Environmental Pollution 352 (2024) 124121

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Review

Geographical and ecological factors affect microplastic body burden in marine fish at global scale☆

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ARTICLE INFO

Keywords:
Body size
Ingestion
Fish
Microplastics
Milieu
Trophic strategy

ABSTRACT

Microplastic (MP) contamination has been identified as a worrisome environmental issue at the global level. Fish are the taxonomic group more extensively investigated to assess MP contamination in marine environment. A large variability in MP bioaccumulation (i.e., body burden) was reported in fish but to date there is a dearth of information concerning the drivers underlying this process. The present systematic review aimed at summarizing the results of the scientific literature on MP body burden in the digestive tract of marine fish to quantitatively shed light on the contribution of different geographical (i.e., latitudinal origin of the sample, distance from the coastline and field- or marked-collected) and ecological (i.e., trophic strategy, milieu, and body size) factors driving bioaccumulation. The mean (±SE) MPs/individual was 4.13 ± 2.87, and the mean MPs/ww (i.e., MPs/g) was 5.92 ± 0.94. Overall, MP abundance expressed as MPs/individual of fish from tropical areas was significantly higher compared to the other latitudinal bands, with species sampled close to the coastline that accumulated a larger number of MPs compared to those collected offshore. Neither the trophic strategy, nor the milieu and the market or field origin of fish explained the MP body burden. However, fish body size resulted as a determinant of MP body burden (as MPs/individual), with small fish accumulating a lower amount of MPs compared to larger ones. Qualitatively, but not statistically significant, similar results were generally obtained for MPs/ww, except for an opposite, and significant, variation according to species body size. Our findings showed that geographical, rather than ecological factors represent the main drivers of MP body burden in marine fish, suggesting that environmental variables and/or local pollution sources mainly contribute to explaining the large variability underlying the ingestion and bioaccumulation processes of these contaminants.

1. Introduction

Plastic is one of the main materials defining our society (Van Rensburg et al., 2020). Because of their peculiar chemical-physical features, including durability, versatility, resistance, light weight and low-cost production, plastic production has increased since 2004 from 225 million tons to 367 million tons in 2020 (PlasticsEurope, 2022), with a 4% annual increase from 2012 up to date (Jambeck et al., 2015; García-Rivera et al., 2017). This massive global production and use often resulted in an improper management on the post-consumer stage of plastic materials and in the subsequent release of a huge amount of plastic waste into the environment. The plastic leakage to the environment has been projected to double to 44 million tons (Mt) a year at global level (OECD, 2022). Thus, plastic pollution is considered as one of the top 10 emerging global environmental issues that our society must face up (Peng et al., 2020). Although plastic waste has been found in all the ecosystems worldwide, the attention of the scientific community has been mainly focused on marine ecosystems. Plastic items with different shape, size, color and polymer composition, has been identified from the surface to the seafloor of all the seas and oceans worldwide, including the Artic and the Antarctica (Rota et al., 2022). In 2019, 170 trillion plastic items, corresponding to a mass of 2.33 million tons (Eriksen et al., 2023), covered the global surface of the oceans. However, if plastic production and use remain unchanged, it has been estimated that the mass of buoyant plastic items could reach 6.67 million tons by the 2050 (Lebreton and Andrady, 2019). Once in marine ecosystems, plastic items experience weathering due to physical (Efimova et al., 2018; Chubarenko et al., 2020), chemical (Andrady, 2011, 2017; Song et al., 2017) and biological (Kooi et al., 2017) processes, leading to degradation and/or fragmentation of large-sized items in the small-sized ones.

☆ This paper has been recommended for acceptance by Eddy Y. Zeng.

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https://doi.org/10.1016/j.envpol.2024.124121
Received 27 January 2024; Received in revised form 5 May 2024; Accepted 6 May 2024
Available online 7 May 2024

Microplastics (MPs) are any synthetic solid particle or polymeric matrix, insoluble in water, with regular or irregular shape and with size ranging from 1 μm to 5 mm (Frias and Nash, 2019). Microplastics contribute to a global contamination, which includes surface water, sediments and shorelines, as well as biota (Gola et al., 2021; Sharma et al., 2023; Ugwu et al., 2021). Either primary (i.e., manufacturing origin) or secondary (i.e., as a consequence of weathering of large-sized items) MPs enter marine environment through different sources, mainly including coastal land and river input, atmospheric transportation, and offshore operation activities (Andrady, 2011; Zhang et al., 2020). The most of primary MPs (98%) come from terrestrial environment (Peng et al., 2020), while river transport represents the main source of secondary MPs (Xu et al., 2020).

Fish represents the taxonomic group more extensively investigated to assess MP contamination in marine environment (see e.g., Parolini et al., 2023). Microplastics have been detected in more than 890 fish species from shallow to deep waters, marine and estuarine ecosystems (Azevedo-Santos et al., 2019; Markic et al., 2020; Zazouli et al., 2022). Approximately half of all fish sampled globally has been estimated to ingest MPs, with a mean abundance of ca. 3.5 items per fish (Wootton et al., 2021). Fish can ingest MPs directly, usually by confusing them for food or through accidental ingestion (Worm et al., 2017), or by secondary digestion after ingestion of preys that already contained MPs (Watts et al., 2014). Secondary digestion refers to trophic transfer and can potentially lead to MP bioaccumulation and biomagnification over the trophic chain (Provencher et al., 2019; Zhang et al., 2019; Miller et al., 2020). The ingestion and accumulation of MPs can cause diverse detrimental, albeit variable, impact on fish, including the decrease in consumption, digestion, and assimilation of food, changes in growth and feeding behavior, physiological and immunological responses, while neutral effects on body condition, fecundity, hatching success and survival were observed (Hossain and Olden, 2022).

