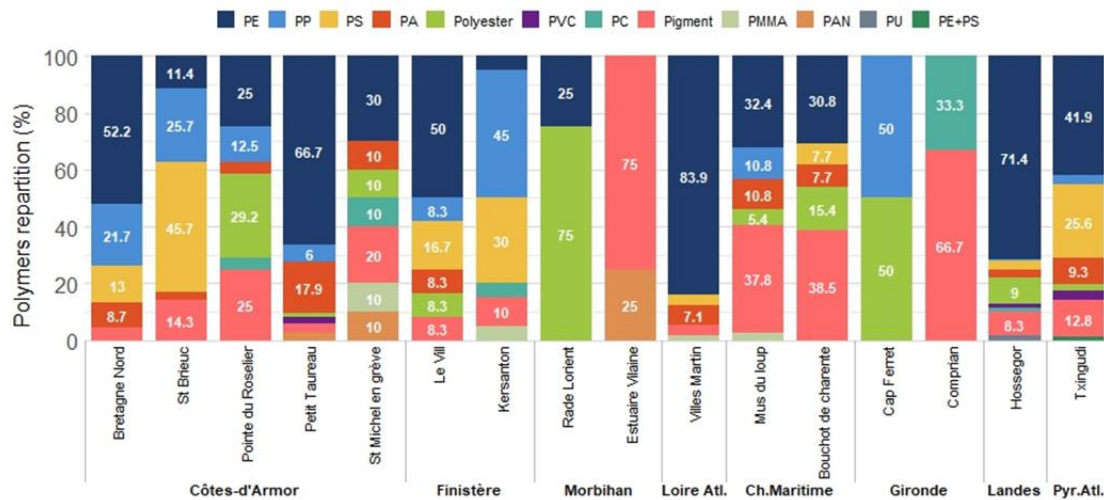


Figure 15: Spatial distribution of microplastic (MP) polymer composition in sediment along French coast.

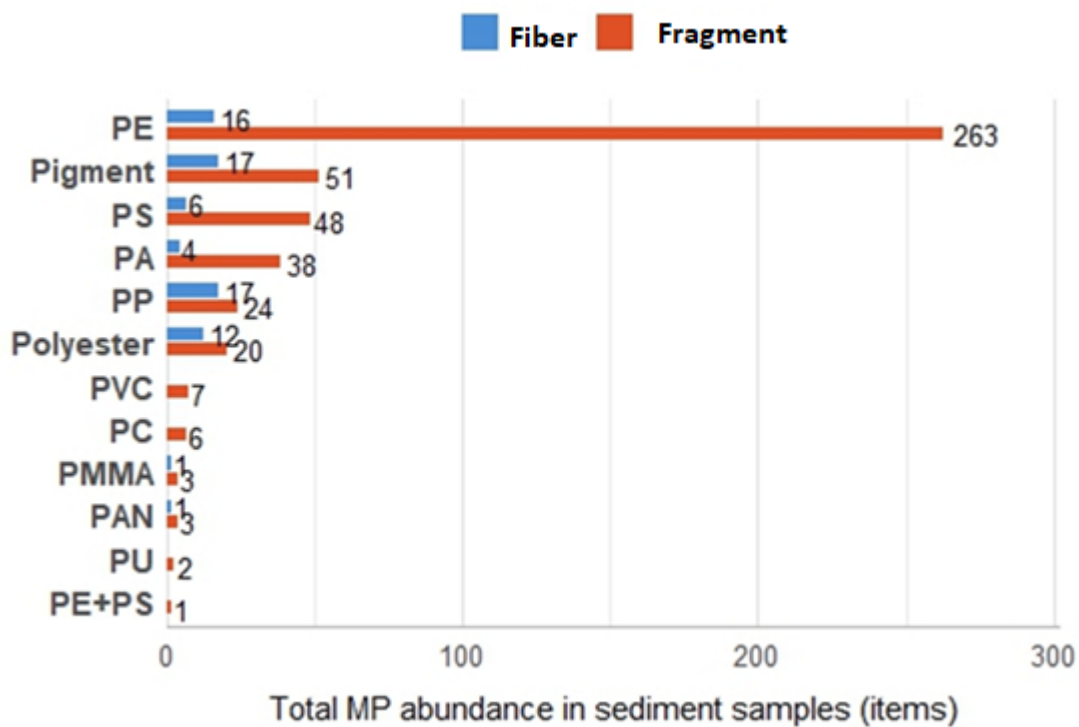


Figure 16: Distribution of microplastic (MP) typologies by polymer type in sediment collected along the French coastline.



4.2. Plastic concentrations in mussels

4.2.1. Total concentrations

The mussels collected had a mean length of 49.51 mm (s.d.: 12.41 mm) and a mean width of 24.65 mm (s.d.: 5.58 mm).

For the following parts, contamination levels are expressed as items per gram of wet weight (items/g w.w.). These results are positively correlated with the results of concentration by individual (items/ind.) and by dry weight (items/g d.w.), with correlation coefficients of 0.4 and 0.7 respectively ($p < 0.05$, $n = 16$). These results are also provided for informational purposes in Table 4 and Supplementary Materials (Figure 35; Figure 36).

87.5% of stations were contaminated by plastic particles (14 out of 16 stations). The samples collected at “Bouchot de Charente” and “Cap Breton Ouest” stations were free of detectable plastic particles. Total plastic concentrations, including mesoplastics (>5mm) and MPs (<5mm), ranged from 0 to 0.982 item/g w.w., with a mean of 0.307 item/g w.w. (s.d.: 0.270 item/g w.w.) and a median of 0.306 item/g w.w. (Table 4).

Table 4. Statistics of total concentrations of plastic particles (mesoplastics (> 5mm) and MPs (< 5mm)) in mussels by items/g w.w., items/g d.w. and items/ind. for the French Atlantic samples (n = 16).

Total Plastic Concentration	Items/g w.w	Items/g d.w	Items/ind
Mean	0.307	2.08	1.17
Standard deviation	0.270	3.17	1.32
Median	0.306	1.17	0.62
Min	0	0	0
Max	0.982	13.13	5.08

Mesoplastics were only observed in three stations: “Le Vill” (0.009 item/g w.w.), “Camaret” (0.011 item/g w.w.) and “Houat” (0.014 item/g w.w.), corresponding to around 6%, 3% and 7% of total plastic particles respectively. The average concentration over all stations was 0.002 item/g w.w. (s.d.: 0.005 item/g w.w.). The mesoplastics represented on average 1% of total plastic particles found in all mussel samples.

The mean concentration of MPs was 0.305 item/g w.w. (s.d.: 0.271 item/g w.w.), with a median of 0.300 item/g w.w. Values ranged from 0 to 0.982 item/g w.w. (Table 5).



Table 5. Statistics of the concentrations of total plastic particles, mesoplastics (> 5 mm) and MPs (< 5mm) in mussels by items/g w.w. for the French Atlantic samples (n = 16).

Items/g w.w	Microplastics	Mesoplastics	Total plastic particles
Mean	0.305	0.002	0.307
Standard deviation	0.271	0.005	0.270
Median	0.300	0	0.306
Min	0	0	0
Max	0.982	0.014	0.982

“Bouchot de Charente” and “Cap Breton Ouest” were the only two stations with no MPs in mussels (Figure 17). Apart from these two stations, the lowest contamination was at “Cap Ferret” with 0.043 item/g w.w., followed by “Le Vill” with 0.089 item/g w.w. Ten stations presented a contamination between 0.100 and 0.500 item/g w.w. The station “La Jument” was the most contaminated, with 0.982 item/g.w.w., followed by “Pointe du Roselier”, with 0.830 item/g w.w. The Kruskal-Wallis test shows a statistical difference between the stations according to MP concentrations (p-value < 0.05).



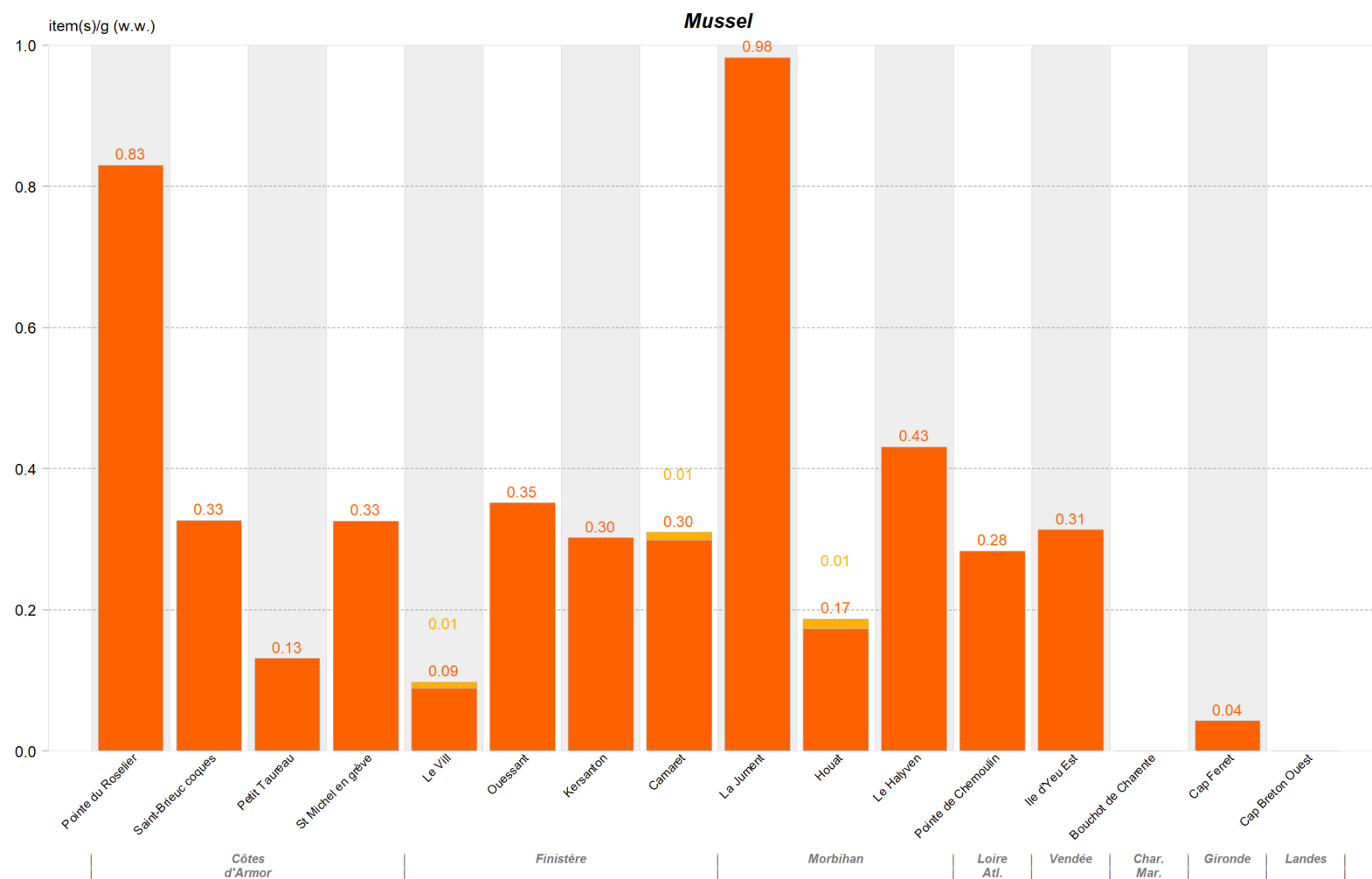


Figure 17. Concentrations of microplastics (dark orange) and mesoplastics (light orange) in mussels for the French stations.



4.2.2. Sizes of plastic particles

On average, more than half (55%) of plastic particles were between 100 and 1,000 μm in size, of which 26% between 500 μm and 1 mm, 16% between 300 and 500 μm and 13% between 100 and 300 μm in size (Figure 18). Particles between 1 and 2 mm represented on average 34% of the particles, followed by particles between 2 and 5 mm, with a mean of 9%. Mesoplastics (> 5 mm) represented on average 1% of plastic particles found in a sample. Geographical repartition of size particles is presented in Figure 19. No clear geographical pattern is observed, except than the three stations at the south of the Bay of Biscay were either devoid of plastic particles, either composed exclusively of particles between 100 and 300 μm . Particles between 100 and 1,000 μm represented a majority for 10 stations whereas the last 4 stations are essentially contaminated by particles between 1 and 2 mm. Similarly, to sediment samples, three of them were located at the North of the Bay of Biscay and the last one at the tip of Brittany. In most cases for the particles between 100 and 1,000 μm in size, there was a predominance of particles from 500 to 1000 μm .

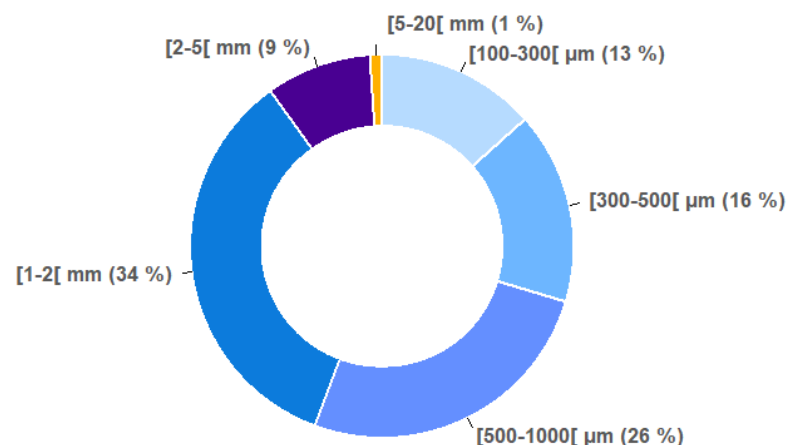


Figure 18. Average percentage of total plastic particles (mesoplastics and MPs) across all stations, per size range, for the French mussel samples

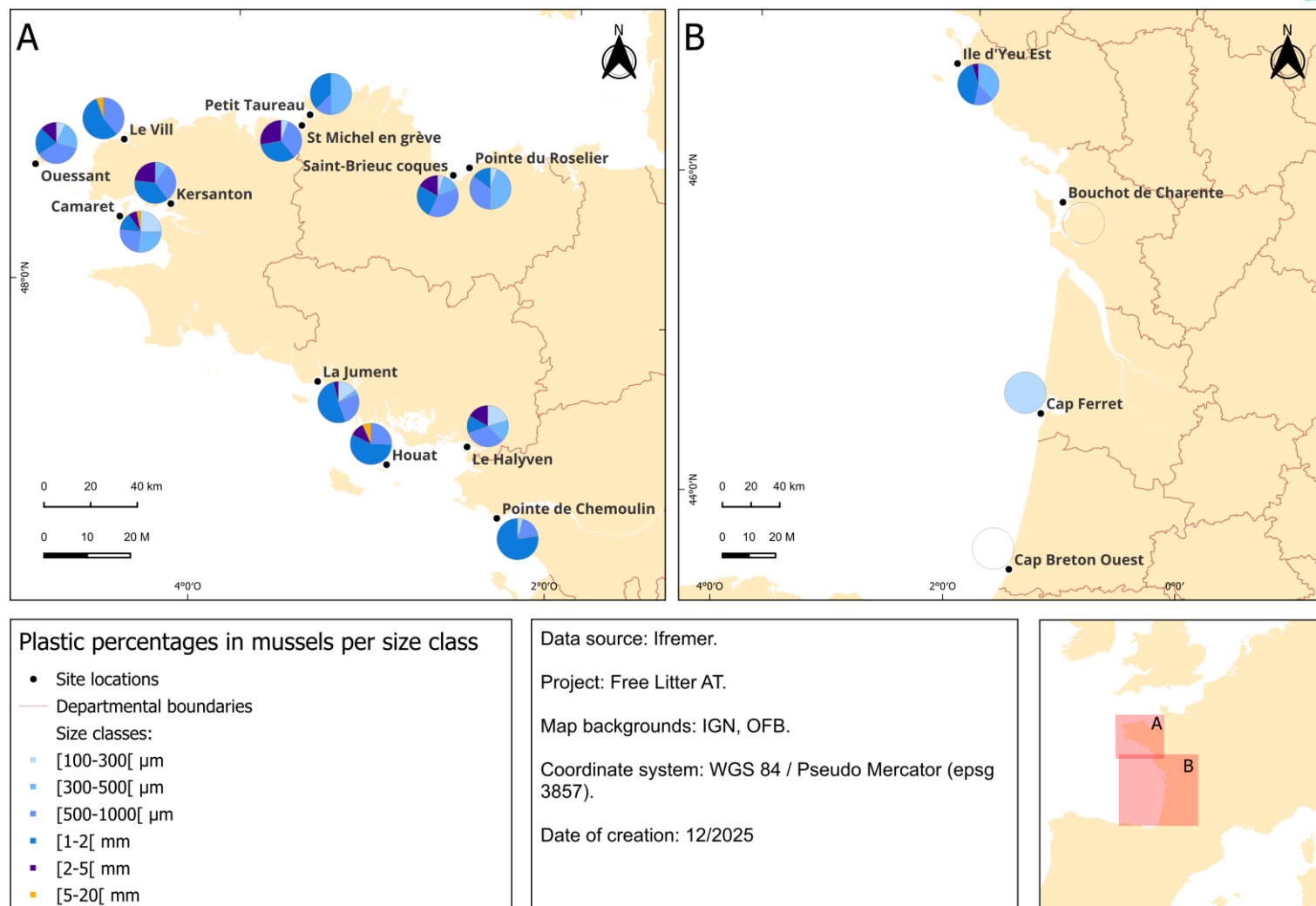


Figure 19. Average percentages across all replicates of total plastic particles (mesoplastics and MPs), per size range, in mussels for each station along the French Atlantic coast



4.2.3. Typologies of microplastic particles

Given the low level of mesoplastics observed, only the typologies of MPs are considered. All MPs were either fibers (70%) or fragments (30%) (Figure 20).

