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Temporal distribution of microplastics and other anthropogenic particles in four marine species from the Atlantic coast (France)☆

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ABSTRACT

The characterization of microplastic (MP) contamination in marine species is increasing as concerns about environmental and food safety are more and more discussed. Here, we reported a quantitative and qualitative assessment of the contamination by anthropogenic particles (from visual sorting; AP) and MP (plastic-made) in the whole soft body or digestive tract of marine species. Four commercial species were studied, namely the Pacific oyster (*Magallana gigas*), the spiny spider crab (*Maja sp.*), the common sole (*Solea solea*) and seabass (*Dicentrarchus labrax* or *punctatus*). AP and MP uptake were studied over three to four seasons depending on the species. After tissues digestion, particles were extracted under a stereomicroscope and morphometric characteristics were reported. Then, polymers were identified by ATR-FTIR spectroscopy. Seasonal variations were mainly described in the Pacific oyster as AP uptake was lower in autumn and MP uptake was higher in spring. These variations may be linked to the reproduction and growth cycles of this species. Moreover, seabass ingestion was lower in autumn compared to winter. Contamination in spider crabs and soles showed either weak or no seasonal trends, both quantitatively and qualitatively. Overall, AP contamination in all studied species ranged from 1.17 ± 1.89 AP.ind^{-1} (in sole) to 4.07 ± 6.69 AP.ind^{-1} (in seabass) while MP contamination ranged from 0.10 ± 0.37 MP.ind^{-1} (in sole) to 1.09 ± 3.06 MP.ind^{-1} (in spider crab). Fibers were mostly reported in all species (at least 77.7%), along with cellulosic polymers (at least 43.7%). AP and MP uptake were detected in all species and at almost all seasons, with the only exception of the common sole during autumn. Therefore, this study emphasizes the ubiquity of AP and MP contamination in marine species and provides new knowledges about seasonal uptake by commercial species.

1. Introduction

It was estimated that 60% of the entire plastic production made between 1950 and 2015 accumulates in landfill and in the natural environment, which corresponds to 4900 million metric tons of plastic (Geyer et al., 2017). Among plastic litter, microplastics (MP) could be defined as *"any synthetic solid particle or polymeric matrix, with regular or irregular shape and with size ranging from 1 μm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water"* (Frias and Nash, 2019).

In marine environments, taxa from zooplankton to large mammals can interact with MP (e.g. Carlsson et al., 2021; Cole et al., 2013). Indeed, MP can adhere to feeding appendages (e.g. Cole et al., 2013), be ingested (e.g. Pellini et al., 2018; Reinold et al., 2021; Rezania et al., 2018) or accumulate in tissue (e.g. Collard et al., 2017; Zeytin et al., 2020). Moreover, chemicals can be adsorbed onto or absorbed into MP (Wang et al., 2018), and can be bioavailable for marine organisms (Cormier et al., 2021). These different interactions could lead to diverse impacts, such as impairment of feeding rates (Cole et al., 2013), inflammation of tissues (Von Moos et al., 2012), induction of oxidative stress (Gao et al., 2022) or growth disruption (Pannetier et al., 2020). Thus, evaluating the environmental exposition across marine taxa is necessary to improve risk assessment studies on these organisms (GESAMP, 2015). As such, MP concentrations along with qualitative

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factors have to be characterized (Bucci and Rochman, 2022). Additionally, understanding the contamination of the biotic compartment is crucial as aquatic species play a key role in MP distribution and its fate in marine ecosystems. For instance, MP can be fragmented after being ingested (Dawson et al., 2018) or can be transported within fecal pellets (Katija et al., 2017; Pérez-Guevara et al., 2021).

Even though the above-cited definition includes particles from all manufacturing origins, MP terminology is not yet harmonized in this recent research field. As a consequence, it can lead to important limitations when it comes to comparing studies or implementing monitoring programs and new legislations. Furthermore, not only particles made of fully synthetic plastics have been found in marine environments and they can be included under the term “anthropogenic particles” (e.g. Adams et al., 2021; Collard et al., 2018; Compa et al., 2022). For instance, cellulosic fibers and rubbery fragments are more and more reported in MP contamination studies (e.g. Arias et al., 2022; Mishra et al., 2019) even though their description is not yet systematic. In particular, cellulosic fibers were commonly found in all ocean’s basin (Suaria et al., 2020) and raise new concerns. For instance, recent findings showed that cellulosic fibers can have adverse effects on marine organisms, such as shown for juvenile mussels (Walkinshaw et al., 2023). Nonetheless, knowledge on AP is still scarce and there is a need to study them (Andersson-Sköld et al., 2020; Henry et al., 2019). In this study, anthropogenic particles (AP) refers to all particles that have a manufactured origin. It includes particles made of plastic, semi-synthetic particles, and non-synthetic particles that are transformed by human activities (Collard et al., 2018; Adams et al., 2021).

In this overall context, we studied the dynamic of AP and MP contamination over one year in four marine species from the Arcachon Bay, a coastal lagoon located in the Southeastern part of the Bay of Biscay. This area is largely influenced by semi-diurnal tide cycles and supports several anthropic economic activities such as oyster farming, fishing or tourism. This study assesses AP and MP uptake by four species; pacific oyster (*Magallana gigas*, formerly known as *Crassostrea gigas)*, sea spider crab (*Maja* sp.), the common sole (*Solea solea*) and seabass (*Dicentrarchus labrax* or *punctatus)* during three to four seasons. The main objectives were i) to describe qualitatively and quantitatively AP and MP contamination in four marine species of commercial interest and ii) to study AP and MP distributions over seasons.

2. Methods

2.1. Studied area

The Arcachon Bay is a semi-enclosed coastal lagoon located in the South West coast of France (44°40′N, 1°10′W; Fig. 1) and connected to the Atlantic Ocean through a tidal inlet. The hydrodynamics of the bay is mainly driven by tides (Plus et al., 2009) and water renewal is around 13 days in summer and 16 days in winter (IFREMER, 2007). Freshwater inputs are mostly coming from the Leyre River (Fig. 1; Plus et al., 2009), for which the mean annual flow is 17.1 $m^3 s^{-1}$ (calculated over the past 56 years, http://www.hydro.eaufrance.fr/; *last visit on November 11th, 2023*).

This lagoon supports different anthropic activities, among which the most famous ones are oyster-farming activities (e.g., spat collection, spat and adult sales). More than 300 firms of oyster farming are registered in the bay, using 80 ha of the total area, for an annual production of 8000–10 000 tons (SIBA, 2013). There is also professional and recreational fishing (e.g. angling, shore fishing or by vessel) in oceanic and inner parts of the lagoon. The Arcachon Bay is also an attractive area with an increase in population density and tourism. Many different recreational activities have been implemented in the bay area. It includes activities on- or under-water, on the beach or around the bay. Additionally, wastewaters are collected all around the lagoon and treated effluents are discharged directly in the ocean, near the “*Salie*” station (Fig. 1).