Ingestion of MPs represent the main exposure pathway for fish (Li et al., 2021). The amount and the type of MPs ingested by different fish species can be affected by different individual and ecological factors, including body size, feeding strategy, habitat and position in the water column, and trophic level (Chen et al., 2022). Moreover, considering that MPs in the water are the main contributor to MP body burden of fish (Chen et al., 2022) and the global variation of MP abundances in marine ecosystems, the geographical origin and the distance from the coastline might affect MP ingestion and accumulation. Lastly, a variable amount of MPs has been found in digestive tracts, gills and tissues of diverse commercially harvested fish species and individuals collected from markets (Wootton et al., 2021; Dawson et al., 2021; Mistri et al., 2022). Despite these findings, the information concerning the relationship between the MP body burden in marine fish with ecological and geographical variables is still limited, but it deserves attention. In fact, the identification of potential ecological and geographical drivers of MP ingestion in marine fish represents a pivotal step in determining the exposure and the impact towards fish globally. Moreover, it also allows enlarging the knowledge on the mechanism of accumulation and the transfer across the marine trophic chain (Wootton et al., 2021; Chen et al., 2022). Lastly, as fish represent a major source of protein for humans, the ingestion of fish contaminated by MP might represent a risk for human health. The ingestion of MP has been observed in the digestive tract of diverse fish species intended for human consumption (Alberghini et al., 2022), but rarely in edible tissues (e.g., muscles; Kwon et al., 2020). As most fish are eviscerated before consumption, direct human exposure to MPs should be low or negligible. However, the evisceration does not necessarily eliminate the risk of human intake of MPs and related additives, so the study of MP body burden in fish represents a priority for food safety assessment.

The present study aimed at providing a global synthesis of MP bioaccumulation in marine fish to identify the main drivers affecting this process. Bioaccumulation (or body burden) of MPs occurs when their uptake from the environment by all possible routes, from any source, including prey, exceeds the capability of the organism to excrete them (Wang et al., 2016). We explored the contribution of geographical (i.e., geographical origin of sample, distance from the coastline and wild or market origin of fish) and ecological (i.e., trophic strategy, milieu, and body size) factors on MP body burden in marine fish species. Investigating the global extent and the contribution of biogeographical and ecological factors potentially affecting the bioaccumulation should help to identify the risk or propensity for marine fish to MP exposure. Moreover, this information should allow developing and/or actuating strategies to safeguard not only environmental, but also food safety and human health, because of the notable commercial value of diverse fish species.

2. Methods

2.1. Data extraction and selection

A systematic review of the global literature on MP contamination in individuals of diverse marine fish species was performed following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Moher et al., 2009), according to an established protocol (i.e., Miller et al., 2020; Parolini et al., 2023). The literature search was performed in Google Scholar, Scopus and Web of Science search engines and it was concluded in July 2023, covering a period ranging between 2010 and 2023. For literature search, we included the following search strings: “microplastics + marine + fish”, “microplastics + ingestion + fish”, “microplastics + bioaccumulation + fish”, “microplastics + ingestion + marine + fish” and “microplastics + bioaccumulation + marine + fish”.

The systematic review of the literature identified ∼17,400 documents, including paper reviews, meta-analyses, scientific papers, proceeding of conferences and thesis dissertations. After removing duplicate records, publications concerning studies on MP bioaccumulation in freshwater organisms (but studies performed in brackish environments were included even if analyses were performed on usually freshwater species; e.g., Rasta et al., 2021; Sainio et al., 2021), laboratory experiments assessing MP ingestion and/or bioaccumulation, bioaccumulation of MPs in tissues and organs other than the gut, toxicity assessment of MPs towards marine fish, and monitoring of macroplastics (i.e., plastic debris larger than 5 mm in size) were excluded. Full-text articles were analyzed to extract data of MP body burden to identify the ecological and geographical variables driving bioaccumulation in marine fish.

Two variables accounting for the MP body burden were considered, namely the number of MPs per individual (MPs/individual) and the number of MPs per wet weight (MPs/ww, i.e., MPs/g) (see also Parolini et al., 2023). The presence or the absence of MPs was not considered as a binary variable. Data of MP body burden were considered at the species level, but we also included information at the genus level when papers did not report species-specific information (∼2% of the datapoints). We excluded data at taxonomic levels higher than the genus, as well as data obtained on different genera but reporting only the average level of MP contamination (i.e., a single mean datum for multiple genera/species). Data that were reported in different units compared to those mentioned above (e.g., data reported as a percentage, or no quantification of the number of items isolated) were not considered for the analyses. The lack of polymer characterization of putative MPs with a validated laboratory method (e.g., FTIR or Raman Spectroscopy, or gas chromatography-mass spectrometry) was not considered as an exclusion criterion because it should have resulted in the exclusion of too many reports from the dataset (see Miller et al., 2020). At the end of this procedure, 257 publications containing 1,629 data on MP body burden were selected (see Appendix A). Only a limited number (n = 76) of these publications were used in a previous work (Parolini et al., 2023). After the identification of suitable papers, we extracted information on the ecological and geographical factors potentially affecting MP body burden of fish (see below). At this step, we had to omit an additional datum because it referred to a genus (*Pachycormus*) extinct during the Lower Jurassic (Zhu et al., 2019). Thus, 1,396 data on MP/individual from 241 studies, and 231 data on MPs/ww from 47 studies were isolated. However, 5 data (2 concerning MPs/ww and 3 concerning MPs/individual) from 3 studies (Ibrahim et al., 2017; Ningrum et al., 2019; Nabila and Patria, 2021) were not considered for statistical analyses (but maintained in the description of the MP features; see Results 3.1) because they were identified as statistical outliers. The final dataset used for statistical analyses was therefore 1,393 MPs/individual and 229 MPs/ww data from 238 to 45 studies (31 studies contained both information), respectively. Moreover, we also extracted, only when available because of the large inconsistency of these data among the studies, the information on intrinsic features of MPs, such as the polymeric composition, the colour, the size and the shape.

