



Microplastic contamination of intertidal sediment and cockles (*Cerastoderma edule*)

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ABSTRACT

Microplastic pollution represents a new threat to both marine environments and the species that reside within them. This study examined the temporal concentrations of microplastics found in the commercially and ecologically important bivalve, *Cerastoderma edule* and the presence of microplastics in intertidal sediment from the Special Area of Conservation (SAC) and Special Protected Area (SPA) of Dundalk Bay, Ireland. A microplastic range of 1.55 ± 1.38 to $1.92 \pm 1.00 \text{ g}^{-1}$ and 3.43 ± 2.47 to $6.90 \pm 3.68 \text{ ind}^{-1}$ was reported between seasons. Microfibres dominated the shape of microplastics present in both sediment and cockles. While a wider range of polymers were identified in cockles than in sediment, microplastic concentrations recovered from both intertidal sites studied were approximately double the estimated safe loading levels for this pollutant. The potential of cockles to perform as shallow environment biomonitors of microplastic pollution was identified as they presented buoyant microplastics that were not identified in sediment samples.

1. Introduction

Marine sediment can serve as both a source and a sink of microplastic pollution as well as regulating microplastic distribution in aquatic environments (Woodall et al., 2014; Jambeck et al., 2015; Uddin et al., 2021). Microplastics can adsorb organic and inorganic pollutants from their surrounding environment. Polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), organo-halogenated pesticides, nonylphenol and dioxins have been detected in plastic pellets from beaches worldwide (Ogata et al., 2009; Avio et al., 2015). If contaminated microplastics are ingested, they may desorb these pollutants into organisms (Bakir et al., 2014).

Although microplastics have been recorded in many marine environments, the quantity of microplastics can be elevated in coastal locations due to the proximity of potential sources from the terrestrial environment (e.g. artificial turf, paint, washing wastewater, sewage sludge) and also tidal processes (e.g. gravitational circulation, tidal pumping) that can encourage their deposition and accumulation (Ryan et al., 2009; Weinstein et al., 2016; Gray et al., 2018; Jalón-Rojas et al., 2024). In Ireland, several studies have examined the presence of microplastics in marine sediments (e.g., Martin et al., 2017; Frias et al.,

2020; Mendes et al., 2021; Pagter et al., 2020), with one study documenting particle concentrations ranging from 0 to 553 particles per kilogram (Mendes et al., 2021).

Microplastics have been identified in various shellfish species, prompting concerns regarding potential implications for human health through direct dietary exposure (Li et al., 2021a, 2021b). Recent investigations have substantiated the presence of microplastics in a diverse array of bivalve species (Cho et al., 2019; Hermabessiere et al., 2019; Baechler et al., 2020; Sui et al., 2020; Wakkaf et al., 2020; Ding et al., 2021; Aung et al., 2022). Although substantial attention has been accorded to mussel species, notably *Mytilus edulis*, limited research has been undertaken on the common cockle (*Cerastoderma edule*). Only two studies have scrutinized microplastic presence in this species, one along the French Channel coast (Hermabessiere et al., 2019) and a more recent investigation in Portuguese lagoons (Botelho et al., 2023) with both studies noting their presence in this species of bivalve.

Despite ecotoxicology studies suggesting negligible impact on bivalve body condition, microplastics can exert influence on the behaviour of bivalves residing in sediment, potentially perturbing benthic ecosystems (Bour et al., 2018; Urban-Malinga et al., 2021). In a study conducted by Urban-Malinga et al. (2021) showed that near-

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Fig. 1. Intertidal beach locations of this study, cockles were collected from Rockmarshall beach at the same site as sediment collection occurred.

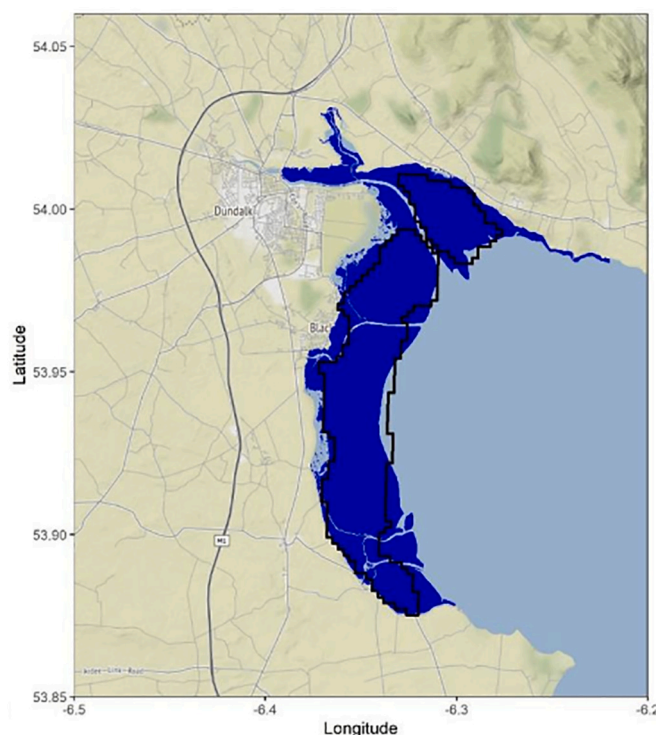


Fig. 2. Estuaries, mudflats and sandflats of Dundalk Bay not covered by water at low tide in blue, the cockle fishery area outlined in black. (Marine Institute, 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

surface dwelling species (i.e., *Cerastoderma glaucum*), emerged less often and in lower numbers in sediment spiked with microplastics, while the Baltic clam (*Limecola balthica*) buried itself deeper in similarly treated sediment when compared to the controls (Urban-Malinga et al., 2021). A similar behaviour could be expected in bivalves, such as the common cockle (*Cerastoderma edule*) a pivotal species in Dundalk Bay and have adverse repercussions for benthic habitats, impacting seabed dynamics during cockle harvesting and impinging upon the foraging behaviour of seabirds.

Dundalk Bay is a large shallow marine bay located on the east coast of Ireland, approximately 70 km north of the capital of Dublin (Fig. 1), classified as a special area of conservation (SAC), special protection area (SPA) under the EU Birds and Habitats Directives (NPWS) and a Ramsar site (no. 834) (Ramsar Sites Information Service). Dundalk Bay is a classified Bivalve Mollusc Production Area, and it has supported a commercial dredge cockle (*Cerastoderma edule*) fishery since 2001 (Hervas et al., 2008).

Cockles have been documented as a key resource supporting overwintering wader populations in species such as oystercatchers who require an estimated 105–232 kg cockle flesh per bird per winter in the absence of mussel beds (main alternative food source). Insufficient food availability leads to effects such as reduced individual body condition, increased mortality and reduced population sizes (Ens et al., 2004; Verhulst et al., 2004). A change in feeding and/or burial behaviour on the *Cerastoderma edule* — a pivotal species in Dundalk Bay, Ireland — may have adverse repercussions for benthic habitats, impacting seabed dynamics during cockle harvesting and impinging upon the foraging behaviour of seabirds. The deeper fluidizing of the seabed as is the case currently for razor clam in Dundalk Bay (harvesting up to a depth of 0.25 m) can lead to a greater impact on benthic communities (Legare et al., 2020). An increase in the area fished to a greater depth would further jeopardise *Ensis magnus*, *Pharus legume*, the spiny cockle (*Acanthocardia* spp.) clams (*Venus* spp.), *Chamelia* spp. and the endangered and long-lived Icelandic clam (*Arctica islandica*) in this SAC and SPA where abundances of these species are already low with richness declining since 2017 with *A. islandica* not recorded since 2018 (Institute and Mhara, 2023). Furthermore, an increased burial depth of *C. edule* could lead to the inability of seabirds in the area to feed effectively on them.

The importance of a resilient cockle population in Dundalk Bay is threefold; 1) the economic value of the fishery, (€80,500 average per vessel in 2020), 2) supporting the seabird population that feeds upon them during winter, and 3) the ecosystem engineering roles it has in bioturbation, water-filtration and biodeposition (Carss et al., 2020). Due to the importance of cockles, both financially and ecologically to the habitat of Dundalk Bay, it is of paramount importance to assess the levels of microplastics in both this species and in the sediment, they reside in.

Previous studies carried out on assessing microplastic presence in *C. edule* did not examine microplastic contamination of sediment despite the fact that sediment-dwelling bivalves have been shown to possess higher concentrations of microplastics than water column-dwelling bivalves (Botelho et al., 2023; Ding et al., 2021; Liu et al., 2021) likely due to microplastics sinking as their density increases (Karkanorachaki et al., 2021). This knowledge gap is addressed in this study and microplastic types compared between *C. edule* and their surrounding sediment to understand their reliability in biomonitoring for microplastics in shallow marine environments.

This study represents a first look at temporal microplastic concentrations in a natural non-cultured population of commercially valuable bivalves in Irish fishing grounds. The common cockle, assessed in this study has potential as a biomonitor for microplastic pollution at the water-sediment interface in the marine environment for a number of reasons, including its proximity to coastlines, its large geographical range and the fact it is easy to collect - generally residing in the top 5 cm of marine sediment (Santos et al., 2022; Tyler-Walters, 2007).

Furthermore, *C. edule* is monitored for *E. coli* presence by the Sea Fisheries Protection Authority (SFPA). While it is difficult to draw direct comparisons between studies given that tissue digestion and identification methods vary (Bom and Sá, 2021), microplastics presence is increasingly documented in marine species and further evidence of this is the presence of microplastics noted in rarer species from more remote regions (Li et al., 2021b).

