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REVIEWS

Uncovering the global status of plastic presence in marine chondrichthyans

Yi Gong · Huachen Gao · Zehao Guo · Xuemin Huang · Yunkai Li · Zezheng Li · Chenxuan Du · Feng Wu

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Abstract Plastic pollution represents a global environmental issue. Awareness of plastic pollution in marine organisms increased strongly during the last decades, including chondrichthyans. Due to a lack of a broad and comprehensive view of this global issue in chondrichthyans, we synthesized the 48 publications covering 54 species since 2002, and employed bibliometric analysis and data exploration to summarize the historical progression of the development, characteristics of plastics in chondrichthyans and evaluate their potential impacts across various regions, habitats, and Red List categories. The bibliometric analysis revealed that the investigation of plastic distribution in demersal sharks inhabiting the nearshore areas of the Mediterranean and northeastern Atlantic Ocean is a major research focus. Based on the current evaluation, plastics have been ubiquitously discovered within sharks, skates, and rays; however, only less than 5% of chondrichthyans worldwide have been investigated. Among these, 25 species are classified under one of the three threatened categories (critically endangered, endangered or vulnerable), according to IUCN Red List. The average abundance (all specimens) and load (specimens that contained plastics) in chondrichthyans were 2.86 ± 7.71 items/individual and 4.91 ± 9.39 items/individual, respectively. Plastic abundance/load is not influenced by the sampling regions, habitats, or Red List categories; however, higher records were found in the endangered and near threatened species. The plastics are predominantly fibrous in shape, with blue and black being the predominant colors, along with polypropylene and polyethylene in polymer type. Notably, inconsistencies in sampling, processing, and identification methods across studies might impeded the integration and comparison of data. This review highlights the potential implications of plastic pollution from chondrichthyans on biodiversity

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Y. Gong (✉) · H. Gao · Z. Guo · X. Huang (✉) · Y. Li (✉) · Z. Li · C. Du · F. Wu
College of Marine Living Resource Sciences and Management, Shanghai Ocean University, Shanghai, China
e-mail: ygong@shou.edu.cn

X. Huang
e-mail: xmhuang202210@163.com

Y. Li
e-mail: ykli@shou.edu.cn

Y. Gong · Y. Li · F. Wu
Key Laboratory of Sustainable Exploitation of Oceanic Fisheries Resources, Ministry of Education, Shanghai, China

Y. Gong · Y. Li · F. Wu
National Engineering Research Centre for Oceanic Fisheries, Shanghai Ocean University, Shanghai, China

Y. Gong · Y. Li · F. Wu
Key Laboratory of Oceanic Fisheries Exploration, Ministry of Agriculture and Rural Affairs, Shanghai, China

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conservation and emphasizes the necessity to consider intra- and inter-specific variations in biometric and ecological characteristics, as well as establish standardized protocols to facilitate effective comparisons in contamination dynamics between studies of chondrichthyans.

Keywords Plastic pollution · Chondrichthyan · Shark · Skate · Ray · Global synthesis

Introduction

The production of plastic products has shown a significant increase since their widespread use began in the 1950s. The plastic age is continuously evolving, leading to the emergence of plastic pollution as a prominent global environmental issue. The majority of disposable plastics that enter the ocean can be transported by multiple dimensions of currents, resulting in their presence in oceans (Haward 2018), deep sea (Woodall et al. 2014), and polar waters (Mishra et al. 2021). Plastic waste degrades due to mechanical weathering and photodegradation (Lee and Li 2021), resulting in its progressive fragmentation into smaller particles. When the particles having sizes smaller than 5 mm, they are referred to as microplastics. Plastic waste in the ocean can not only directly affect the marine environment but also be bioavailable and readily ingested by marine organisms, either through direct capture or by feeding on contaminated prey. For example, microplastics are easily ingested by small fishes due to their preference for marine plankton. Large marine organisms may also mistake macroplastic debris for prey and ingest it, resulting in blockages in their digestive tracts and causing other physical damage (Wright et al. 2013; Santos et al. 2015). There is a burgeoning literature documenting the plastic pollution in marine organisms; however, as most studies have been conducted on teleost fish, crustacean, and cephalopod (Zhang et al. 2019; Santos de Moura and Vianna 2020; Gong et al. 2021), plastic presence in chondrichthyans has not yet been studied extensively (Parton et al. 2019). Furthermore, there is currently no systematic and comprehensive overview of the ingestion of macro- and microplastics by chondrichthyans. A better understanding of the global presence of plastic in chondrichthyans can be beneficial for implementing appropriate management and conservation measures.