2.2. Geographic and ecological data collection

For each species/genus included in the dataset, we collected information about some ecological features. Information was retrieved from the FishBase website (https://fishbase.org) and from scientific literature. First, information about its trophic level, coded on a four-level scale: 1) primary consumers, feeding mostly on phytoplankton and/or algae, 2) secondary consumers, feeding mostly on zooplankton, small invertebrates and corals, 3) tertiary consumers, feeding on invertebrates and small fish, and 4) top predators, feeding mostly on fish and cephalopods. Second, the milieu mostly exploited by each species/genus: 1) bentho-pelagic taxa, 2) demersal taxa, 3) pelagic taxa, 4) reef-associated taxa. Third, we collected information about whether the species/genus lives in estuarine, coastal or offshore waters (hereafter "distance from the coastline"). Fourth, for each species we also collected information about the mean and maximum body length and the maximum body mass. Then, we categorized the information on maximum body length into four levels: 1) small: species reaching a maximum length of 20 cm (average maximum length: 15.24 cm; average mean length: 11.56 cm; average maximum body mass: 0.30 kg), 2) medium: species ranging between 20.1 and 50 cm in length (average maximum length: 34.67 cm; average mean length: 22.11 cm; average maximum body mass: 1.19 kg), 3) large: species ranging between 50.1 and 100 cm in length (average maximum length: 72.35 cm; average mean length: 38.73 cm; average maximum body mass: 4.14 kg), 4) very large: species larger than 100 cm in length (average maximum length: 172.88 cm; average mean length: 87.63 cm; average maximum body mass: 61.54 kg). The thresholds for each size category was chosen because both average mean and maximum length of a given level was approximately half of the value of the following level, and to provide an approximatively even data distribution among the levels. However, different categorizations of body size (e.g., $\leq$10 cm = very small, 10 cm $<\leq$ 20 cm = small, 20 cm $<\leq$ 40 cm = medium, 40 cm $<\leq$ 80 cm = large; >80 cm = very large; or $\leq$ 25 cm = small, 25 cm $<\leq$ 50 cm = medium, 50 cm $<\leq$ 75 cm = large, >75 cm = very large) provided results qualitatively similar to those reported below (details were not included for brevity). We opted for using maximum body length because it was the most available information about body size, at least for the species included in our dataset, and because a categorization allowed also to including genus-level data, thus the entire dataset. In addition, because the information reported in FishBase was either the standard length or the full length (i.e. respectively, excluding or including the length of the tail, that is usually a small fraction of the total length), such a procedure allowed us to include most of the species in the same category (e.g. a species with total length of 25 cm and standard length of 21 cm was always included in the category of medium-sized species). However, the analyses were also repeated on the smaller samples of species for which mean and maximum body length were available.

When data were available only at the genus level, we used the most common features among the species composing each genus. For example, if a genus included 7 species, of which 5 are secondary consumers and 2 tertiary consumers, the genus was coded as a secondary consumer. However, data at the genus level were omitted for the collateral analyses using mean and maximum body length.

For each available datum, we also collected two information about the sampling location. As the exact coordinates of fish sampling were not available for a large number of papers, we relied on a categorization indicating if the sample was collected in the tropical (i.e., between the Tropics at latitudes between 23° 27′ and −23° 27′), subtropical (i.e., between the Tropics and polar circles at latitudes between 23° 27′and 66° 33′, and −23° 27′ and −66° 33′) or polar (i.e., latitudes higher or smaller than 66° 33′ and −66° 33′, respectively) region (hereafter "latitudinal band"; Parolini et al., 2023). As in many cases the traceability of market fish is unknown, a binary factor indicating if the analyzed sample was collected in a market or in the wild was considered to explore whether species of commercial interest are differently or similarly contaminated than the other ones. Considering the caveat on the lack of geographical coordinates, we were not able to test for the relationships between the MP body burden and local factors such as coastal population density, mouths of large rivers and predominant marine currents.

2.3. Statistical analysis

Variation in the number of MPs per individual (MPs/individual) and MPs per wet weight (MPs/ww) according to ecological and geographical features was analyzed using linear mixed models (LMMs) with the *lmer* function fitted with the package *lme4* (Bates et al., 2015) implemented in R (version 3.2.1; R Core Team, 2019). As both dependent variables were not normally distributed, they were included in the models after a square root transformation. Statistical significance was set at $P < 0.05$.

The models included trophic level, milieu, body size category, distance from coastline, latitudinal band and market (yes = 1; no = 0), as multilevel fixed factors. Because many papers reported data on multiple species/genera, the random factor "ManuscriptID" was also included in the models to account for non-independence of the data collected by single studies (e.g., same location, same authors, same analytical methods). Models were repeated replacing body size category with mean body length and maximum body length, respectively. These continuous covariates were log-transformed before analyses. Collinearity among predictors was explored using the package *performance* (Lüdecke et al., 2021). Variance inflation factor was always smaller than 2, thus showing no collinearity among predictors.

3. Results

Regardless the units expressing MP body burden and including the outliers, the publications returned the MP abundance measured in the digestive tract of 758 fish species, belonging to 432 genera and 49 orders.

3.1. Body burden and MP features

No MP in the digestive tract of marine fish was observed in 190 cases (13.5% of the total data) considering body burden in terms of MPs/individual, while only in two cases considering MPs/ww. Considering all the data extracted from studies meeting the eligibility criteria, excluding the statistical outliers, the mean (±SE) of MPs/individual in marine fish species was 3.79 ± 0.26 (n = 1,392), while the mean MPs/ww was 2.67 ± 0.41 (n = 229). The mean length (± standard deviation) of MPs found in the digestive tract of marine fish from publications satisfying the eligibility criteria was 1.438 ± 0.956 mm (range 0.002–3.825 mm). The main shape (mean ± standard deviation), in terms of the ratio between the number of fibres and items with other shapes (i.e., fragment, film, pellet and foam), was 0.708 ± 0.268, suggesting a predominance of fibres contributing to MPs body burden of fish. The 71% (182 of 257) of studies provided the characterization of polymer composition of MPs isolated from fish digestive tract. Sixty-one different polymers were identified during chemical characterization of MPs. Fifty-eight polymers were attributable to plastics, while three were natural polymers. Polyethylene was the most frequent polymer composing MPs (33%), followed by polypropylene (14%), polyethylene terephthalate (12%), polyamide (11%), polyester (8%) and polystyrene (5%), while in 17% of papers other polymers (polymers that did not refer to those listed as the more frequent) were the main component of the MPs isolated from fish (Fig. 1). The 5% (14 of 257) of studies identified natural polymers, specifically cellulose, as the main polymer composing MPs isolated from fish. The more frequent colours of MPs were blue (41%) and black (32%), while other colours were less represented (Fig. 1).