This study aimed to achieve three primary objectives: 1) comprehending the concentrations of microplastics in cockles inhabiting Dundalk Bay and discerning the polymer types contaminating these organisms, 2) contrasting the levels and polymer composition of microplastics in the sediment of two intertidal sites within the bay, and 3) investigating the correlation of microplastics between the two assessed matrices.

2. Materials and methods

2.1. Study area

The Dundalk Bay area is a prominent exporter of the common cockle which reaches markets for human consumption in Spain, valued at €1,249,500 and €2,254,000 and weighed 595 and 1127 t in the years 2019 and 2020 respectively. A cockle permit is required to fish for cockles in Dundalk Bay with the number of vessels permits limited to 28 based on the historical fishing record of the vessel (Consultation on Dundalk Cockle Natura Permits Policy). Additionally, razor clams and in particular cockles are consumed by seabirds residing in the bay. As they are found closer to shore than razor clams, and up to 70 % of the bay is exposed at low tide, cockles are an important source of food for wading birds residing there (Fig. 2). Dundalk Bay is internationally important for water birds, supporting over 1 % of the Northwest European/East Atlantic flyway populations of the protected black-tailed godwit (*Limosa limosa*) (<https://rsis.ramsar.org/ris/834>). The shallow nature of Dundalk Bay is advantageous to cockle growth. Cockles found in the bay need to survive only one winter to reach commercial size while in most other areas growth rates are lower and cockles need to survive over two winters to reach commercial size (Shellfish stocks and fisheries review, 2021).

Possible sources of microplastics to Dundalk Bay include; three wastewater treatment plants along its coast, the urban centres of Dundalk and Blackrock as well as agricultural sources and domestic settings further inland which can release microplastics that may be transported by rivers that drain the catchment area and empty into the bay. These microplastics can end up deposited in the sediment of the bay or be ingested by fauna residing there. Blackrock beach is near a secondary wastewater treatment plant, a busy regional road (R172) and sees frequent beach users and is hypothesised to display elevated microplastic levels. Rockmarshall beach is a more secluded site, with very limited access and contains an extensive vegetative buffer (Saltmarsh vegetation) between the nearest road and the sampling site. While it is expected to display reduced microplastic levels compared to Blackrock beach, however, the tidal movements in the bay can represent a site where microplastic pollution is deposited.

2.2. Sampling

Cockles ($n = 140$) were collected by hand raking from the intertidal area of Rockmarshall beach on the North side of Dundalk Bay (54.002674 N, -6.3000154 W), from February 2020 to January 2021. An uneven number was collected across the sampling period (Spring and Summer, $n = 28$, while Autumn and Winter, $n = 42$) due to Covid-19 restrictions. These were stored in metal food containers, labelled and frozen at -20°C .

Sediments from the intertidal zones were collected from the Rockmarshall beach and Blackrock beach (53.961880 N, -6.3651247 W) during 2021 (Fig. 1). The coordinates represent the central point of the

grids used to determine microplastic contamination on these beaches. Sediment sampling was conducted to that described by Frias et al. (2018). Briefly, sediment was collected using a metal trowel ($<5\text{ cm}$) across 3 line transects (hereafter referred to as; upper-shore, middle-shore, lower-shore) located 50 m from each other and 3 points were sampled across each transect line to give a total of 9 sampling points per beach in a square-like formation. Care was taken when digging up the sediment to avoid mixing deeper layers with the surface layer. Between sampling points the trowel was rinsed with Milli-Q water ($0.22\text{ }\mu\text{m}$) to avoid cross-contamination. Samples were processed immediately upon returning to the laboratory.

2.3. Tissue digestion and microplastic extraction

Prior to microplastic extraction cockles biometric data was recorded. Digestion was carried out using a protocol adapted from Thiele et al. (2019). Briefly, cockles were shucked, rinsed with Milli-Q water ($0.22\text{ }\mu\text{m}$) and weighed before placing in 500 ml Erlenmeyer flasks with 200 ml of 10 % potassium hydroxide (KOH). Tinfoil covered flasks were placed inside an incubator at 40°C for 24 h set to 250 rpm, after which they were left to cool at room temperature. The samples were neutralised using 1 M citric acid solution and vacuum-filtered onto clean filters (Whatman, 47 mm diameter GF/C $1.2\text{ }\mu\text{m}$ glass microfiber). Filters were then placed in closed petri dishes until further analysis was carried out.

2.4. Sediment separation

Sediment samples were oven dried at 40°C for 24–48 h depending on moisture content. Microplastic extraction from dried samples was carried out according to Mani et al. (2019). Briefly, 10 g of sediment was collected using a spatula and placed in a 1 L separation funnel and 100 ml of Milli-Q water ($0.22\text{ }\mu\text{m}$) and 10 ml of castor oil were added. Separation funnels were then shaken by hand for 1 min and the inner walls of the funnel were rinsed with Milli-Q water ($0.22\text{ }\mu\text{m}$) to ensure all material was returned to the bottom. The funnel was left to settle for 15 min after which the underlying sediment layer was filtered from the separation funnel and set aside. The middle layer of water and upper layer of castor oil were vacuum-filtered onto filter papers (Whatman, 47 mm diameter GF/C $1.2\text{ }\mu\text{m}$ glass microfiber). While the separation funnel was being emptied the walls were rinsed with pre-filtered (Whatman, 47 mm diameter GF/C $1.2\text{ }\mu\text{m}$ glass microfiber) 70 % ethanol to ensure all material was removed. The inner walls of the top part of the vacuum filtration unit were then rinsed with 70 % ethanol to help to remove any castor oil left on top of the filter paper which may obscure subsequent microplastic visualisation. For each of the 9 points where samples were collected per beach, $3 \times 10\text{ g}$ samples were analysed.

2.5. Grain size analysis

Samples were oven-dried at 60°C and 100 g of dry sediment from the central sampling location for each beach was weighed and placed in a 6-sieve stack (2 mm (gravel), 1 mm (very coarse sand), 500 μm (coarse sand), 250 μm (medium sand), 125 μm (fine sand) and 63 μm (very fine sand) and a receiver for sediments $<63\text{ }\mu\text{m}$. Sediment was classified using an adaptation of the Wentworth grain size classification (Frias et al., 2018).

2.6. Visual examination and Raman analysis

Filter papers containing both digested cockle tissue and material extracted from the marine beach sediment was observed under an Olympus SZX7 microscope. Microplastics were counted, measured and their respective colour and shape was recorded. Microplastic colours were classified as; transparent/white, blue, red, green, black, multi-coloured, or other. Microplastics were measured along their largest

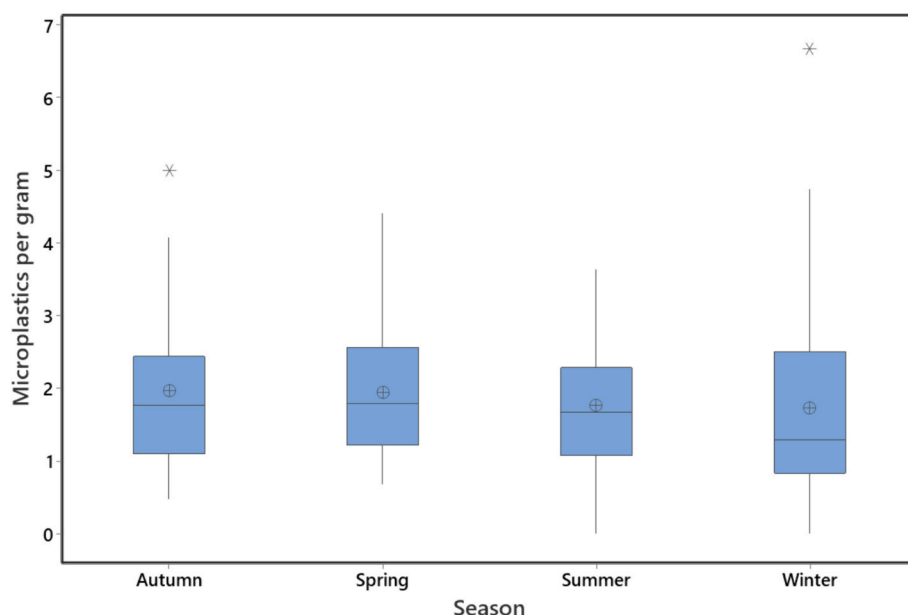


Fig. 3. Seasonal microplastic contamination per gram wet weight of cockles. Asterisks represent outliers. Circles with cross interior represent the mean. Solid horizontal lines represent the median. Blue rectangles represent the interquartile range Q1 – Q3 and whiskers represent the range. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

diameter. Finally, microplastics were designated a shape profile as fibre, fragment, film, or bead and characterised based on their response to metal tweezers (plastics should not break under stress but should flex or bend) (Keene and Turner, 2023). Microscopic analysis was carried out by an individual researcher to allow consistent comparisons between shapes and colours. Microplastics (typically over 100 μm) from the sediment and cockle samples were selected at random for characterisation and polymer identification using Raman Spectroscopy. The Raman Spectrometer was equipped with a 600 groove mm^{-1} diffraction grating, a confocal optical system, a Peltier-cooled CCD detector, and an Olympus BX41 microscope (Ó Briain et al., 2020; Loughlin et al., 2021) and spectra were obtained at a range of 100–3500 cm^{-1} using a 532 nm laser. Spectra obtained when analysing particles extracted from cockles and sediment were compared to a spectral reference library (KnowItAll, Bio-Rad), an in-house extension of the library with additional spectra from environmental plastics collected from the intertidal zone and known virgin polymer types (purchased from CARAT GmbH, Bocholt, Germany) (Mendes et al., 2021). In addition, SLOPP and SLOPP-E libraries (Munno et al., 2020) were employed, and the ‘fingerprint’ region of each spectrum was used to identify the polymer type. The websites ‘Open Specy’ (Cowger et al., 2021) (<https://openanalysis.org/openspecy/>) was also used to verify polymer type for spectra captured via Raman in addition to PublicSpectra (<https://publicspectra.com/SpectralSearch>). Furthermore, the Infrared & Raman Users Group (<http://www.irug.org/search-spectral-database>) was also consulted.

