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Spatial monitoring of microplastics in environmental matrices from Galway Bay, Ireland

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ABSTRACT

Microplastic concentrations have been reported in a variety of environmental matrices and organisms across the world. Assessments of environmental concentrations are essential to understand trends and ensure decision-making processes that reduce environmental pressure. In this study, a combined sampling approach to surface waters, benthic sediments and biota in Galway Bay, Ireland, was carried out. Average concentrations of microplastics in surface waters were 1.42 ± 0.33 MPs m^{-3}, in biota were 4.46 ± 0.36 MPs ind^{-1} and in benthic sediments were 5.60 ± 1.54 MPs kg^{-1}. The diversity of polymers, microplastic types and colours were more abundant in surface waters and biota, when compared to benthic sediments. Integrated assessments of microplastics that follow existing monitoring programmes are essential to understand environmental trends. This work contributes to provide valuable information to descriptor 10 of the Marine Strategy Framework Directive in Ireland.

1. Introduction

Of the several environmental challenges the planet is currently facing, climate change and plastic pollution are the most pressing ones. Both are directly linked to human activities and require combined multidisciplinary and multistakeholder approaches to be solved (UNEP, 2016). Significant policy advances have been made recently by the United Nations (UN), particularly on the High Seas Treaty, which was signed by all member states in 2023 (UN, 2023). Additionally, the UN is leading discussions on a legally binding instrument on plastic pollution since 2022 (UN, 2022), and a zero-draft of the treaty has been published recently. The international debate and commitments on plastic pollution (e.g., G20 Action Plan on Marine Litter), reflect the willingness of decision makers to solve this global environmental and socio-economic problem.

Plastic has tremendously shaped human consumption since the 1950s, when its global production started. Its inexpensive manufacturing price and lightweight properties allowed this material to be widely used across diverse economic sectors, replacing traditional items made of glass or metal (Shashoua, 2008). Plastic has a strong socio-economic relevance in modern world (Ten Brink et al., 2009), allowing medical research and technological activities to develop, of which as a species we depend on. However, non-essential single-use items contribute to a cumulative solid waste management problem that is often highlighted in international reports (Geyer et al., 2017; Rochman et al., 2019; SAPEA, 2019; OECD, 2022).

Plastic pollution is a consequence of three simultaneous actions: (1) high consumption rates; (2) lack of/or inefficient global solid waste management; and (3) unregulated import & export of waste between continents (Geyer et al., 2017; Brooks et al., 2018; PlasticsEurope, 2022.). Furthermore, these actions or processes have similar production and/or maintenance costs (Newman et al., 2015; Dalberg, 2021), that influence decision-making- processes in global financial markets. In Europe, the EU (European Union) Plastics Strategy and Single Use Plastics (SUP) Directive was designed to promote systemic change in the plastics value chain, particularly in relation to design, sustainable production, use and recycling of plastic materials. The biggest challenge markets will face is shifting paradigms from linear systems into circular economy models (EC, 2018). This transition towards a circular economy is driven by the need for a reduction in plastic usage and its

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environmental impact. Two separate lines of thought emerge, one focussed on monitoring environmental matrices to assess concentrations of plastics and microplastics in environmental matrices, whose data will shape policy; and another focussed on the use of market-based instruments (MBIs) to regulate and control markets (Ten Brink et al., 2009). These two lines of thought described align with policy goals (EC, 2020), in fact, policies targeting single-use plastics (bags and microbeads), based on market-based instruments such as taxes, levies, bans, deposit-refund systems, etc., have already been implemented across the world (Xanthos and Walker, 2017). In the Circular Economy Action Plan adopted in March 2020, the European Commission not only addressed the presence of microplastics in the environment, as it proposed a 30 % reduction of all microplastics released into the environment by 2030. Therefore, long-term monitoring in diverse environmental matrices over space and time is advised, as the data gathered it serves as an input to policy goals.

Assessment of sources, pathways, and fate of microplastics in freshwater and marine ecosystems have been carried out over the three decades, from surface waters to benthic sediments, as well as commercially important and ecologically relevant biota species (Koelmans et al., 2019; Yao et al., 2019; Zhang et al., 2020; Ugwi et al., 2021; Kye et al., 2023). Airborne microplastic fallout (Amato-Lourenço et al., 2022), marine snow deposition (Porter et al., 2018) and riverine and coastal accumulation of plastics are also being monitored as part of a holistic assessment of sources and pathways of plastic pollution. Additionally, assessment of plastics being incorporated in nests (Escalona-Segura et al., 2022) and monitoring of key biota groups (e.g., fulmars, sea turtles, decapod crustaceans) have also been proposed as indicators in riverine, coastal, and marine habitats (Joyce et al., 2023). Rather than focussing solely on separate matrices, an ecosystem-based management approach has been highlighted as priority given forward (AAORIA, 2023). As such, the objectives of this work are to 1) assess the concentrations of microplastics in three environmental matrices (surface water, biota and benthic sediment) collected simultaneously, in Galway Bay, West of Ireland; 2) to assess whether the benthos (sediment and benthic species) has a higher MP concentration and 3) to explore potential trends in Galway Bay, and how these results compare to bays globally. This data contributes to the objectives, indicators, and descriptors of the Marine Strategy Framework Directive (MSFD). Throughout this manuscript, the definition of microplastics is the one proposed by Frias et al. (2018).

2. Materials and methods

2.1. Study area

Located in the West coast of Ireland, Galway Bay is a large enclosed coastal embayment, protected from the Atlantic Ocean swells by three islands (Inis Mór, Inis Meain and Inis Oirr), known as the Aran islands (53 07.207 N, 9 29.048 W; Fig. 1). The periphery includes Rossaveel pier, the Galway shipping harbour, and the Mutton Island wastewater treatment plant (Frias et al., 2020; Joshi and Farrell, 2020). The Corrib River is the main input of freshwater to the bay, at an average flow of 100 m^3s^{-1} (Joshi and Farrell, 2020). The water circulation in the bay follows an anticlockwise pattern, starting from the South Sound and exiting the bay through the North of the Aran islands (Frias et al., 2020). In terms of population, Galway County has approximately 193,000 inhabitants of which 43 % live in Galway city (CSO, 2022). The selection of sampling sites within Galway Bay were chosen to account for the inner and outer currents and benthic sediments in proximity to urban and rural areas.