Chondrichthyans, including Selachii (sharks), Batoidei (skates and rays), and Holocephali (chimaeras), are one of the three lineages of fishes, and they represent the most evolutionarily distinct radiation of vertebrates. Marine chondrichthyans are particularly vulnerable to anthropogenic pressure and habitat-related threats, such as climate change, habitat loss, and marine pollution (Dulvy et al. 2021). According to the assessment by the International Union for Conservation of Nature (IUCN) Red List, chondrichthyans are one of the first major marine fish lineages for which extinction risk has been determined across the entire clade. Most chondrichthyans, especially pelagic sharks, are wide-ranging predator that occur globally in tropical and subtropical waters. They are recognized as voracious predators of a broad range of prey including cephalopods, fishes (including cannibalism), and crustaceans (Cavanagh et al. 2005). Such foraging behavior exhibited by chondrichthyans enables them to dominate upper trophic levels and exert predation pressure in many marine ecosystems (Ferretti et al. 2010; Dulvy et al. 2014), but also renders them vulnerable to plastic pollution, either through direct capture or indirect ingestion via prey items (Gong et al. 2023). Therefore, it is imperative to comprehensively investigate this issue from multiple perspectives and enhance the management and conservation of chondrichthyans in order to safeguard biodiversity and maintain equilibrium within marine ecosystems.

In this review, a systematic procedure for literature collection, data screening, and statistical analysis was carried out in order to effectively integrate and analyze the relevant datasets on the plastic pollution in chondrichthyans (sharks, skates, rays, and chimaeras) from global literature. We aimed to clarify the bioavailability of plastics in chondrichthyans and evaluate their potential impacts across various regions, habitats, and Red List categories. To the best of our knowledge, this review represents the first comprehensive meta-analysis investigating the characteristics of plastics in chondrichthyans, thereby providing valuable insights into the global status and ecological implications of plastic pollution in these species while informing the development of effective conservation management strategies.

Materials and methods

Literature review

To conduct a systematic review and meta-analyses of the global literature on plastic pollution data for chondrichthyans, we followed an established protocol based on PRISMA guidelines (Moher et al. 2009, Fig. 1). The Google Scholar and Web of Science™ were used to search for the relevant literature, and the selection of the fitting studies was finalized on April 30, 2024, and covered the years from 2002 to 2024. The search included the following terms: microplastic, macroplastic, plastic, ingestion, cartilaginous fish, shark, stingray, ray, skate, elasmobranch, and chondrichthyan. Additional records were also identified from the reference lists in various review studies. Following removal of duplicates, a total of 72 full-text articles were screened. Eligibility checks excluded 26 articles, because they did not examine plastics in chondrichthyans from coastal, pelagic, and deep-sea environments and/or not support useable datasets for further quantitative analysis.

Information on the habitats (pelagic/demersal) and characteristics of ingested plastics (abundance, shape, size, color, and polymer type) were recorded from the searched literature. Publications that did not recorded habitats of species were supplemented with the information acquired from FishBase (www.