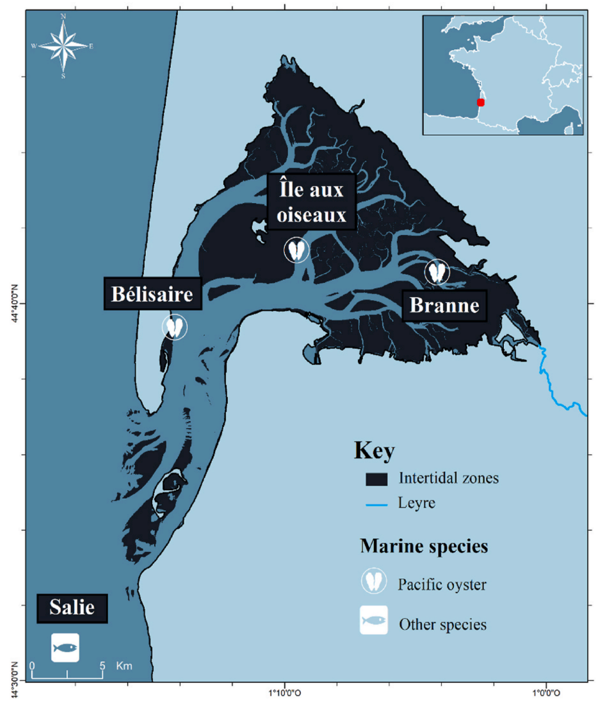

Fig. 1. Map of the studied area and localization of the samplings. Created with ArcGis software (V10.7.1).

2.2. Precautions and control of contamination

To minimize contamination, several precautions were set up during samplings and analyses. All precautions are listed and described in Lefebvre et al. (2023). It included 100% cotton lab coat wearing, filtration of the solutions (i.e. UltraPure water and 70% Ethanol) on MCE filter (0.22 μm mesh size) and filtration of 10% KOH on nylon filter (0.47 μm mesh size). Lab benches and devices were thoroughly cleaned with filtered 70% ethanol. Tools, stainless steel filters and glass containers were rinsed three times with filtered solution of 70% ethanol and then two times with filtered UltraPure water. Plus, filtration and digestion steps were undertaken in a cleaned biosafety cabinet of class 2.

To control the level and type of procedural contamination, blanks were performed during sample analyses, and followed the same process as biotic samples from preparation to identification steps. To fully consider the air-born contamination, petri dishes blanks contained filtered UltraPure water and were left open during the whole procedure of the sample analysis. For oyster samples, there were fifteen blanks in total and for each of the other studied species three blanks were set up (i.e. sole, spider crab, seabass).

2.3. Sampling of organisms

Organisms were sampled between April 2019 and February 2020 (see Supp. Mat. 1 for details by species and seasons).

Wild Pacific oysters (*Magallana gigas*, formerly known as *Crassostrea gigas*), were manually collected at three sites (*Bélisaire*, *Ile aux oiseaux* and *Branne*; Fig. 1) during spring (April), summer (July), autumn (October) and winter (January/February). From 13 to 15 individuals were studied for each season and site for a total of 178 individuals analyzed (see Supp. Mat. 1 for details). Individuals were frozen at −20 °C prior to further treatments and analyses.

Spider crab (*Maja sp.,* sold as *Maja squinado*), common sole (*Solea solea*) and seabass (*Dicentrarchus labrax* and *Dicentrarchus punctatus* depending on the season, see Supp. Mat. 1) were fished by a professional fisherman from the Arcachon Bay. These species were caught at one site just outside the Arcachon Bay (i.e. *Salie*, Fig. 1). Spider crabs and soles were caught in spring (April), summer (July), and autumn (October) while seabass were fished in spring (April), autumn (October) and winter (January). From 12 to 17 individuals were sampled at each season (see Supp. Mat. 1 for details). In total, 42 spider crabs, 42 common soles, and 44 seabass were analyzed. Individuals were stored at −20 °C prior to further treatments. For fish species, the index of condition was calculated according to the Fulton's condition factors (K; Eq. (1)):

$$K = 100 \times \frac{TW}{TL^3} \quad \text{(Eq. 1)}$$

where TW is the total weight in grams and TL is the total length in cm (Fulton, 1904).

2.4. Preparation of samples

Individuals from all studied species were rinsed with filtered Ultra-Pure water, and biometrics were measured. Specifically, oyster total length (TL), total weight (TW) and tissue wet weight (ww) were reported. For spider crabs, common soles and seabass, biometrics data include TL (from snout to tail for fish species and shell maximal length for spider crabs), TW, weight of the digestive tracts and the sex of the individual (if possible). All biometric data can be found in Supp. Mat. 1. The sex ratio (SR) was rather equilibrated for spider crab (SR = 0.48) and for sole (SR = 0.49) and it was rather in favor of males for seabass (SR = 0.57).

Soft tissues of Pacific oysters were analyzed. To study particles uptake by spider crabs, soles and seabass, the digestive tracts were carefully removed during their dissection. Soft tissues or digestive tracts were placed individually in pre-cleaned glass bottles. A chemical digestion with 10 % KOH (10:1, v/w ratio) was performed for 24 h at 50 °C and 180 rpm. Indeed, tissues digestion is often performed for MP analyses in biotic samples (e.g. Kazour et al., 2019; Phuong et al., 2018b). After this chemical digestion, oyster samples were filtered on a stainless filter of 26 μm mesh size, except for oyster from spring that were filtered on 50 μm. Samples from all other species were filtered on a 50 μm mesh size stainless filter. Before AP and MP analysis, all samples were kept in sealed glass petri dishes with covers in a cold chamber at 4 °C.

2.5. Visual sorting and morphometric description

All filters were visually sorted under a stereomicroscope (Leica MZ75; magnification range: ×6.3 – x 50) combined with a cold light source (Volpi, Intralux 4100) providing light over the sample. Visual sorting criteria were based on recommendations from Hidalgo-Ruz et al. (2012) and Zhao et al. (2016). Strict criteria based on visual characteristics and mechanical responses were used to discriminate AP from natural particles. Particles with visible organic structures or the ones that crumbled when being gently pressed were not considered as AP. However, particles regaining their shape after being pressed or not naturally colored particles were considered as potential AP/MP, and were kept for further characterization. Fiber-shaped particles with regular thickness, homogenous internal structure and which do not break when pressed were also kept, in particular when colored. Fibers must not show any segmentation and a particular care was taken for white-transparent fibers by using a black background. Overall, used criteria were in accordance with the identification key proposed by Lusher et al. (2020). A total of 785 particles were extracted using stereomicroscopy (detail by species in Supp. Mat. 2). Length, width, shape and color were reported for each particle. Sorted particles were placed in 24-well plates.

2.6. Polymer characterization

Overall polymer analysis was performed on 73.5% of the sorted particles (abundance detailed in Supp. Mat. 2). Some particles were not analyzed, either when similar particles were found in important amounts or due to losses during manipulation. Still, the percentage of chemically analyzed particles is much higher than the recommended one (10%, European Commission. Joint Research Centre and MSFD Technical Group on Marine Litter., 2023). Particles were analyzed by Attenuated Total Reflectance Fourier-Transform Infrared spectroscopy (ATR-FTIR; Nicolet, Nexus 870) equipped with Pike technology, MIRacle (diamond crystal). Acquisition was made over the 400–4000 cm^{-1} range at a resolution of 4 cm^{-1} (OMNIC software V9.2.98, Thermofisher). For each spectrum, an ATR-correction was applied and the baseline was manually corrected. Matching of spectra was done using a spectral database containing 6528 spectra from six industrial libraries and one environmental library created for the ARPLASTIC project (see Lefebvre et al., 2023 and its supplementary material). A polymer was attributed based on library matching and manual verification of absorption spectral signature. Identified polymers were polyethylene (PE), polyethylene terephthalate (and associated polyester; PET), polypropylene (PP), polystyrene (PS), polyamide (including nylon; PA), a mixture of polyamide and cellulose (PA/CELL) and cellulose (CELL; e.g. cotton, rayon, viscose, Tencel, Lyocell and linen). Additionally, four plastic polymers displaying low occurrences were pooled under the polymer category "Other" (OTH). This former category gathered ethylene propylene diene monomer (EPDM), polyacrylonitrile (PAN), polydimethylsiloxane (PDMS), polybutadiene acrylonitrile and an elastomer coating. Lastly, some spectra did not match with any polymer due to their poor quality, technical issues or no correspondences in libraries. As such, these spectra were gathered into the category "unknown" (UNK).