3.2. Geographical and ecological correlates of MP body burden

The body burden expressed as the number of MPs per individual (i.e., MPs/individual) showed a significant variation according to latitudinal belt ($F_{2,359.52} = 7.66$; $P < 0.001$), distance from the coastline ($F_{2,1213.58} = 3.61$; $P = 0.027$) and body size category ($F_{3,1166.65} = 4.66$; $P = 0.003$). In particular, MPs/individual significantly decreased at increasing latitudinal belt, with the largest values observed between the tropics (i.e., Tropical latitudinal band; Fig. 2).

In addition, MPs/individual progressively decreased with distance from the coastline, being the highest in estuarine species and the lowest in those living in offshore waters (Fig. 2B). Moreover, MPs/individual increased with body size category, reaching the minimum and the maximum values, respectively, in the smallest and the largest species (Fig. 2E). This effect was also confirmed in the subset of species for which mean body length (0.002 ± 0.001, $P = 0.021$) and maximum body length (0.009 ± 0.004, $P = 0.030$) were available. However, trophic level ($F_{3,1164.88} = 0.90$; $P = 0.44$; Fig. 2C) and milieu ($F_{3,1171.32} = 4.66$; $P = 0.80$; Fig. 2D) of the species did not significantly explain any variation in MPs/individual, as well as no difference was documented in fish sampled in markets vs. in the wild ($F_{1,1324.98} = 2.26$; $P = 0.13$; Fig. 2F).

Concerning the body burden expressed as the number of MPs on wet weight (i.e., MPs/ww), the only significant predictor was body size category, but in the opposite direction than for MP/individual ($F_{3,176.58} = 3.34$; $P = 0.021$). Indeed, the far highest values were observed in the smallest species, while the other categories showed a similar MP body burden (Fig. 3E). All the other predictors did not explain a significant variation in MP/ww (latitudinal band: $F_{1,39.07} = 1.56$; $P = 0.22$; distance from coastline: $F_{2,180.55} = 0.02$; $P = 0.98$; trophic level: $F_{3,174.89} = 0.55$; $P = 0.65$; milieu: $F_{3,177.50} = 1.79$; $P = 0.15$; market: $F_{1,38.88} = 0.04$; $P = 0.84$). However, latitudinal belt and distance from the coastline showed a very similar trend to MPs/individual (Fig. 3A–F).

4. Discussion

4.1. General pattern of MP body burden

The present review summarizes the results of a large scientific literature on MP bioaccumulation in marine fish and showed that mean body burden in terms of MPs/individual resulted higher compared to previous investigations (2.8 ± 1.3; Wootton et al., 2021 and 2.6 ± 0.2; Markic et al., 2020). This discrepancy could be due to the higher number of data included in our dataset, which also considered the results from recent papers reporting very high MP body burden. Indeed, the MP body burden in the digestive tract of marine fish was confirmed to be highly variable and heterogeneous among orders, genera and species (Martí et al., 2020), as observed for other taxonomic groups (e.g., Savoca et al., 2019; Schuyler et al., 2014; Parolini et al., 2023). Fibres resulted as the dominant shape of MPs in marine fish in accordance with the shape of MPs observed in intertidal ecosystems (Mizraji et al., 2017), deep-sea sediments (Woodall et al., 2014), surface waters (Hale et al., 2020) and different marine taxa (Parolini et al., 2023). This finding can depend on large length-to-diameter of fibres, which are more prone to be retained into the organisms compared to fragments, foams, pellets or films, resulting in a larger body burden (Qiao et al., 2019). The main colours of MPs accumulated in marine fish were blue and black, but also transparent, agreeing with previous findings on fish (Martí et al., 2020; Ugwu et al., 2021) and a global survey reporting that the 47% of floating