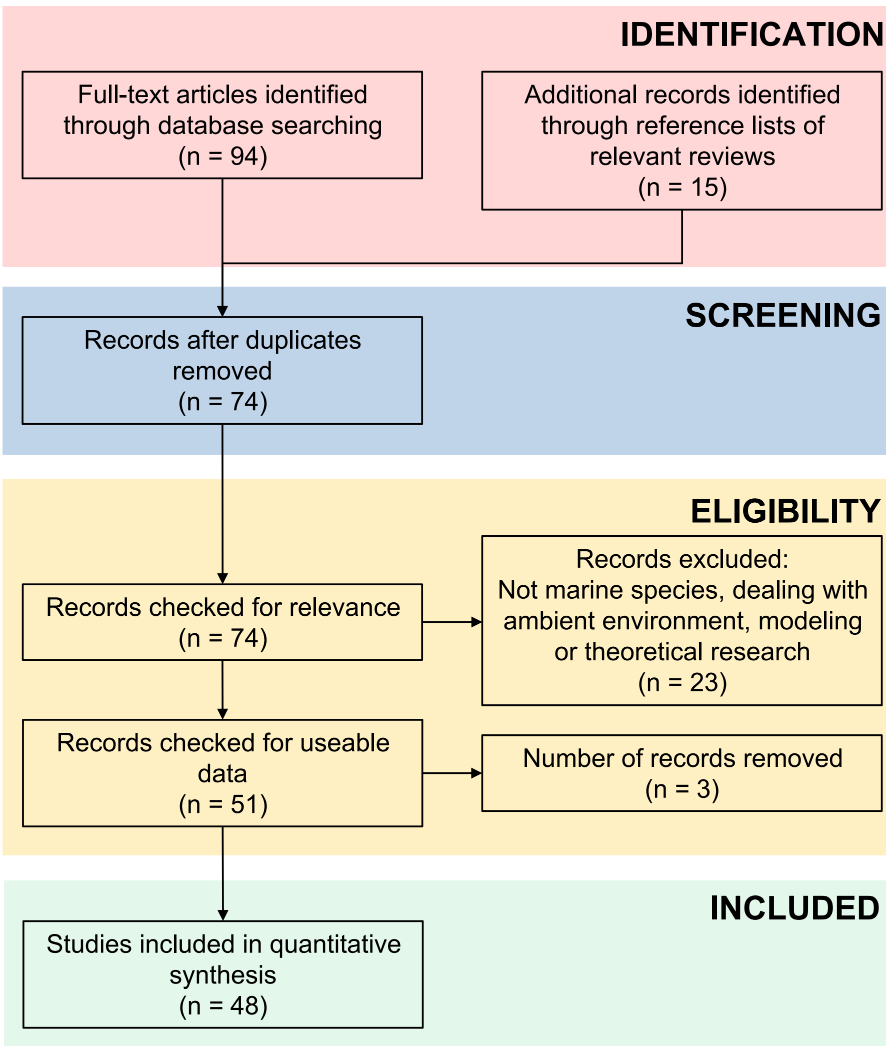

Fig. 1 Flowchart providing the steps of data collection for the systematic review following the PRISMA guidelines

fishbase.org), and the endangerment categories of species was determined using the IUCN Red List assessment.

Statistical analysis

Plastic abundance and plastic load were calculated according to the guidelines by (Provencher et al. 2017). Plastic abundance was calculated as the number of plastic items found in all specimens sampled, while plastic load was the number of plastic items in the specimens that contained plastics. Since this is commonly misreported in the publications and can lead to difficult data comparisons, the corrected dataset from each publication was used in the analysis. Notably, the statistical analysis employed average values when the reviewed publication only provides aggregated datasets of macro- and microplastic abundance across multiple species. In this review, plastic items were classified into microplastic (<5 mm) and all items larger than 5 mm were grouped as macroplastics.

Since the data did not satisfy the assumptions of normality and homogeneity of variance, the non-parametric Kruskal–Wallis test was used to if there were any significant differences between the region, habitat (pelagic/demersal), and Red List category. All statistical analyses and graphics were carried out in software OriginPro Version 2022 with a significance level of $p \leq 0.05$. All results are presented as the mean value ± standard deviation (SD).

Results and discussion

Following removal of duplicate records, a total of 48 publications remained for further analysis (see Online Resources 1 for detailed information on the publications, and characteristics of chondrichthyans and detected plastics). The number of publications exhibited a generally upward and fluctuating trend (Fig. 2). Before 2018, the annual average number of publications concerning shark species was less than three studies. During the period from 2018 to 2023, there was a surge in research focusing on the ingestion of plastics by chondrichthyans, accounting for 62.5% of the total number of published studies.