2.7. Data treatment and statistical analysis

The quantification of all anthropogenic particles (AP) included all extracted microparticles (i.e. microplastics, anthropogenic cellulosic particles and unknown anthropogenic particles). The quantification of MP specifically refers to particles that were clearly identified as plastic (PE, PP, PS, PET, PA, PA/CELL and OTH categories).

Mean AP and MP abundances per blank for each season and species were subtracted to all individual abundances for the corresponding season and species. All means are presented with the standard deviation (SD). All statistical analysis and figures were produced using R Studio (V2023.09.1, RStudio Team, 2016) and the following packages: reshape (Wickham, 2007), dplyr (Wickham et al., 2021), car (Fox and Weisberg, 2018), janitor (Firke, 2021), FSA (Ogle et al., 2021), ggplot2 (Wickham, 2016), scales (Wickham and Seidel, 2020), hrbrthemes (Rudis, 2020), RColorBrewer (Neuwirth, 2014). As assumptions were never met, the non-parametric test of Kruskall-Wallis (H-test) was performed to analyze variabilities across seasons and species. The null hypothesis of similar distribution between seasons was tested. If significant variabilities were found, the multiple comparison Dunn test was performed to determine which pair of seasons were different. Moreover, Spearman correlation test was used to check the relationship between individual's TW, TL or K and the abundances of AP and MP. The significance level was set at 0.05.

3. Results

The characterization of AP and MP contamination was investigated in the whole soft tissue of Pacific oysters (Fig. 2) and in the entire digestive tract of spiny spider crabs (Fig. 3), common soles (Fig. 4) and seabass (Fig. 5). It includes overall and seasonal distribution of particles' morphometrics, polymer types and abundances (per individual). Additional results are available in the Supplementary Material, including AP mean width (Supp. Mat. 3), length distribution by size class (Supp. Mat.

4), AP and MP concentrations in samples (per gram; Supp. Mat. 3) and AP and MP abundances in blanks (Supp. Mat. 5).

3.1. Pacific oysters

3.1.1. Morphometric characteristics

Overall, AP length ranged between 0.04 and 4.93 mm and the mean length was 1.48 ± 1.08 mm (Supp. Mat. 3). At seasonal scale, means ranged from 1.10 ± 0.97 mm in winter to 1.67 ± 1.12 mm in summer.

Fibers were clearly overwhelming regarding overall shape distribution (93.9%; Supp. Mat. 6) as well as seasonal shape distribution (from 89.4% to 98.5%, Fig. 2A).

Considering the whole study, AP were mainly blue (45.3%), white (24.7%) and then black (13.5%, Supp. Mat. 7). At seasonal scale, AP were mainly blue in summer, autumn and winter (at least 53.0%), while they were mainly white in spring (45.2%).

3.1.2. Polymer identification

Overall, 306 particles were analyzed among the 413 AP sorted and the prevailing chemical type was CELL (61.8%) followed by UNK category (22.6%; Supp. Mat. 8). At seasonal scale, CELL was systematically the main polymer found in Pacific oysters (from 56.4% in summer to 75.0% in autumn; Fig. 2B). There were 11.3 % of PA/Cell in spring and 11.4 % of PET in autumn. Moreover, proportions of UNK polymers were non-negligible in spring and winter (respectively 28.6% and 30.4%; Fig. 2B, Supp. Mat. 8).

3.1.3. Occurrence and abundance of AP and MP

AP were found in 64.6% of Pacific oyster individuals and overall mean AP abundance was 1.74 ± 2.30 $AP.ind^{-1}$ (or 0.28 ± 0.51 $AP.g^{-1}$, Supp. Mat. 3). Particle abundance per oyster ranged from 0 to 14. There were no correlations between AP abundance in individuals and their TW, TL or tissue weight (Spearman, N = 178, p-values >0.43). Abundance of AP was minimal in autumn (0.88 ± 1.33 $AP.ind^{-1}$) and maximal in spring and summer (respectively 2.07 ± 2.36 and 2.07 ± 2.70 $AP.ind^{-1}$; Fig. 2C). Significant differences were noticed between seasons (H-test, N = 178, p-value = 0.04), and mean abundance was systematically lower in autumn (Dunn test, p-values <0.02). Other comparisons between seasons did not show significant differences (Dunn test, p-values ≥0.97).

Regarding MP contamination, they were detected in 20.8% of individuals and overall mean abundance was 0.39 ± 0.96 $MP.ind^{-1}$ (or 0.06 ± 0.17 MP g^{-1}, Supp. Mat. 3). No correlations were found between biometrical parameters and MP abundances (Spearman, N = 178, p-values >0.35). At seasonal scale, mean abundance per individual ranged between 0.06 ± 0.19 $MP.ind^{-1}$ in autumn and 0.95 ± 1.56 $MP.ind^{-1}$ in spring (Fig. 2C, Supp. Mat. 3). Mean abundance per individual was different between seasons (H-test, N = 178, p-value = 0.01) as spring systematically displayed higher mean abundance than all other seasons (Dunn test, p-values ≤0.03). Other comparisons between seasons were not significant (Dunn test, p-values >0.26).

3.2. Spider crab

3.2.1. Morphometric characteristics

Overall, recorded length of AP were between 0.167 and 4.88 mm and mean length was 1.96 ± 1.34 mm. At seasonal scale, mean length of AP ranged from 1.62 ± 1.18 mm in spring and 2.57 ± 1.38 mm in autumn

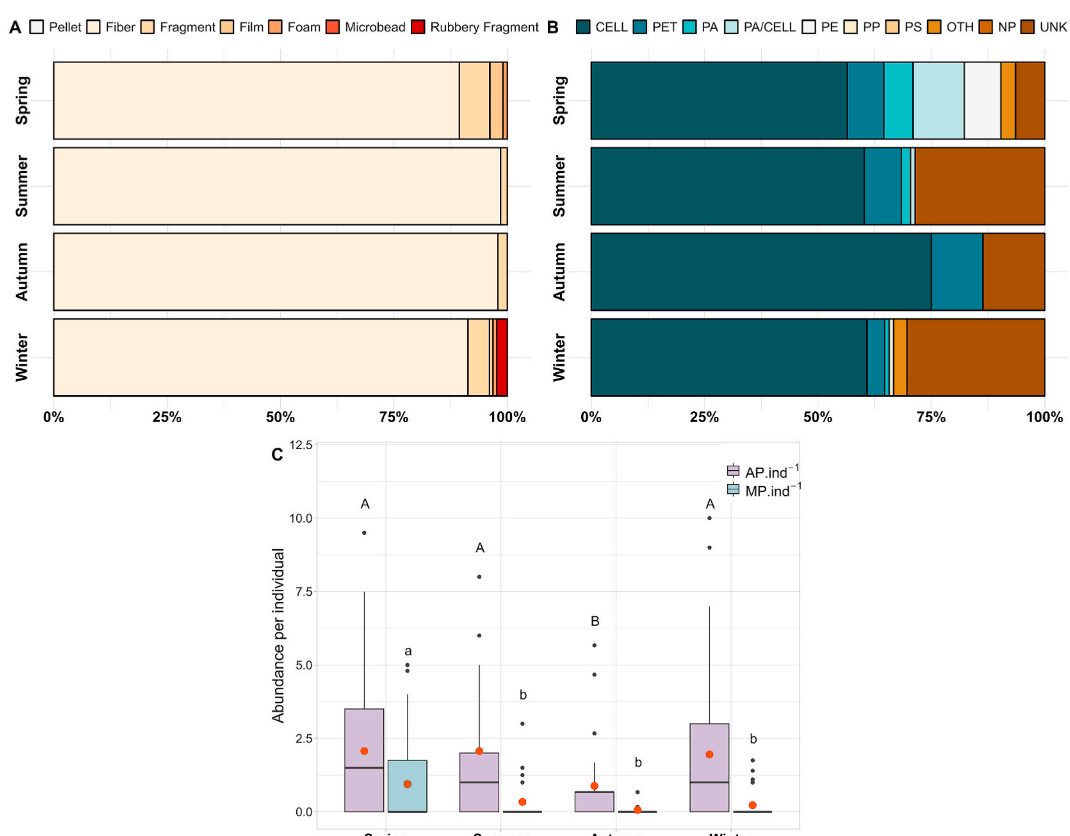

Fig. 2. Relative proportions of A) shapes, B) polymers and C) abundances of AP and MP for Pacific oysters according to the studied season (red points indicate mean abundances). For visualization purpose, upper scale limit was set at 12.5 $particle.ind^{-1}$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(Supp. Mat. 3).