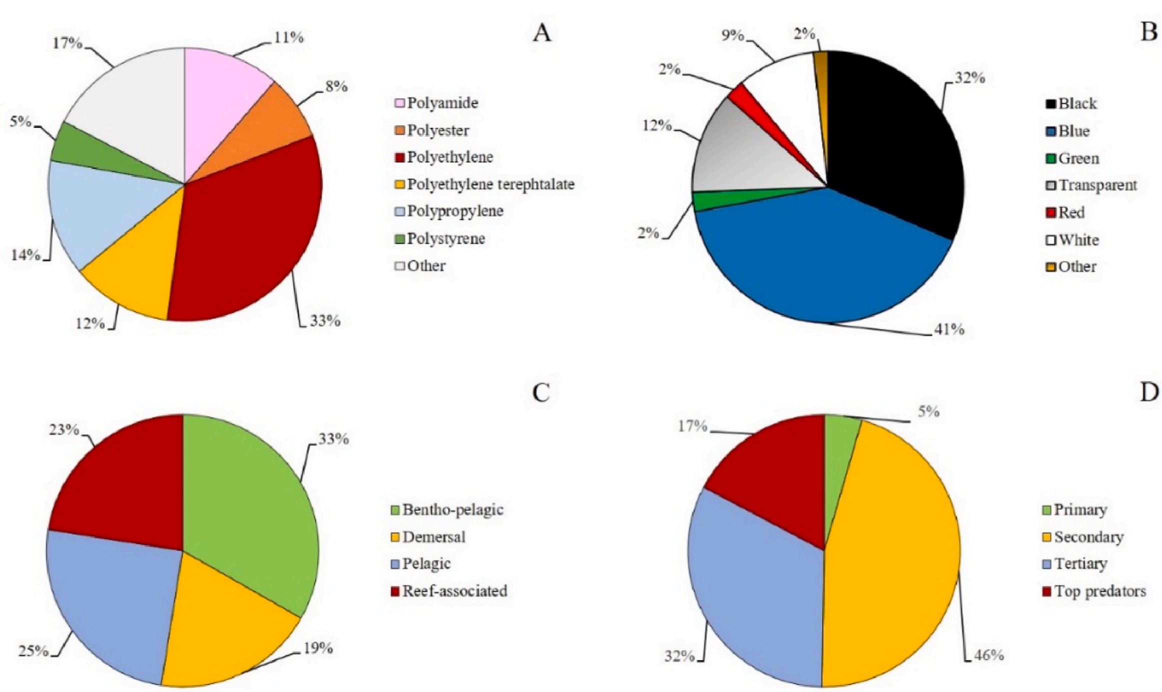

Fig. 1. Frequency of polymers (A) and colours (B) characterizing the MPs isolated from the digestive tract of marine fish, as well as fish grouped for their milieu (C) and position in the trophic chain (D). 'Other' category refers to all the polymers (A) or colours (B) not included in the main categories. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

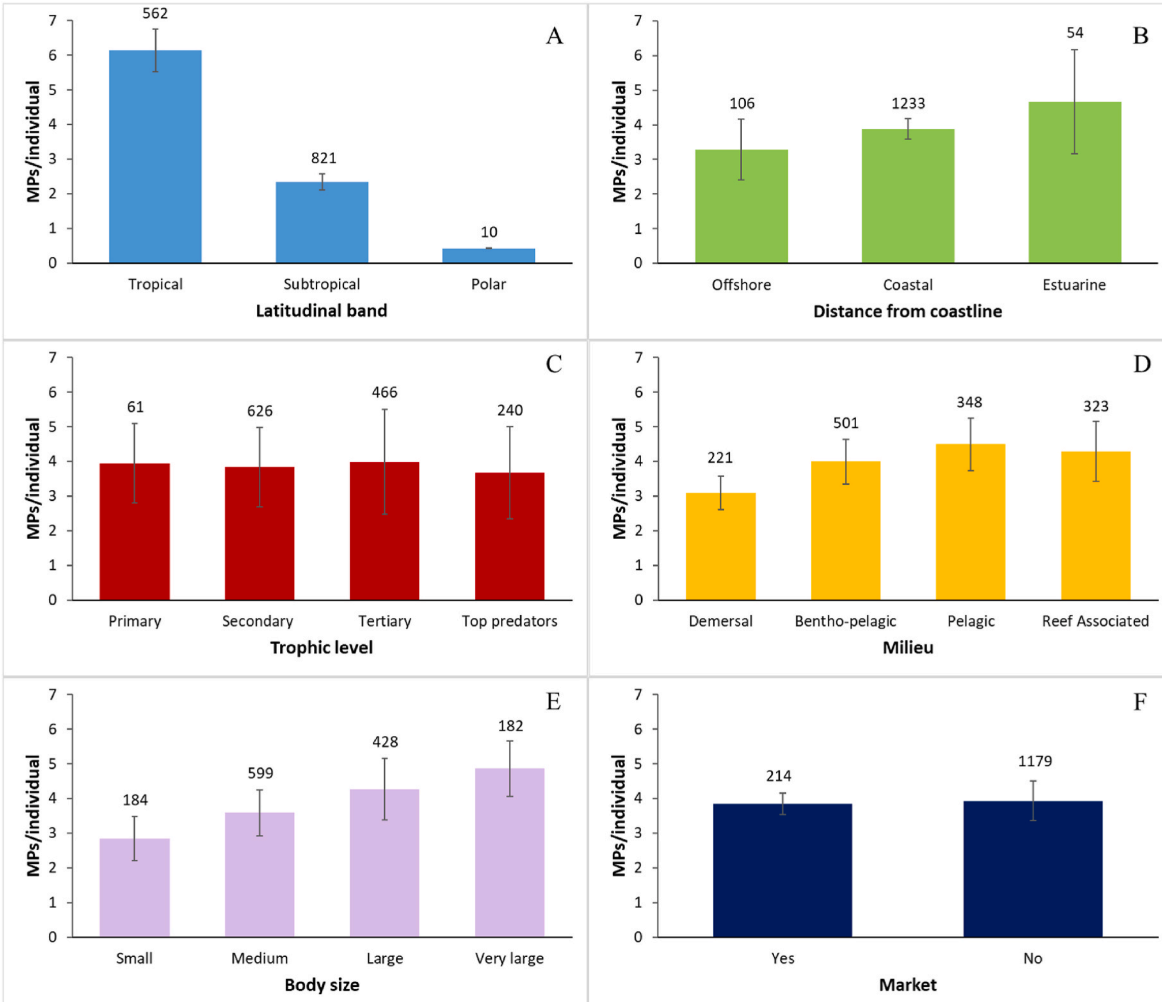

Fig. 2. Mean (±SE) microplastic body burden expressed as the number of MPs per individual (i.e., MPs/individual) depending on latitudinal band (A), distance from the coastline (B), trophic level (C), milieu (D), body size (E) and market or field origin (F). The number of datapoints per each category is reported above the histograms.

plastic items were clear/transparent and black (Martí et al., 2020). The prevalence of blue MPs in fish might depend on prey misdetection because floating MPs can be confounded with prey of the same colour (e.g., Ory et al., 2017; Rios-Fuster et al., 2019). For instance, the plankton-feeder fish species Amberstripe scad (*Decapterus muroadsi*) showed a preference for blue items because their natural prey are blue copepods (Ory et al., 2017). Moreover, it has been demonstrated that animals observing plastics from below preferentially ingest blue-to-black coloured items (Santos et al., 2016). Polyethylene and polypropylene were the main polymers composing MPs isolated from marine fish, followed by PET/polyester and PA. This fingerprint matches that observed for MPs floating or sinking in marine environments (Watt et al., 2021), as well as that recorded in other taxonomic groups of marine organisms (Parolini et al., 2023).