2.2. Sampling

Samples were collected during a microplastic collection dedicated scientific cruise (CV19003), on board of the Irish Marine Institute R/V Celtic Voyager, during February 2019. A total of 675 samples were

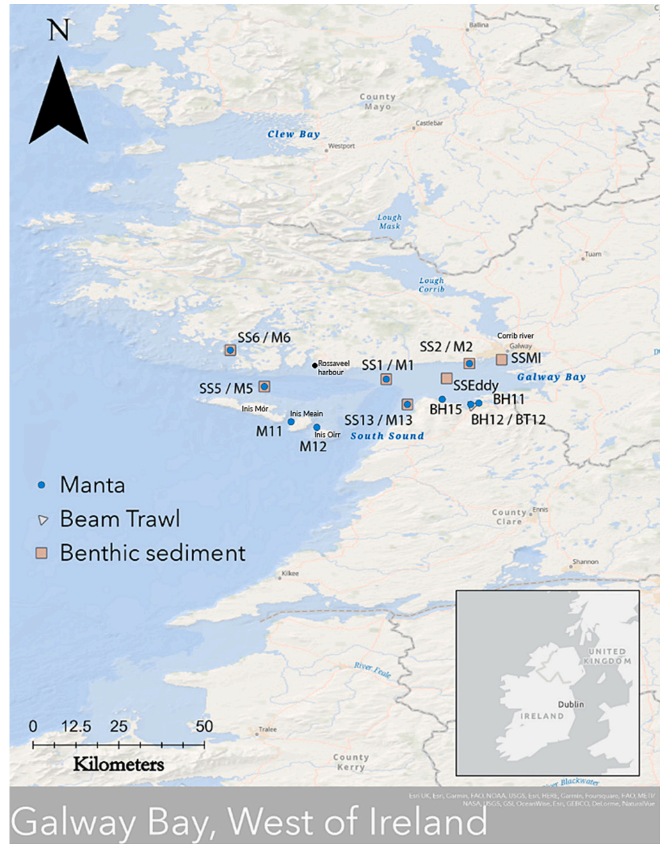

Fig. 1. Sampling stations within Galway Bay, West of Ireland.

collected, which correspond to 11 individual surface water manta trawl samples; 657 biota samples, corresponding to 657 individuals of 9 distinct species; and 7 benthic sediments samples, each with 6 sediment replicates.

2.3. Surface water

Samples were collected using an aluminium manta trawl frame to which a 2-m long, 300 μm mesh size nylon net with a 30 × 10 cm^2 cod end was attached. The frame has a rectangular aperture of 15 × 61 cm, and the cod end is made of 3 mm tick grey PVC (polyvinyl chloride) tube, with a diameter of 11 cm. A Hydro-bios mechanical flowmeter with back-run stop was equipped in the rectangular aperture, and revolutions were recorded prior to and immediately after each tow. Initial and final GPS coordinates were also recorded. The manta was deployed on the starboard side of the vessel, at an average speed of 2 knots for approximately 20 mins. This was done to prevent collecting water affected by turbulence in the wake zone.

After each deployment, manta was thoroughly rinsed from the outside, starting at the mouth, and moving towards the cod end, using a hose connected to the vessel water reservoir. Ultrapure water was used to rinse the cod end, and contents were washed through a series of decontaminated stainless-steel sieves (100 and 300 μm). Natural items (seaweed, wood) and large fragments >5 mm were carefully removed using metal tweezers and not included here. Filtrate was washed and rinsed three times with filtered (1.2 μm) seawater and was washed into decontaminated honey glass jars with a labelled metal lid. Samples were immediately frozen at −20 °C, without adding fixing agents, until further analysis.

2.4. Benthic sediment

Subtidal sediment samples were collected from 7 stations within Galway Gay, in waters >10 m. Collection was done using a Reineck box corer (20x30cm), where the top 5 cm of sediment were collected and stored in decontaminated glass jars with metal lids. Box corer was deployed three times per station with two replicates being retrieved with each deployment. Samples in glass jars were immediately frozen at −20 °C, until further analysis.

2.5. Biota

Samples were collected in one station south of Galway Bay, using a 3 m beam trawl, at a speed of 2–3 knots, for approximately 20 mins. On deck, organisms were sorted into species. A total of 657 individuals of nine different species were identified using taxonomic keys and analysed for MPs: solenette ($n = 79$, *Buglossidium luteum*); megrim ($n = 55$, *Lepidorhombus whiffiagonis*); whiting ($n = 171$, *Merlangius merlangus*); European sprat ($n = 59$, *Sprattus sprattus); common dragonet* ($n = 153$, *Callionymid lyra); sand goby* ($n = 60$, *Pomatoschistus minutus*); *grey gurnard* ($n = 45$, *Eutrigla gurnardus*); common dab ($n = 25$, *Limanda limanda*); and butterfly blenny ($n = 10$, *Blennius ocellaris*). These taxa represent diverse feeding habits, habitats, economic importance, and ecological relevance. After sorting, individuals were stored in labelled plastic bags, and immediately frozen at −20 °C, until further analysis.

2.6. Processing

In the laboratory, samples were defrosted at room temperature, for at least 24 h. Processing methodologies are matrix dependent and were different for sediment (density separation) and for seawater and biota (alkaline digestion).