2.7. Statistical analysis

Data was tested for normality using Anderson-Darling test which determined that both MPs g^{-1} and MPs ind^{-1} were non-parametric. MPs g^{-1} values were successfully transformed using Johnson transformation ($P = 0.807$) while MPs ind^{-1} values were not. One-way Analysis of Variance (ANOVA) tests and Tukey post-hoc analysis was used to determine statistically significant differences between average microplastics per gram wet weight (MPs g^{-1}). The Kruskal-Wallis test was carried out on the non-parametric determining that significant differences existed between the seasons in terms of microplastics ind^{-1} . Mann-Whitney tests were then carried out for each potential set of seasons to examine which were statistically different from each other.

Regression analysis was carried out on the average microplastics of cockles per individual and gram wet weight and the seawater temperature. The non-parametric Spearman's correlation coefficient was calculated to evaluate correlations between carried out on the total cockle group ($n = 140$) to determine if there was a statistical relationship between the weight of cockles and their microplastic content. Mann-Whitney tests were carried out to assess microplastic amounts in contamination controls and those recovered from cockles as prescribed by Dawson et al., (2023). The level of significance used for all tests was 0.05. Anderson-Darling tests revealed that distribution of microplastics in sediment followed normal distribution for both beach locations and one-way ANOVA tests was used to determine if the values of microplastics from any points used to collect samples on each beach were significantly different to each other. Statistical analysis was carried out using Microsoft Excel 2016 and Minitab Statistical Software (version Minitab® 21.1.1 (64-bit) which was also used for the creation of figures.

2.8. Quality control measures

To ensure good laboratory practises when analysing samples for microplastics protocols for mitigating microplastic contamination were adhered to where applicable following Hermesen et al. (2018). When conducting lab-work 100 % cotton lab coats were always worn. All work conducted on samples including the vacuum-filtrations were carried out in a “clean room” which was specifically used for microplastic work exclusively by a lone operator. Equipment such as tweezers, sieves and glassware were covered in tinfoil when not in use, additionally the vacuum-filtration unit was covered in tinfoil when filtering digested cockle or sediment samples. While cockles were being dissected, a petri dish containing a filter paper was placed adjacent to quantify airborne contamination. Procedural blanks were carried out at the same time as the digestion of cockle tissue and sediment separation. All equipment used for sample collection and analysis were triple-rinsed using Milli-Q water (0.22 μm) before use, and glassware was left to dry upside down to avoid airborne particles settling on them. These measures were necessary to avoid microplastic contamination from particles that may be present in the air and settle on equipment leading to an overestimation of microplastic numbers. Fibrous microplastics which are present in outdoor and indoor air have the potential to settle on equipment which

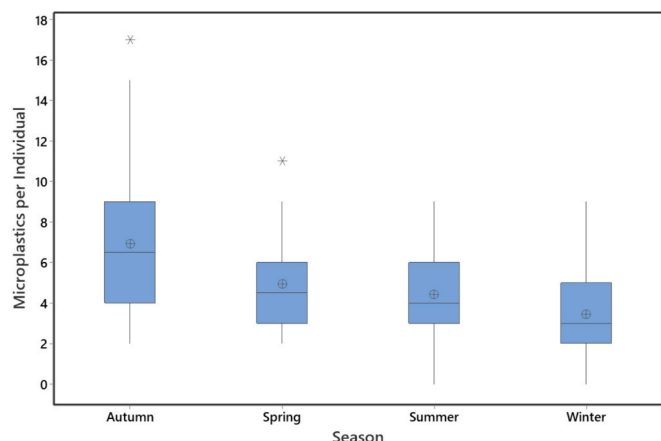


Fig. 4. Seasonal microplastic contamination per individual for cockles. Asterisks represent outliers. Circles with cross interior represent the mean. Solid horizontal lines represent the median. Blue rectangles represent the inter-quartile range Q1 – Q3 and whiskers represent the range. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

may lead to an overestimation of the amount present in a sample matrix (Gasperi et al., 2018). All solutions used in this study were vacuum-filtered through clean filter papers before use with samples (Whatman, 47 mm diameter GF/C 1.2 μ m glass microfiber). Despite following these procedures, it is often impossible to completely mitigate microplastic contamination and it is therefore important to quantify it. For each beach site, 6 oil separation blanks were carried out in order to account for contamination while for each group of cockles ($n = 14$) a solution blank was also examined. As with numerous other microplastic studies (e.g., Baechler et al., 2020; Rochman et al., 2019; Davidson and Dudas, 2016) contamination results from the blanks are displayed (Supplementary material: Tables 2, 3) rather than subtracted from environmental results which is ill-advisable given the diversity available in

microplastic shape, size, colour and composition (Dawson et al., 2023). These are intended to indicate the range of possible contamination levels present introduced from laboratory procedures. Mann-Whitney tests carried out for microplastic contamination in terms of both MPs g^{-1} and MPs Ind^{-1} found that amounts present in control blanks were significantly lower than those present in environmental samples ($P = 0.000$, $P = 0.000$) respectively. The mean microplastic contamination for Rock-marshall and Blackrock beaches accounted for 9.1 % and 13.3 % of the mean microplastics in 10 g samples for each beach.

2.9. Biometric data

Biometric data of cockles analysed in this study were as follows: wet weight of cockles ranged from 0.9 to 7 g, (mean: 2.81 ± 1.04), length ranged from 2 to 4 cm (mean: 2.86 ± 0.38 cm) and the width ranged from 2.3 to 4.2 cm (mean: 3.19 ± 0.42). Seasonal differences are displayed in 'supplementary material: Table 1'. The cockles in this study were on average above the legal landing shell size width of 17 mm and the effective landing minimum size of 22 mm which is used to separate Irish from UK fisheries cockles on the market (Fishery Natura Plan for cockle (*Cerastoderma edule*) in Dundalk Bay, 2021–2025).

3. Results and discussion

3.1. Microplastics in cockles

A total of 697 microplastics were visually isolated and sorted from 140 bivalves in this study. Just two cockles analysed during this study were free of microplastics while the vast majority had microplastics present in their tissue resulting in a 98.6 % contamination rate of the cockles analysed. When assessing mean microplastics per gram wet weight (MPs g^{-1}) this value ranged from the lowest in winter 1.55 ± 1.38 MPs g^{-1} to a highest value in spring 1.82 ± 0.99 MPs g^{-1} for cockles sampled (Fig. 3).

One-way ANOVA test at the 95 % confidence interval showed that average MPs g^{-1} of cockles were not significantly different between

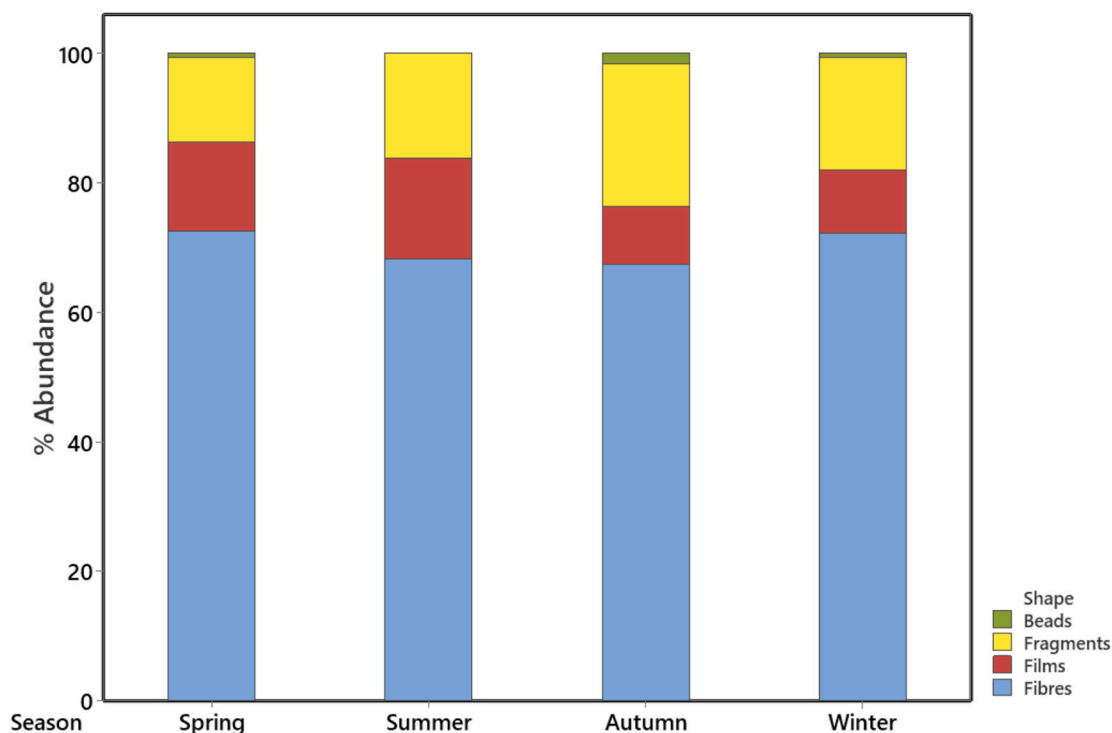


Fig. 5. Shape composition of microplastics recovered from cockles for different seasons.