4.2. Geographical drivers of MP body burden

Regardless of their size, plastics can be transported over long distances in the ocean through horizontal large-scale flow, resulting in the massive accumulation located in the subtropical circulation known as the 'garbage patches' (Onink et al., 2019; van Sebille et al., 2020). Because of the lower occurrence and concentrations observed in the tropics and polar areas, the models estimated that the MPs should have similar patterns (van Sebille et al., 2015). However, we found a different geographic pattern of MPs body burden in fish, with the largest contamination recorded within the Tropical latitudinal belt. These results could be partially explained because of the 88% of plastics entering the ocean come from inland, with an estimated amount of 1.15–2.41 million tons of plastic waste flowing annually from rivers into the ocean (Jambeck et al., 2015; Lebreton et al., 2017). Specifically, the main rivers contributing to the plastic load of oceans flow within the tropical latitudinal band. A recent modelling study confirmed that rivers from Asia, Africa, and South America contribute for about the 90% of the global riverine plastic export to the seas, mainly transporting large-sized plastics (i.e., macroplastics) coming from diffuse sources because of the mismanagement of solid waste (Strokal et al., 2023). Once in marine environment, plastic waste can experience degradation and/or fragmentation due to different weathering processes (Turner et al., 2020). Weathering results in the release of MPs of secondary origin, which together with MPs of primary origin can interact with marine organisms at each level of the ecological hierarchy, and therefore explain the present findings.

This finding could also explain why the largest MP body burden was observed in fish sampled in estuarine and coastal ecosystems compared to open sea. Although plastics and MPs can be pushed offshore by wind-induced waves and nearshore currents and become stranded in sediments when washed ashore by waves (van Sebille et al., 2020), local hydrodynamic conditions and factors, such as tidal and coastal currents,

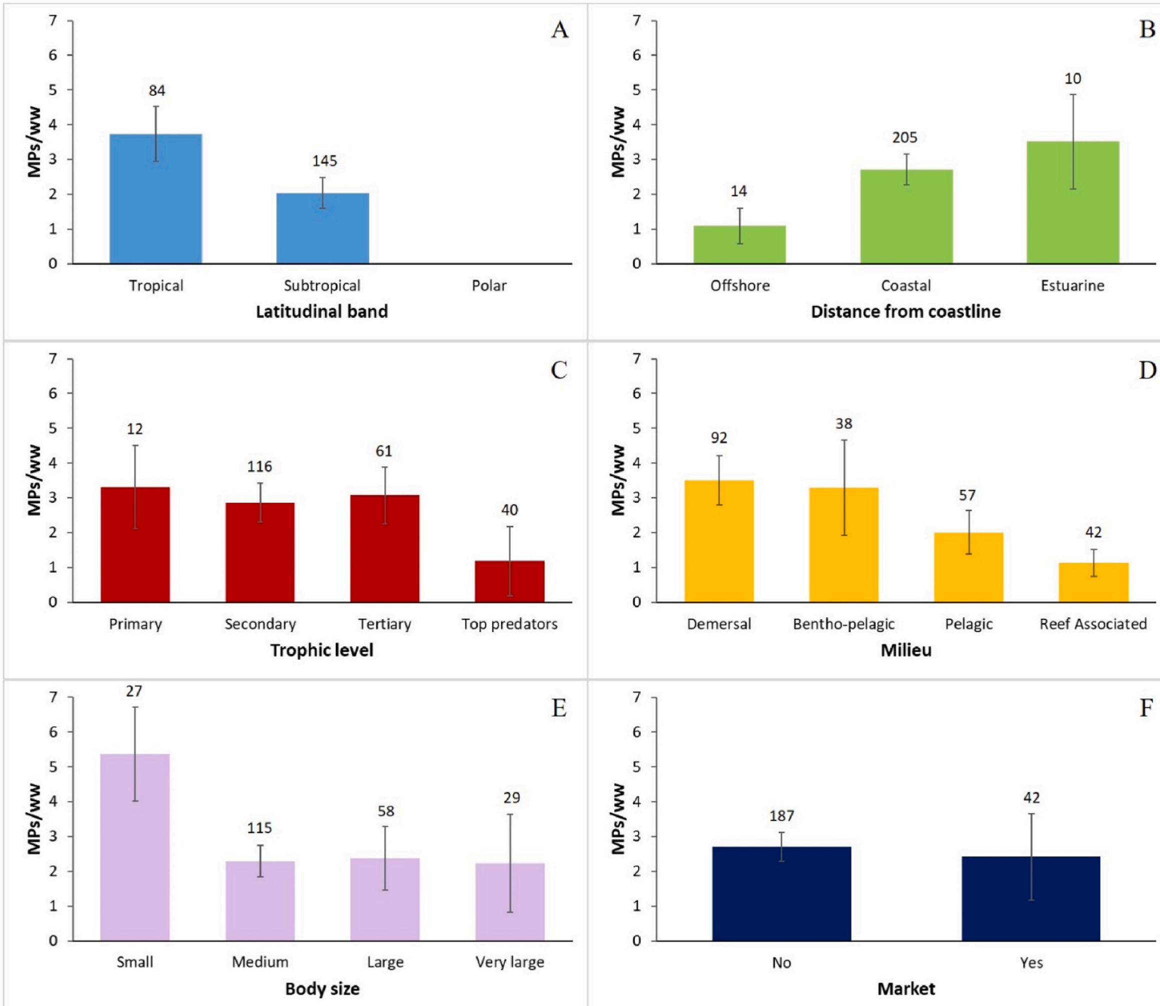

Fig. 3. Mean (±SE) microplastic body burden expressed as the number of MPs on wet weight (i.e., MPs/ww) depending on latitudinal band (A), distance from the coastline (B), trophic level (C), milieu (D), body size (E) and market or field origin (F). The number of datapoints per each category is reported above the histograms.

strandings, winds, waves and thermohaline gradients (Zhang, 2017) can affect their transport in poorly deep coastal waters. Moreover, the tectonic morphology of continental margins might control the transfer pathways of plastics from rivers to deep marine environments, such as submarine canyons and deep trenches (Kane and Clare, 2019). The combination of such and other factors, including the intense coastal activities worldwide (Jambeck et al., 2015) and direct littering near beaches (GESAMP et al., 2016), suggests that local environmental variables, coupled with local sources of plastic input, can influence the bioavailability and the accumulation of MPs in marine fish, regardless of their milieu, position in the trophic chain and body size.