2.6.1. Density separation

Density separation methodology followed protocols previously tested in our research lab (Pagter et al., 2018 & 2020b). In brief: after defrosting, sediment samples were transferred into labelled metal trays under a fume hood, where they were weighed before and after drying. Samples were covered in aluminium foil and dried in a Binder oven at 40 °C for approximately 3–5 days. Afterwards, they were transferred to decontaminated glass jars, where a sodium tungstate dihydrate ($Na_2WO_4 \bullet 2H_2O$) solution (40 % w/w 1.4 g/cm^3), as recommended by Frias et al., 2018, was introduced (ratio 3:1) and stirred continuously for 2 mins. Samples were covered with aluminium foil and left to settle for 24 h. After the settling period, the supernatant was pipetted out into a Buchner funnel attached to a VWR® VCP130 vacuum pump and filtered through 47 mm Whatman® (GF/C) glass microfibre filters (1.2 μm mesh). After filtration, the walls of the funnel were rinsed with sodium tungstate solution to retrieve any particles that might have been retained in funnel. Filtered sodium tungstate solution was recovered and added again to the glass jar, where it was mixed and left to settle for another 24 h. This process was repeated 3 times. The filtration system was thoroughly washed and rinsed prior to the following sample being processed.

2.6.2. Alkaline digestion

Alkaline digestion protocols followed earlier tested protocols conducted in our laboratory (Frias et al., 2020; Joyce et al., 2022). In brief: seawater and biota samples were defrosted at room temperature for at least 24 h. Seawater samples were divided into 3 fractions (≥90, 90–53 and ≤53 μm) using a metal sieve battery system and reintroduced to labelled decontaminated glass jars, using ultrapure water. Biometrics, namely weight in grams and size in centimetres of biota, were measured prior to digestion. Individual organisms were rinsed in ultrapure water prior to being introduced into labelled decontaminated glass jars, where the full body digestion was performed. A 10 % potassium hydroxide (KOH) solution was added to each jar in a 3:1 ratio, and jars were covered with aluminium foil prior to being left to digest in a Binder oven at 40 °C, for 24 h. After digestion, samples were left to acclimatise at room temperature. The resulting supernatant was poured into a Buchner funnel attached to a VWR® VCP130 vacuum pump and filtered through 47 mm Whatman® (GF/C) glass microfibre filters (1.2 μm mesh). After filtration, the walls of the jars and the funnel were rinsed with a new stock of filtered potassium hydroxide solution to retrieve any potential retained particles. This process was repeated 3 times. The filtration system was thoroughly washed and rinsed to prior to the following sample being processed.

2.7. Microplastics analysis

Filters were stored in labelled Petri dishes inside of a desiccator containing copper (II) sulphate crystals in the bottom, to remove excessive moisture from the air. Microplastics were counted, photographed, and measured using Olympus CellSens® software. Polymer identification was carried out in a random subsample of 100 suspected particles across all environmental matrices, namely: 23 from sediment, 50 from biota and 27 from surface water samples. The identification was performed in a Bruker® Hyperion 2000 series μ–FTIR (Fourier Transform Infrared) microscope, on transmission mode, within the wavenumber range 4000–400 cm^{-1} using a spectral resolution of 4 cm^{-1}, using 128 scans per sample. The background spectrum was measured with the same parameters prior to scanning other samples.

2.8. Quality assurance and contamination control (QA/QC)

To ensure QA/QC, a set of preventive approaches were conducted while collecting and processing samples. All solutions were made using 18 MΩ ultrapure water from a Elga® Purelab© purification system and were previously filtered through a 1 μm mesh to guarantee that sodium tungstate or potassium hydroxide salts would not introduce factory cross-contamination to the samples. Operators wore 100 % cotton lab coats (Pagter et al., 2018) and synthetic garments wore underneath were avoided (Hermsen et al., 2018). Decontamination of glassware was carried out in a dilute 10 % nitric acid (HNO_3) solution. Air controls were used solely during processing, as it was challenging to control sampling conditions while at sea. Contamination and cross-contamination blanks and controls were run for the solutions, and analysed to verify no potential microplastics were being added to samples during processing. Recommended methodologies to ensure reduction of cross-contamination were followed (Frias et al., 2018; Gago et al., 2019; Bessa et al., 2019). All surfaces and dissection equipment were cleaned before and after dissection of each organism. Surfaces were cleaned with industrialised methylated spirit (IMS) prior to examination.

3. Results

A total of 3382 potential microplastic particles were retrieved from the 675 samples processed. The average microplastic concentration in surface waters was 1.42 ± 0.33 MPs m^{-3} (Fig. 2a), while biota was 4.46 ± 0.36 MPs ind^{-1} (Fig. 3a), and benthic sediment was 5.60 ± 1.54 MPs kg^{-1} (Fig. 5a). A description of each matrix is presented in the following sub-sections, and detailed data provided in the supplementary material. Harmonisation of data was specific to each environmental matrix. For surface waters, the number of microplastics in each fraction were divided by the initial volume of water; for sediments, number of microplastics were divided by sediment dry weight and for biota, number of microplastics were divided by the number of individuals per species processed (Supplementary tables S1, S2 and S3).