Regarding AP shapes over all studied seasons, spider crabs mostly ingested fibers (77.7%) while fragments and films were barely identified (at most 9.9%; Supp. Mat. 6). In autumn, almost only fibers were found in digestive tracts of spider crabs (90.9%; Fig. 3A). In spring and summer, fibers were also mostly represented (77.8% and 72.2%, respectively), far behind fragments and films (at most 13.0%, Fig. 3C, Supp. Mat. 6).

All seasons considered, ingested AP were white (46.3%), blue (31.4%), black (13.2%) and then red AP (9.1%). At seasonal scale, white-colored AP prevailed systematically (from 38.9% to 53.3%), followed by blue ones (from 28.9% to 40.9%, Supp. Mat. 6).

3.2.2. Polymer identification

Overall, 87 particles were analyzed among the 121 AP ingested by spider crabs. The main polymer identified in spider crabs was CELL (43.7%), followed by PA (17.2%) and PET (10.3%, Supp. Mat. 8). In spring, most of the analyzed particles remained unidentified (38.1%), while CELL and OTH represented respectively 33.3% and 19.0% of analyzed particles (Fig. 3B). In summer and autumn, the first polymer type was CELL (40.9% and 59.1%, respectively), followed by PA (20.4% and 27.3%, respectively). In summer, non-negligible proportions of PET (18.2%) and PA/Cell (11.4%) were detected (Fig. 3B, Supp. Mat. 8).

3.2.3. Occurrence and abundance of AP and MP

AP were detected in 47.6% of spider crabs' digestive tracts and mean concentration was 1.90 ± 3.06 AP.ind^{-1} (Supp. Mat. 3). Abundance of AP per individual ranged between 0 and 13. There were no correlations between biometrical parameters and AP abundances (Spearman, N = 42, p-values >0.05). At seasonal scale, ingestion was minimal in autumn (1.47 ± 1.88 AP.ind^{-1}) and maximal in spring (2.92 ± 3.48 AP.ind^{-1}; Fig. 3C). However, there were no differences in mean AP abundance per individual between the studied seasons (H-test, N = 42, p-value = 0.10).

Regarding MP, 31.0% of spider crabs' digestive tracts contained at least one MP and the mean abundance was 1.09 ± 2.33 MP.ind^{-1} (Supp. Mat. 3). No correlations were found between the abundance of MP and TW, TL and digestive tract weight (Spearman, N = 42, p-values >0.29). Regarding seasonal distribution, mean abundances ranged from 0.42 ± 0.85 MP.ind^{-1} in autumn to 1.68 ± 2.97 MP.ind^{-1} in summer (Fig. 3C). However, no significant differences were found between seasons (H-test, N = 42, p-value = 0.55).

3.3. Sole

3.3.1. Morphometric characteristics

Overall mean length of AP in the digestive tract of common soles was 1.16 ± 0.84 mm (length range: 221 μm - 4.34 mm). At seasonal scale, mean length ranged from 1.07 ± 0.40 mm in spring to 1.21 ± 1.03 mm in autumn (Supp. Mat. 3).

Fibers were clearly prevailing in overall sole samples (95.2%) while fragments and films were barely observed (3.2% at most, Supp. Mat. 6). At seasonal scale, fibers were largely predominant as well (from 88.9% to 100.0%, Fig. 4A). Nonetheless, fragments represented 10.0% of AP in spring, meanwhile in summer films represented 11.1% of AP.

Overall, blue AP prevailed (74.6%) followed by white ones (22.2%). Blue AP were firstly detected at seasonal scale (from 70.0% in spring to 83.3% in summer) and white AP were secondly described (from 11.1% in summer to 28.6% in autumn, Supp. Mat. 7).

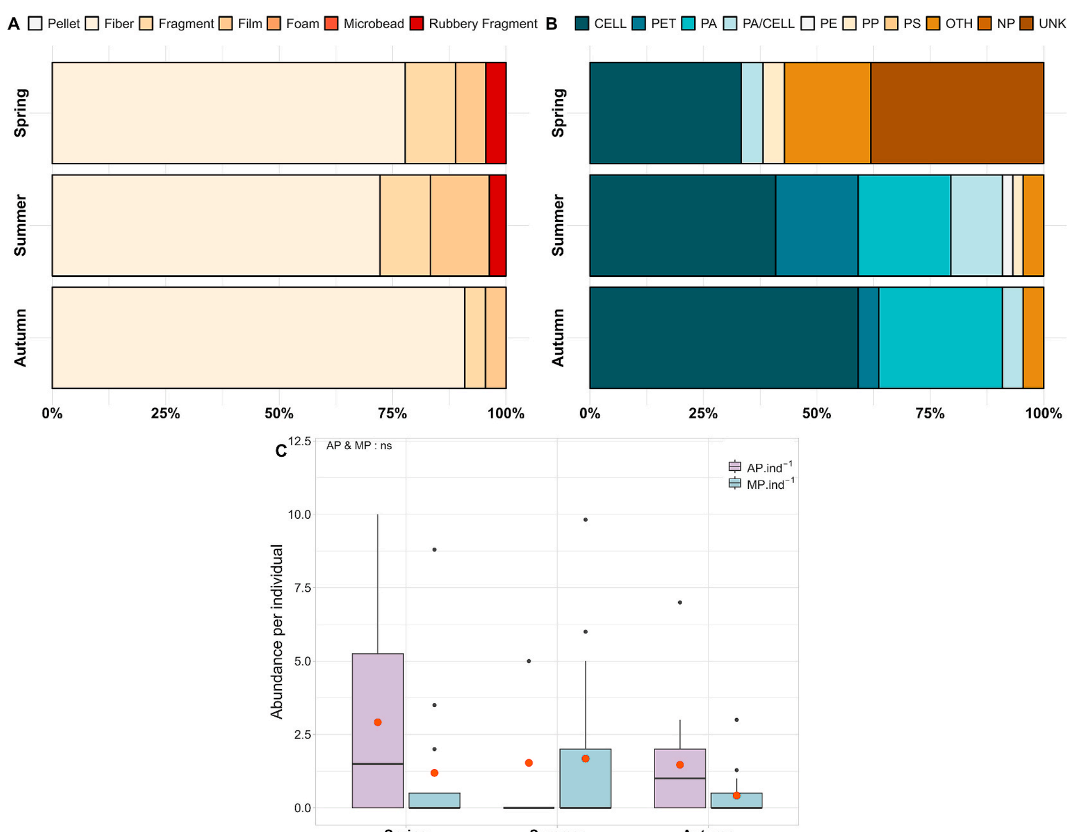

Fig. 3. Relative proportions of A) shapes, B) polymers and C) abundances of AP and MP in spider crabs according to the studied season (red points indicate mean abundances). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