We note that our previous investigation of MPs in organisms from different taxonomic groups did not show any clear geographical pattern of MP body burden (Parolini et al., 2023). The apparent discrepancy between the findings of these two studies might be due to different factors. In particular, the current dataset includes a much larger sample size that allowed us to collect data over a much wider geographic coverage, and therefore potentially capturing differences that in the previous one were not evident. In addition, and most importantly, in the previous study we analyzed geographic variation in MP contamination in multiple taxa, including, beyond fish, also zooplankton, bivalves mussels, crustaceans, as well as marine mammals, birds and reptiles. Therefore, the previous study did not provide evidence for spatial variation in MP contamination in the entire marine community, composed of taxonomic groups that differ in body size and pathways of ingestion, accumulation and egestion of MPs, possibly precluding the opportunity to provide a clear and unambiguous picture for the biota. In contrast, focusing on a single taxonomic group, such as fish, this variability was inevitably reduced, shedding light on geographical differences of MP bioaccumulation.

Lastly, regardless the geographical origin of the fish, no differences in MP body burden occurred between wild-caught and commercial fish-market, suggesting that MP contamination comes from the environment where they grow up and/or were collected, rather than from the market. Indeed, several studies showed that fish collected from markets, wild-caught and bred for aquaculture purposes showed a very large variability in the amounts of MPs in their guts, gills and tissues (Wootton et al., 2021 and references therein), precluding the opportunity to shed light on differences in body burden related to the origin of the fish.

4.3. Ecological drivers of MP body burden

Several studies supposed that different ecological factors, including milieu, feeding strategies, position in the trophic chain and body size, can affect the amount of ingested and accumulated MPs in marine fish (Wootton et al., 2021 and references therein). However, the literature is not coherent about the contribution of each specific feature on MP body burden in fish. Concerning the milieu and feeding strategies, some studies reported that pelagic feeding species ingest higher amount of MPs compared to bottom feeding species (Lusher et al., 2013; Rummel et al., 2016). For instance, pilchards are unable to select the ingested particles (Fossi et al., 2018) and might ingest indiscriminately MPs together with their planktonic prey (Renzi et al., 2019). In contrast, other investigations observed significantly higher MP body burden in demersal rather than pelagic fish (Neves et al., 2015; Bellas et al., 2016; Jabeen et al., 2017). Demersal and benthic species can be more contaminated than pelagic ones because they can ingest plastic debris close to the seafloor, which is the ultimate sink for plastics of any size in marine ecosystems (Woodall et al., 2014).

Similarly, some studies suggested that marine fish at low trophic levels could suffer a greater risk of MP ingestion (and accumulation) than those at the higher ones (e.g., Walkinshaw et al., 2020). Small, planktonic feeders might experience the greatest risk of ingestion and accumulate the highest amount of MPs because of their peculiar ecological features (i.e., particulate- and filter-feeding strategies; Collard et al., 2017; Capone et al., 2020). Clupeids such as anchovy, sardines and sprats, are generally mid-water feeders that selectively ingest plankton or semi-selectively filter suspended particles from the water using their gill rakers, but they can often switch between the two feeding strategies (James, 1988). In some studies, clupeids showed higher (i.e., more than twice) MP body burden compared to other fish families (Covernton et al., 2021). Moreover, MPs were detected more frequently and in higher amount in detritivores than in carnivore fish (Covernton et al., 2021). All these findings disproved the expectation that fish at higher trophic level can accumulate more MPs than lower trophic levels via bioaccumulation and/or biomagnification across the food web (Carbery et al., 2018; Watts et al., 2014). It is therefore difficult to generalize such contrasting results at a local scale, which may depend on the specific features of each study area and fish community. Indeed, our statistical analyses showed that neither the trophic strategy nor the milieu affect MP body burden. These findings agree previous studies demonstrating that the ingestion, the amount in the digestive tract and the occurrence rate of MPs in marine fish was not explained neither by the milieu (Wootton et al., 2021) nor by the trophic level (Walkinshaw et al., 2020; Gouin, 2020; Miller et al., 2020; Covernton et al., 2021).

The lack of significant differences in MP body burden between fish belonging to the different milieu or trophic level might have resulted because of the considerable intra- and interspecific variability in ingestion and accumulation of MPs, but also because data of species differing in milieu and trophic level could be collected in different latitudinal bands. Thus, the large geographic variation in MP body burden might have masked more subtle ecological effects, which could be evident in single study areas. However, these results cannot be considered as conclusive because there is a dearth of information for many species and taxonomic groups that are understudied. Thus, further studies to clarify the bioaccumulation and/or biomagnification potential in wild caught neglected fish species, with different habits and role in the trophic web are necessary.

Intra- and inter-specific variability in MP body burden might be due to the different body size and/or age of wild-caught organisms, as shown in literature both at the intra- and inter-specific levels. Our analyses returned that body size can be considered a determinant of MP body burden, whereby larger is the species higher is the number of MPs accumulated, coherently with previous studies on specific marine fish (e.g., Alomar et al., 2017; de Vries et al., 2020). This trend may occur because, during different ontogenetic or life-stages, organisms can differ in the rate of MP ingestion and accumulation (Alomar et al., 2017; Steer et al., 2017; Bernardini et al., 2018), as well as in the response to MP exposure (Pannetier et al., 2020). The body growth along individual lifespan represents one of the main factors affecting the rate of MP ingestion and accumulation (Prokìc et al., 2019) because a large body size requires a greater amount of food intake and consequently a larger MP burden. However, our results did not completely agree those from a previous work performed by Covernton et al. (2021), showing a minor effect of body size on the overall mean MP gut concentrations, with negative or neutral relationships between average total length and MP concentration. This discrepancy could be due to the different statistical approaches, size of the dataset and length information used to check the relationship between body size and MP concentration in the digestive tract of fish. Nevertheless, Covernton et al. (2021) pointed out a positive and consistent correlation between body size and MP occurrence rate. However, and compatibly with this finding, we showed an opposite trend when considering the MP body burden expressed as MPs/ww. Therefore, overall, these studies suggested that larger fish are more prone to ingest MPs, but they do not necessarily retain more items in their digestive tracts, compared to small ones. Probably, larger fish need to eat more food than smaller fish due to metabolic scaling (Clarke and Johnston, 1999) and they tend to eat larger prey items and a wider range of prey sizes (Scharf et al., 2000), resulting in a higher ingestion of MPs. However, this would not necessarily result in a larger MPs concentration in their bodies when normalized to the body weight.