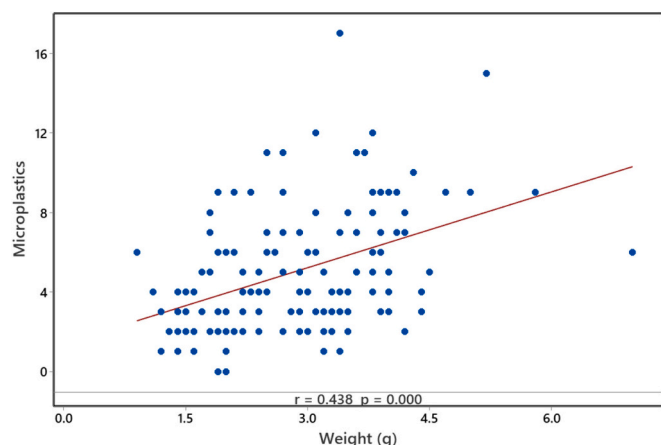


Fig. 6. Relationship between microplastic burden and weight of cockle. The correlation coefficient value ($r = 0.438$) describes a weak positive linear relationship between microplastic numbers and cockle weight indicating that weight is not a good indicator of microplastic levels for this species in Dundalk Bay.

seasons ($P = 0.283$), although the median and mean values for cockles harvested in winter were lower than the other seasons. Cockles examined from a Portuguese lagoon displayed significant difference in their microplastic concentrations between seasons and similarly had lowest reported concentrations for winter (Botelho et al., 2023). Similarly, four species of bivalves studied by Ding et al. (2021) displayed no seasonal variation either in terms of microplastics g^{-1} of microplastics ind^{-1} . Cockles analysed in this study had generally higher microplastic concentrations than reported in the same species along the French Channel coasts by Hermabessiere et al. (2019), which contained 0.94 ± 0.31 items g^{-1} wet weight, however, cockles in that study were collected from areas with a small human population and low anthropogenic pressures. This range fell within reported median values for *C. edule* sampled from a Portuguese lagoon of 0.83 items g^{-1} and 5.1 items g^{-1} and also mussels (*M. galloprovincialis*) in the same study 0.77 items g^{-1} in January to 4.3 items g^{-1} in October (Botelho et al., 2023).

Average microplastics per cockle (MPs ind^{-1}) ranged from 3.43 ± 2.47 particles per cockle in Winter to 6.90 ± 3.68 particles per cockle in autumn (Figs. 4–7). Kruskal-Wallis testing revealed statistically

significant differences between seasons in terms of MPs ind^{-1} ($P = 0.000$). Mann-Whitney tests carried out between seasons revealed that the only seasons that did not significantly differ between medians were spring and summer ($P = 0.422$) but every other comparison displayed significant differences between seasons with regard to this parameter. In real-world terms, however, Autumn was the season that had biological significance compared to the other seasons studied and the mean and median for this season was much greater than the others studied (Fig. 4). Cockles were on average larger for this season than those collected in the other seasons which may help to attribute to this difference, especially as MPs g^{-1} did not display significant differences between seasons. The higher abundances of microplastics in cockles collected in autumn for this study highlights the potential entry to the human diet that these can have as the cockle fishery closes on the first of November annually when it has been preceded by 14 weeks open and cockles are harvested for human consumption in this period (autumn).

These values are similar to some other reported microplastic levels noted for different species of bivalve such as 1.5 – 7.6 reported for *M. edulis* collected from Chinese coasts and 6.9 ± 3.84 reported for *M. bilineata* from Southeast India (Li et al., 2016; Patterson et al., 2019). In general, however, the upper values of individual contamination range found in cockles in this study (autumn) is higher than reported individual contamination of bivalves than in other studies. Samples of the same species taken along the French Coast also had lower levels of microplastics than those reported in this current study with reported values of 2.46 ± 1.16 MP ind^{-1} (Hermabessiere et al., 2019) while Botelho et al. (2023) did not provide this data.

Microfibres were the most commonly noted microplastic shape and accounted for 69.6 % ($n = 485$) of those recovered. Other shapes were identified with lower frequency; fragments (18.2 %, $n = 127$), films (11.2 %, $n = 78$) and finally beads were seen with the lowest frequency accounting for 1.01 % ($n = 7$) of the total recovered. Fibre proportions were similar between seasons ranging from 67.5 % of the total recovered in autumn to 72.5 % of the total recovered in spring which could indicate a stable input of this sort of microplastic into this marine environment. Cockles from locations along the coasts of France had comparatively lower microfibre levels than those analysed in the current study and ranged from 2.4 % to 45.5 % per site (Hermabessiere et al., 2019). Similarly, a lower proportion of fibres were documented in cockles collected from a Portuguese lagoon for both winter and summer seasons studied with fibres accounting for 50 % and 38 % of those recovered (Botelho et al., 2023). The proximity of the WWTP located on

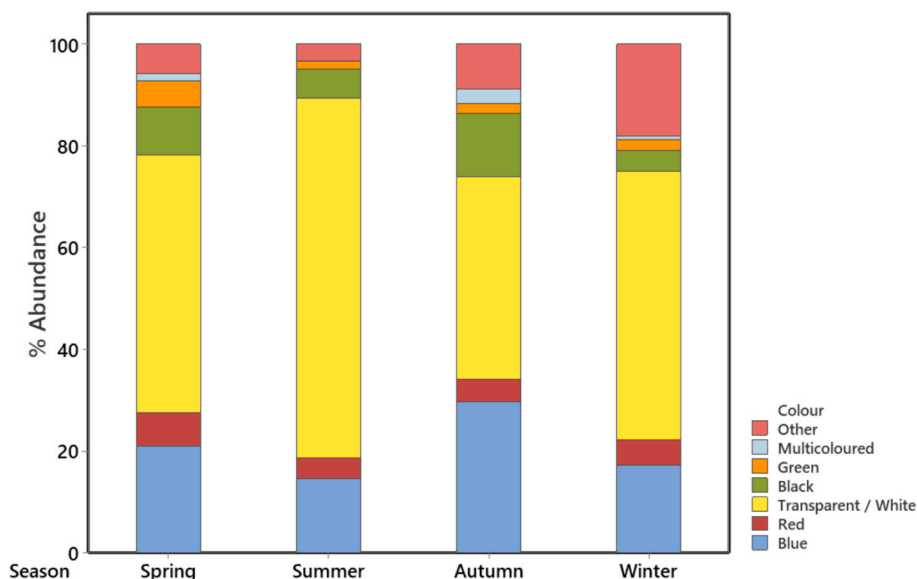


Fig. 7. Seasonal microplastics colour composition found in cockles.

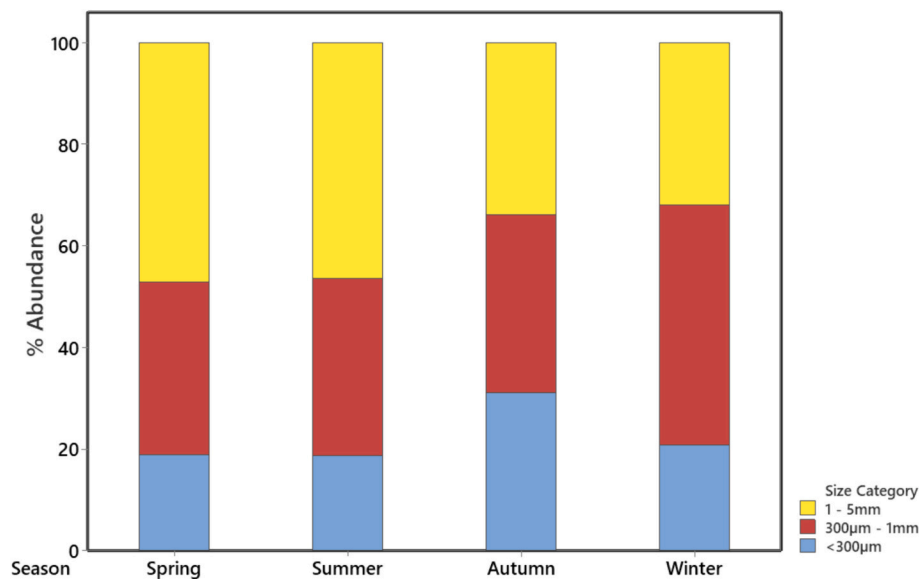


Fig. 8. Seasonal microplastic size composition found in cockles.

the Castletown River may be a source of microfibrs seen in this study as its effluent location is located just 3.5 km from the location cockles were collected from for this study.

Although microfibre concentrations in cockles varied between seasons, microfibrs were still the dominant shape found every season, with fragments and films representing a smaller proportion (Fig. 5). This is in agreement with research on marine species as a whole, as per Mizraji et al., (2017) microfibrs constitute the dominant shape category of microplastics consumed by marine fishes, crustaceans and bivalves while microplastic fragments, foams, and films represent a smaller proportion of microplastics found in these species (Jabeen et al., 2017).

Fibre contamination of cockles in this study was also similar to those found in oysters harvested from New South Wales which possessed fibre concentrations in the range 43 % - 80 % (Jahan et al., 2019; Li et al., 2018). The high proportion of microfibrs found in cockles despite the fact they possess gills that can trap particles prior to transport to the mouth of the organism and ingestion may suggest, that just as microfibrs when orientated correctly can pass through the meshes of sieves (Walkinshaw et al., 2022), a similar phenomenon occurs with the gills of cockles.