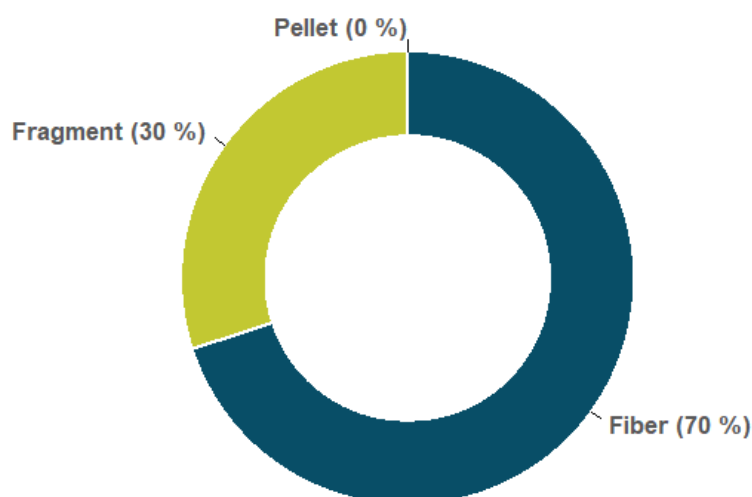


Figure 20. Average percentages across all stations of MPs typologies for the French mussel samples

Ten stations were contaminated by both fibers and fragments. Three stations were contaminated by fibers only ("Petit Taureau", "Houat" and "Le Vill"). The "Cap Ferret" station was contaminated by fragments only (Figure 21).

Fiber concentrations ranged from 0.09 ("Le Vill") to 0.86 item/g w.w. ("La Jument"). Fragment concentrations ranged from 0.02 ("Ouessant") to 0.58 item/g w.w. ("Pointe du Roselier").

Geographical repartition of MPs typologies is presented in Figure 22. It is not possible to visually discern a regional spatial trend for the MPs typologies, except that the stations located in the south of the Bay of Biscay seem to be devoid of fibers.



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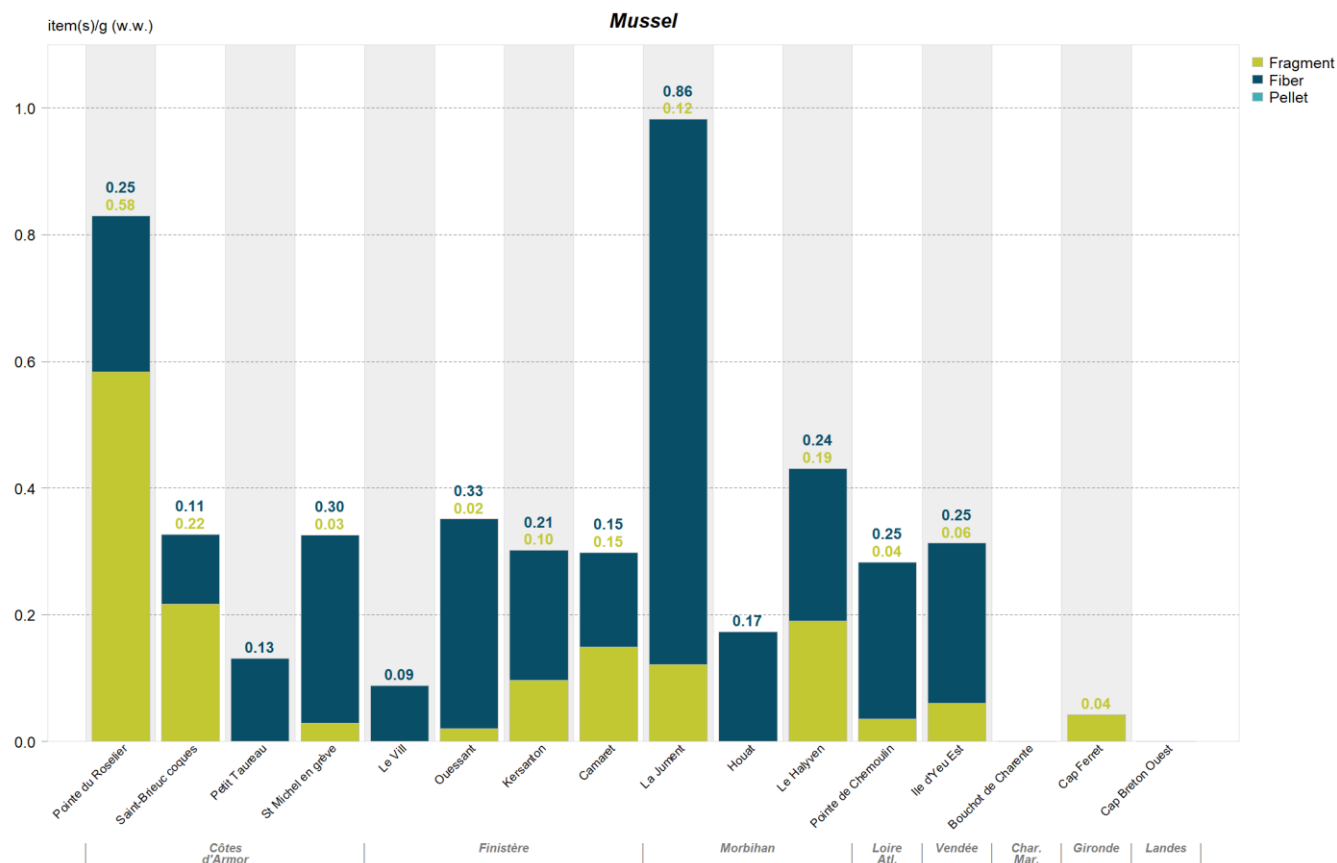


Figure 21. Concentrations of MPs per typology (items/g w.w.) in mussels for French stations

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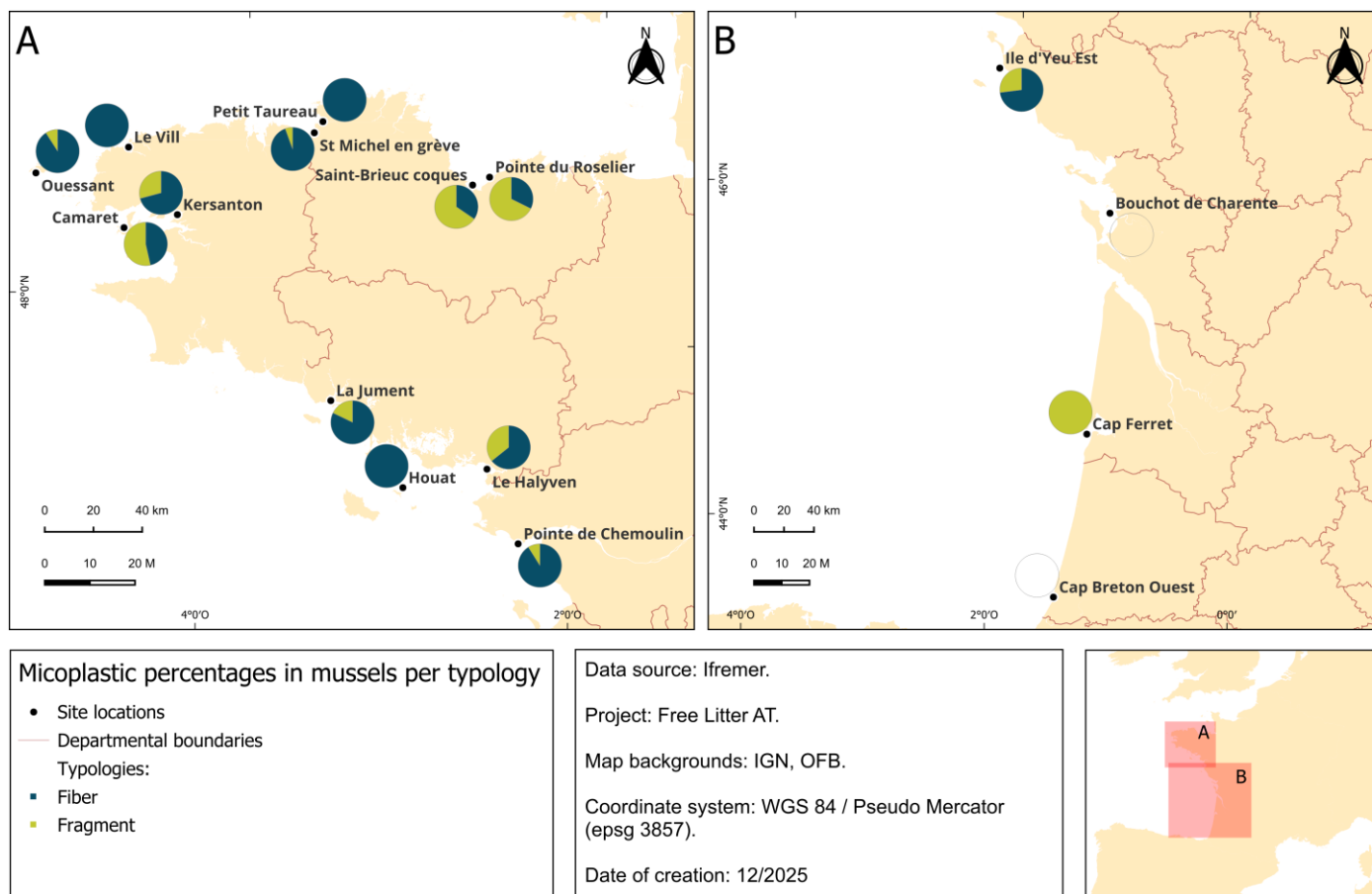


Figure 22. Average percentages across all replicates of MPs, per typology, in mussels for each station along the French Atlantic coast.



4.2.4. Composition of microplastic particles

The polymer composition of MP in mussels showed pronounced spatial variability among sampling sites and between species (Figure 23). Polyethylene (PE) and polypropylene (PP) were generally dominant, although their relative proportions varied markedly across locations. PE reached particularly high levels at certain sites (e.g., up to 80% at La Jument and 50% at Cap Breton ouest), while PP was also abundant in several areas such as Camaret and Cap Ferret (up to ~52.6%). In contrast, some sites were characterized by a strong contribution of polyester and pigments, notably at Petit Tureau (63.6% polyester) and Pointe du Roselier (72.7% pigment), suggesting localized contamination sources. Polystyrene (PS) and polyamide (PA) were overall less represented but locally significant, for example at Ouessant (50% PS) and Pointe de Chémoulin (33.3% PA).

When considering MP typologies in mussels (Figure 24), fragments clearly dominate over fibers for most polymer types. This trend is particularly pronounced for polyethylene (PE), with a higher number of fragments ($n = 28$) compared to fibers ($n = 12$), as well as for polypropylene (PP) (23 vs 7) and polystyrene (PS) (10 vs 3), supporting fragmentation as a major pathway of MP generation. Pigments also follow this pattern, although with a relatively higher contribution of fibers (30 vs 20). In contrast, polymers such as polyester (14 vs 13) and polyamide (PA) (6 vs 6) exhibit a more balanced distribution.

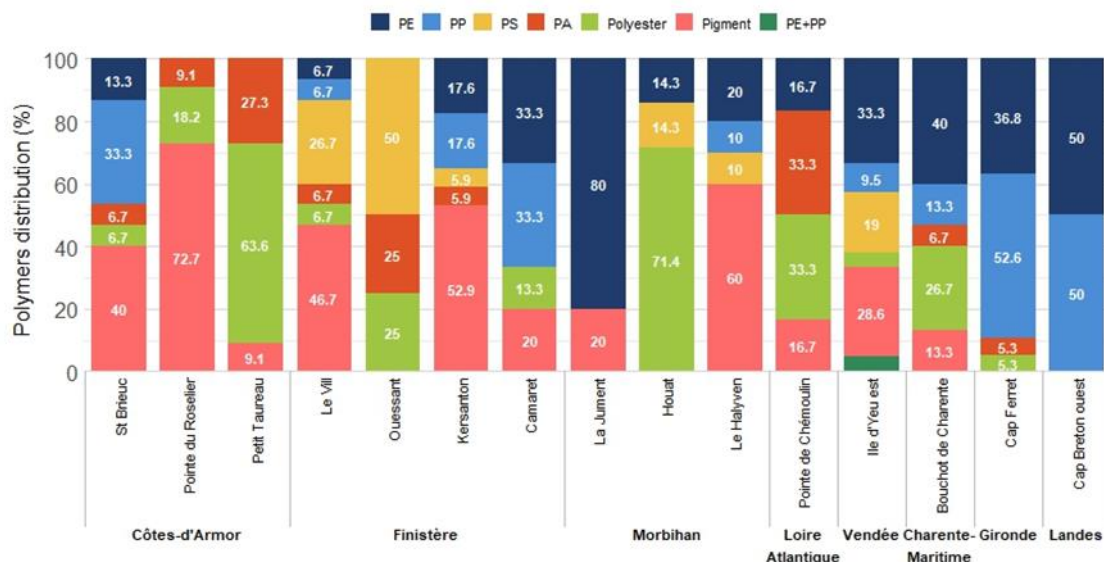


Figure 23: Spatial distribution of microplastic polymer composition in mussels along French coast

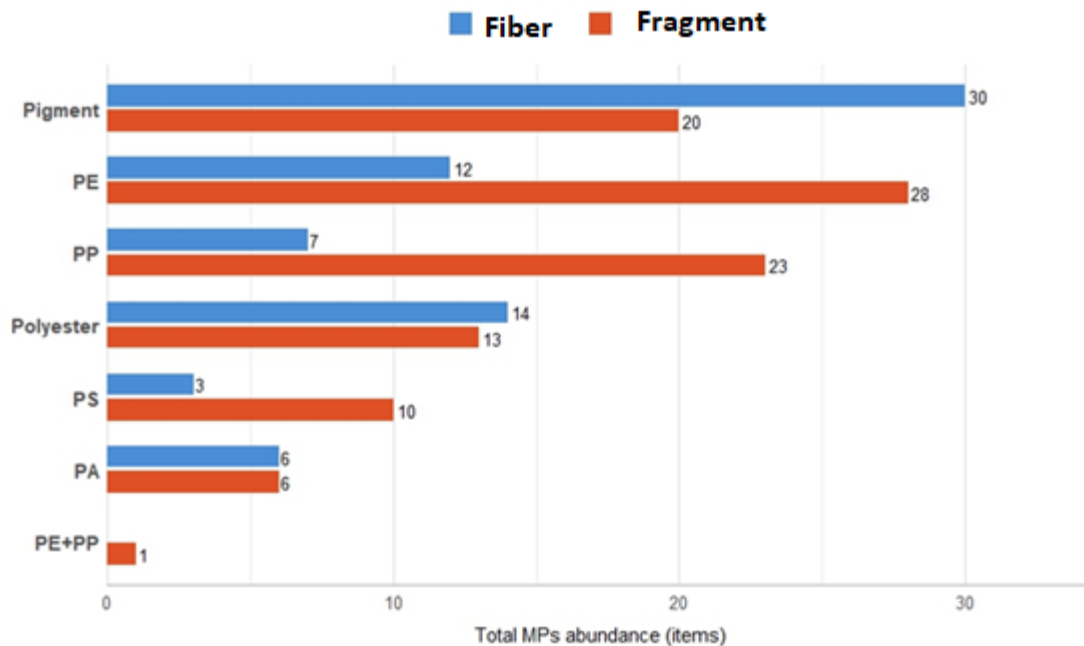


Figure 24: Total microplastic (MP) polymeric composition in mussel samples (items)

4.3. Plastic concentrations in oysters

4.3.1. Total concentrations

The oysters used for analyses had a mean length of 85.77 mm (s.d.: 10.25 mm) and a mean width of 43.46 mm (s.d.: 3.97 mm).

For the following parts, contamination levels are expressed as items per gram of wet weight (items/g w.w.). Results expressed as item numbers per individual (items/ind.) and per gram of dry weight (items/g d.w.) are also provided for informational purposes in Table 6 and Supplementary Materials (Figure 38).



Table 6. Statistics of total concentrations of plastic particles (mesoplastics (> 5mm) and MPs (<5mm)) in oysters by items/ind., items/g d.w and items/g w.w for the French Atlantic samples

Total Plastic Concentration	Items/g w.w.	Items/g d.w.	Items/ind.
Mean	0.512	6.39	4.62
Standard deviation	0.185	7.64	2.49
Median	0.437	2.44	4.00
Min	0.377	1.53	2.50
Max	0.723	15.19	7.36

The three stations were contaminated. Total plastic concentrations including mesoplastics (>5mm) and MPs (<5mm), ranged from 0.377 to 0.723 item/g w.w., with a mean of 0.512 item/g w.w. (s.d.: 0.185 item/g w.w.) and a median of 0.437 item/g w.w.