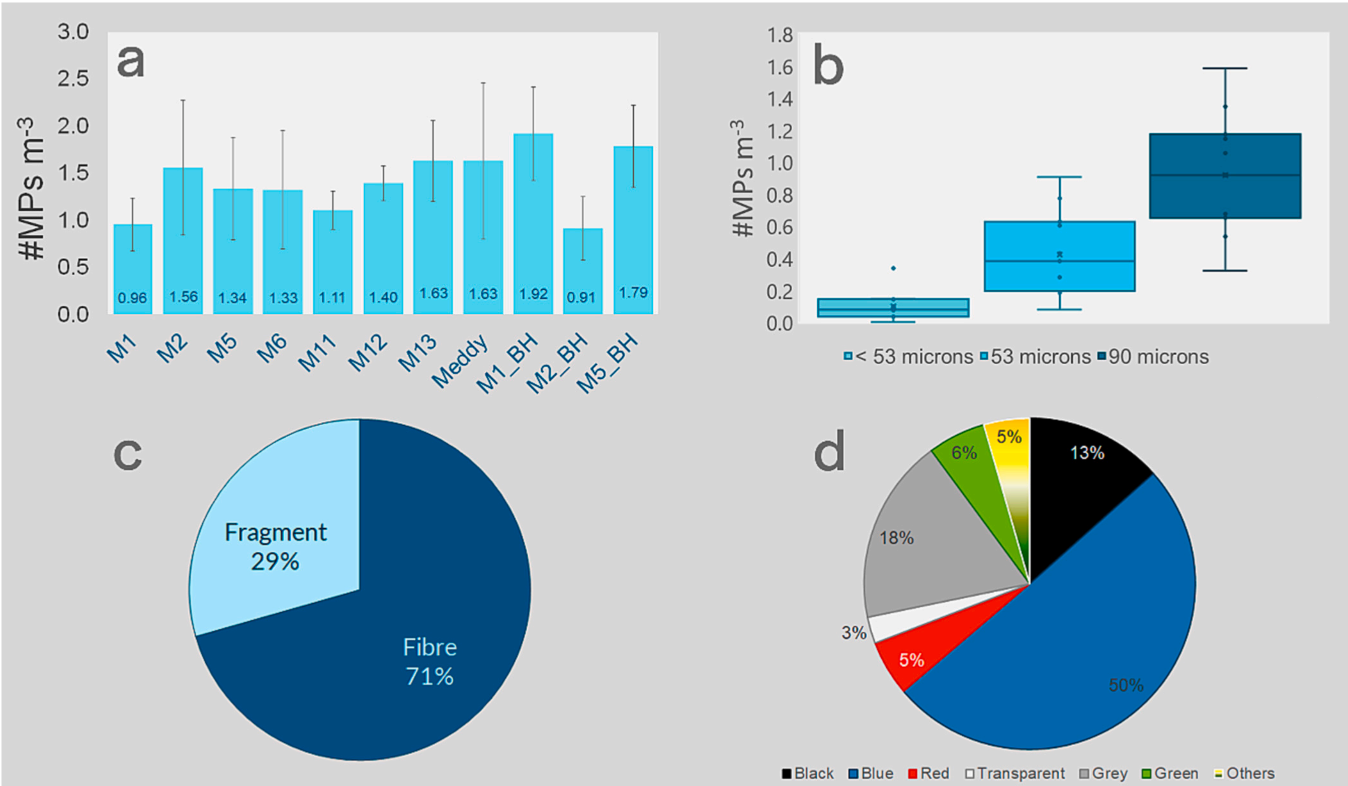

Fig. 2. Seawater results. a) harmonised results per cubic meter in each station; b) fraction distribution of microplastics; c) MP types; d) MP colours.

3.1. Surface seawater

A total of 426 potential microplastics were retrieved from surface seawater, where fibres represented 71 % and fragments the remaining 29 % (Fig. 2c). Microplastics ranged between 4.02 and 1112.70 μm in length, and between 0.62 and 338.86 μm in thickness. Distribution of microplastics per size was higher in the larger fractions (90 and 53 μm) (Fig. 2b). Most surface microplastics were blue fibres, followed by grey fragments (Fig. 2c and d).

3.2. Biota

A total of 2933 suspected microplastics were retrieved from 9 species, where the highest concentrations were found in solenette (63.44 MPs ind^{-1}), a bottom feeder, demersal species, and the lowest concentration was found in the European sprat, a pelagic predator (0.32 MPs ind^{-1}) (Fig. 3a). Most microplastics were fibres (98 %) with a small number of fragments (Fig. 3b). Regarding MP colours, blue and black were the dominant colours, with small amounts of red, green, transparent, and multicolour items (Fig. 3b).

Concentrations of microplastics in bottom feeding species were higher than in predators (Fig. 4a), and demersal species had higher concentrations of microplastics when compared to pelagic species (Fig. 4b).

3.3. Benthic sediment

Microplastics ($n = 23$) retrieved from seafloor sediments were all fibres (Fig. 5b), with length ranges 250–8468 μm in length (includes entangled fibres, which is the reason why there are fibres >5000 μm) and 7.5–40.3 μm in thickness. The dominant colours (Fig. 5c) were black and blue, followed by transparent and red. Diversity of microplastics in benthic sediments was lower when compared to other environmental matrices.

3.4. Polymer identification

A subsample of 100 suspected particles (27 from surface waters, 50 from biota and 23 from benthic sediments) were processed in the μ-FTIR for polymer identification. Most microplastics were of synthetic origin (96 %), however there were 4 % of natural items (cotton fibres), corresponding to approximately 135 items in total. Natural fibres were only found in biota, which in conjunction with samples from surface waters had a higher diversity of polymers, when compared to benthic sediments. Nylon is the most prevalent polymer across the environmental matrices sampled in Galway Bay.

3.5. QA/QC

Air controls used while processing the three environmental matrices showed no contamination or cross-contamination. KOH controls revealed 20 % contamination, associated with washing and rinsing. Correction methods were applied to improve accuracy of data reporting, particularly with specific colour and MP types associated to operators clothing. The QA/QC methods follow earlier work conducted by our research team, namely Frias et al., 2018, Frias et al., 2020, Hara et al., 2020, Pagter et al., 2020a, Pagter et al., 2020b, Joyce et al., 2022 and Polt et al., 2023.