Zoonotic protozoan parasites (*Toxoplasma gondii*, *Cryptosporidium parvum*, and *Giardia enterica*) that can infect, and harm humans and marine mammals were shown to have a greater ability to associate with microfibrs than with microbeads (Zhang et al., 2022). The World Health Organisation recognises these pathogens as underestimated causes of illness from shellfish consumption additionally they are persistent in the marine environment. Furthermore, faeces of seabirds feeding on cockles found in Dundalk Bay have been shown to contain *Vibrio* bacteria common to both sediment and cockles (Albuixech-Martí et al., 2021) thus highlighting the potential for microplastics to act as vectors of disease transmission for this area.

It is implied that the amounts of microplastics in mussels increase with their growth (Berglund et al., 2019), as cockles are also filter feeders this relationship between cockle wet weight and microplastic burden was examined. Based on the Spearman correlation test there was a weak but statistically significant relationship between cockle weight and microplastic abundance (correlation = 0.438, $P < 0.000$) (Fig. 6).

Filtration rates for seawater generally increase with cockle body size (increased gill surface area), however factors such as food availability, temperature and physiological (mainly reproductive) conditions can also play a role (Smaal et al., 1997; Iglesias et al., 1996). Cockle filtration rates tend to be highest in the temperature range of 8–20 °C (Brock and

Kofoed, 1987), especially for the spring season in order to provide the energy necessary for gonad development (Newell and Bayne, 1980). Filtration rates, however, strongly reduce in water temperatures < 8 °C even with the abundant availability of food (Smaal et al., 1997).

The highest amounts of microplastics were found in cockles harvested in autumn both in terms of MPs g^{-1} and MP ind^{-1} when the mean water temperature in Dundalk Bay was 14.3 °C which was the highest average seasonal temperature (Sea water and Dundalk Ireland today, 2022). The fact that there were no significant differences in microplastic concentrations in terms of MPs g^{-1} between seasons may indicate that microplastics in this species are potentially escaping egestion and may have relatively long residual times. More likely, however, is that due to the shallow nature of Dundalk Bay (which lends to the productivity of the cockle fishery) that even in colder month's cockle filtration rates increase when submerged in a few inches of water which is rapidly warmed by solar radiation during the day. Furthermore, the similar microplastic concentrations between seasons may be due to a combination of environmental factors for the marine environment of Dundalk Bay. In warmer seasons, the temperature increases leads to increased filtration rate of cockles which could increase the exposure to microplastics present in the water while in colder seasons the filtration rate decreases but the freshwater inputs increase as the flow rates increase for rivers that enter Dundalk Bay (EPA Hydronet, 2022) which can lead to an increase in terrestrially based microplastics entering the Bay. This may result in a similar microplastic exposure level even as filtration rates decrease. Furthermore, the possibility of import of microplastics from nearby coastal waters should not be excluded (Lozano-Hernández et al., 2021) as several studies in coastal environs have displayed the import of suspended particles from the sea during periods of low river discharges (Dias et al., 2007; Falcão and Vale, 2003; Vale, 1990).

In bivalves collected in a Portuguese lagoon, median concentration of microplastics in cockles were statistically lower in winter than summer and was attributed to the temperature decrease in winter potentially triggering a lower filtration rate, resulting in lower concentrations in the whole-soft body tissues of organisms (Botelho et al., 2023). Given that sea temperature can be a factor governing cockle filtration rates, this was examined as a predictor for microplastic concentrations and numbers in individuals using regression analysis. However, this was not deemed to have an overall strong impact on the relationship for either accounting for 33.3 % of the variation in MPs ind^{-1} and 16.7 % of the variation for MPs g^{-1} .

Although cockles do not select food based on sight and therefore

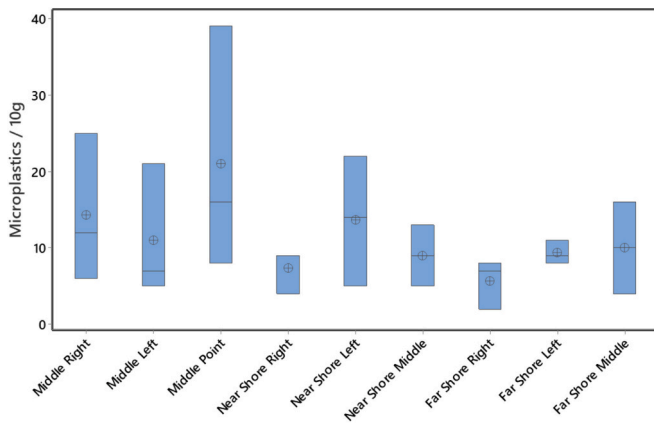


Fig. 9. Microplastic levels of sediment from 9 sampling points on Blackrock beach.

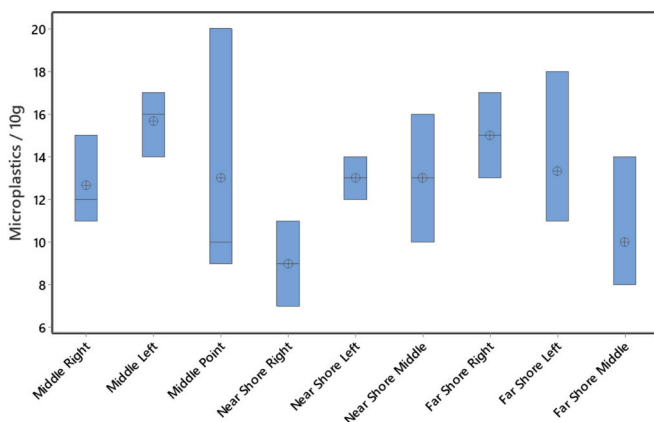


Fig. 10. Microplastic levels of sediment from 9 sampling points on Rockmarshall beach.

colour unlike some species of fish (de Sá et al., 2015), it can be important to record the colours of microplastics, as it can be an indication of their age. Song et al., (2017) documented that polystyrene that underwent long-term exposure of UV irradiation changed the colour from white to yellow and became fragile. Transparent / white microplastics primarily fibrous in nature were the most commonly recovered in the current study, accounting for 50.1 % ($n = 349$) of total microplastics recovered and were the predominant colour found for every season studied. Blue microplastics were the next most commonly recovered and accounted for 22.8 % ($n = 159$). Black ($n = 62$, 8.9 %), red ($n = 34$, 4.9 %), green ($n = 18$, 2.6 %), multi-coloured ($n = 11$, 1.6 %) and other colours ($n = 64$, 9.2 %) were also recovered (Fig. 7).

Documenting the size profile of microplastics is important as it can demonstrate their bioavailability to organisms that encounter them. In this current study the majority of microplastics were < 1 mm in size for each season. The proportions within these smaller categories (< 1 mm) differed between seasons (Fig. 8). These findings are in line with the findings of Joyce et al. (2022) who found that microplastics < 1 mm was the most common size recorded in the benthic Dublin Bay prawn, *Nephrops norvegicus*. Microplastics in the size category 1–5 mm accounted for 38.3 % of the total 697 microplastics recovered from bivalves respectively.

Microplastics recovered from cockles in this current study were generally larger than those found in cockles and mussels on the channel coasts of France where 0.9 % were larger than 500 μm (Hermabessiere et al., 2019). However, larger particles have been documented in this species previously (Karlsson et al., 2003; Kristensen, 1957). It has also

been noted that for particles with a high aspect ratio such as fibres ingestion is less constrained in bivalves provided that one dimension is within the size that can be ingested (Ward et al., 2019). Larger microplastics ($> 25 \mu\text{m}$) are likely to have relatively short transit times in bivalves and will primarily be concentrated in biodeposits (pseudofeces and faeces) (Huffman Ringwood, 2021). This, however, means that cockles can act as transporters of microplastics in the water column to marine sediment and may have effects on other species found there.

The assessment of the microplastic content of cockles related to total body content (no organ specific digestion was performed) and this in combination with the rapid freezing of the bivalve samples (no-depuration) provided relevant environmental results (including potential trophic transfer) as predators (crabs, seabirds etc.) do not target specific organs or parts of cockles when preying upon them and can themselves be exposed to the total microplastic content of the cockles. Predation of contaminated prey items is one of the primary routes of microplastic exposure (Nelms et al., 2018). Cockles harvested in this area have the potential to transport microplastics into the human diet as they are canned for consumption by humans for European markets. Microplastics have recently been found in human blood (Leslie et al., 2022) and living lung tissue (Jenner et al., 2022) for the first time and have been linked to increased death rates when present in arterial plaque (Marfella et al., 2024), the consumption of bivalves contaminated with microplastics could therefore be a direct entry route of these pollutants to humans.

Ecologically important cockle beds in Dundalk Bay are a prominent source of food for wading birds and it is likely they are ingesting microplastics with the potential for transferring potential pathogenic bacteria to these species before being egested themselves to other areas. This network of pathogen / microplastic transport between cockles and seabirds for this area requires further study. Furthermore, populations of cockles have been subject to mass mortality events in the past resulting from a variety of causes, including: harsh winter conditions, overfishing, predation, failed recruitment, pollution and diseases (Ducrotoy et al., 1989). Recently, the potentially pathogenic group, *Vibrio*, was detected in *C. edule*, sediment and bird faecal samples where the oystercatcher, *Haematopus ostralegus* and other waders were observed to be feeding on cockles at intertidal areas around the Irish coast (Albuxech-Martí et al., 2021). This could lead to impaired health effects on seabirds feeding on contaminated cockles for this study area potentially leading to ecosystem-level impacts in the SPA of Dundalk Bay.