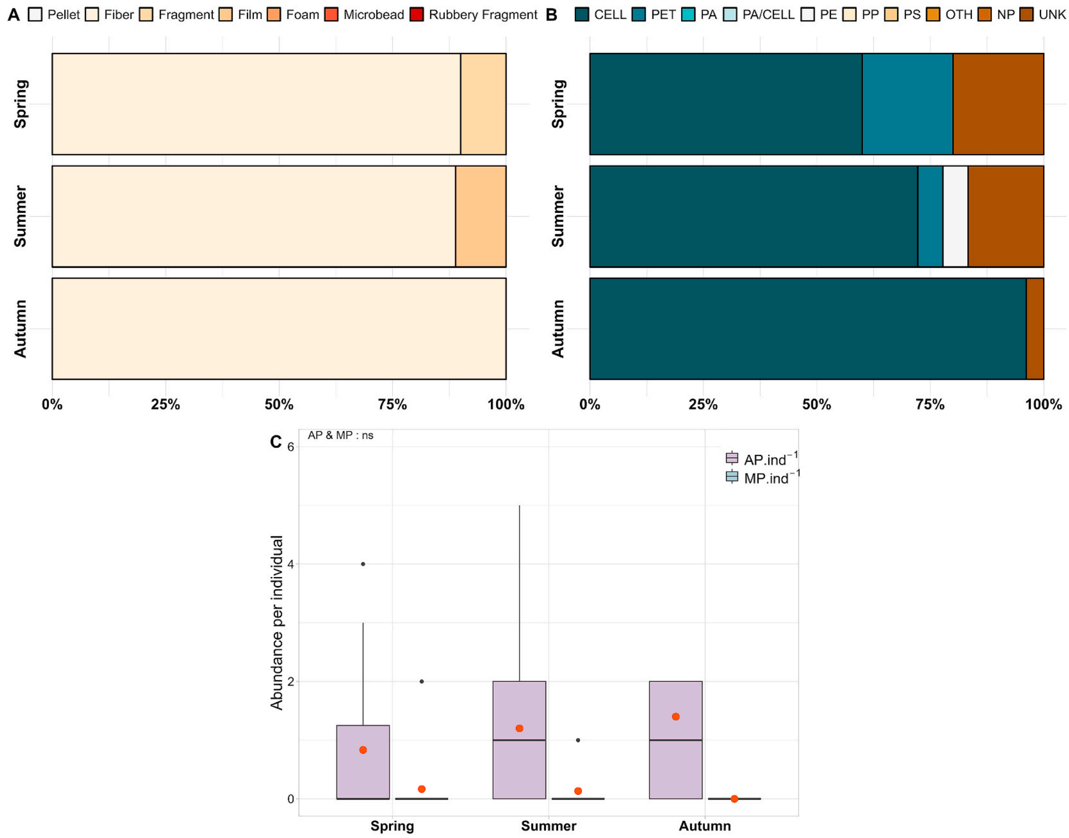

Fig. 4. Relative proportions of (A) shapes, (B) polymers and (C) abundances of AP and MP in common soles according to the studied season (red points indicate mean abundances). For visualization purpose, upper scale limit was set to 6.0 particle.ind^{-1}. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.3.2. Polymer identification

Overall, 54 particles were analyzed among the 63 AP found in soles' digestive tracts. Cellulosic AP were mainly identified (81.5%), far followed by PET (5.6%) and PE (1.9%). All other polymers were not detected (Supp. Mat. 8). Whatever the studied season, there were mostly cellulose-based polymers in soles samples (from 60.0% to 96.6%, Fig. 4B). Still, PET was identified at 20.0% and 5.6%, respectively in spring and in summer. There were between 3.8% and 20.0% of particles with unidentified polymers (Fig. 4B, Supp. Mat. 8).

3.3.3. Occurrence and abundance of AP and MP

AP were detected in 47.5% of common sole's digestive tract and the overall mean abundance was 1.17 ± 1.89 AP.ind^{-1}. There were between 0 and 10 AP per individual. No correlation was found between AP abundances and Fulton's index of individuals (Spearman, N = 42, p-value = 0.70). At seasonal scale, mean abundances ranged from 0.83 ± 1.40 AP.ind^{-1} in spring to 1.40 ± 2.53 AP.ind^{-1} in autumn (Fig. 4C, Supp. Mat. 3). There were no significant differences between seasons (H-test, N = 42, p-value = 0.67).

MP were detected in solely 7.1% of digestive tract of soles and mean MP abundance over all seasons was 0.10 ± 0.37 MP.ind^{-1} (Supp. Mat. 3). There was no correlation between MP abundances and K of individuals (Spearman, N = 42, p-value = 0.75). At seasonal scale, mean abundance was null in autumn while the maximal one was recorded in spring (0.17 ± 0.58 MP.ind^{-1}, Fig. 4C). Nonetheless, no seasonal variations were found (H-test, N = 42, p-value = 0.38).

Regarding contamination level between species, mean abundance of AP was similar between all of them (H-test, N = 306, p-value = 0.17) while MP abundance were not similar (H-test, N = 306, p-value = 0.03). Actually, MP contamination in digestive tracts of soles was lower than in oysters' soft tissues and spider crabs' digestive tracts (Dunn, p-values <0.05). All other comparisons were not significant (Dunn, p-values >0.07).

3.4. Seabass

3.4.1. Morphometric characteristics

Overall, recorded lengths ranged from 0.06 to 4.88 mm and mean overall length was 1.38 ± 1.09 mm. At seasonal scale, mean AP length in seabass' digestive tracts ranged from 0.99 ± 0.88 mm in spring and 1.49 ± 1.04 mm in autumn (Supp. Mat. 3).

Digestive tracts of seabass mostly contained fiber-shaped AP (91.5%), while fragments, films and rubbers were found in low proportions (7.5% at most, Supp. Mat. 6). At seasonal scale, fibers were described from 71.4% in spring to 97.3% in winter (Fig. 5A). Additionally, fragments were detected at 25.7% in spring (Fig. 5A, Supp. Mat. 6).

Colors of AP in seabass samples were mostly blue (70.8%), followed by black and white (10.6%, both). At seasonal scale, blue AP represented between 34.3% and 85.0% of all AP (Supp. Mat. 7).

3.4.2. Chemical identification

Overall, 188 AP were sorted from digestive tracts of seabass, which were all analyzed by ATR-FTIR. CELL was mostly identified in seabass digestive tracts (90.8%, Supp. Mat. 8). At seasonal scale, CELL was the major polymer characterized at all studied seasons (from 85.2% in spring to 94.6% in winter, Fig. 5B).