4. Discussion

4.1. MP concentrations in Galway Bay

Due to its geographical location in the North Atlantic, Galway Bay offers an interesting case study for research into microplastic pollution. The bay is influenced by strong hydrodynamic processes and by local environmental factors (e.g. rainfall intensity), as previously identified by Frias et al. (2020). The combination of these processes is known to play an important role on microplastic distribution and accumulation

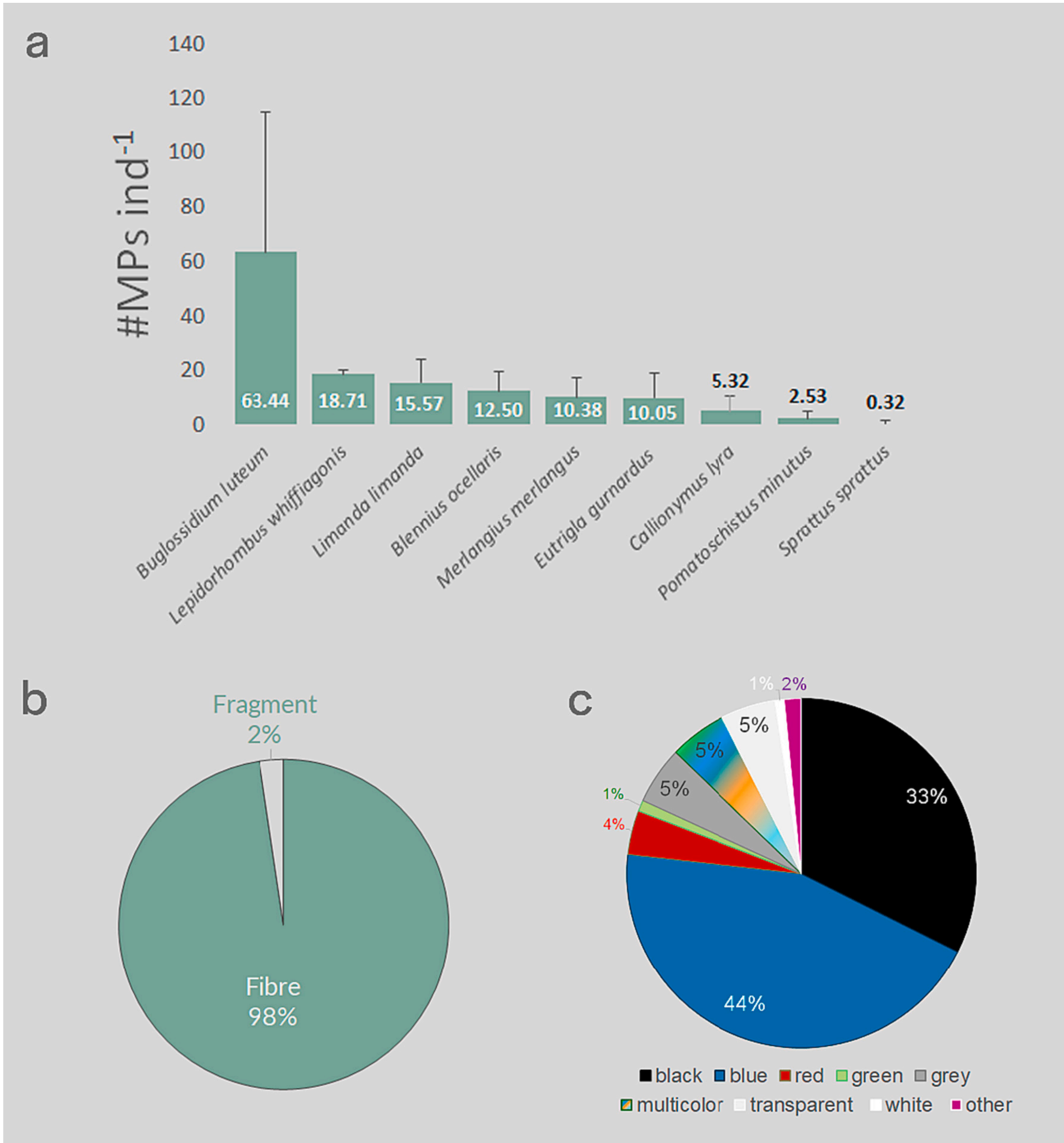

Fig. 3. Biota results. a) harmonised results per species; b) MP types; c) MP colours.

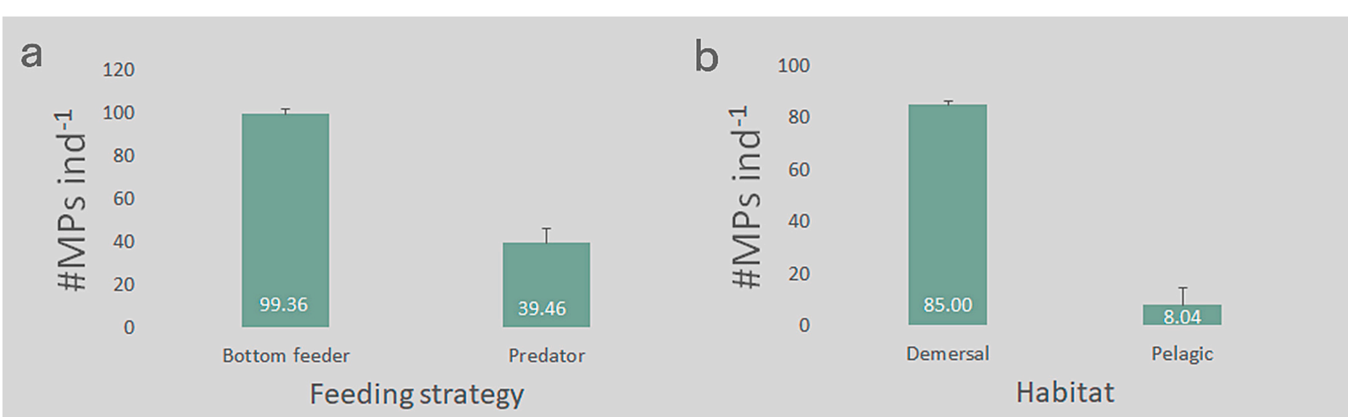

Fig. 4. MP concentrations in biota by a) feeding strategy and b) habitat.