3.2. Microplastics in marine beach sediment

For each of the sampling points ($n = 9$) per beach, the average microplastic content was taken from the 3×10 g samples that were analysed. The raw data is displayed in boxplots for both beach locations and their respective nine sampling points below and shows the variability between replicates (Figs. 9, 10). The average number of microplastics per beach was determined by taking the average number of microplastics from the 3×10 g samples analysed per point before extrapolating to MPs kg^{-1} dry weight.

From Rockmarshall beach, the maximum number of microplastics found in a 10 g replicate was 20 while for Blackrock beach the maximum number was 39 microplastics. This is much lower than the study by Liebezeit and Dubaish (2012) which recorded a maximum of 496 microplastics in one 10 g sediment sample. Mathalon and Hill (2014) reported microfibre concentrations ranging from 20 to 80 / 10 g from Halifax Harbour beach, while bays and beaches of Huatulco, Mexico had values ranging from 0 to 69 microplastics per 10 g dry weight of sediment (Retama et al., 2016). One-way ANOVA testing found that there was no significant difference between the mean microplastic concentrations for sampling points on each separate beach, (Rockmarshall beach; $P = 0.29$) (Blackrock beach; $P = 0.48$). While there were no significant differences in microplastic numbers between sampling points on the two beaches there was high variability between replicates which underlines the potential of under- or overestimating microplastics in the

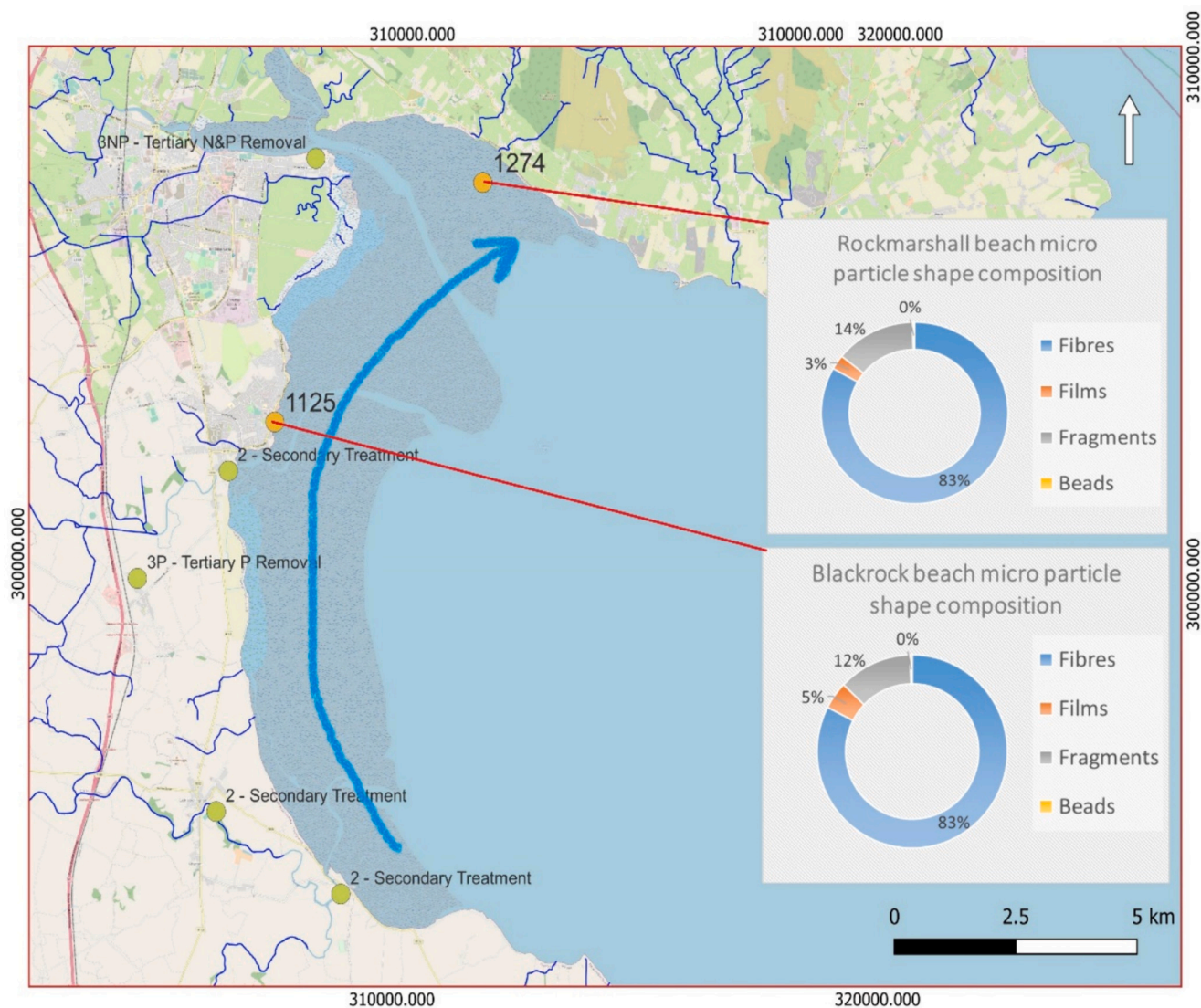


Fig. 11. Concentrations (MPs Kg⁻¹) and shape composition of microplastics recovered from sediment of Dundalk Bay and proximity to wastewater treatment plants and rivers that enter the bay. The bay fills from the South when the tide comes in, the direction of which is indicated with a blue arrow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

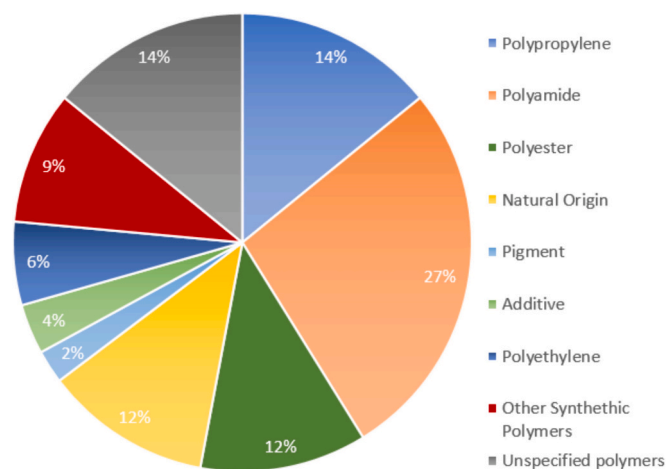


Fig. 12. Polymer composition of microplastics recovered from tissue of *C. edule*.

environment in instances where replicates are not taken which has previously been noted in another study on microplastics in sediment of the Irish marine environment (Pagter et al., 2020).

Microplastics were recovered from every replicate sample taken from all locations. Generally speaking, this is in line with most studies on beach or intertidal locations, however some studies on shallow coastal environments have reported at least one replicate where no microplastics were detected (e.g., Ferreira et al., 2020; Sandre et al., 2019; Laglbauer et al., 2014). In total 344 microplastics were recovered from 270 g of beach sediment (1274 MPs Kg⁻¹ dw) from Rockmarshall beach on the North coast of Dundalk Bay whilst 304 microplastics were recovered from beach sediment (1125 MP kg⁻¹) from Blackrock Beach inner coastline. Microplastics were recovered in a variety of shapes, sizes and colours at both study sites. Microfibres were the most commonly observed shape of particle recovered at both locations. Accounting for 83.1 % and 82.5 % of the total microplastics recovered from Rockmarshall and Blackrock beach respectively (Fig. 11). The next most common particle shape recovered at both beaches were fragments (Rockmarshall; 13.9 %; Blackrock; 12.5 %) followed by films (Rockmarshall; 2.6 %; Blackrock; 4.6 %) and finally microbeads accounted for 0.003 % of total microplastics recovered at both locations. The