3.4.3. Occurrence and abundance of AP and MP

AP were detected in 59.1% of seabass and mean AP abundance was 4.07 ± 6.69 AP.ind^{-1} (Supp. Mat. 3). Abundance of AP per individual ranged between 0 and 34. The K of individuals was not correlated to AP

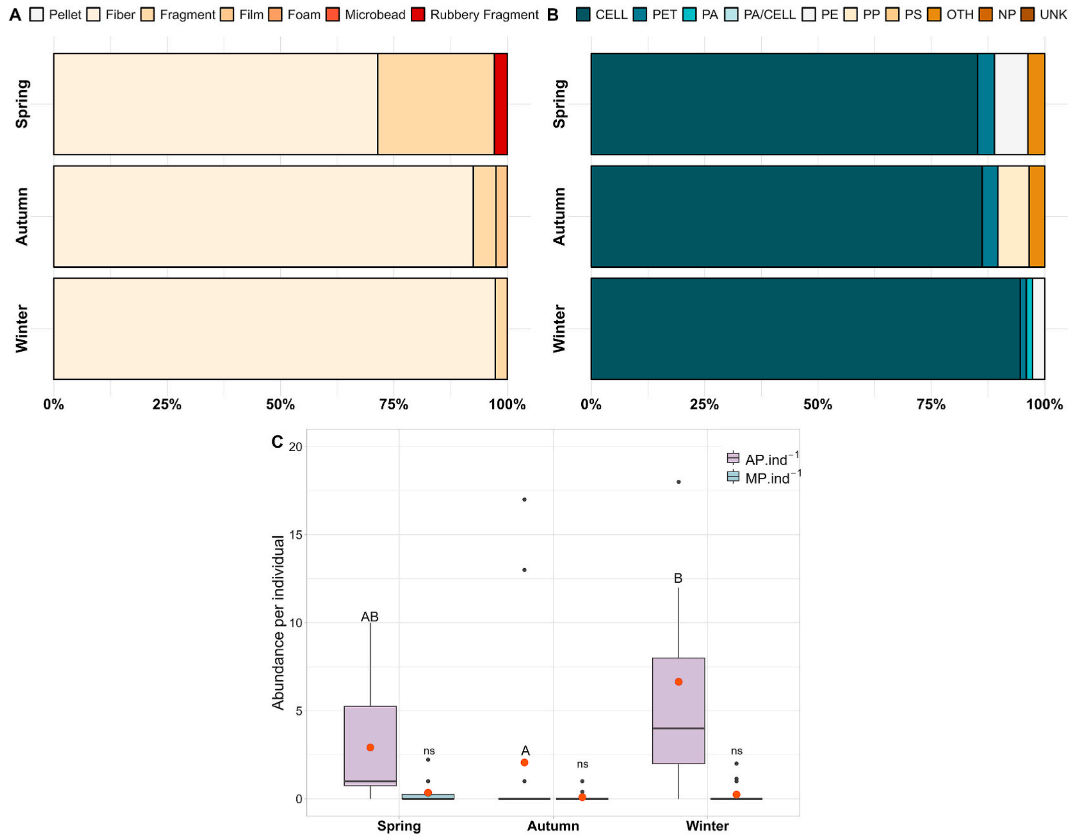

Fig. 5. Relative proportions of A) shapes, B) polymers and C) abundances of AP and MP in seabass according to the studied season (red points indicate mean abundances). For visualization purpose, upper scale limit was set to 20.0 particle.ind^{-1}. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

abundance in digestive tracts (Spearman, N = 44, p-value = 0.20). At seasonal scale, mean AP abundance varied between 2.07 ± 5.31 AP.ind^{-1} in autumn to 6.65 ± 8.65 AP.ind^{-1} in winter (Fig. 5C). Significant seasonal variations were found (H-test, N = 44, p-value <0.01) as mean abundance was significantly higher in winter compared to autumn (Dunn test, p-value <0.01). No other seasonal variations were observed (Dunn test, p-values >0.06).

MP were identified in 18.2% of individuals' digestive tracts and mean MP abundance was 0.22 ± 0.53 MP.ind^{-1} (Supp. Mat. 3). There was a weak positive correlation between K and MP abundance (Spearman, N = 44, p-value = 0.02, rho = 0.34). At seasonal scale, mean MP abundances ranged from 0.09 ± 0.27 MP.ind^{-1} in autumn to 0.35 ± 0.70 MP.ind^{-1} in spring (Fig. 5C). However, there was no difference between seasons (H-test, N = 44, p-value = 0.67).

4. Discussion

4.1. *Pacific oyster*

In Pacific oysters, shape and polymer distribution tended to be similar between seasons as fibers and cellulose clearly prevailed whatever the season (at least 91.3% and 56.4%, respectively). Nonetheless, there were few seasonal variations as AP and MP abundances were systematically lower in autumn (0.88 ± 1.33 AP.ind^{-1} and 0.06 ± 0.19 MP.ind^{-1}) than in spring (2.07 ± 2.36 AP.ind^{-1} and 0.95 ± 1.56 MP.ind^{-1}). Notwithstanding, autumn (i.e. October month in this study) is a resting phase that also corresponds to the end of the reproduction period for this species (Chávez-Villalba et al., 2002; Fabioux et al., 2005). Moreover, it was shown that caged oysters from the Atlantic coast have a limited growth from September to January (Lerebours et al., 2022). It suggests that seasonal variations in physiological functions might influence oyster AP and MP uptake, as resting may lead to a lower food uptake and thus a lower AP and MP uptake at this season. Conversely, MP uptake was higher in spring, which corresponds to a growth period for oyster in the French Atlantic West coast (Berthome et al., 1986; Robert et al., 1993). In spring, oysters filter more water to increase food intake and consequently they may have increased their contamination level by AP and MP. Additionally, the mean length of AP was the lowest in spring and the highest in autumn in the water column of the Arcachon Bay (respectively 0.80 and 1.17 mm; Lefebvre, 2022), which may also partly explain this result.

Overall, fibers represented more than 90% of particles in Pacific oyster samples which was similar to wild Pacific oysters from the Salish Sea, the Bay of Bizerte or the Jiaozhou Bay, for instance (Table 1). Polymer distribution was driven by CELL (61.8%), which was similar to previous studies that included cellulosic polymer analysis, such as Du et al. (2022) and Zhang et al. (2022). However, different polymers were detected in the Bay of Bizerte or in the Pertuis Charentais (Table 1). Moreover, in the Aiguillon Bay in France, PP and PE fragments were mainly found in farmed and wild Pacific oysters (Phuong et al., 2018b), just like in sediments from this area (Phuong et al., 2018a). This later difference could be partly due to the contamination of the surrounding environment as already suggested in Lerebours et al. (2022). Indeed, oysters are filter feeders that ingest suspended matter from the water column. They are also associated with the sediment compartment as they live on hard substrates in intertidal and subtidal areas. In inner part of the Arcachon Bay, the contamination by AP and MP in intertidal sediments and water column are mainly represented by fibers (at least 79.3%) and cellulose (at least 50.8%; Lefebvre et al., 2023), similarly to oyster from this area. Hence, Pacific oyster contamination could be influenced by the contamination of their habitats and their feeding strategy.

Table 1
Contamination by AP and MP reported in the literature for studied species. Shape and polymer percentage are shown in bracket when available. Same abbreviations as in this study were used to facilitate the reading. (*) wild and farmed or only farmed individual. (**) caged individual. (–) data not available.