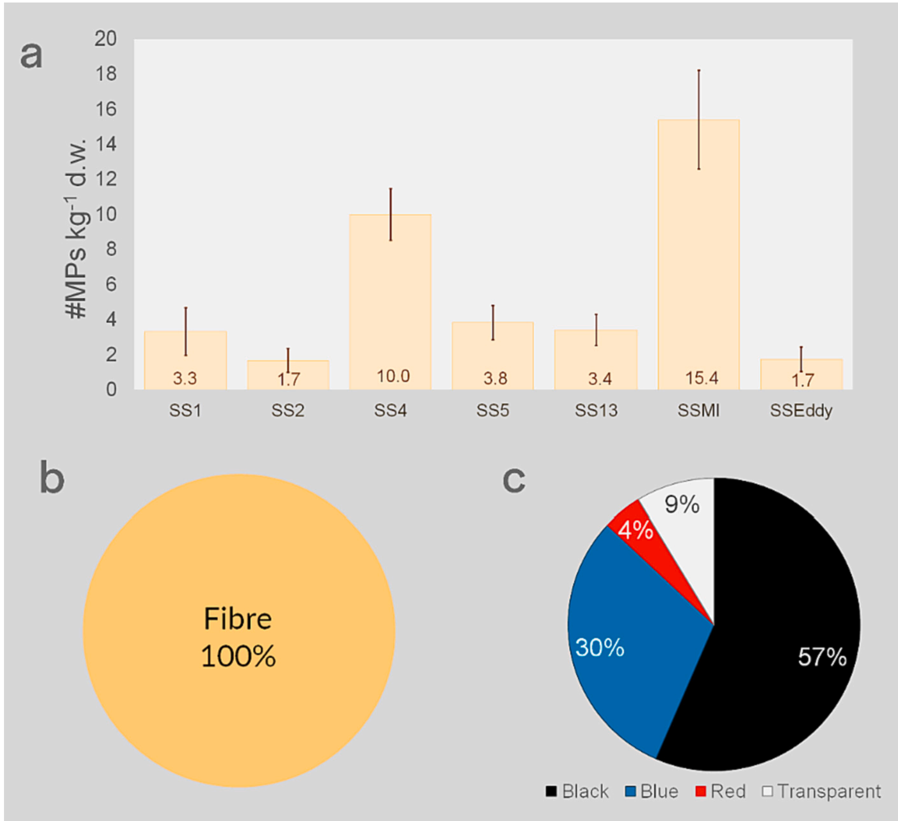

Fig. 5-. Benthic sediment results. a) harmonised results per kilogram of dry weight in each station; b) MP types; c) MP colours.

(Pagter et al., 2020a; Pagter et al., 2020b).

Previous research efforts in this bay have taken place since 2013 (Table 1), where individual environmental matrices samples had been collected. The current work provides a base for ecosystem-based monitoring approaches, as it combines several environmental matrices, on a simultaneous sampling effort. As sampling at sea is a time-consuming and cost-intensive activity, such an ecosystem-based approach would substantially contribute to a holistic understanding of microplastic contamination. This is particularly relevant as there are species that are commercially grown for human consumption in the bay (Polt et al., 2023), or in surrounding waters (Joyce et al., 2022).

Water sampling across Ireland was first conducted by Lusher et al. (2014), retrieving a wide range of concentrations (0–22.5 particles m^{-3}). This led to a targeted sampling approach in Galway Bay, between 2018 and 2020 (Table 1), whose aim was to provide data for descriptor 10 (Marine litter) of the EU Marine Strategy Framework Directive (MSFD). Sampling of surface water for microplastic assessment represents snapshots in time, and more data is required to assess spatio-temporal trends at the surface water level. In the two case studies in Galway Bay, sampling and processing methodologies were the same, however, because the number and location of stations is different, care must be taken when comparing between the two different years. Similar concerns should be considered for biota species, because of different habitats and behaviours.

Microplastic concentrations on biota samples are species dependent, and therefore results expressed in Table 1 are illustrative of the species and their habitats across Galway Bay. For example, in the case of gastropods (*Littorina littorea*), organisms from Galway Bay have slightly lower MP concentrations when compared to the Wadden Sea (2.5–5.4 MPs g^{-1}) (Polt et al., 2023). Similarly, decapod crustaceans in Galway Bay have lower microplastic concentrations when compared to the Mediterranean (5.5 MPs ind^{-1}) (Cau et al., 2019) or the Irish Sea (3.6 MPs ind^{-1}) (Hara et al., 2020; Joyce et al., 2022). In relation to fish species, microplastic concentrations focus on both species of commercial interest and of ecological importance, which highlights the importance of an ecosystem-based approach. In Pagter et al., 2020a, it was

Table 1
A compilation of microplastic concentrations in Galway Bay. Lines marked in bold are the results from this study.

Sampling year	Environmental matrix	MP concentration	Reference
2013	Surface water	2.46 ± 2.43 MPs m^{-3} (across Ireland)	Lusher et al., 2014
2017	Surface water	0.56 ± 0.33 MPs m^{-3}	Frias et al., 2020
2019	**Surface water**	**1.42 ± 0.33 MPs m^{-3}**	***This study***
2017	Biota (several species)	0 – 4.67 MPs ind^{-1}	Pagter et al., 2020b
2017	Biota (benthic species)	0 – 6 MPs ind^{-1}	Pagter et al., 2021
2019	Biota (*Littorina littorea*)	0.59 - 2.4 MPs ind^{-1} 2.14 MPs g^{-1}	Doyle et al., 2019
2019	**Biota (several species)**	**4.46 ± 0.36 MPs ind^{-1}**	***This study***
2020	Biota (*Nephrops norvegicus*)	2.2 MPs ind^{-1} (ICES FU17)	Joyce et al., 2022
2020	Biota (*Nephrops norvegicus*)	0.90 ± 1.03 MPs ind^{-1} Aran Prawn Grounds	Hara et al., 2020
2022	Biota (*Ostrea edulis* & *Magallana gigas*)	*O. edulis* 0.4 MP g^{-1} | 5.6 ± 4.5 MP ind^{-1} *M. gigas* 0.6 MP g^{-1} | 6.4 ± 3.0 MP ind^{-1}	Paul et al., 2023
2014	Benthic sediment	7.67 ± 2.09 MPs kg^{-1}	Martin et al., 2017
2017	Benthic sediment	104 MPs kg^{-1} d.w.	Pagter et al., 2018
2017	Benthic sediment	73 MPs kg^{-1} d.w.	Pagter et al., 2020a
2019	**Benthic sediment**	**5.60 ± 1.54 MPs kg^{-1}**	***This study***