Mesoplastics were only detected in “Mus du Loup” station, with a concentration of 0.01 item/g w.w. (one fiber of 6.4 mm in one oyster). The mean concentration over all stations was 0.003 item/g w.w. (s.d.: 0.006 item/g w.w.). The mesoplastics represented only 2% of total plastic particles found in all oyster samples. The three stations were contaminated by MPs. The mean concentration of MPs was 0.509 item/g w.w. (s.d.: 0.189 item/g w.w.), with a median of 0.437 item/g w.w. (Table 7).

Table 7. Statistics of the concentrations of total plastic particles, mesoplastics (> 5 mm) and MPs (< 5 mm) in oysters by items/g w.w. for the French Atlantic samples (n = 3)

Items/g.w.w	Microplastics	Mesoplastics	Total plastic particles
Mean	0.509	0.003	0.512
Standard deviation	0.189	0.006	0.185
Median	0.437	0	0.437
Min	0.367	0	0.377
Max	0.723	0.010	0.723

“Mus du Loup” is the less contaminated station with 0.367 item/g w.w. (Figure 25), followed by “Txingudi” (0.44 item/g w.w.) and “Comprian”, which was the most contaminated station with 0.723 item/g w.w. No statistical differences for plastic contamination were observed between the stations, probably because of the low number of stations for this matrix.

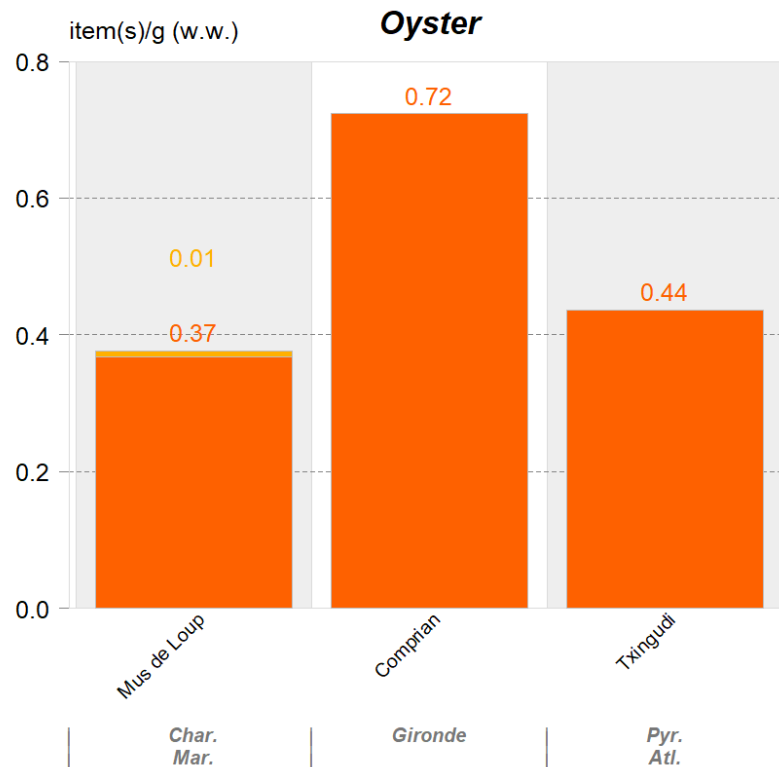


Figure 25. Concentrations of microplastics (dark orange) and mesoplastics (light orange) in oysters for French stations

4.3.2. Sizes of plastic particles

On average, most MPs were between 100 and 1,000 μm in size (63%), of which 15% between 100 and 300 μm , 16% between 300 and 500 μm and 32% between 500 μm and 1 mm in size (Figure 26). Then, the particles between 1 and 2 mm represented on average 31% of plastics in a sample, whereas particles between 2 and 5 mm represented only 4% of plastics. Finally, mesoplastics (> 5 mm) represented 2% of total plastic particles in the samples. Geographical repartition of size particles is presented in Figure 27. “Mus du Loup” presented more larger plastic particles (> 1 mm, 50%) and very few MP between 100 and 300 μm compared to the two other stations. “Txingudi” and “Comprian” showed similar patterns according to plastic particle sizes.

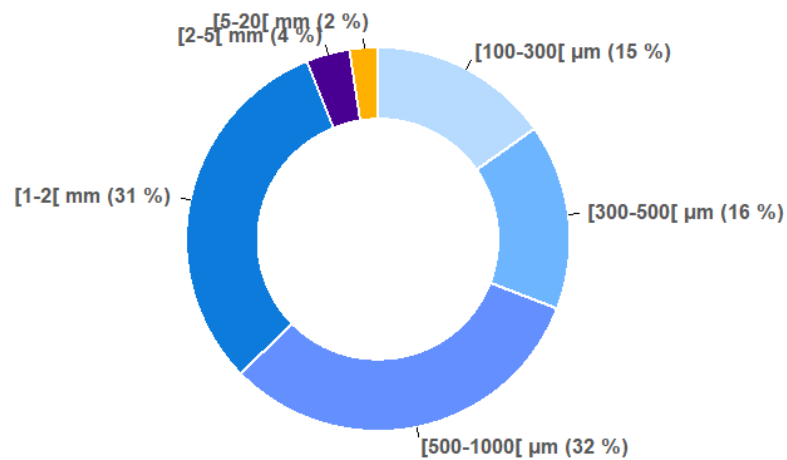


Figure 26. Average percentages of total plastic particles (mesoplastics and MPs) across all stations, per size range, for the French oyster stations

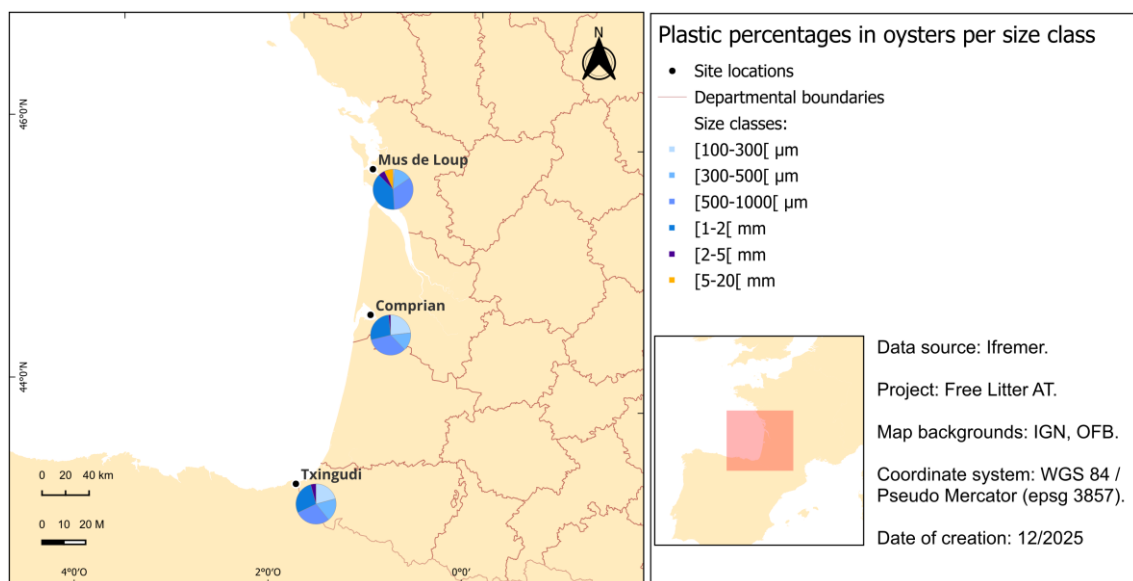


Figure 27. Average percentages of total plastic particles (mesoplastics and MPs), across all replicates, per size range, in oysters along the French Atlantic coast.

4.3.3. Typologies of microplastic particles

Given the low level of mesoplastics observed, only the typologies of MPs are considered. The microplastics were on average composed of 88% fibers and 12% fragments (Figure 28).

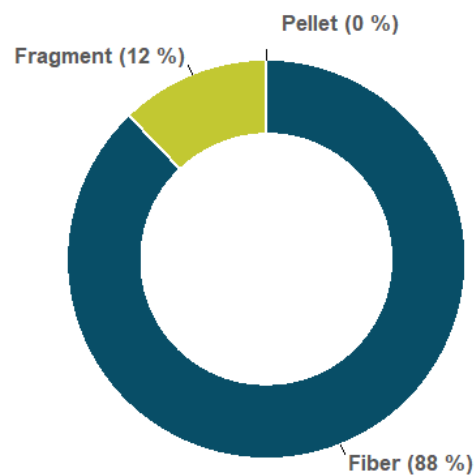


Figure 28. Average percentages across all stations of MP typologies in oysters of the French stations

The three stations were contaminated by fibers (Figure 29), ranging from 0.37 (“Mus du Loup” and “Txingudi”) to 0.46 item/g w.w. (“Comprian”). “Mus du Loup” station was contaminated by fibers only, whereas “Comprian” and “Txingudi” stations presented also fragments, with 0.26 and 0.07 item/g w.w. respectively.

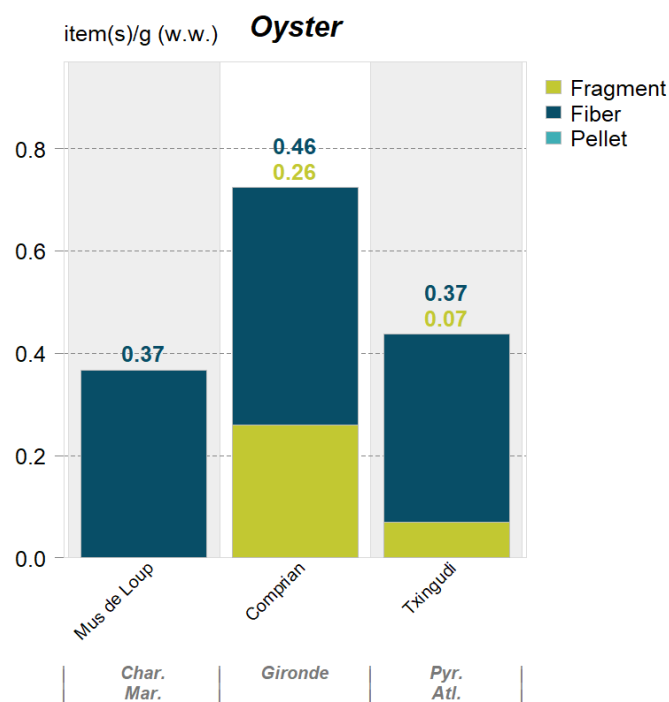


Figure 29. Concentrations of MPs per typology (items/g w.w.) in oysters for French stations



4.3.4. Composition of microplastic particles

In oysters (Figure 30), polymer distributions also displayed site-specific differences but with distinct patterns compared to mussels. Oysters from Charente-Maritime were largely dominated by PS (46.2%) and PP (23.1%), whereas those from Gironde showed a more balanced distribution, with notable contributions of polyester (25%), PA (25%), and PE (25%). In Pyrénées-Atlantiques, PE was the predominant polymer (up to 45.5%), followed by PA (27.3%), while other polymer types were present in lower proportions. Pigments were consistently detected across all oyster samples, albeit at moderate levels.

In oysters (Figure 31), fragments also tend to dominate over fibers, although overall abundances are lower compared to mussels. This pattern is observed for several polymer types, including polystyrene (PS) (5 vs 1), polypropylene (PP) (4 vs 1), and polyethylene (PE) (4 vs 3). In contrast, polyester is exclusively present as fibers (n = 3). Pigments remain more abundant as fragments (2 vs 1).

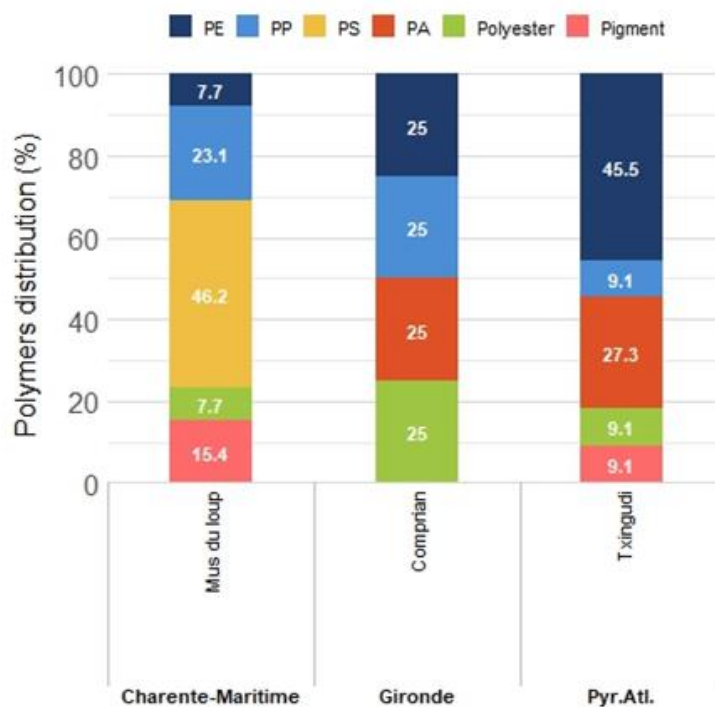


Figure 30. Relative abundance (%) of polymer types identified in oysters across sampling sites, grouped by geographic regions. Values are expressed as percentages of total MPs identified per site.

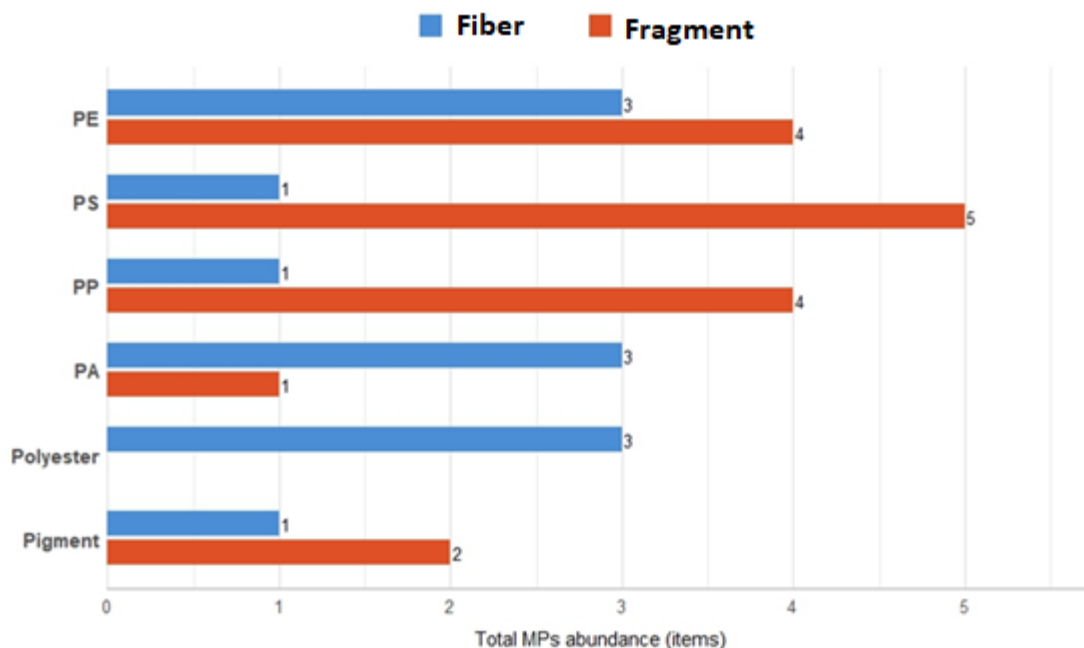


Figure 31. Total abundance (number of items) of fibers and fragments for each polymer type identified in oysters.

5. Discussion

5.1. MP contamination in sediment

Sediments are considered the ultimate sink for debris introduced into the marine environment (Galgani et al., 2015). Biofouling which accumulates around plastic particles on the surface and in the water column, enhances their transport to the seafloor by increasing their effective density (Bergmann et al., 2025). According to Chubarenko et al. (2016), the settling of MPs to the seabed may require approximately 6–8 months for fibrous particles and up to 15 years for spherical MPs. Once deposited on the seafloor, MPs are shielded from UV radiation, which significantly slows their degradation (Corcoran, 2015). Therefore, investigating MP contamination within sediment matrix is essential for understanding long-term environmental pollution.

The Free LitterAT dataset (average of 226 ± 179 MPs/kg d.w., $n = 34$), places it within the intermediate range of contamination observed in French and European coastal environments (Figure 32) and indicate a dataset coherent with existing assessments (Lefebvre et al., 2023; Phuong et al., 2018; G rigny et al., 2020; Lerebours et al., 2022; G rigny et al., 2021).



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At the European scale, MP contamination recorded during Free LitterAT was generally higher than values reported for some Atlantic regions (Lorenz et al., 2019; Mendes et al., 2021; Carretero et al., 2021). These differences may partly reflect variations in anthropogenic pressure, population density, and hydrodynamic conditions. Numerous studies have highlighted the strong relationship between MP abundance and human population density or type of activities in coastal and riverine environments (Browne et al., 2011; Van Cauwenberghe et al., 2015; Strady et al., 2020; Tang et al., 2023). The Free LitterAT results are consistent with this interpretation, numerous monitoring points being located near activities such as marine farming or nautical activities and showing the higher values, supporting the robustness of the dataset.