Species	Area	Mesh size	Shape	Polymer	Mean abundance ± SD (per individual)	Mean concentration ± SD (per gram)	Reference
Pacific Oyster	Salish Sea	1 µm	Fiber (96%)	UNK, Other	~1.75 $AP.ind^{-1}$	–	Martinelli et al. (2020)
	Bay of Bizerte, Tunisia	1 µm	Fiber (~90%)	PP, PE	–	1.48 ± 0.02 $AP.g^{-1}$	Abidli et al. (2019)
	Jiaozhou Bay, China	2.7 µm	Fiber (>90%)	CELL (60%)	2.96 ± 2.09 $AP.ind^{-1}$	0.91 ± 0.87 $AP.g^{-1}$	Zhang et al. (2022)
	Aiguillon Bay, France*	12 µm	Fragment (79%)	PP (47%), PE (25%)	2.1 ± 1.7 $MP.ind^{-1}$	0.18 ± 0.16 MP g^{-1}	Phuong et al. (2018b)
	Yellow Sea, Bohai Sea	8 µm	Fiber (98%)	CELL (71%)	2.92 ± 0.10 $AP.ind^{-1}$	0.36 ± 0.02 $AP.g^{-1}$	Du et al. (2022)
	Pertuis Charentais, France**	1.6 µm	Fiber	PS, PA, PET polycarbonate	–	0.4 ± 0.4 $AP.g^{-1}$	Lerebours et al. (2022)
	Arcachon Bay, France	26/50 µm	Fiber (94%)	CELL (62%)	1.70 ± 2.30 $AP.ind^{-1}$ 0.39 ± 0.96 $MP.ind^{-1}$	0.28 ± 0.51 $AP.g^{-1}$ 0.06 ± 0.17 MP g^{-1}	**This study**
Spider crab	Celtic Sea	No filtration	Fiber	–	1.39 ± 0.79 $AP.ind^{-1}$	–	Welden et al. (2018)
	Arcachon Bay, France	50 µm	Fiber (78%)	CELL (44%)	1.90 ± 3.06 $AP.ind^{-1}$ 1.09 ± 2.33 $MP.ind^{-1}$	0.23 ± 0.47 $AP.g^{-1}$ 0.12 ± 0.28 $MP.g^{-1}$	**This study**
Common sole	Seine estuary, France	26 µm	Fiber	CELL (47%)	–	–	Gaspéri and Cachot (2021)
	Adriatic Sea	1.6 µm	Fragment (72%)	PE, PP, PA, PET (~20 % each)	1.73 ± 0.05 $AP.ind^{-1}$	–	Pellini et al. (2018)
	Galway Bay, Ireland	1.2 µm	–	–	0.17 $AP.ind^{-1}$	–	Pagter et al. (2020)
	Arcachon Bay, France	50 µm	Fiber (95%)	CELL (82%)	1.17 ± 1.89 $AP.ind^{-1}$ 0.17 ± 0.58 $MP.ind^{-1}$	0.24 ± 0.41 $AP.g^{-1}$ 0.02 ± 0.06 MP g^{-1}	**This study**
Seabass	Seine estuary	26 µm	Fiber (77 %)	PET (45%), CELL (24%)	1.38 ± 0.99 $AP.ind^{-1}$	–	Gaspéri and Cachot (2021)
	Mondego estuary	1.2 µm	–	–	0.30 ± 0.61 $AP.ind^{-1}$	–	Bessa et al. (2018)
	Canary Island, Spain*	25 µm	Fiber (81%)	CELL (55%), PA (27%)	1.43 ± 1.75 AP.ind	–	Reinold et al. (2021)
	Canary Island, Spain*	50 µm	Fiber (100%)	CELL (60%), UNK (21%)	5.4 ± 4.2 $AP.ind^{-1}$	–	Sánchez-Almeida et al. (2022)
	Turkey	50 µm	Fiber (80%)	PE (25%), PET (20%), PA (10%)	0.95 ± 1.1 $MP.ind^{-1}$	–	Kılıç (2022)
	Arcachon Bay, France	50 µm	Fiber (92%)	CELL (91%)	4.07 ± 6.69 $AP.ind^{-1}$ 0.22 ± 0.53 $MP.ind^{-1}$	0.16 ± 0.40 $AP.g^{-1}$ 0.01 ± 0.02 MP g^{-1}	**This study**

In the present study, contamination by AP was 1.70 ± 2.30 $AP.ind^{-1}$ (or 0.28 ± 0.51 $AP.g^{-1}$). It was quite similar to the ones recorded in the Yellow and Bohai sea and the Pertuis Charentais but it was lower than in Jiaozhou Bay and the Bay of Bizerte (Table 1). Regarding the contamination by confirmed MP (0.39 ± 0.96 $MP.ind^{-1}$ or 0.06 ± 0.17 MP g^{-1}), it was five times lower than in oysters from the Aiguillon Bay. The different levels of contamination by AP and MP between studies can be partly explained by the different methodologies used. For instance, higher contamination may be due to the use of a lower mesh size (from 1 µm to 12 µm) compare to this study (26 µm, except in spring). However, implementation of lower cutting sizes did not result systematically in higher contamination. Thus, it suggests that particle uptake can be influence by other factors, such as the level and type of the contamination in the surrounding environment or abiotic parameters that influence the physiology of individuals (e.g. particle concentration and size).

4.2. Spider crab

In spider crab, shape composition tended to be homogenous between seasons as the prevailing shape ingested by spider crabs was systematically fibers (at least 72.2%). Even though CELL was mainly identified (at least 33.3%), some tendencies were noticed regarding polymer distribution. Indeed, an important proportion of particles remain unidentified in spring (38.1%) while non-negligible proportions of PA were found in autumn (27.3%) and summer (20.4%). Transparent fishing thread pieces made of PA were found stranding the body and legs of some individuals and the same pieces were also recovered inside the digestive tracts of few individuals. They certainly come from the transparent fishing net made of PA (ø = 8 µm) which was eaten by the spider crab during the caught. Welden et al. (2018) previously reported the adhesion of fibers similar to fishing nets onto the shell of spider crabs. Moreover, the ingestion of fishing gears pieces was already documented for another crustacean species, *Palinurus elephas* (Cau et al., 2023), suggesting that fishing gears can be a source of MP contamination at least for trapped individuals. Finally, no seasonal variations regarding AP and MP mean abundances were observed.

To the best of our knowledge, only one study reported AP contamination in *Maja spp.* (Welden et al., 2018). Most particles were fiber-shaped, like in this study, despite proportion was not reported. Regarding the level of contamination, 47.6% of individuals from the Arcachon Bay ingested AP, which was similar from occurrence found in the Celtic Sea (42.5%; Welden et al., 2018). Overall, AP abundance was 1.90 ± 3.06 $AP.ind^{-1}$, which is in accordance with the abundance found in individuals from the Celtic Sea (1.39 ± 0.79 $particle.ind^{-1}$, Welden et al., 2018). Nonetheless, MP uptake (1.09 ± 2.33 $MP.ind^{-1}$) cannot be compared due to the lack of information in the literature.

4.3. Common sole

Fibers were overwhelming whatever the studied season (at least 88.9%) as well as CELL polymers (at least 60.0%), even though in summer PET was found at a notable proportion (20.0%). Additionally, AP and MP abundances did not display seasonal variations.

Overall, fibers and cellulose were clearly overwhelming in soles' digestive tracts of the Arcachon Bay (more than 80%). Fibers and cellulose were already detected in sole collected in the Seine estuary while different shapes and polymers were described in individuals from the Adriatic Sea (Table 1). Additionally, sole from the Adriatic Sea showed similar level of contamination while individuals from Galway Bay were less contaminated than in this study (1.17 ± 1.89 $AP.ind^{-1}$, Table 1). Here, differences in methodologies do not seems to explain differences in the level of contamination. Indeed, lower mesh sizes show similar or lower contaminations. However, only two individuals were studied in Galway Bay, which limits representativeness of the contamination and thus proper comparison. Moreover, particles uptake could be influenced by other factors such as the contamination of soles' habitat or the age of the individuals.

4.4. Seabass

The most frequently observed particles in digestive tracts of seabass were fibers throughout all seasons (at least 71.4%) and the main polymer was cellulose (at least 85.2%). AP ingestion was lower in autumn (2.07 ± 5.31 $AP.ind^{-1}$) and higher in winter (6.65 ± 8.65 $AP.ind^{-1}$) while no seasonal variations were observed for MP abundance. This difference may be related to the seabass species caught, as it was *D. punctatus* in autumn and *D. labrax* in winter. Moreover, a lower K was found for individual fished in Autumn, which may express lower food intake and lower contamination. Additionally, European seabass (*D. labrax*) is a partial migratory species that moves during winter (de Pontual et al., 2023). Individuals fished in winter might have come from other geographical area for which the exposure level and type is not known. Yet, seasonal variation regarding AP contamination was not fully understood yet.