highlighted that although non-commercial species represented 39 % of the catch, they accounted for more than half of the microplastics recovered. In this study, *Limanda limanda* ($n = 25$) and *Blennius ocellaris* ($n = 10$) were the third and fourth species with higher microplastic concentrations. Both are demersal species with bottom feeding strategies, and since the seafloor sediment is a sink for microplastics (Woodall et al., 2014; Matsuguma et al., 2017; Bergmann et al., 2017), it is not surprising that these species had higher concentrations. Although both commercially important and economically relevant species have been assessed, it is crucial to understand flows of microplastics between environmental matrices. One way of contributing to this understanding is to assess the relationships between pelagic species and surface waters and between demersal species and benthic sediment.

Existing monitoring programmes in Ireland could expand from solely economically relevant species to include in the assessment bycatch and ecologically important species so that a trend of plastic pollution over time could be established (Pagter et al., 2020b). This recommendation would allow for sample collection to increase, without additional financial impact to existing monitoring programmes. An integrated ecosystem-based approach, that would also include monitoring of airborne microplastics around the bay, could be a relevant add-on to increase data collection to benefit more environmental policies. Microplastics should be monitoring to provide spatiotemporal analysis of diverse environmental matrices and enhance -decision making processes, as recommended by Joyce et al., 2022, in her work interlinking *Nephrops* and microplastic pollution around Ireland.

Previous studies suggest that MP concentrations in the bay are relatively stable for surface waters and biota, with concentrations below <3 MPs m^{-3} and <7 MPs ind^{-1}, respectively. In contrast, the seafloor recorded a higher variability (5.6–104 MPs kg^{-1}), which could be a reflection of the heterogenous nature of the seabed in addition to the local environmental and hydrodynamic conditions within each sampling station. A compilation of MP concentration data from Galway Bay, across several years and in diverse environmental matrices is presented in Table 1.

4.2. Distribution and accumulation of MPs in Galway Bay

Similarly to scientific reports from around the world, (Acharya et al., 2021), fibres are the dominant microplastic type in Galway Bay, across all the environmental matrices assessed. Again, in similarity to other studies where the seafloor is considered the ultimate sink for microplastic deposition (Martin et al., 2023), MP concentrations in the bay were higher in benthic environments than in surface waters (Table 1).

In relation to MP polymer type and colour, this work shows that this diversity decreases with depth (Fig. 6). Overall, the dominant colours are black, blue, red and transparent, which are consistent with previous results in the area (Doyle et al., 2019; Frias et al., 2020; Pagter et al., 2020a, 2020b). The diversity of polymer types also aligns with recent work conducted in the North Atlantic Ocean (Nash et al., 2022).

There are similarities in MP types and colours between waters and biota, which shows potential transfer between the two matrices. Ensuring this result in correct requires further investigation to understand whether there is accumulation, or even potential bioaccumulation of microplastics. Future studies in Galway Bay should focus on the relationship between surface waters and pelagic species and on the relationship between demersal species and benthic environments. Additionally, the highest concentration of microplastics was found in the seafloor, highlighting that seafloor sediments are the ultimate sink for microplastics in the Bay.

4.3. Comparison with other sites

The present study highlights that concentrations of microplastics in Galway Bay are complex, variable and depend on their environmental matrix (Frias et al., 2020; Pagter et al., 2018; Pagter et al., 2021), however, it is important to see these results in a wider context.

A recent study in the North Atlantic provided insight into the relationships between concentrations of surface microplastics and a wide range of species (Egger et al., 2022). This study established a connection between concentrations of plastic and fish, however, concentrations were higher closer to the Azores archipelago in the North Atlantic Gyre, and in the Netherlands, than in the area south of Ireland (Egger et al., 2022). In a different study conducted in the Azores archipelago, benthic fish species had a lower colour range and polymer diversity (Pereira et al., 2020), which is in accordance with the results of the present study. Nonetheless, this same study reported lower concentrations of microplastics across the fish species assessed (Table 2).

It is known that benthic sediments are a sink to microplastic pollution, and a recent study by Nash et al., 2022, revealed that microplastic pollution extents out to deep sea sediments in the Porcupine Seabright, in the Irish Economic Exclusive Zone (EEZ), in the Northeast Atlantic Ocean. In that study, 83 particles (74 synthetic and 9 natural) were retired from 33 out of 44 stations sampled (Nash et al., 2022). Despite its low concentrations (5–18 MPs kg^{-1} d.w.), the fact that microplastics were found at depths ranging from about 150 to 3000 m, showcases the need to have wider integrated approaches, and to assess the pathways of how these plastics are reaching the depth.