From a national perspective, MP contamination along the French Atlantic coast appears lower than that reported for the Mediterranean Sea (Alcaíno et al., 2025; Alomar et al., 2016) because of its semi-enclosed nature, contributing to its recognition as a hotspot of marine MP pollution (Faure et al., 2015; Schmidt et al., 2018). At the global scale, MP contamination in Atlantic sediments remains substantially lower than levels reported in the Indian and Pacific Oceans (Connan et al., 2021; Sin et al., 2023; Pan et al., 2022; Ramadoss et al., 2025; Luo et al., 2022; Wong et al., 1974). Finally, when compared with remote polar environments, MP contamination in Atlantic sediments falls within the lower range of concentrations reported for Arctic and Antarctic seabed sediments (De la Torre et al., 2024; Huang et al., 2023; Ramasamy et al., 2021; Huang et al., 2023).

Oceanographic processes, including the role of the seafloor as a sink for plastic debris, further explain MP occurrence in these environments (Cozar et al., 2017; D'Avignon et al., 2022). Overall, the Free LitterAT results confirm that the French Atlantic coast exhibits moderate MP contamination relative to national, European, and global contexts (Figure 32).



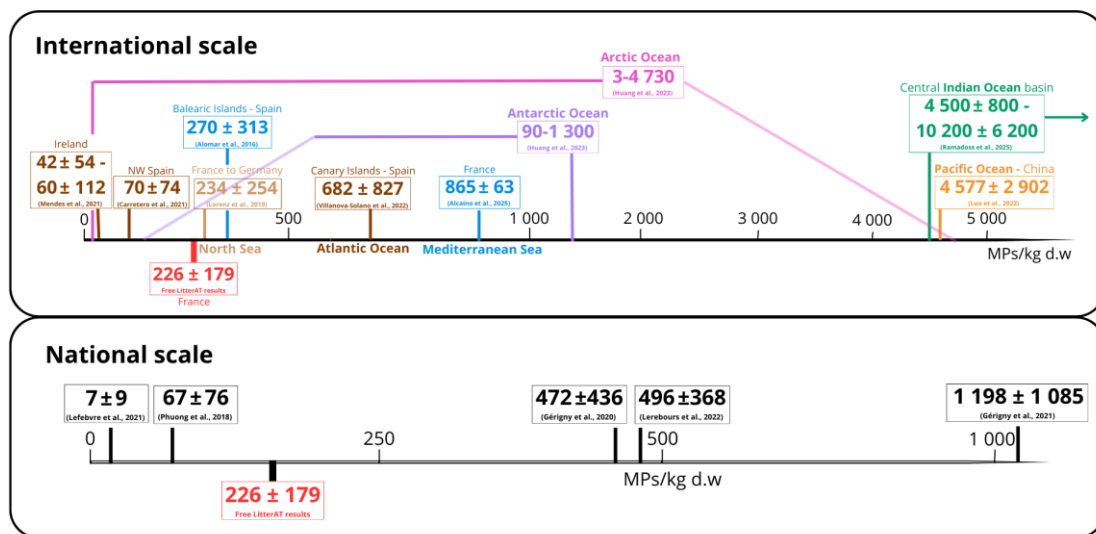


Figure 32. Comparison of MP contamination levels (items/kg d.w.) in sediment between this study and previous studies

5.2. MP contamination assessment in mussels

Blue mussels, widely used as indicator species, are sessile filter feeders that reflect the water quality of very localized areas (Chandurvelan et al., 2015; De Bruijn, 2024). Through filtration, they can accumulate contaminants, including MPs (Multisanti et al., 2022). Although they can selectively excrete certain particles, leading others to accumulate in the gut. This selective process contributes to explain discrepancies between MPs found in mussels and those present in surrounding waters, but is still largely unknown (Li et al., 2021). The combined assessment of MP contamination in sediment and mussels is therefore of great interest.

With an average 0.3 ± 0.27 item/g w.w. ($n = 16$), the MP concentrations in mussels from Free LitterAT were consistent with values reported in the literature (Phuong et al., 2018; Lerebours et al., 2022; Gérigny et al., 2023; Figure 33) and correspond to an intermediate contamination level in the French Atlantic coast and the wider Atlantic Ocean. Differences observed among French studies may be partly explained by local anthropogenic pressures, particularly in shellfish farming areas where aquaculture-related plastic materials can contribute to increased MP contamination (Phuong et al., 2018).

A North-South decreasing gradient in MP contamination of mussels has been reported across several studies in the literature (Catarino et al., 2018; De Bruijn, 2024; Ferreira et al., 2023). Several factors may contribute to this north-south gradient, including



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seasonal variability, differences in feeding behaviour and rainfall patterns (Collard et al., 2017; Baechler et al., 2020; Lozano-Hernandez et al., 2021; Lerebours et al., 2022), as well as the oceanographic processes which can enhance the accumulation and redistribution of MPs in northern and subpolar Atlantic waters (Wichmann et al., 2019). Although the Free LitterAT data are not associated with these studies, they are consistent with this observed pattern and supporting the consistency of the dataset.

From a global perspective, Free LitterAT mussels exhibited slightly higher MP contamination levels than those reported for the Western Mediterranean Sea (Alcaíno et al., 2025; Vandermeersch et al., 2015; G rigny et al., 2022). This difference may be related to the oligotrophic nature of the Western Mediterranean, which can alter mussel feeding conditions and consequently affect MP uptake and retention (Chae & An, 2020; Liang et al., 2024; Weiss et al., 2024; Yin et al., 2022). However, Free LitterAT mussel contaminations appear lower than those reported in the Indian and Pacific Oceans, reflecting the influence of dense coastal populations and increased plastic inputs into marine environments (Manh Do et al., 2024; Ding et al., 2021; Jang et al., 2020) (Figure 33).

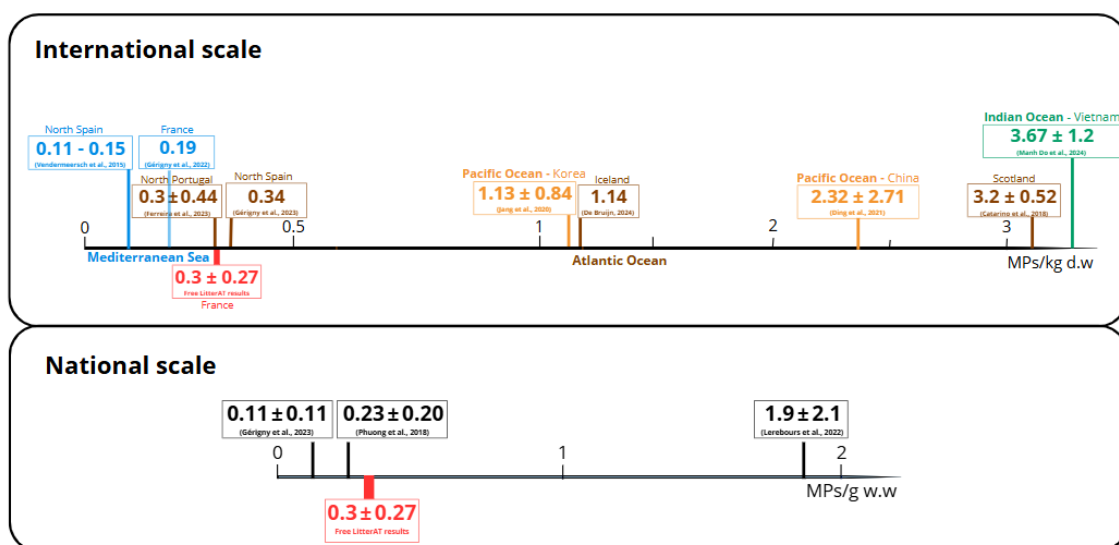


Figure 33. Comparison of MP contamination levels (items/g w.w.) in mussels between the present and previous studies

5.3. MP contamination assessment in oysters

As sedentary filter feeders, bivalves efficiently intercept and retain MPs in marine environments. When mussel sites were unavailable near some sediment sampling



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stations, oysters were used as alternative bioindicators due to their ability to reflect site-specific MP contamination (Zhu et al., 2020). Although oysters are the second most consumed bivalve group, they remain poorly studied in field investigations (Wooton et al., 2022). Consequently, comparisons with the literature were limited and should be interpreted with caution. With an average of 0.51 ± 0.19 item/g w.w. ($n = 3$), the MP concentrations in oysters from Free LitterAT were consistent with values reported in the literature (Phuong et al., 2018; Lefebvre et al., 2023; Lerebours et al., 2022) and correspond to an intermediate contamination level compared to European studies, while being slightly higher than values previously reported along the French Atlantic coast (Phuong et al., 2018; Lefebvre et al., 2023; Lerebours et al., 2022).

MP contamination in oysters shows marked spatial variability, from local to global scales. Along the French Atlantic coast, differences observed between Free LitterAT stations suggest that regional hydrodynamics and coastal circulation patterns influence MP transport and accumulation, with lower contamination in Charente-Maritime than in Arcachon Bay and near the Spanish border (Lerebours et al., 2022; Lefebvre et al., 2023). To go further in the analysis of the MP contamination in oysters and to determine the role of this species as a bio-indicator, this study would need to be expanded with a larger number of samples and a greater spatio-temporal coverage.

At the European scale, the Free LitterAT data showed intermediate contamination levels compared with those reported in other Atlantic regions (Moura et al., 2025; Paul et al., 2023). In contrast to mussels, MP contamination in oysters appears higher than that reported in the Mediterranean Sea but remains lower than levels observed in China, Korea, Vietnam, and India (Ding et al., 2021; Jang et al., 2020; Manh Do et al., 2022; Saha et al., 2021). This variability could be driven by dense coastal populations, intense anthropogenic activities, riverine inputs, and hydrodynamic conditions that favour MP accumulation and bioavailability (Exposito et al., 2022; Papini & Rakaj, 2025) (Figure 34).

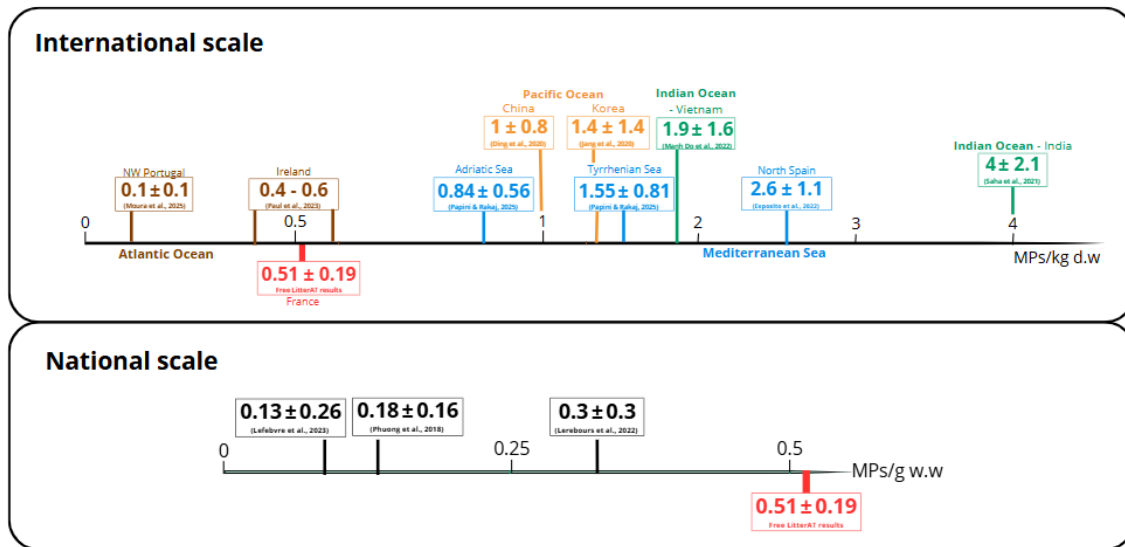


Figure 34. Comparison of MP contamination levels (items/g w.w.) in oysters between the present and previous studies

5.4. Size class

MP size distributions can yield indirect information on particle ageing and transport dynamics. In general, smaller particles indicate older materials or long-range transport via atmospheric pathways, while larger particles suggest local input or less degradation. In fact, the measured concentration of MPs tends to increase with decreasing mesh size (Corcoran et al., 2015; Galgani et al., 2021; Lindeque et al., 2020). Our findings suggested long time contamination in most of stations. On average, more than half of the MPs (60% in sediment, 55% in mussels and 63% in oysters) detected in a sample for biota and sediments belonged to the size class ranging from 100 μ m to 1 mm.

The spatial distribution of mesoplastics may be explained by proximity to estuaries, industrial-port areas, and zones of intense maritime activity. For instance, the Villes Martin and Pointe de Chemoulin stations are located near the Nantes/Saint-Nazaire industrial-port complex, one of the three major French Atlantic ports, and close to the Loire estuary, where industrial activities and maritime traffic may contribute to plastic contamination (Mongruel et al., 2019). In addition, river plumes such as those of the Loire and Le Vill are recognized as major pathways transporting plastic waste from land to coastal environments (Lebreton et al., 2017; Strokol et al., 2023).

In contrast, no mesoplastics were detected in sediment samples from the ROCCHSED monitoring program along the English Channel coast, confirming previous observations by G rigny et al. (2021). This absence suggests that microplastic (MP) contamination in this region is mainly influenced by large-scale marine circulation rather than local sources. The English Channel is characterized by a west-to-east coastal current that



flows northward into the North Sea (Lazure and Desmare, 2012). Furthermore, the Seine and Somme rivers discharge into this area. The Seine watershed is extensive, densely populated, and subject to numerous litter-producing human activities (Gérigny et al., 2018), making it a potential source of plastic contamination, while the long transport distance likely promotes fragmentation into smaller particles before reaching the estuary.

5.5. Typology

Fibers were the dominant microplastic (MP) typology (>70%) across all matrices, followed by fragments (<30%). Sediments, recognized as the main sink for plastic pollution (Constant, 2018), predominantly accumulate fibers, which are also preferentially ingested by mussels and oysters (Constant, 2018; Vandermeersch et al., 2015). This predominance reflects the widespread occurrence of fibers in the marine environment, mainly originating from textiles (Napper and Thompson, 2016) and fishing gear (Claessens et al., 2011). Their accumulation in sediments is further favoured by the relatively high density of polymers such as polystyrene and polyacrylamides, which readily sink in seawater (Cheung and Fok, 2016). Additional sources include the degradation of fishing nets and dolly ropes (Devriese et al., 2015), wastewater and laundry effluents, as well as sewage sludge and dredged sediments (Browne et al., 2011). However, identifying the dominant sources remains difficult because MPs can originate from multiple pathways, including atmospheric deposition (Andrady, 2015; Dris et al., 2016).

The distribution of MP typologies is also influenced by local environmental conditions. For example, at Cap Ferret, fibers dominated in sediments whereas only fragments were detected in mussels, suggesting differences in transport and bioavailability. Potential inputs include wastewater treatment plant effluents, the Leyre River, and oyster farming (Kazour et al., 2019b; Parker-Jurd et al., 2021). In addition, hydrodynamic processes, tidal channels, and oceanic fronts regulate the transport and accumulation of MPs by limiting water mixing and trapping particles (Suaria et al., 2021; Wang et al., 2022), while polymer density further influences their vertical distribution within the water column (Farrell and Nelson, 2013).

Pellets were detected in sediments at two Atlantic stations (Hossegor and Bouchot de Charente), consistent with previous observations near Hossegor (Tarnos) reported by Gérigny et al. (2021), suggesting persistent contamination. As primary microplastics, pellets are typically associated with industrial sources. Their presence at these stations may be linked to nearby estuaries (Adour and Charente), which drain industrial areas including waste-treatment, plastic-processing, railway, and aeronautics facilities. Pellet losses can result from industrial handling, recycling activities, inadequate waste management, or container spills during maritime transport (Karlsson et al., 2018).



Pellets were even more frequent in ROCCHSED samples, occurring at 7 of 18 stations and at higher concentrations than along the Atlantic coast. This pattern is consistent with the intense shipping activity of the English Channel and North Sea, one of the world's busiest maritime corridors, where maritime transport—including container losses—represents a major source of marine litter (Mongruel et al., 2019; UNEP, 2005). Additional inputs may originate from major industrial zones around Dunkerque, Boulogne, Rouen, and Le Havre, as well as from the Seine and Somme estuaries, which transport plastic litter from densely populated and industrialized catchments.

5.6. Polymers repartition

The predominance of polyethylene (PE) and polypropylene (PP) across MPs found in sediments, mussels, and oysters is consistent with their global production volumes, widespread use in packaging, and low density, which favours transport and accumulation in coastal environments. Their frequent dominance (PE up to ~80–83.9%, PP up to ~50%) across matrices suggests common and pervasive sources, likely linked to land-based inputs and maritime activities (Sand, et al., 2024; Song, et al., 2023). The occurrence of other polymers such as polystyrene (PS), polyester (mainly PET), and polyamide (PA) at high proportions in specific locations highlights the influence of localized sources, including urban discharges, fishing activities, and textile-derived inputs (Hossain and Engelhardt, 2025). The detection of pigments, sometimes in very high proportions, further supports the contribution of anthropogenic debris, although their presence also underlines analytical limitations, as strong Raman signals may mask the underlying polymer matrix.