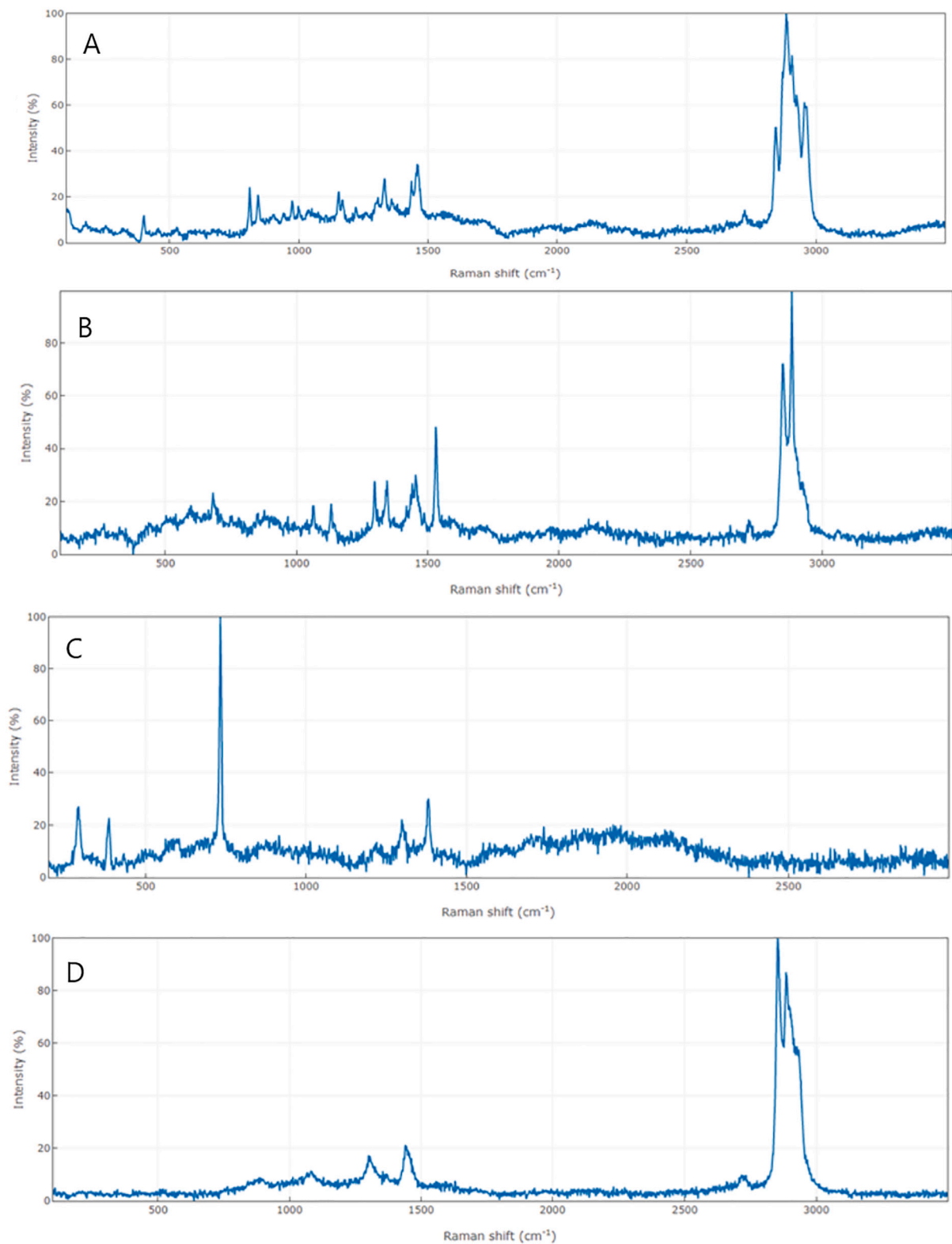


Fig. 13. Examples of polymers identified from cockles. A: polypropylene, B: polyethylene, C: perfluoroalkoxy alkane, D: poly(ethylene-co-1-hexene).

predominance of microfibrils found in sediment in this study was similar to results observed in other studies on Irish marine sediment (Mendes et al., 2021; Martin et al., 2017; Joyce et al., 2022) and in the cockles analysed for microplastic contamination as part of this study. A review of microplastic contamination of marine coastal environments by Harris (2020) found that all but 3 of 13 studies that reported shape composition

of recovered microplastics from beaches had microfibre compositions above 70 %, and that the median number of microplastics that are fibres from 12 studies on shallow coastal environments was 60 %. The presence of two nearby WWTPs to both sampling locations may help to explain the high proportions of microfibrils found at both beach locations as they are less likely to be trapped in WWTPs than other shapes

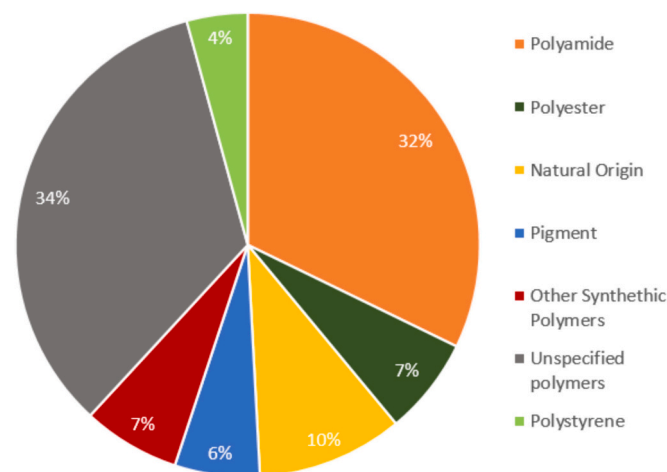


Fig. 14. Polymer composition of microplastics recovered from intertidal beach sediment.

(Ben-David et al., 2021). Although the WWTP plant located next to Blackrock beach caters for a smaller population equivalent (PE) than the WWTP located nearer to Rockmarshall beach it must be noted that this is a secondary wastewater treatment facility compared to the WWTP located nearer to Rockmarshall beach which has tertiary treatment but caters for a larger PE. The differences in microplastics removal efficiency between these facilities has been noted previously with tertiary treatment plants more effective at capturing microplastics (Magni et al., 2019; Tang and Hadibarata, 2021; Edo et al., 2020).

The majority of microplastics recovered from both beach sites were transparent / white in colour and accounted for 53.7 % ($n = 185$) and 49.3 % ($n = 150$) of the total recovered Rockmarshall and Blackrock sites respectively, material blue and black in colour were the next most abundant with 57 (16.5 %) and 43 (12.5 %) items recovered at Rockmarshall. Red ($n = 28$, 8.1 %), green ($n = 10$, 2.9 %), multi-coloured ($n = 5$, 1.4 %) and other colours ($n = 16$, 4.6 %) made up the colour profile of the remaining portion of recovered items from Rockmarshall beach. A similar pattern in colour composition was seen in microplastics from Blackrock beach. Blue was the next most abundant colour found there ($n = 63$, 20.7 %), followed by; red and black (both; $n = 25$, 8.2 %), other ($n = 26$, 8.5 %), green ($n = 13$, 4.3 %) and multi-coloured ($n = 2$, 0.6 %). A similar colour profile of microplastics has been documented previously in marine sediments with white, black, blue and transparent particles occurring frequently (Díaz-Jaramillo et al., 2021; Baptista Neto et al., 2019; Martin et al., 2017). It must be remembered that the colour of a plastic particle cannot easily be used to deduce its type or origin as microplastics may change colour to transparent or yellow due to weathering or sample processing and also have originally been transparent in nature (Zhang et al., 2020; Su et al., 2019). Colour composition of sediment sampled from the same location as cockles (Rockmarshall beach) was similar to that found in cockles. Colour composition was also similar between both clams and sediment studied in a Southern Philippine Estuary with black and blue particles dominating (Bonifacio et al., 2022).

It is important to categorise the size distribution of reported microplastics as not only does it provide information regarding potential bioavailability, but it also enables a better understanding of their potential transport and dispersal in the marine environment via currents and waves in relation to their hydraulic equivalence to natural sediment particles (Harris, 2020). Microplastics larger than 1 mm made up the majority found at Blackrock beach (54.9 %) while they made up the minority (33.1 %) found in sediment at Rockmarshall beach. One possible reason for this difference is the close proximity of the WWTP located at Blackrock to the sampling location meaning that microplastics are readily deposited in the upper layers of sediment here without

undergoing subsequent breakdown in the natural environment to form smaller microplastics, while the beach location at Rockmarshall is further from both WWTPs on the coast of Dundalk Bay, potentially receiving more degraded and therefore smaller 'older' microplastics. Further research is needed to test this hypothesis though and the transport mechanisms for differently sized microplastics differ, moving either as suspended load or bedload which can further fragment them (Harris, 2020).

3.3. Polymer analysis of microplastics isolated from cockles

A subsample of suspected microplastics ($n = 110$, 15.7 %) was randomly selected from cockles for polymer identification using Raman spectroscopy and matches were identified for 85 of these. The most commonly identified were Polyamide (PA), Polypropylene (PP), and polyesters (Fig. 12). Unspecified polymers were material which had spectra similar to anthropogenic material, namely PA, however, could not be definitively identified as one specific polymer. Material of natural origin, namely, cellulose made up 9 % of the total identified using Raman spectroscopy. Some examples of identified polymers are displayed below (Fig. 13).

3.4. Polymer analysis of microplastics isolated from marine beach sediment

A subsample of suspected microplastics ($n = 144$, 22.2 %) was selected at random from those recovered from beach sediments and positive matches were obtained for 112 of these (Fig. 14). The most commonly noted polymers were PA, unspecified polymers and polyesters which made up 77 % of those recovered. There was a wider range of polymers recovered from the sediment from Blackrock beach with 9 identified (PA, PS, Polyethylene terephthalate (PET), Polyvinyl chloride (PVC), ethylene vinyl alcohol (EVOH), Polycyclohexylenedimethylene terephthalate (PCT), Polystyrene-poly(ethylene propylene)block-poly-styrene (SEP) and a copolymer of poly(butylene terephthalate) and poly(tetramethylene glycol) (PBT-PTMG). Cellulose made up the majority of material of natural origin found in both cockles and beach sediment. Examples of some polymers identified in sediment are displayed below (Fig. 15).

3.5. Comparison of identified polymers between matrices

While polyethylene and polypropylene were both recovered from cockle tissue it was not recovered from the sediment of either beach and is likely due to their densities. These polymers are the two most commonly produced plastics accounting for approximately 49 % of plastics demand distribution by resin type in 2019 with many widespread uses such as; packaging, agricultural film, piping, houseware and automotive parts (Plastics Europe, 2020).

However, this is not a totally unprecedented occurrence, Martin et al. (2017) noted that PA was the dominant polymer recovered from marine sediment from the Irish continental shelf while polypropylene made up just 3 % of those identified. Additionally, the presence of PE or PP was not detected in subtidal sediments taken from the West of Ireland (Pagter et al., 2020). While both of these plastics are commonly used in fishing equipment as components of nets, ropes or floats they have a density lower than that of seawater which accounts for their abundance in ocean surfaces (Morét-Ferguson et al., 2010) while being less dense than PA and PVC which are also used in fishing gear (Lusher et al., 2017; Andradý, 2011). PA and polyesters were also frequently recovered from the bottom dwelling Dublin Bay prawn *Nephrops norvegicus* and sediment from Irish fishing grounds in a recent study (Joyce et al., 2022).