Over all seasons, fiber proportion was relatively similar to the one described in the literature (Table 1). In this study, CELL was overwhelming and this polymer type was also recorded in important proportion in Canary Island studies while PET or PE were mainly found in seabass from the Seine estuary and Turkish coast. Regarding mean AP abundance (4.07 ± 6.69 $AP.ind^{-1}$), it was in the same order of magnitude than in seabass from markets and farms in Canary Island (Table 1; Sánchez-Almeida et al., 2022). However, AP ingestion was at least three times higher in this study compared to farmed seabass from the Canary Islands, wild caught individuals from the Seine estuary (adult individuals of 2018), the Mondego estuary and Turkish coast (Table 1). The mesh size used hardly explain these differences as similar abundances were not systematically found when similar mesh size was used, plus lower meshes do not correspond to higher contamination. Thus, it suggests that other factors can influence AP uptake by seabass, such as their origin (aquaculture or wild) or the contamination of crossed zones.

4.5. Inter-species comparison and consequences of AP and MP uptake

Globally, ingestion was rather similar between the studied species as no trends were detected regarding AP and MP type (shape and polymer) and few differences were found regarding AP and MP abundances. Indeed, fibers and cellulose were mostly found in all studied species, similarly as in the water column of their close environment. Indeed, we found that fibers and cellulosic polymers represented respectively at least 79.3% and 50.8% in the water column and intertidal sediments near the sampling stations of oysters. In this study, we found that oyster soft tissues mainly contained fibers and cellulose too (respectively 93.9% and 61.8%). Similarly, contamination in the water column at the sampling station of spider crabs, soles and seabass was mainly composed of fibers (84.4%) and cellulosic polymers (69.9%; Lefebvre et al., 2023) and in digestive tracts of these species (at least 77.7% and 43.7%, respectively). Additionally, particles sizes were rather between 0.10 and 1.00 mm in studied species (from 33.1% in spider crab to 55.5% in soles) like in water column (at least 55.5% at same sampling site; Lefebvre et al., 2023). These findings support the hypothesis of an influence of the surrounding contamination in AP and MP uptake by the studied species in the Arcachon Bay.

However, soles showed lower MP abundances than spider crabs, and oysters to a lesser extent. The common sole is a benthic predator (Fanelli et al., 2022) while the spider crab has an omnivorous diet (Bernárdez et al., 2000) and the Pacific oyster is a filter feeder (Cognie et al., 2001). Previous studies investigated possible links between MP contamination in marine species and their feeding habits. For instance, it was suggested that omnivorous fish and generalist species are more prone to MP uptake (Garcia et al., 2020; Mizraji et al., 2017; Scacco et al., 2022). On the contrary, it was also suggested that carnivorous species and filter feeders can be more affected by this contamination (Bajt, 2021; Cáceres-Farias et al., 2023). Here, it seems like the predatory behavior of the sole did not favor AP and MP uptake. On the contrary, soles might have selected preys and avoid AP and MP ingestion. Meanwhile, the non-selective behavior and the omnivorous diet of spider crab may have increase AP and MP uptake. Additionally, some of the spider crabs sampled seem to have ingested fishing line pieces intentionally (see section 4.2), which may also have contributed to this result. The filter-feeding strategy of oysters may partly explain the difference of ingestion compared to common soles. Meanwhile, oyster ability to excrete pseudo-feces containing MP (Craig et al., 2022) could explain that this difference is less marked than the one between sole and spider crab.

The ingestion of AP and MP can lead to adverse effects for aquatic organisms. For instance, mussel species (*Mytilus* spp.*)* sp show a reduction of their growth rate and filtration rates when expose to MP fibers (Woods et al., 2018) or a cell internalization and inflammatory response when exposed to MP particles (Von Moos et al., 2012). Another study assessed the toxicity of MP fibers on goldfish (*Carassius auratus*) and found several effects such as an alteration of the predatory behavior or an increasing production of mucus (Liang et al., 2023). Moreover, MP can act as a vector of sorbed chemical pollutants (Cormier et al., 2021), and the distribution of these pollutants into the different organs of fish could be modify when contamination occurs via MP ingestion (Bour et al., 2020). Cellulosic fibers used in the textile industry, such as cotton and rayon, are not safer than MP. Indeed, their manufacturing involved the use of solvents, dyes and additives that can account for up to 27% of their mass (Lacasse et al., 2004). For instance, cotton microfiber can reduce mussel growth rate (Walkinshaw et al., 2023) and rayon microfiber could affect the enzymatic activity and gut microbiota of mussels (Jiang et al., 2024). However, toxicity studies on cellulosic textile fibers (natural and semi-synthetic) are very scarce to date (Kwak et al., 2022).

AP and MP interaction with biota are not restricted to the potential harmful impact on aquatic organisms. Organisms are also able to excrete these particles, as shown for bivalves after ingestion of MP microbeads (*M. gigas*, Choi et al., 2022), fibers, fragments and films (*Crassostrea virginica*, Craig et al., 2022) and for fishes after ingestion of MP fibers, microbead, irregular and tubular particles (Grigorakis et al., 2017; Ory et al., 2018; Santana et al., 2021). Excreted MP can be found in pseudo-feces or feces, and their presence can either increased or decreased the feces sinking rate as shown for microcrustacean or tunicate species for instance (Pérez-Guevara et al., 2021). Thus, MP transport between sea surface and seabed is also influence by interaction with biota (Clark et al., 2016; Pérez-Guevara et al., 2021). Motile and migratory organisms are probably able to influence horizontal transport of AP and MP by moving from an area to another via their excretion system (Pérez-Guevara et al., 2021).

5. Conclusion

This study described the uptake of AP and MP by four marine species at different seasons in the Arcachon Bay (South-West coast of France). AP and MP were reported in all studied species and at each studied season, with one exception only (no MP in the digestive system of soles in autumn). Shape distribution was globally stable over the studied seasons with a majority of fibers for all species, which highlights the considerable and all-pervasive contamination of fibers across different marine taxa. Regarding polymer types identified, distribution tended to be quite homogenous over seasons despite there were minor exceptions. Nevertheless, cellulose was systematically prevailing (at season and species levels). There were few seasonal variations regarding AP and MP uptake by Pacific oysters and seabass. This may be due to seasonal changes in the physiology of Pacific oysters (resting and growing period) and different species studied concerning seabass. AP and MP abundances in digestive tracts of common soles and spider crabs were similar over seasons. Biometrical parameters were mostly not correlated with AP and MP uptake, and the contamination in biota was similar to the contamination previously described in the water column and intertidal sediments of the Arcachon Bay.

Globally, this study highlights the predominance of fibers and cellulose particles in different marine species living in a coastal lagoon. These findings agree with recent studies that emphasize the need for a detailed description of the contamination including all AP (e.g. cellulosic fibers). Indeed, we need to correctly understand the current state of the AP contamination in marine systems in order to implement effective mitigation measures and develop representative risk assessment studies.

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CRediT authorship contribution statement

Charlotte Lefebvre: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bettie Cormier:** Writing – review & editing, Investigation, Formal analysis. **Florane Le Bihanic:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Gabriel Rampazzo Magalhães:** Writing – review & editing, Investigation. **Bénédicte Morin:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Sophie Lecomte:** Writing – review & editing, Resources, Methodology, Funding acquisition, Conceptualization. **Jérôme Cachot:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

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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