Across all matrices, the clear dominance of fragments over fibers for most polymer types indicates that secondary microplastics generated through the fragmentation of larger plastic items represent the main source of contamination. This is particularly evident for PE, PS, and PA, which are largely present as fragments in both sediments and biota. In contrast, polymers such as polyester and, to a lesser extent, PP exhibit a more balanced distribution between fibers and fragments, pointing to mixed origins that include both textile fibers and degraded plastic materials. The exclusive or dominant presence of fibers for certain polymers in oysters (e.g., polyester) further supports the role of wastewater-derived inputs. Minor polymers (e.g., PVC, PC, PMMA, PU, PAN) are predominantly detected as fragments, suggesting limited but specific sources and a strong contribution from degradation processes. These findings are in good agreement with the study of Lebfevre et al., 2023, which reported a widespread occurrence of microplastics in both sediments and oysters, with polyethylene and fragments dominating in more dynamic zones in Arcachon bay.



Differences observed between sediments and organisms, as well as between mussels and oysters, likely reflect a combination of environmental availability and species-specific feeding behaviours (Fraissinet et al., 2024; Porter et al., 2023). While sediments integrate a broad spectrum of MPs present in the environment, filter-feeding organisms selectively ingest particles based on size, shape, and bioavailability, which can compromise their use as bioindicators of MPs. The generally lower abundance but similar typological trends observed in oysters compared to mussels may indicate differences in filtration efficiency, habitat conditions, or exposure pathways. Overall, the consistency in polymer types and the predominance of fragments across all matrices emphasize the key role of environmental weathering and fragmentation processes, while local variations point to the importance of site-specific sources and hydrodynamic conditions in shaping MP contamination profiles.

An important refinement of these observations concerns the contribution of cellulosic fibers. In sediments, cellulosic fibers (905 items·kg⁻¹) occur at levels comparable to plastic particles (998 items·kg⁻¹). In biota, a clear predominance of cellulosic fibers is observed, with mussels containing on average 0.78 fibres·g⁻¹ of tissue compared to 0.69 plastic items·g⁻¹, and oysters showing an even stronger contrast (2.96 vs 0.78 items·g⁻¹). When these cellulosic (semi-) natural and anthropogenic-derived fibers are included, fibers become the dominant typology across all matrices, in contrast to the fragment-dominated pattern observed when considering plastics alone.

These results are in line with previous studies, notably by Suaria et al., 2022 which demonstrated that approximately 80–90% of marine microfibers are natural or semi-synthetic (mainly cellulosic), challenging the prevailing assumption that most microfibers are synthetic polymers (Suaria et al. 2022a; 2022b). More recently, El Rakwe et al. showed that cellulosic fibers are the most abundant anthropogenic microfibers and dominate in the upper layers of the Atlantic Ocean (El Rakwe et al., 2026). Altogether, these findings highlight the major contribution of textile and natural fiber inputs in coastal environments and emphasize the need to distinguish between synthetic polymers and cellulosic materials, as their inclusion significantly shifts the interpretation of particle typologies and associated sources.

5.7. Parameters influencing the spatio-temporal distribution of microlitter along French Atlantic coast

MP contamination showed marked spatial variability, with significant differences between stations in sediments and mussels, consistent with previous observations (Gérigny et al., 2022). This spatial heterogeneity reflects the combined influence of local contamination sources and hydrodynamic processes (van Sebillé et al., 2020).



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In the English Channel, strong tidal dynamics and large-scale circulation likely enhance MP transport and resuspension, explaining the high contamination observed in St Brieuc Bay (St Brieuc and Pointe du Roselier) and the eastward increase in sediment contamination along northern Brittany under the dominant west–east coastal current (Lazure and Desmare, 2012).

In the Bay of Biscay, seasonal northward shelf circulation may similarly explain the higher MP concentrations measured in mussels from Île d'Yeu to La Jument compared with more southern stations (Lazure and Desmare, 2012).

River discharges further contribute to MP inputs, particularly during winter and after heavy rainfall (Pabortsava and Lampitt, 2020; Baechler et al., 2020; Constant et al., 2020; Weiss et al., 2024b). The Loire, Garonne, Dordogne, Charente, Adour, Seine, and Somme rivers likely explain elevated contamination near their respective plumes or estuaries (Schmitt and Chaumillon, 2023). Anthropogenic pressures also strongly influence MP distribution. Stations located near wastewater treatment plant discharges (Mus du Loup), tourist areas (Txingudi), or industrial and fishing zones (Comprian) displayed relatively high contamination levels. Fishing, shellfish farming, and maritime transport are recognized sources of marine litter in both the Bay of Biscay and the English Channel (UNEP, 2005; Mongruel et al., 2019). While maritime traffic is moderate in the Bay of Biscay, the English Channel–North Sea system is one of the busiest shipping corridors worldwide, carrying nearly 20% of global maritime traffic (Gérigny et al., 2018). The higher contamination observed in the ROCCHSED stations is therefore consistent with the combined influence of intense shipping activity, coastal circulation, and shellfish farming.

5.8. Towards an apprehension of the plastic contamination continuum across matrices

The present study highlights contrasting MP contamination levels between sediments and filter-feeding bivalves, with higher concentrations observed in mussels and oysters than in sediments, in agreement with previous studies (Phuong et al., 2018; Karlsson et al., 2017). The higher MP abundance measured in oysters compared with mussels may be partly explained by species-specific biological traits, particularly their higher filtration rate (Clausen and Riisgard, 1996; Barillé et al., 1997), although the mechanisms controlling MP uptake, retention and elimination remain poorly understood.

Interpretation of MP contamination in biota should nevertheless remain cautious. Seasonal variations have been reported, with generally higher concentrations in spring than winter (Lerebours et al., 2022; Moura et al., 2025), but this trend was not consistently observed in all studies. Such discrepancies suggest that MP contamination is influenced by multiple environmental and biological factors, emphasizing the need for further investigations, particularly for oysters, which remain less studied.



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The comparison of sediment and biota provides complementary information on MP distribution. While bivalves integrate recent contamination through the filtration of suspended particles, sediments represent the long-term accumulation of deposited MPs. However, the study of MP transfer between environmental matrices remains relatively recent, and the processes governing particle transport, deposition and bioavailability are still incompletely understood. Consequently, relationships between contamination measured in sediments and organisms should be interpreted with caution.

Overall, this work from Free LitterAT provides valuable baseline data for understanding MP distribution across environmental compartments and contributes to the development of future studies investigating MP transfer pathways. It also complements existing monitoring initiatives such as OSPAR and the Marine Strategy Framework Directive (MSFD) Candidate Indicator Assessment on microlitter in biota. Finally, building on the harmonized protocols developed within the FreeLitter project, further methodological harmonization between studies (GESAMP, 2019), together with the implementation of multi-matrix monitoring strategies, will be essential to improve data comparability and strengthen future assessments of MP contamination in coastal ecosystems.

6. Conclusion

The Interreg Free LitterAT project provides the first large-scale assessment of MP contamination in both sediments and biota along the French coastlines, revealing the widespread presence of MPs across these matrices. To ensure data reliability and comparability, analyses were conducted using harmonized protocols developed during the project. Moreover, to limit the monitoring and assessment costs in framework national and international monitoring networks, fluorescence-based methods have been developed in Ifremer. These fluorescence-based methods enabled large-scale monitoring across multiple matrices at cost-effective and in shorter time than referential methods (RAMAN, FTIR methods). However, to validate and confirm the results of fluorescence identification, a replicate from each station and matrix was analysed using RAMAN spectroscopy.

In parallel, methodological developments were implemented to optimize MP detection and data acquisition. The comparison between Nile Red staining and Raman microspectroscopy highlights a clear complementarity between the two approaches. Nile Red staining offers rapid screening capabilities and enables the efficient localization of potential microplastic particles, making it particularly attractive for handling large sample sets and reducing analysis time. In contrast, Raman microspectroscopy provides a robust and unambiguous identification of particle composition, ensuring high analytical reliability. While variability in sensitivity and the occurrence of false



positives—particularly in the presence of inorganic and cellulosic materials—remain important constraints, Nile Red staining use appears much more efficient when applied to well-prepared samples underlying the importance of the reduction of Organic Matter (OM) and Inorganic Matter (IM). In addition, when implemented on large numbers of samples, the averaging effect tends to smooth classification errors, improving the overall reliability of the dataset at a broader scale. Under such conditions, Nile Red staining can represent a valuable high-throughput screening tool.

In this context, future work will focus on evaluating the coupling of Nile Red screening with Raman confirmation within a subsampling strategy. The objective is to use fluorescence-based detection to pre-select particles of interest, followed by targeted Raman analysis on a reduced subset of particles. Such an approach has strong potential to significantly decrease overall analysis time while maintaining reliable identification, and to reduce classification errors through optimized selection criteria.

Sediments, as a relatively stable matrix, provide an integrated view of long-term MP contamination, whereas biota monitoring contributes to understanding biological exposure and potential impacts of MPs. However, this matrix remains poorly understood due to the combined influence of hydrodynamic and biological factors. Therefore, the combined analysis of sediments and filter-feeding organisms enables a more comprehensive characterization of MP transfer between marine compartments.

Overall, the results are consistent with the literature, supporting the robustness of the harmonized methodologies applied in this study. The dataset generated supplies supplementary data for the definition of national-scale baselines of MP contamination along the French Atlantic coastline and provides a crucial reference for future monitoring efforts. These baseline data are essential for long-term trend assessments and threshold development within national and international regulatory frameworks, including OSPAR (Candidate indicator assessment on microlitter (including MPs) in seafloor sediments) and MSFD (D10C2: seafloor microlitter and a Candidate Indicator: microlitter in biota). Nevertheless, further works are required to expand spatially the dataset by incorporating additional countries and increasing sample coverage for both matrices.



7. References

Alcaïno, A., Licari, L., Vidal, L., Chevalier, C., Conrod, S., Dauvier, J., Delanghe, D., Garidel-Thoron, T. de, Grelaud, M., Malengros, D., Mazur, J.-C., Montavon, V., Paillès, C., Pinazo, C., Sulpis, O., Surmont, A., Rigaud, S., 2025. CONTAMINATION BY MICROPLASTICS IN THE BAY OF MARSEILLE (Gulf of Lion, France): AN INTEGRATIVE DIAGNOSIS FROM THE SURFACE TO THE SEAFLOOR (No. OOS2025-1516). Presented at the OOS2025, Copernicus Meetings. <https://doi.org/10.5194/oos2025-1516>

Alimba, C.G., Faggio, C., 2019. Microplastics in the marine environment: Current trends in environmental pollution and mechanisms of toxicological profile. *Environmental Toxicology and Pharmacology* 68, 61–74. <https://doi.org/10.1016/j.etap.2019.03.001>
Alomar, C., Estarellas, F., Deudero, S., 2016. Microplastics in the Mediterranean Sea: Deposition in coastal shallow sediments, spatial variation and preferential grain size. *Marine Environmental Research* 115, 1–10. <https://doi.org/10.1016/j.marenvres.2016.01.005>

Andrady, A.L., 2011. Microplastics in the marine environment. *Marine Pollution Bulletin* 62, 1596–1605. <https://doi.org/10.1016/j.marpolbul.2011.05.030>

Arthur, C., Baker, J.E., Bamford, H.A., 2009. Proceedings of the International Research Workshop on the Occurrence, Effects, and Fate of Microplastic Marine Debris, September 9-11, 2008, University of Washington Tacoma, Tacoma, WA, USA [WWW Document]. URL <https://repository.library.noaa.gov> (accessed 1.29.26).

Baechler, B.R., Granek, E.F., Hunter, M.V., Conn, K.E., 2020. Microplastic concentrations in two Oregon bivalve species: Spatial, temporal, and species variability. *Limnology and Oceanography Letters* 5, 54–65. <https://doi.org/10.1002/lol2.10124>

Bakir, A., Rowland, S.J., Thompson, R.C., 2014. Transport of persistent organic pollutants by microplastics in estuarine conditions. *Estuarine, Coastal and Shelf Science* 140, 14–21. <https://doi.org/10.1016/j.ecss.2014.01.004>

Barillé, L., Prou, J., Héral, M., Razet, D., 1997. Effects of high natural seston concentrations on the feeding, selection, and absorption of the oyster *Crassostrea gigas* (Thunberg). *Journal of Experimental Marine Biology and Ecology* 212, 149–172. [https://doi.org/10.1016/S0022-0981\(96\)02756-6](https://doi.org/10.1016/S0022-0981(96)02756-6)

Bergmann, M., Gutow, L., Klages, M., 2015. Marine Anthropogenic Litter. <https://doi.org/10.1007/978-3-319-16510-3>



Free LitterAT deliverable D.2.2.6 (WP2-A2-Task2)

Bråte, I.L.N., Hurley, R., Iversen, K., Beyer, J., Thomas, K.V., Steindal, C.C., Green, N.W., Olsen, M., Lusher, A., 2018. *Mytilus* spp. as sentinels for monitoring microplastic pollution in Norwegian coastal waters: A qualitative and quantitative study. *Environmental Pollution* 243, 383–393. <https://doi.org/10.1016/j.envpol.2018.08.077>

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R., 2011. Accumulation of Microplastic on Shorelines Worldwide: Sources and Sinks. *Environ. Sci. Technol.* 45, 9175–9179. <https://doi.org/10.1021/es201811s>

Browne, M.A., Dissanayake, A., Galloway, T.S., Lowe, D.M., Thompson, R.C., 2008. Ingested Microscopic Plastic Translocates to the Circulatory System of the Mussel, *Mytilus edulis* (L.). *Environ. Sci. Technol.* 42, 5026–5031. <https://doi.org/10.1021/es800249a>

Bruijn 1998-, R.A.D., 2024. Microplastic presence in blue mussels (*Mytilus edulis*) from the Westfjords, Iceland (Thesis).

Campos da Rocha, F.O., Martinez, S.T., Campos, V.P., da Rocha, G.O., de Andrade, J.B., 2021. Microplastic pollution in Southern Atlantic marine waters: Review of current trends, sources, and perspectives. *Science of The Total Environment* 782, 146541. <https://doi.org/10.1016/j.scitotenv.2021.146541>

Carretero, O., Gago, J., Viñas, L., 2021. From the coast to the shelf: Microplastics in Rías Baixas and Miño River shelf sediments (NW Spain). *Marine Pollution Bulletin* 162, 111814. <https://doi.org/10.1016/j.marpolbul.2020.111814>

Catarino, A.I., Macchia, V., Sanderson, W.G., Thompson, R.C., Henry, T.B., 2018. Low levels of microplastics (MP) in wild mussels indicate that MP ingestion by humans is minimal compared to exposure via household fibres fallout during a meal. *Environmental Pollution* 237, 675–684. <https://doi.org/10.1016/j.envpol.2018.02.069>

Čerkasova, N., Enders, K., Lenz, R., Oberbeckmann, S., Brandt, J., Fischer, D., Fischer, F., Labrenz, M., Schernewski, G., 2023. A Public Database for Microplastics in the Environment. *Microplastics* 2, 132–146. <https://doi.org/10.3390/microplastics2010010>

Chae, Y., An, Y.-J., 2020. Effects of food presence on microplastic ingestion and egestion in *Mytilus galloprovincialis*. *Chemosphere* 240, 124855. <https://doi.org/10.1016/j.chemosphere.2019.124855>

Chandurvelan, R., Marsden, I.D., Glover, C.N., Gaw, S., 2015. Assessment of a mussel as a metal bioindicator of coastal contamination: Relationships between metal



Free LitterAT deliverable D.2.2.6 (WP2-A2-Task2)

bioaccumulation and multiple biomarker responses. *Science of The Total Environment* 511, 663–675. <https://doi.org/10.1016/j.scitotenv.2014.12.064>

Chen, G., Li, Y., Wang, J., 2021. Occurrence and ecological impact of microplastics in aquaculture ecosystems. *Chemosphere* 274, 129989. <https://doi.org/10.1016/j.chemosphere.2021.129989>

Cheung, P.K., Fok, L., 2016. Evidence of microbeads from personal care product contaminating the sea. *Marine Pollution Bulletin* 109, 582–585. <https://doi.org/10.1016/j.marpolbul.2016.05.046>

Chubarenko, I., Bagaev, A., Zobkov, M., Esiukova, E., 2016. On some physical and dynamical properties of microplastic particles in marine environment. *Marine Pollution Bulletin* 108, 105–112. <https://doi.org/10.1016/j.marpolbul.2016.04.048>

Claessens, M., Meester, S.D., Landuyt, L.V., Clerck, K.D., Janssen, C.R., 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. *Marine Pollution Bulletin* 62, 2199–2204. <https://doi.org/10.1016/j.marpolbul.2011.06.030>

Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: A review. *Marine Pollution Bulletin* 62, 2588–2597. <https://doi.org/10.1016/j.marpolbul.2011.09.025>

Collard, F., Gilbert, B., Compère, P., Eppe, G., Das, K., Jauniaux, T., Parmentier, E., 2017. Microplastics in livers of European anchovies (*Engraulis encrasicolus*, L.). *Environmental Pollution* 229, 1000–1005. <https://doi.org/10.1016/j.envpol.2017.07.089>

Connan, M., Perold, V., Dilley, B.J., Barbraud, C., Cherel, Y., Ryan, P.G., 2021. The Indian Ocean ‘garbage patch’: Empirical evidence from floating macro-litter. *Marine Pollution Bulletin* 169, 112559. <https://doi.org/10.1016/j.marpolbul.2021.112559>

Constant, M., 2018. Source, transfert et devenir des microplastiques (MPs) en mer Méditerranée Nord-Occidentale (Theses). Université de Perpignan.