4.4. Limitations on results interpretation

Although we showed that geographical factors can drive the accumulation of MPs in marine fish, we did not find any significant relationship between MP body burden, milieu and trophic level. This might be due to the high variability in MP abundance measured in different fish species and locations, which in turn may depend on the diverse approaches used to collect and to process samples or to methodological/analytical issues for isolating and characterizing MPs. All these factors can cause the scattering of data, precluding the identification of clear, solid relationships between the considered variables. The main limitations can be referred to the lack of harmonization and standardization of sampling strategies and analytical methods for the isolation and the identification of MPs. Fish samples were collected in different geographical areas, often opportunistically, with different fishing techniques or bought from the market. The collection of a balanced sample of fish in terms of body size, geographical origin or life stage (i.e., age) is often not possible and this information is rarely considered and reported in studies of MP contamination. As many studies highlighted that the MP body burden can vary according to the ontogenetic or life stage of fish, the lack of this information can affect the interpretation of the data, mainly concerning the relationship between MP body burden and fish body size. Moreover, different fish species belonging to the same trophic level or milieu were collected in different geographical areas. As MP body burden significantly differs between geographic areas, integrating results obtained on different fish species of the same trophic level or milieu collected in different areas might mask the relationships among these variables. Another critical issue in data interpretation and analysis refers to the inconsistency in the definition of the lower threshold for the size of MP and, mainly, in the lack of quality assurance and quality control analyses, potentially causing wrong counting of MP abundances due external or laboratory contamination. Similarly, a large proportion of the studies (29%) did not perform the chemical identification of the polymer composition of MPs isolated from the digestive tract of fish through the application of validated laboratory methods (e.g., FTIR or Raman Spectroscopy, or gas chromatography-mass spectrometry). This procedure is mandatory to disentangle synthetic polymers, which can be considered as MPs, and natural ones. Including in the MP count items made of natural polymers leads to an overestimation of the MP body burden and to an increase in the variability of the measurements. Lastly, when a high number of MPs is isolated, in some cases the characterization of the polymer composition can be performed on a subsample of items and then the proportion of items made of synthetic polymers and natural ones estimated. All these methodological/analytical issues should result in misestimating of MP body burden in fish collected in the field, potentially reducing the opportunity to identify clear patterns and relationships, as well as to disentangle the role of different ecological variables in determining MP body burden. Therefore, harmonic data of MP body burden can help to identify suitable ecological indicators for assessing contamination levels, distribution patterns and temporal trends at local and global scale, as well as to estimate the exposure levels and the potential risk for fish.

Another issue affecting the relationships between MP body burden and ecological variables refers to the difficulty or inconsistency in the extraction of the ecological features of different fish species. The information of the ecology of fish can be extracted from the Fishbase.org website, which is the global encyclopedia about fish. However, the information is not available and/or is not unique for all the species. For instance, although our results confirmed that the fish body size, in terms of body length of the fish grouped in different categories, could be a determinant of MP body burden, it is important to consider that we relied on maximum body length of the species. Indeed, the maximum body length was the only biometric indicator of body size available for all the species in the Fishbase website. However, this measurement might not be representative of the mean body size of the fish species analyzed in each single paper included in the dataset. An additional factor of uncertainty concerns the different measures of fish length. For some species, either total length (TL) or standard length (SL) was reported, but for most of cases, the reported information was expressed as TL. For this reason, the relationship between fish body size and MP body burden could be over- or underestimated and considered with caution.

5. Conclusion

Our study confirmed the ubiquity of MP contamination in marine fish at global scale and the large variability in MP body burden, which precluded the opportunity to shed light on the contribution of some ecological features of the fish species (i.e., the milieu, the feeding strategies and the position in the trophic chain) to MP accumulation. Our synthesis identified that the geographical origin of the sample, in terms of latitudinal band and closeness to the coast, represents a determinant of MP body burden in marine fish, with the largest contamination found in fish collected along coastal areas in the tropical band. In contrast, ecological factors apparently give a lower contribution to explain the bioaccumulation of MPs in fish. In fact, neither the milieu nor the trophic strategy affected the MP body burden, suggesting that accidental ingestion rather than secondary digestion of contaminated prey might be considered as the main pathway of MP accumulation in fish. However, our results confirmed that the fish body size could be a determinant of MP accumulation, with larger fish showing a greater MP body burden. These findings suggest that marine fish can be considered as good ecological indicators to shed light on global geographical patterns of MP contamination, but the large variability in body burden precludes the opportunity to univocally identify the ecological drivers of ingestion and accumulation. To confirm the extent of bioaccumulation in fish with different ecological features, further studies exploring the differences in uptake efficiency and retention time, as well as the investigation of the relationships between the abundance of MPs in the fish and in seawater and/or sediments from the same areas where the organisms were sampled, should be necessary. Lastly, an improved understanding of MP body burden and its geographical and ecological drivers represent a crucial step to develop further strategies aimed at protecting environmental and food safety requirements, particularly considering the commercial value of global fisheries.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Marco Parolini: Writing – original draft, Data curation, Conceptualization. **Andrea Romano:** Writing – review & editing, Formal analysis, 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.

Acknowledgements

The authors thank Dr. Maria Stella Masciotta for her help in extracting data and preparing the dataset. The authors would like to thank the anonymous reviewers for their comments and suggestions to revised the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2024.124121.

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