Table 2 compiles published data on each environmental matrix in different bays or enclosed water bodies around the world, to allow our

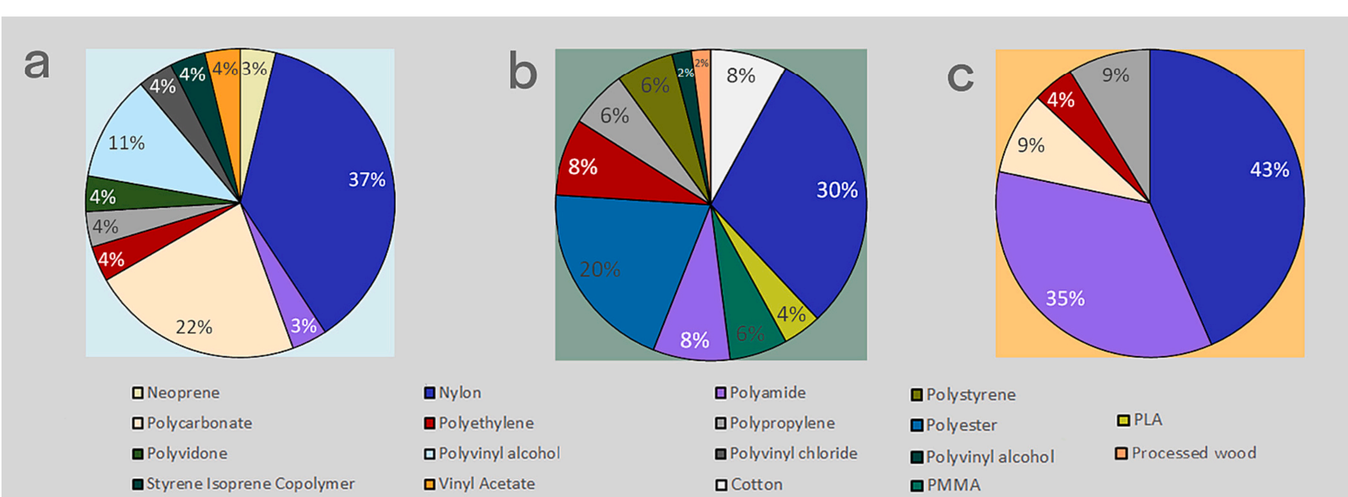

Fig. 6. FTIR results a) surface waters b) biota and c) benthic sediment.

Table 2
Data comparison with other sites. Lines marked in bold are the results from this study.

Site	Environmental matrix	MP concentration	Reference
Yangtze River, China	Surface water	67.5 ± 94.4 MPs m^{-3}	Li et al. 2020
Asuncion Bay, Paraguay	Surface water	3.6 – 27.4 MPs m^{-3}	Diez-Perez et al., 2023
Gulf of Finland, Finland	Surface water	0.92 ± 0.61 MPs m^{-3}	Uurasjärvi, et al., 2021
Galway Bay, Ireland	**Surface water**	**1.42 ± 0.33 MPs m^{-3}**	***This study***
Haizhou Bay, China	Biota (several species)	22.21 ± 1.7 MPs ind^{-1}	Feng et al., 2019
Azores Archipelago, Portugal	Biota (several species)	0.13 ± 0.02 MPs ind^{-1}	Pereira et al., 2020
West Coast, Iceland	Biota (several species)	Cod 0.23 MPs ind^{-1} Saithe 0.28 MPs ind^{-1}	De Vries et al., 2020
Northwest Sardinia, Italy	Biota (*Nephrops norvegicus*)	2.1 ± 0.6 MPs ind^{-1} 3.9 ± 0.5 MPs ind^{-1}	Cau et al., 2020
Northeast Atlantic, Scotland	Biota (several species)	Range 0.0 ± 0.00 - 1.3 ± 1.67 MPs ind^{-1}	Murphy et al., 2017
Galway Bay, Ireland	**Biota (several species)**	**4.46 ± 0.36 MPs ind^{-1}**	***This study***
Guanabara Bay, Brazil	Benthic sediment	400 – 650 MPs kg^{-1}	Alves and Figueiredo, 2019
Pearl River Estuary, China	Benthic sediment	1669 MPs kg^{-1}	Lin et al., 2018
Ebro Delta, Spain	Benthic sediment	2052 ± 746 MPs kg^{-1}	Simon-Sanchez et al., 2019
Galway Bay, Ireland	**Benthic sediment**	**5.60 ± 1.54 MPs kg^{-1}**	***This study***

results to be put into perspective. For surface waters, in comparison with other bays and gulfs in Asia and South America, Galway has lower concentrations of floating microplastics. The concentrations are relatively higher in Galway than in the Baltic Sea (Gulf of Finland), however the difference is not as staggering when compared to the Mediterranean Sea (Sharma et al., 2021) or to surface waters in other continents (Table 2).

Microplastic concentrations for biota in Galway Bay are substantially lower than similar bays in Asia. When compared to other sites in the North Atlantic, fish species from Galway Bay have higher concentrations compared to the Azores archipelago, Iceland, or Scotland (Table 2). A comparison between biota species is challenging because not all species exist in the same sites or habitats, and since they have different behaviours, results should be analysed with care.

Furthermore, the sediment results presented are substantially lower than other bays and sites in Latin America, Asia, and even the Mediterranean, showing that Galway Bay is a relatively clean site in the North Atlantic.

5. Conclusion

Sampling for microplastics in environmental matrices is a complex, time-consuming and cost demanding process. Nonetheless, the data collected here contributes to strengthen current and future monitoring programmes and strategies, particularly in widening spatial and temporal scales that can serve as a basis to estimate and model MP concentrations over time.

This study reinforces that benthic sediments are a sink for microplastics. Fibres are the dominant microplastic type and the most common colours and polymer types are, respectively, black, blue, and red, and nylon, polyamide, and polycarbonate, which is in accordance to similar studies in the North Atlantic Ocean and around the globe.

The results from this study contributes to policy goals highlighted in the MSFD, as it gathers data on microplastic concentrations that can be used to enhance existing monitoring programmes and improve prediction and estimation models.

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CRediT authorship contribution statement

João Frias: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Haleigh Joyce:** Methodology, Investigation. **Loann Brozetti:** Methodology, Investigation. **Elena Pagter:** Methodology, Investigation. **Mateja Švonja:** Methodology, Investigation. **Fiona Kavangh:** Writing – review & editing. **Róisín Nash:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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