Constant, M., Ludwig, W., Kerhervé, P., Sola, J., Charrière, B., Sanchez-Vidal, A., Canals, M., Heussner, S., 2020. Microplastic fluxes in a large and a small Mediterranean river catchment: The Têt and the Rhône, Northwestern Mediterranean Sea. *Science of The Total Environment* 716, 136984. <https://doi.org/10.1016/j.scitotenv.2020.136984>

Corcoran, P.L., Norris, T., Ceccanese, T., Walzak, M.J., Helm, P.A., Marvin, C.H., 2015. Hidden plastics of Lake Ontario, Canada and their potential preservation in the sediment



Free LitterAT deliverable D.2.2.6 (WP2-A2-Task2)

record. Environmental Pollution 204, 17–25.
<https://doi.org/10.1016/j.envpol.2015.04.009>

Cózar, A., Martí, E., Duarte, C.M., García-de-Lomas, J., van Seville, E., Ballatore, T.J., Eguíluz, V.M., González-Gordillo, J.I., Pedrotti, M.L., Echevarría, F., Troublè, R., Irigoien, X., 2017. The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the Thermohaline Circulation. *Science Advances* 3, e1600582.
<https://doi.org/10.1126/sciadv.1600582>

D'Avignon, G., Gregory-Eaves, I., Ricciardi, A., 2022. Microplastics in lakes and rivers: an issue of emerging significance to limnology. *Environ. Rev.* 30, 228–244.
<https://doi.org/10.1139/er-2021-0048>

de Haan, W.P., Sanchez-Vidal, A., Canals, M., 2019. Floating microplastics and aggregate formation in the Western Mediterranean Sea. *Marine Pollution Bulletin* 140, 523–535.
<https://doi.org/10.1016/j.marpolbul.2019.01.053>

de Vergie, S., de Chavanes, É., 2012. Action de l'État en mer. Sous-région marine Golfe de Gascogne. *Evaluation initiale DCSMM*.

De-la-Torre, G.E., Forero López, A.D., Colombo, C.V., Rimondino, G.N., Malanca, F.E., Barahona, M., Santillán, L., 2024. Low prevalence of microplastic contamination in the bottom sediments and deep-sea waters of the Bransfield strait, Antarctica. *Chemosphere* 364, 143310. <https://doi.org/10.1016/j.chemosphere.2024.143310>

Devriese, L.I., van der Meulen, M.D., Maes, T., Bekaert, K., Paul-Pont, I., Frère, L., Robbens, J., Vethaak, A.D., 2015. Microplastic contamination in brown shrimp (*Crangon crangon*, Linnaeus 1758) from coastal waters of the Southern North Sea and Channel area. *Marine Pollution Bulletin* 98, 179–187.
<https://doi.org/10.1016/j.marpolbul.2015.06.051>

Ding, J., Sun, C., He, C., Li, J., Ju, P., Li, F., 2021. Microplastics in four bivalve species and basis for using bivalves as bioindicators of microplastic pollution. *Science of The Total Environment* 782, 146830. <https://doi.org/10.1016/j.scitotenv.2021.146830>

Do, V.M., Dang, T.T., Le, X.T.T., Nguyen, D.T., Phung, T.V., Vu, D.N., Pham, H.V., 2022. Abundance of microplastics in cultured oysters (*Crassostrea gigas*) from Danang Bay of Vietnam. *Marine Pollution Bulletin* 180, 113800.
<https://doi.org/10.1016/j.marpolbul.2022.113800>



Free LitterAT deliverable D.2.2.6 (WP2-A2-Task2)

Dris, R., Gasperi, J., Saad, M., Mirande, C., Tassin, B., 2016. Synthetic fibers in atmospheric fallout: A source of microplastics in the environment? *Marine Pollution Bulletin* 104, 290–293. <https://doi.org/10.1016/j.marpolbul.2016.01.006>

El Rakwe, M., Morin, B., Thomas, L., Burger, V., Dusacre, E., Mazeas, F., Amédéo, F., Dreanno, C., Lecomte, S., Maes, C., Cachot, J., Prado, E., 2026. Dominance of cellulosic and synthetic microfibers in upper layers of the Atlantic Ocean: evidence from the Vendée globe 2020 race. *Mar Pollut Bull* 225, 119173.

Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G., Reisser, J., 2014. Plastic Pollution in the World's Oceans: More than 5 Trillion Plastic Pieces Weighing over 250,000 Tons Afloat at Sea. *PLOS ONE* 9, e111913. <https://doi.org/10.1371/journal.pone.0111913>

Expósito, N., Rovira, J., Sierra, J., Gimenez, G., Domingo, J.L., Schuhmacher, M., 2022. Levels of microplastics and their characteristics in molluscs from North-West Mediterranean Sea: Human intake. *Marine Pollution Bulletin* 181, 113843. <https://doi.org/10.1016/j.marpolbul.2022.113843>

Farrell, P., Nelson, K., 2013. Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.). *Environmental Pollution* 177, 1–3. <https://doi.org/10.1016/j.envpol.2013.01.046>

Faure, F., Saini, C., Potter, G., Galgani, F., de Alencastro, L.F., Hagmann, P., 2015. An evaluation of surface micro- and mesoplastic pollution in pelagic ecosystems of the Western Mediterranean Sea. *Environ Sci Pollut Res* 22, 12190–12197. <https://doi.org/10.1007/s11356-015-4453-3>

Ferreira, O., Barboza, L.G.A., Rudnitskaya, A., Moreirinha, C., Vieira, L.R., Botelho, M.J., Vale, C., Fernandes, J.O., Cunha, S., Guilhermino, L., 2023. Microplastics in marine mussels, biological effects and human risk of intake: A case study in a multi-stressor environment. *Marine Pollution Bulletin* 197, 115704. <https://doi.org/10.1016/j.marpolbul.2023.115704>

Fraissinet, S., Arduini, D., Martines, A., De Benedetto, G.E., Malitesta, C., Giangrande, A., Rossi, S., 2024. Microplastics Uptake by Four Filter Feeders. *Journal of Marine Science and Engineering* 12, 1000.

Galgani, F., 2015. Marine litter, future prospects for research. *Front. Mar. Sci.* 2. <https://doi.org/10.3389/fmars.2015.00087>



Free LitterAT deliverable D.2.2.6 (WP2-A2-Task2)

Galgani, F., Brien, A.S., Weis, J., Ioakeimidis, C., Schuyler, Q., Makarenko, I., Griffiths, H., Bondareff, J., Vethaak, D., Deidun, A., Sobral, P., Topouzelis, K., Vlahos, P., Lana, F., Hasselov, M., Gerigny, O., Arsonina, B., Ambulkar, A., Azzaro, M., Bebianno, M.J., 2021. Are litter, plastic and microplastic quantities increasing in the ocean? *Micropl.&Nanopl.* 1, 2. <https://doi.org/10.1186/s43591-020-00002-8>

Galgani, F., Ruiz, O.S.P.L., Ronchi, F., Tallec, K., Fischer, E., Matiddi, M., Anastasopoulou, A., Andresmaa, E., Angiolillo, M., Bakker, P.M., Booth, A.M., Buhhalko, N., Cadiou, B., Claro, F., Consoli, P., Darmon, G., Deudero, S., Fleet, D., Fortibuoni, T., Fossi, M.C., Gago, J., Gerigny, O., Giorgetti, A., Gonzalez, F.D., Guse, N., Haseler, M., Ioakeimidis, C., Kammann, U., Kühn, S., Lacroix, C., Lips, I., Loza, A.L., Molina, J.M.E., Noren, K., Papadoyannakis, M., Pragnell-Raasch, H., Rindorf, A., Ruiz, M., Setälä, O., Schulz, M., Schultze, M., Silvestri, C., Soederberg, L., Stoica, E., Storr-Paulsen, M., Strand, J., Valente, T., Van, F.J.A., Van, L.W., Vighi, M., Vinci, M., Vlachogianni, T., Volckaert, A., Weiel, S., Wenneker, B., Werner, S., Zeri, C., Zorzo, P., Hanke, G., 2023. Guidance on the monitoring of marine litter in European seas [WWW Document]. JRC Publications Repository. <https://doi.org/10.2760/59137>

Gérigny, O., Chouteau, L., El Rakwe, M., Gago, J., Incera Filgueira, M., Le Moigne, M., Perez, P., Prado, E., Russel, J., Thomas, L., McGoran, A. 2023. CleanAtlantic Tackling Marine Litter in the Atlantic Area. Characterization of microplastics ingested by mussel. Toward a determination of bio-sentinel species of the marine environment contamination by microplastics? WP 5.3: Monitoring the interaction of marine litter with fauna. CleanAtlantic project deliverable.

Gérigny, O., Lacroix, C., Brun, M., Olsommer, M., André, S., Tomasino, C., Paul, M., Beauvais, S., Georges, E., Galgani, F., Brun, M., Olsommer, M., André, S., Tomasino, C., Paul, M., Beauvais, S., Georges, E., Galgani, F., 2022. Évaluation du descripteur 10 « Déchets marins » en France métropolitaine. Rapport scientifique pour l'évaluation 2024 au titre de la DCSMM. <https://doi.org/10.13155/97951>

Gérigny, O., Pedrotti, M.-L., El Rakwe, M., Brun, M., Pavéc, M., Henry, M., Mazeas, F., Maury, J., Garreau, P., Galgani, F., 2022. Characterization of floating microplastic contamination in the bay of Marseille (French Mediterranean Sea) and its impact on zooplankton and mussels. *Marine Pollution Bulletin* 175, 113353. <https://doi.org/10.1016/j.marpolbul.2022.113353>

GESAMP (2015). "Sources, fate and effects of microplastics in the marine environment: a global assessment" (Kershaw, P. J., ed.). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 90, 96 p



Free LitterAT deliverable D.2.2.6 (WP2-A2-Task2)

Gran, A., Vidal-Barrachina, D., Casado-Coy, N., Encizo-Cuartas, D., Masó-Herrero, S., Sanz-Lazaro, C., 2025. Comparing methods for optimising microplastic extraction in sediment through density separation. *Environmental Pollution* 383, 126894. <https://doi.org/10.1016/j.envpol.2025.126894>

He, D., Zhang, Y., Gao, W., 2021. Micro(nano)plastic contaminations from soils to plants: human food risks. *Current Opinion in Food Science* 41, 116–121. <https://doi.org/10.1016/j.cofs.2021.04.001>

Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the Marine Environment: A Review of the Methods Used for Identification and Quantification. *Environ. Sci. Technol.* 46, 3060–3075. <https://doi.org/10.1021/es2031505>

Hossain, M., Engelhardt, I., 2025. Global plastic footprint: unveiling property trends, environmental fate, and emerging threats of microplastic and nanoplastics pollution across ecosystems. *Energy, Ecology and Environment* 10, 637-674.

Huang, L., Zhang, Shoufeng, Li, L., Zhang, Siyu, Wang, J., Liu, X., Zhang, W., 2023. Research progress on microplastics pollution in polar oceans. *Polar Science* 36, 100946. <https://doi.org/10.1016/j.polar.2023.100946>

I, C., Hu, R., 1996. Growth, filtration and respiration in the mussel *Mytilus edulis*: no evidence for physiological regulation of the filter-pump to nutritional needs. *Marine Ecology Progress Series* 141, 37–45. <https://doi.org/10.3354/meps141037>

Jang, M., Shim, W.J., Cho, Y., Han, G.M., Song, Y.K., Hong, S.H., 2020. A close relationship between microplastic contamination and coastal area use pattern. *Water Research* 171, 115400. <https://doi.org/10.1016/j.watres.2019.115400>

Karlsson, T.M., Arneborg, L., Broström, G., Almroth, B.C., Gipperth, L., Hassellöv, M., 2018. The unaccountability case of plastic pellet pollution. *Marine Pollution Bulletin* 129, 52–60. <https://doi.org/10.1016/j.marpolbul.2018.01.041>

Karlsson, T.M., Vethaak, A.D., Almroth, B.C., Ariese, F., van Velzen, M., Hassellöv, M., Leslie, H.A., 2017. Screening for microplastics in sediment, water, marine invertebrates and fish: Method development and microplastic accumulation. *Marine Pollution Bulletin* 122, 403–408. <https://doi.org/10.1016/j.marpolbul.2017.06.081>

Kazour, M., Terki, S., Rabhi, K., Jemaa, S., Khalaf, G., Amara, R., 2019. Sources of microplastics pollution in the marine environment: Importance of wastewater treatment plant and coastal landfill. *Marine Pollution Bulletin* 146, 608–618. <https://doi.org/10.1016/j.marpolbul.2019.06.066>



Free LitterAT deliverable D.2.2.6 (WP2-A2-Task2)

Koelmans, A.A., Bakir, A., Burton, G.A., Janssen, C.R., 2016. Microplastic as a Vector for Chemicals in the Aquatic Environment: Critical Review and Model-Supported Reinterpretation of Empirical Studies. *Environ. Sci. Technol.* 50, 3315–3326. <https://doi.org/10.1021/acs.est.5b06069>

Kumar, R., Verma, A., Rakib, Md.R.J., Gupta, P.K., Sharma, P., Garg, A., Girard, P., Aminabhavi, T.M., 2023. Adsorptive behavior of micro(nano)plastics through biochar: Co-existence, consequences, and challenges in contaminated ecosystems. *Science of The Total Environment* 856, 159097. <https://doi.org/10.1016/j.scitotenv.2022.159097>

Lazure, P., Desmare, S., 2012a. *Courantologie. Sous-région marine Golfe de Gascogne. Evaluation initiale DCSMM.*

Lazure, P., Desmare, S., 2012b. *Courantologie. Sous-région marine Manche - Mer du Nord. Evaluation initiale DCSMM.*

Lebreton, L.C.M., van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. *Nat Commun* 8, 15611. <https://doi.org/10.1038/ncomms15611>

Lefebvre, C., Le Bihanic, F., Jalón-Rojas, I., Dusacre, E., Chassaigne--Viscaïno, L., Bichon, J., Clérandeau, C., Morin, B., Lecomte, S., Cachot, J., 2023. Spatial distribution of anthropogenic particles and microplastics in a meso-tidal lagoon (Arcachon Bay, France): A multi-compartment approach. *Science of The Total Environment* 898, 165460. <https://doi.org/10.1016/j.scitotenv.2023.165460>

Lerebours, A., Bathie, M., Kazour, M., Amara, R., Huet, V., Thomas, H., 2022. Spatio-temporal contamination of microplastics in shellfish farming regions: A case study. *Marine Pollution Bulletin* 181, 113842. <https://doi.org/10.1016/j.marpolbul.2022.113842>

Li, J., Qu, X., Su, L., Zhang, W., Yang, D., Kolandhasamy, P., Li, D., Shi, H., 2016. Microplastics in mussels along the coastal waters of China. *Environmental Pollution* 214, 177–184. <https://doi.org/10.1016/j.envpol.2016.04.012>

Li, Q., Ma, C., Zhang, Q., Shi, H., 2021. Microplastics in shellfish and implications for food safety. *Current Opinion in Food Science* 40, 192–197. <https://doi.org/10.1016/j.cofs.2021.04.017>

Liang, T., Ho, Y.-W., Wang, Q., Wang, P., Sun, S., Fang, J.K.-H., Liu, X., 2024. Distribution and risk assessment of microplastics in water, sediment and brine shrimps in a remote



Free LitterAT deliverable D.2.2.6 (WP2-A2-Task2)

salt lake on the Tibetan Plateau, China. *Journal of Hazardous Materials* 476, 134959. <https://doi.org/10.1016/j.jhazmat.2024.134959>

Lindeque, P.K., Cole, M., Coppock, R.L., Lewis, C.N., Miller, R.Z., Watts, A.J.R., Wilson-McNeal, A., Wright, S.L., Galloway, T.S., 2020. Are we underestimating microplastic abundance in the marine environment? A comparison of microplastic capture with nets of different mesh-size. *Environmental Pollution* 265, 114721. <https://doi.org/10.1016/j.envpol.2020.114721>

Lorenz, C., Roscher, L., Meyer, M.S., Hildebrandt, L., Prume, J., Löder, M.G.J., Primpke, S., Gerdt, G., 2019. Spatial distribution of microplastics in sediments and surface waters of the southern North Sea. *Environmental Pollution* 252, 1719–1729. <https://doi.org/10.1016/j.envpol.2019.06.093>

Luo, Y., Sun, C., Li, C., Liu, Y., Zhao, S., Li, Y., Kong, F., Zheng, H., Luo, X., Chen, L., Li, F., 2022. Spatial Patterns of Microplastics in Surface Seawater, Sediment, and Sand Along Qingdao Coastal Environment. *Front. Mar. Sci.* 9. <https://doi.org/10.3389/fmars.2022.916859>

Marques Mendes, A., Golden, N., Bermejo, R., Morrison, L., 2021. Distribution and abundance of microplastics in coastal sediments depends on grain size and distance from sources. *Marine Pollution Bulletin* 172, 112802. <https://doi.org/10.1016/j.marpolbul.2021.112802>

Mongruel, R., Girard, S., Le Moing, I., 2012. Commercialisation et transformation des produits de la mer. Sous-région marine Manche - Mer du Nord. Evaluation initiale DCSMM.