Their presence in cockle tissue may be due to the feeding mechanism involved with this species filtering seawater for nutrients in and ingesting these buoyant polymers as the tide comes in without them settling down to the sediment upper layer in great numbers. Cockles may

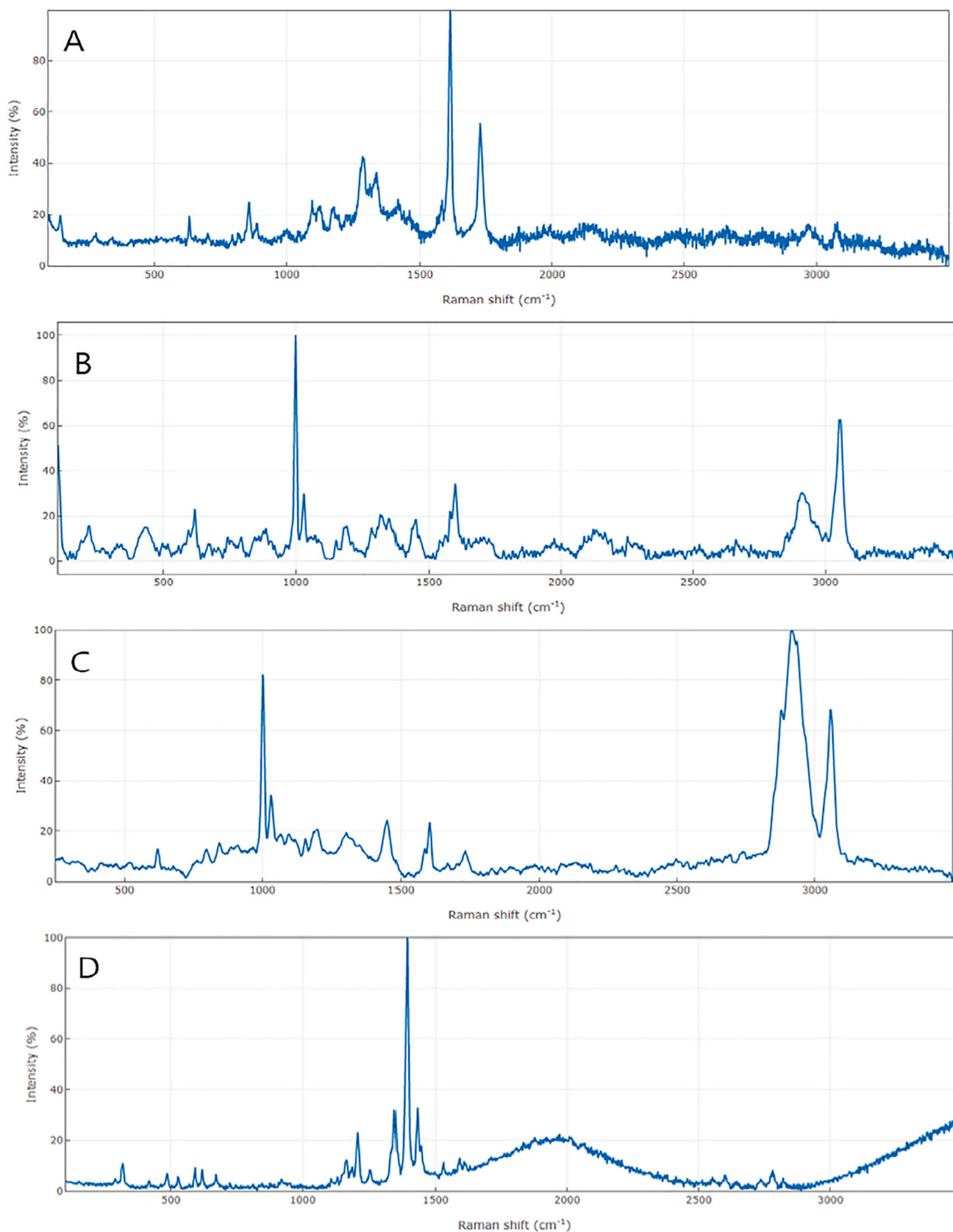


Fig. 15. Examples of polymers identified from sediment. A: polyester, B: polystyrene, C: polystyrene-poly(ethylene propylene)block-polystyrene, D: pigment violet 23 (dioxazine). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

thus give a representation of microplastic presence at the water-sediment interface in shallow marine environments.

While PA may have fishing-based sources they are also used in the production of fabrics (Coyle et al., 2020). PA in the form of nylon 6 and 6,6 in combination with polyester account for the largest global share of synthetic textile microfibrils (Castelvetto et al., 2021). The fact that the vast majority of microplastics recovered from both cockles and sediment were fibrous in nature which leads to the likelihood that they stemmed from sources such as WWTP effluent or being washed from their sludges when applied to land as biosolids (Corradini et al., 2019). A large portion of both inflow and outflow microplastics to WWTPs were found to consist of textile microplastics (Long et al., 2019; Murphy et al., 2016). Polyester and PA are expected to sink faster due to their high density and are mostly found in intertidal and subtidal sediments (Botelho et al., 2023).

There was a wider range of polymers recovered identified in the tissue of cockles than in the sediment of Dundalk Bay. PP, PE, PCT, PA, PE, PET, Poly(butylene terephthalate)-poly(tetramethylene glycol) (PBT-PTMG), Poly(ethylene-co-hexene), an ethylene copolymer, Poly(ethylene-vinyl acetate), acrylic rubber were all identified. Furthermore, titanium dioxide which is used in a broad range of plastics was detected as well perfluoroalkyl alkane, a forever chemical. This wide range of recovered polymers indicate that *C. edule* may be a suitable bioindicator species to be collected in conjunction with sediment samples able to filter both buoyant and sinking plastics. However, alone it is unlikely to be effective as a biomonitor for these buoyant plastics and it may be useful to collect a species that resides in the water body and has greater access to more buoyant polymers such as PE and PP such as the mussel, *M. galloprovincialis* as demonstrated by Botelho et al. (2023) in conjunction with *C. edule*.

3.6. Grain size analysis

The sand grains from both beach locations varied in composition. At Rockmarshall, the sediment consisted of gravel (0.02 %), very coarse sand (0.08 %), coarse sand (0.52 %), medium sand (35.63 %), fine sand (60.05 %), very fine sand (3.34 %) and silt, clay or colloids (0.36 %). Sediment from Blackrock beach was finer in composition and consisted of gravel (0.01 %), very coarse sand (0.08 %), coarse sand (0.42 %), medium sand (4.03 %), fine sand (62.87 %), very fine sand (30.72 %) and silt, clay or colloids (1.87 %). The relationship between sediment grain size and microplastic load has been examined in several studies.

Mendes et al. (2021) established an association between finer sediment particles and greater contamination of microplastics in Irish marine sediment while a lack of relationship displayed between microplastic load and sediment grain size has been noted in other studies such as; Mathalon and Hill (2014), Dodson et al. (2020), Alomar et al. (2016) and Browne et al. (2010). In this current study, however, Rockmarshall beach which had coarser overall sediment content than Blackrock beach had a greater microplastic burden, but this difference was not significant. Additionally, more microplastics in the larger 1–5 mm size range were recovered from Blackrock beach (54.33 %) than from Rockmarshall beach (33.22 %). For beaches in this very shallow and flat bay it is therefore possible that the nearby presence of wastewater treatment plants and the tidal movement in the bay are governing factors for microplastics presence in sediment, however, further study examining microplastic transport in this area is needed to verify this.

4. Conclusion

“In summation, the lack of a strong linear relationship between cockle weight and microplastic burden and biological differences between seasons indicates that cockles in this marine environment ingest and likely egest microplastics continually. In addition, microplastic presence is likely a transient value and a reflection of surrounding microplastic levels. They can also exacerbate the contamination of other

organisms found in the sediment of the bay through the egestion of microplastics they filter from the water column. Microfibrils constituted the greatest proportion of microplastics found in cockles for every season studied in this study, with a range of 67.5 to 72.5% of total abundances and the majority of microplastics found in sediment at both beaches which indicates that cockles are suitable for reflecting environmental microplastics types in shallow marine environments. Furthermore, buoyant microplastics not observed in sediment samples as well as a greater range of polymer types were recovered from cockle samples indicating they are suitable for qualifying microplastic types that may not be observed when studying sediment samples in intertidal locations alone. The high concentrations of microplastics found at both sites (1274 microplastics kg⁻¹ and 1125 microplastics kg⁻¹) may be linked to the shallow nature of these locations accumulating these pollutants, and Dundalk Bay serving as a hotspot for microplastic pollution. Due to the vulnerability of cockles to a wide range of threats, the contamination of cockles in Dundalk Bay by microplastics represents a relatively new threat to this population of vital shellfish that have an economic, ecological and historical importance to this SPA and SAC. The assessment of microplastic pollution falls under descriptor 10 of the Marine Strategy Framework Directive which states that anthropogenic litter should not cause harm to the coastal or marine environment and that quantities of litter entering these environments should be reducing overtime (MSFD; 2008/56/EC). Currently there is no monitoring of quantities of micro litter entering the marine environment in Ireland. The results of this study and others highlighting high proportional microfibre levels in the Irish marine environments and biota illustrate the need for policy and legislative action against this form of pollution to the marine environment.”

CRedit authorship contribution statement

Stephen Kneel: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Caroline Gilleran Stephens:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization, Methodology. **Alec Rolston:** Conceptualization, Methodology. **Ana M. Mendes:** Writing – review & editing, Methodology. **Liam Morrison:** Writing – review & editing, Methodology. **Suzanne Linnane:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization, Methodology.

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

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marpolbul.2024.116568>.

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