Moura, C., Silva, D.M., Espincho, F., Rodrigues, S.M., Pereira, R., Almeida, C.M.R., Ramos, S., Freitas, V., 2025. Assessing Microplastic Contamination and Depuration Effectiveness in Farmed Pacific Oysters (*Crassostrea gigas*). *Environments* 12. <https://doi.org/10.3390/environments12080254>

Multisanti, C.R., Merola, C., Perugini, M., Aliko, V., Faggio, C., 2022. Sentinel species selection for monitoring microplastic pollution: A review on one health approach. *Ecological Indicators* 145, 109587. <https://doi.org/10.1016/j.ecolind.2022.109587>

Napper, I.E., Thompson, R.C., 2016. Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions. *Marine Pollution Bulletin* 112, 39–45. <https://doi.org/10.1016/j.marpolbul.2016.09.025>



Free LitterAT deliverable D.2.2.6 (WP2-A2-Task2)

Pabortsava, K., Lampitt, R.S., 2020. High concentrations of plastic hidden beneath the surface of the Atlantic Ocean. *Nat Commun* 11, 4073. <https://doi.org/10.1038/s41467-020-17932-9>

Pan, Z., Liu, Q., Sun, X., Li, W., Zou, Q., Cai, S., Lin, H., 2022. Widespread occurrence of microplastic pollution in open sea surface waters: Evidence from the mid-North Pacific Ocean. *Gondwana Research, Plasticsphere and its impact on Earth's environment and life* 108, 31–40. <https://doi.org/10.1016/j.gr.2021.10.024>

Papini, G., Rakaj, A., 2025. Microplastic retention in European flat oyster *Ostrea edulis* cultured in two Mediterranean basins. *npj Emerg. Contam.* 1, 7. <https://doi.org/10.1038/s44454-025-00005-1>

Parker-Jurd, F.N.F., Napper, I.E., Abbott, G.D., Hann, S., Thompson, R.C., 2021. Quantifying the release of tyre wear particles to the marine environment via multiple pathways. *Marine Pollution Bulletin* 172, 112897. <https://doi.org/10.1016/j.marpolbul.2021.112897>

Paul, A.T., Hannon, C., Švonja, M., Connellan, I., Frias, J., 2023. Efficacy of microplastic depuration on two commercial oyster species from the west coast of Ireland. *Journal of the World Aquaculture Society* 54, 1217–1234. <https://doi.org/10.1111/jwas.12989>
PlasticsEurope, E. P. R. O. (2020). *Plastics—the Facts 2020*. An analysis of European plastics production, demand and waste data, (22 January 2021).

Phuong, N.N., Poirier, L., Lagarde, F., Kamari, A., Zalouk-Vergnoux, A., 2018a. Microplastic abundance and characteristics in French Atlantic coastal sediments using a new extraction method. *Environmental Pollution* 243, 228–237. <https://doi.org/10.1016/j.envpol.2018.08.032>

Phuong, N.N., Poirier, L., Pham, Q.T., Lagarde, F., Zalouk-Vergnoux, A., 2018b. Factors influencing the microplastic contamination of bivalves from the French Atlantic coast: Location, season and/or mode of life? *Marine Pollution Bulletin* 129, 664–674. <https://doi.org/10.1016/j.marpolbul.2017.10.054>

Phuong, N.N., Zalouk-Vergnoux, A., Kamari, A., Mouneyrac, C., Amiard, F., Poirier, L., Lagarde, F., 2018c. Quantification and characterization of microplastics in blue mussels (*Mytilus edulis*): protocol setup and preliminary data on the contamination of the French Atlantic coast. *Environ Sci Pollut Res* 25, 6135–6144. <https://doi.org/10.1007/s11356-017-8862-3>

Pirsaheb, M., Hossini, H., Makhdoumi, P., 2020. Review of microplastic occurrence and toxicological effects in marine environment: Experimental evidence of inflammation.



Free LitterAT deliverable D.2.2.6 (WP2-A2-Task2)

Process Safety and Environmental Protection 142, 1–14.
<https://doi.org/10.1016/j.psep.2020.05.050>

Plantec, O., Grouhel, A., Munaron, D., Ouisse, V., Gerigny, O., Bruzac, S., Duval, M., Munaron, D., Ouisse, V., Gerigny, O., Bruzac, S., Duval, M., 2025. Contamination Chimique des sédiments des lagunes méditerranéennes françaises. Bilan de la campagne ROCCHSED 2023. <https://doi.org/10.13155/105062>

Porter, A., Godbold, J.A., Lewis, C.N., Savage, G., Solan, M., Galloway, T.S., 2023. Microplastic burden in marine benthic invertebrates depends on species traits and feeding ecology within biogeographical provinces. *Nat Commun* 14, 8023

Ramadoss, D., Biju, A., Rathore, C., Saha, M., Kolandhasamy, P., Palogi, C., John, J., Behera, A.K., 2025. The first report on emerged microplastics in deep-sea sediment: Insights from the Central Indian Ocean Basin. *Marine Pollution Bulletin* 211, 117435. <https://doi.org/10.1016/j.marpolbul.2024.117435>

Ramasamy, E.V., Sruthy, S., Harit, A.K., Mohan, M., Binish, M.B., 2021. Microplastic pollution in the surface sediment of Kongsfjorden, Svalbard, Arctic. *Marine Pollution Bulletin* 173, 112986. <https://doi.org/10.1016/j.marpolbul.2021.112986>

Ruangpanupan, N., Ussawarujikulchai, A., Prapagdee, B., Chavanich, S., 2023. Seasonal variation in the abundance of microplastics in three commercial bivalves from Bandon Bay, Gulf of Thailand. *Marine Pollution Bulletin* 197, 115600. <https://doi.org/10.1016/j.marpolbul.2023.115600>

Saha, M., Naik, A., Desai, A., Nanajkar, M., Rathore, C., Kumar, M., Gupta, P., 2021. Microplastics in seafood as an emerging threat to marine environment: A case study in Goa, west coast of India. *Chemosphere* 270, 129359. <https://doi.org/10.1016/j.chemosphere.2020.129359>

Sand, A., Vyas, A., Tuteja, J., 2024. Introductory Chapter: Polyethylene – Its Properties and Application in Industry and in Households, in: Sand, A., Tuteja, J. (Eds.), *Polyethylene - New Developments and Applications*. IntechOpen, Rijeka. <https://doi.org/10.5772/intechopen.1003974>

Song, Y.K., Hong, S.H., Eo, S., Shim, W.J., 2023. Fragmentation of nano- and microplastics from virgin- and additive-containing polypropylene by accelerated photooxidation. *Environmental Pollution* 327, 121590. <https://doi.org/10.1016/j.envpol.2023.121590>

Schmidt, N., Thibault, D., Galgani, F., Paluselli, A., Sempéré, R., 2018. Occurrence of microplastics in surface waters of the Gulf of Lion (NW Mediterranean Sea). *Progress in*



Free LitterAT deliverable D.2.2.6 (WP2-A2-Task2)

Oceanography, Special issue of MERMEX project: Recent advances in the oceanography of the Mediterranean Sea 163, 214–220. <https://doi.org/10.1016/j.pocean.2017.11.010>

Schmitt, A., Chaumillon, E., 2023. Understanding morphological evolution and sediment dynamics at multi-time scales helps balance human activities and protect coastal ecosystems: An example with the Gironde and Pertuis Marine Park. Science of The Total Environment 887, 163819. <https://doi.org/10.1016/j.scitotenv.2023.163819>

Sharma, Prabhakar, Sharma, Prateek, 2024. Micro(nano)plastics: invisible compounds with a visible impact. <https://doi.org/10.12688/f1000research.142212.2>

Shumway, S.E., Mladinich, K., Blaschik, N., Holohan, B.A., Ward, J.E., 2023. A Critical Assessment of Microplastics in Molluscan Shellfish with Recommendations for Experimental Protocols, Animal Husbandry, Publication, and Future Research. Reviews in Fisheries Science & Aquaculture 0, 1–133. <https://doi.org/10.1080/23308249.2023.2216301>

Sin, L.T., Balakrishnan, V., Bee, S.-T., Bee, S.-L., 2023. A Review of the Current State of Microplastic Pollution in South Asian Countries. Sustainability 15. <https://doi.org/10.3390/su15086813>

Strokal, M., Vriend, P., Bak, M.P., Kroeze, C., van Wijnen, J., van Emmerik, T., 2023. River export of macro- and microplastics to seas by sources worldwide. Nat Commun 14, 4842. <https://doi.org/10.1038/s41467-023-40501-9>

Suaria, G., Achtypi, A., Perold, V., Lee, J.R., Pierucci, A., Bornman, T.G., Aliani, S., Ryan, P.G., 2020a. Microfibers in oceanic surface waters: A global characterization. Science Advances 6, eaay8493. <https://doi.org/10.1126/sciadv.aay8493>

Suaria, G., Perold, V., Lee, J.R., Lebouard, F., Aliani, S., Ryan, P.G., 2020b. Floating macro- and microplastics around the Southern Ocean: Results from the Antarctic Circumnavigation Expedition. Environment International 136, 105494. <https://doi.org/10.1016/j.envint.2020.105494>

Tang, L., Feng, J.-C., Li, C., Liang, J., Zhang, S., Yang, Z., 2023. Global occurrence, drivers, and environmental risks of microplastics in marine environments. Journal of Environmental Management 329, 116961. <https://doi.org/10.1016/j.jenvman.2022.116961>

ter Halle, A., Ladirat, L., Martignac, M., Mingotaud, A.F., Boyron, O., Perez, E., 2017. To what extent are microplastics from the open ocean weathered? Environmental Pollution 227, 167–174. <https://doi.org/10.1016/j.envpol.2017.04.051>



Free LitterAT deliverable D.2.2.6 (WP2-A2-Task2)

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at Sea: Where Is All the Plastic? *Science* 304, 838–838. <https://doi.org/10.1126/science.1094559>

UNEP. 2023. Plastic pollution & marine litter | UNEP - UN Environment Programme [WWW Document]. Microplastics: The long legacy left behind by plastic pollution. URL <https://www.unep.org/topics/ocean-seas-and-coasts/ecosystem-degradation-pollution/plastic-pollution-marine-litter> (accessed 1.29.26).

UNEP. 2020. Plastic pollution & marine litter | UNEP - UN Environment Programme [WWW Document]. Our Planet Is Choking on Plastic. URL <https://www.unep.org/interactives/beat-plastic-pollution/> (accessed 1.29.26).

van Sebille, E., Aliani, S., Law, K.L., Maximenko, N., Alsina, J.M., Bagaev, A., Bergmann, M., Chapron, B., Chubarenko, I., Cózar, A., Delandmeter, P., Egger, M., Fox-Kemper, B., Garaba, S.P., Goddijn-Murphy, L., Hardesty, B.D., Hoffman, M.J., Isobe, A., Jongedijk, C.E., Kaandorp, M.L.A., Khatmullina, L., Koelmans, A.A., Kukulka, T., Laufkötter, C., Lebreton, L., Lobelle, D., Maes, C., Martinez-Vicente, V., Morales Maqueda, M.A., Poulain-Zarcos, M., Rodríguez, E., Ryan, P.G., Shanks, A.L., Shim, W.J., Suaria, G., Thiel, M., van den Bremer, T.S., Wichmann, D., 2020. The physical oceanography of the transport of floating marine debris. *Environ. Res. Lett.* 15, 023003. <https://doi.org/10.1088/1748-9326/ab6d7d>

Vandermeersch, G., Van Cauwenberghe, L., Janssen, C.R., Marques, A., Granby, K., Fait, G., Kotterman, M.J.J., Diogène, J., Bekaert, K., Robbens, J., Devriese, L., 2015. A critical view on microplastic quantification in aquatic organisms. *Environmental Research, Non-regulated environmental contaminants in seafood: contributions of the ECsafeSEAFOOD EU project* 143, 46–55. <https://doi.org/10.1016/j.envres.2015.07.016>

Villanova-Solano, C., Díaz-Peña, F.J., Hernández-Sánchez, C., González-Sálamo, J., González-Pleiter, M., Vega-Moreno, D., Fernández-Piñas, F., Fraile-Nuez, E., Machín, F., Hernández-Borges, J., 2022. Microplastic pollution in sublittoral coastal sediments of a North Atlantic island: The case of La Palma (Canary Islands, Spain). *Chemosphere* 288, 132530. <https://doi.org/10.1016/j.chemosphere.2021.132530>

von Moos, N., Burkhardt-Holm, P., Köhler, A., 2012. Uptake and Effects of Microplastics on Cells and Tissue of the Blue Mussel *Mytilus edulis* L. after an Experimental Exposure. *Environ. Sci. Technol.* 46, 11327–11335. <https://doi.org/10.1021/es302332w>

Wang, Q., Guan, C., Han, J., Chai, M., Li, R., 2022. Microplastics in China Sea: Analysis, status, source, and fate. *Science of The Total Environment* 803, 149887. <https://doi.org/10.1016/j.scitotenv.2021.149887>



Free LitterAT deliverable D.2.2.6 (WP2-A2-Task2)

Weiss, L., Estournel, C., Marsaleix, P., Mikolajczak, G., Constant, M., Ludwig, W., 2025. From source to sink: part 1—characterization and Lagrangian tracking of riverine microplastics in the Mediterranean Basin. *Environ Sci Pollut Res* 32, 10081–10104. <https://doi.org/10.1007/s11356-024-34635-6>

Wichmann, D., Delandmeter, P., van Sebille, E., 2019. Influence of Near-Surface Currents on the Global Dispersal of Marine Microplastic. *Journal of Geophysical Research: Oceans* 124, 6086–6096. <https://doi.org/10.1029/2019JC015328>

Wong, C.S., Green, D.R., Cretney, W.J., 1974. Quantitative Tar and Plastic Waste Distributions in the Pacific Ocean. *Nature* 247, 30–32. <https://doi.org/10.1038/247030a0>

Woodall, L.C., Sanchez-Vidal, A., Canals, M., Paterson, G.L.J., Coppock, R., Sleight, V., Calafat, A., Rogers, A.D., Narayanaswamy, B.E., Thompson, R.C., 2014. The deep sea is a major sink for microplastic debris. *R Soc Open Sci.* 1, 140317. <https://doi.org/10.1098/rsos.140317>

Wootton, N., Sarakinis, K., Varea, R., Reis-Santos, P., Gillanders, B.M., 2022. Microplastic in oysters: A review of global trends and comparison to southern Australia. *Chemosphere* 307, 136065. <https://doi.org/10.1016/j.chemosphere.2022.136065>

Xanthos, D., Walker, T.R., 2017. International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): A review. *Marine Pollution Bulletin* 118, 17–26. <https://doi.org/10.1016/j.marpolbul.2017.02.048>

Yang, X., Zhou, Y., Li, Y., Wang, S., 2024. International Law and Regulation of Marine Microplastics: Current Situation, Problems, and Development. *Sustainability* 16. <https://doi.org/10.3390/su16219337>

Yin, M., Yang, L., Tang, Y., Liang, Y., Wang, Q., Su, L., Liu, J., Zhuang, Y., Li, D., 2023. Microplastics released from artificial turf applied as hedge walls: Their aging-induced properties and uptake by grass carp, mussels and earthworms. *Process Safety and Environmental Protection* 174, 53–62. <https://doi.org/10.1016/j.psep.2023.04.003>

Yutaka, M., Suchana, C., Sanae, C., Reza, C.M., Andrés, C.C., Francois, G., Pascal, H., Hirofumi, H., Atsuhiko, I., Peter, K., Nikolai, K., Daoji, L., Elisa, M., Dhamar, A., Hideshige, T., Richard, T., Tadashi, T., Katerina, V., Juying, W., n.d. 2020. Guidelines for Harmonizing Ocean Surface Microplastic Monitoring Methods.



Free LitterAT deliverable D.2.2.6 (WP2-A2-Task2)

Zhu, X., Qiang, L., Shi, H., Cheng, J., 2020. Bioaccumulation of microplastics and its in vivo interactions with trace metals in edible oysters. Marine Pollution Bulletin 154, 111079. <https://doi.org/10.1016/j.marpolbul.2020.111079>





8. Supplementary Materials

Table 8. Metadata of stations sampled by Ifremer laboratories along the French Atlantic coasts; stations in black text had two matrices sampled; stations in orange represent sediment matrix, stations in blue had mussels sampled and purple represented oysters' stations.

Station	Date	Matrix	Coordinates	
			Latitude	Longitude
Mus de Loup	10/02/2025	Huitres Sediment	45.797806	-1.140268
Bouchot de Charente	11/02/2025	Mussels Sediment	45.977283	-1.144733
Comprian	11/02/2025	Sediment Huitres	44.683949	-1.084576
Txingudi	13/02/2025	Huitres Sediment	43.361944	-1.775555
Cap Ferret	03/02/2025	Sediment Mussels	44.643946	-1.241245
Kersanton	30/01/2025	Sediment Mussels	48.344413	-4.300602
le Vill	13/02/2025	Mussels Sediment	48.575068	-4.605195
Petit Taureau	27/02/2025	Mussels Sediment	48.7327778	-3.5405552
Pointe du Roselier	04/03/2025	Sediment Mussels	48.575778	-2.59167
Saint-Brieuc	04/03/2025	Sediment Mussels	48.5425	-2.6827775
St Michel en Grève	27/02/2025	Mussels Sediment	48.6891667	-3.5830555
Bretagne Nord	26/02/2025	Sediment	48.820556	-3.039444
Estuaire Vilaine	05/02/2025	Sediment	47.50985	-2.525683
Rade Lorient	24/02/2025	Sediment	47.718333	-3.365555
Hossegor	11/02/2025	Sediment	43.668056	-1.427793
Villes Martin	11/02/2025	Sediment	47.257281	-2.224816
Camaret	06/02/2025	Mussels	48.278026	-4.587651
Ouessant	10/02/2025	Mussels	48.446629	-5.102997
Houat	17/02/2025	Mussels	47.410845	-2.942773
Le Halguen	03/02/2025	Mussels	47.50146	-2.49359
La Jument	04/02/2025	Mussels	47.710172	-3.37146
Pointe de Chemoulin	11/02/2025	Mussels	47.234533	-2.297093
Ile d'Yeu	12/02/2025	Mussels	46.8083333	-2.17452
CapBreton	11/02/2025	Mussels	43.655257	-1.445395



Table 9. Metadata of stations sampled during ROCCHSED framework along the French English Channel coast; only sediment matrix (in orange) was sampled

Station	Date	Matrix	Coordinates	
			Latitude	Longitude
GRAB 25-04	08/04/2025	Sediment	51.0229	2.03728333
GRAB 25-05	08/04/2025		51.0128833	1.97798333
GRAB 25-06	08/04/2025		50.9652667	1.85056667
GRAB 25-08	09/04/2025		50.9076667	1.66423333
GRAB 25-10	09/04/2025		50.7346167	1.56905
GRAB 25-11	09/04/2025		50.7027333	1.55618333
GRAB 25-21	10/04/2025		49.6658	0.027
GRAB 25-22	11/04/2025		49.6319667	0.10746667
GRAB 25-23	11/04/2025		49.60385	0.08251667
GRAB 25-24	11/04/2025		49.5749167	0.02873333
GRAB 25-26	12/04/2025		49.4585667	0.08075
GRAB 25-28	12/04/2025		49.4234167	0.01996667
GRAB 25-29	11/04/2025		49.5075167	-0.00231667
GRAB 25-44	15/04/2025		49.7046333	-1.4586
GRAB 25-45	15/04/2025		49.6791667	-1.5066
GRAB 25-46	15/04/2025		49.6714167	-1.61476667
GRAB 25-47	15/04/2025		49.6916667	-1.53706667
GRAB 25-54	17/04/2025		48.7037333	-1.67376667

Plastic contamination in mussels (by items/g d.w. and by items/ind.)

To complete information about mussel contamination, the results are also given in different units (first by items/g d.w. and then by items/ind.). The results with these units differ slightly from those presented in the report (items/g w.w.). Although the international system tends to express results in items/g w.w., some publications indicate them in items/g d.w. or items/ind. This section will therefore provide a basis for comparison for this type of study.

Regarding the concentration by dry weight (Figure 36), the mean total plastic contamination (mesoplastics (>5mm) and MPs (<5mm)) was 2.08 (s.d.: 3.17) items/g d.w. with a median of 1.17 item/g d.w. The values ranged from 0 to 13.13 items/g

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d.w.. Three stations presented mesoplastics, with a mean of 0.006 (s.d.: 0.013) item/g d.w. and a median equal to 0. Le Vill had 0.02 item/g d.w. of mesoplastics, Camaret had 0.04 item/g d.w. and Houat had 0.03 item/g d.w. (Figure 36).

Mean MP concentration was 2.07 (s.d.: 3.18) items/g d.w. and a median of 1.16 item/g d.w. The higher MP concentration in mussels was observed at Pointe du Roselier (13.13 items/g d.w.). Then, St Brieuc, St Michel en Grève and La Jument presented MP concentrations between 3 and 4 items/g d.w.. Seven stations had concentrations between 1 and 2 items/g d.w., 3 stations had a concentration between 0 and 1 item/g d.w. and two stations had no plastic contamination (Bouchot de Charente and Cap Breton).



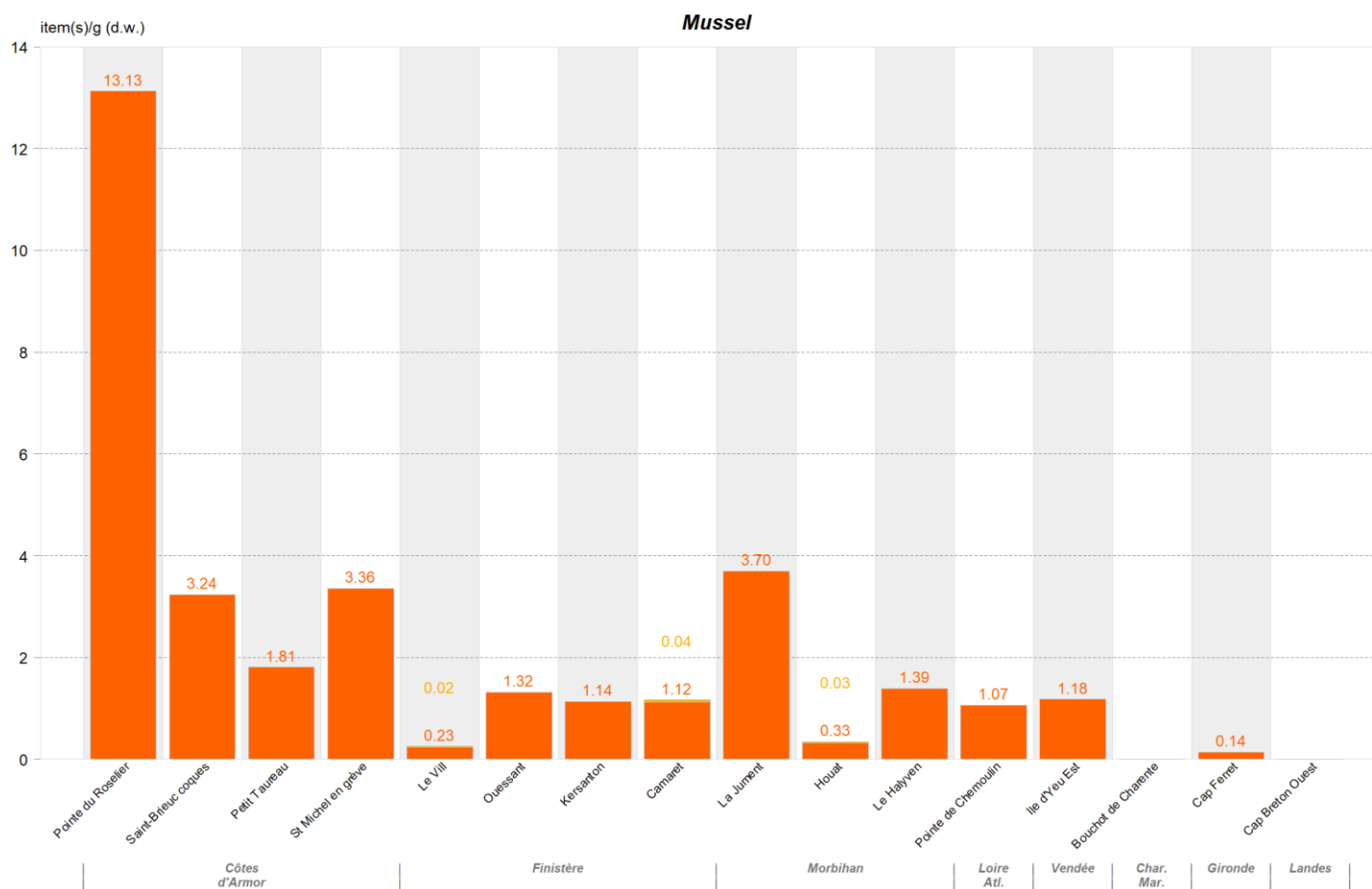


Figure 35. Mean total plastic particle, *i.e.* mesoplastics (light orange) and MPs (dark orange) combined, concentrations (items/g d.w.) in mussels along the French Atlantic coast



Regarding the concentration per individual (Figure 37), the mean total plastic contamination (mesoplastics (>5mm) and MPs (<5mm)) was 1.17 (s.d.: 1.32) item/ind. with a median of 0.62 item/ind.. The values ranged from 0 to 5.08 items/ind.. Two stations had no plastic contamination (Bouchot de Charente and Cap Breton).

Three stations had mesoplastics, with a mean of 0.02 (s.d.: 0.03) item/ind. and a median equal to 0. Le Vill had 0.11 item/ind., Camaret had 0.08 item/ind. and Houat had 0.05 item/ind..

MP concentration was on average 1.15 (s.d.: 1.31) item/ind., with a median of 0.60 item/ind.. The highest MP concentrations in mussels were observed at Ouessant (5.08 items/ind.), La Jument (2.33 items/ind.), Le Halyven (2.06 items/ind.) and Camaret (2.03 items/ind.). Three stations had concentrations between 1 and 2 items/ind.: Pointe du Roselier, Le Vill and Kersanton. Seven out of the 16 French stations had a concentration inferior at 1 item/ind. and two stations had no contamination (Bouchot de Charente and Cap Breton).



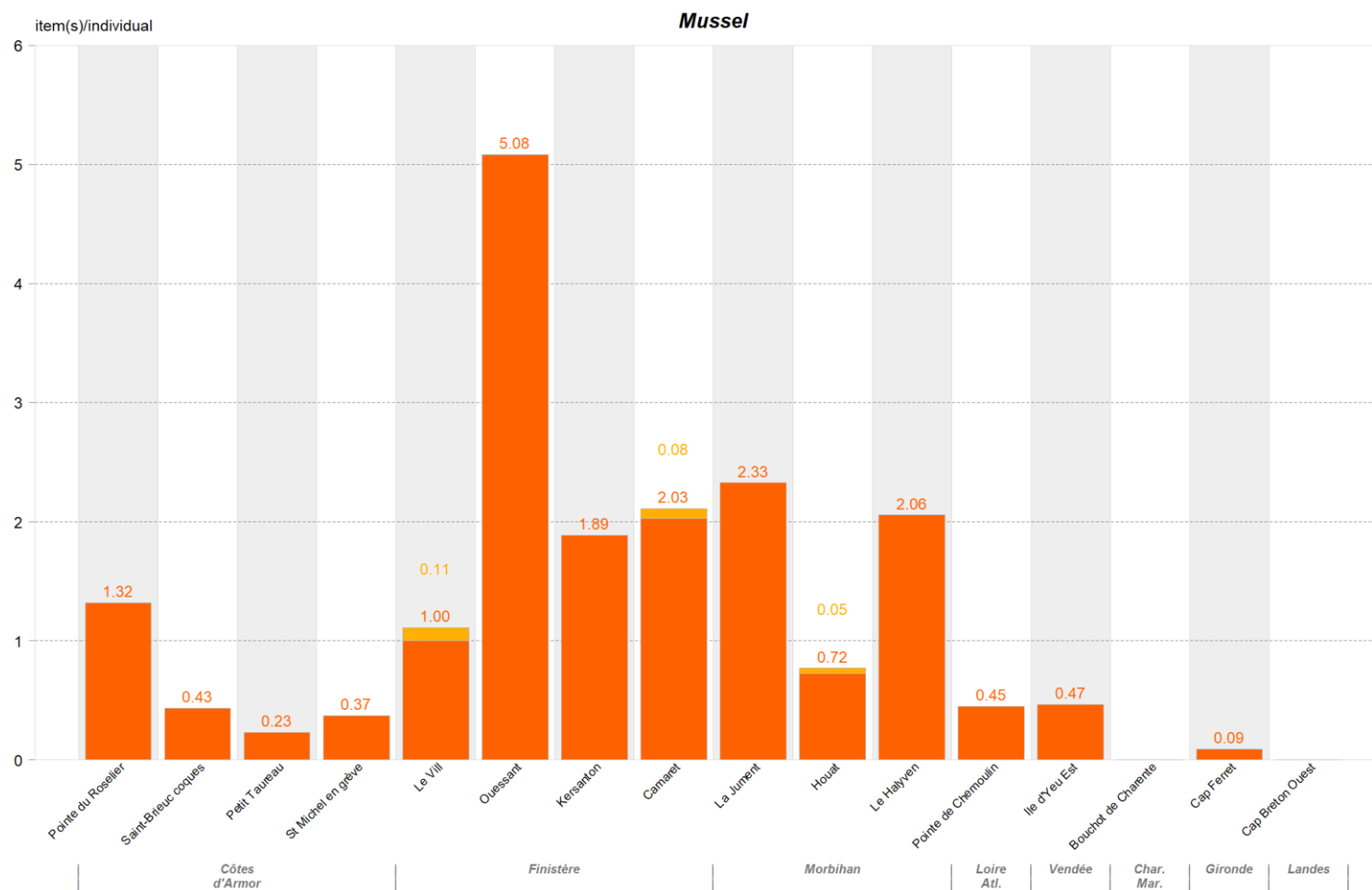


Figure 36. Mean total plastic particle, *i.e.* mesoplastics (light orange) and MPs (dark orange) combined, concentrations (items/ind.) in mussels along the French Atlantic coast





Plastic contamination in oysters (by items/g d.w. and by items/ind.)

To complete the information about oyster contamination, like for mussels, the results are also given in different units: by items/g d.w. (Figure 38) and by items/ind. (Figure 39). The results with these units differ slightly from those presented in the report (items/g w.w.).

The mean total plastic contamination (mesoplastics (>5mm) and MPs (<5mm)) was 6.39 (s.d.: 7.64) items/g d.w., or 4.62 (s.d.: 2.49) items/ind., with a median of 2.44 items/g d.w., or 4 items/ind.. The values ranged from 1.53 to 15.19 items/g d.w., or from 2.5 to 7.36 items/ind..

Only Mus du Loup presented mesoplastics with 0.04 item/g d.w., or 0.07 item/ind., giving an average across all stations of 0.013 (s.d.: 0.023) item/g d.w., or 0.024 (s.d.: 0.041) item/ind., and a median equal to 0.

MP concentration was on average 6.37 (s.d.: 7.65) items/g d.w., or 4.60 (s.d.: 2.52) items/ind., with a median of 2.44 items/g d.w., or 4 items/ind.. MP concentrations, in decreasing order, were 15.19 items/g d.w., or 7.36 items/ind., in Compran, 2.44 items/g d.w., or 4 items/ind., in Txingudi and 1.49 item/g d.w., or 2.43 items/ind, in Mus du Loup.

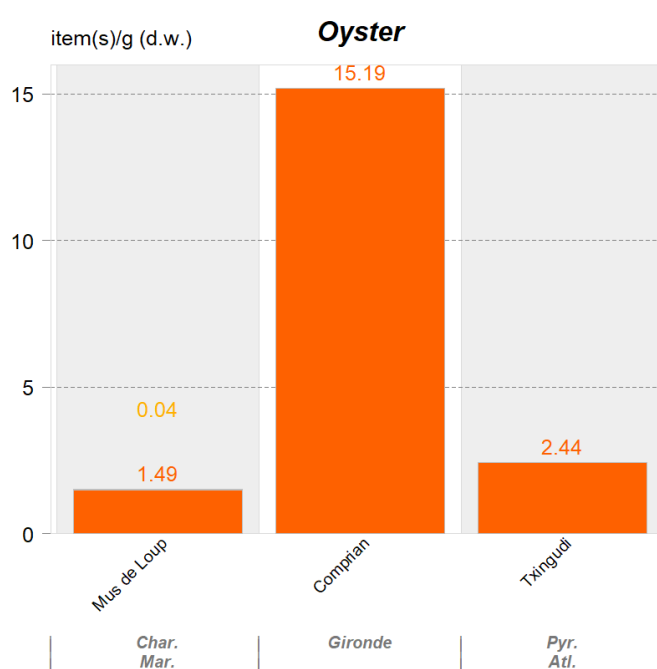


Figure 37. Mean total plastic, *i.e.* mesoplastics (light orange) and MPs (dark orange) combined, concentrations in items/g d.w. in oysters along the French Atlantic coast.

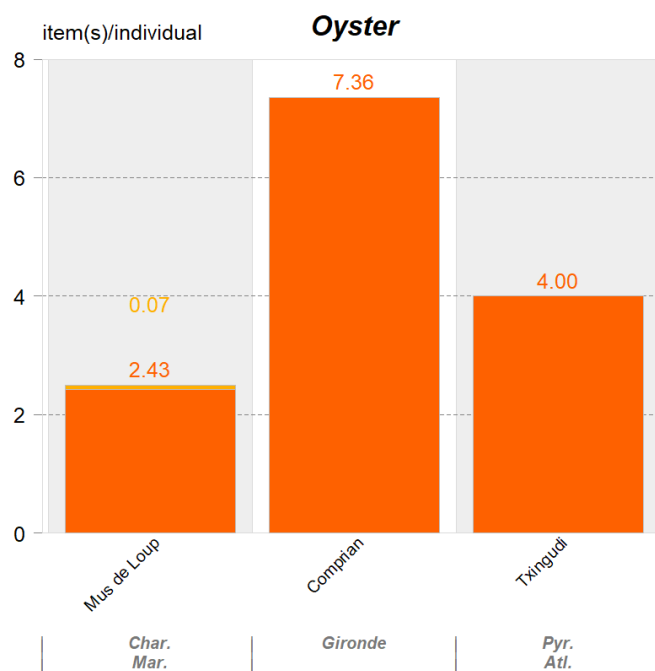


Figure 38. Mean total plastic, *i.e.* mesoplastics (light orange) and MPs (dark orange) combined, concentrations in items/individual in oysters along the French Atlantic coast.