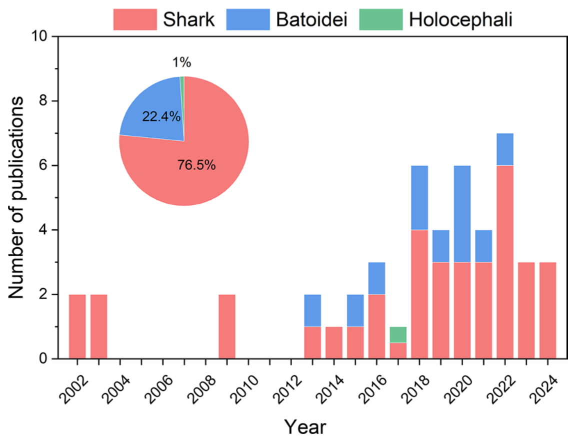

Fig. 2 Results of a bibliometric analysis on the number of publications related to plastic presence in chondrichthyans, which include sharks, Batoidei (skates and rays) and Holocephali (chimaeras)

Study regions and species

Based on the sampling sites of the publications considered, previous studies were classified into four distinct regions: the Mediterranean and Atlantic, Pacific, and Indian Oceans. Among these regions, research efforts primarily focused on the Mediterranean, accounting for 37.5% of total publications, followed by the Atlantic (31.2%), Pacific (20.8%), and Indian oceans (8.3%) (Fig. 3). This observed pattern can be attributed to the recent implementation of various marine plastic pollution monitoring policies in Europe. Due to the intensive anthropogenic activities along the Mediterranean coast and the unique semi-enclosed nature of this sea, the dispersion of plastic debris into the wider oceanic environment is hindered, leading to an accumulation of plastic pollution in this region (Di Mauro et al. 2017).

The majority of studies focused on coastal waters, with particular emphasis on the nearshore areas of the Mediterranean and the northeastern Atlantic Ocean (Wootton et al. 2021). The lack of relevant records in offshore areas may be attributed to the challenges faced in conducting field investigations and obtaining the specimens for laboratory analysis from oceanic environments. Furthermore, previous studies on oceanic chondrichthyans have predominantly focused on the feeding ecology of pelagic sharks. In these studies, the gastrointestinal tract has conventionally been employed for stomach content analysis and/or

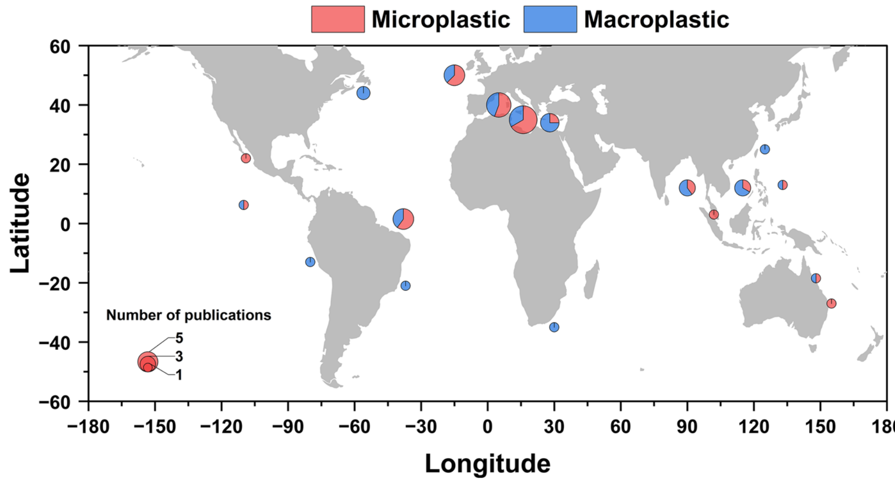

Fig. 3 A cartographic representation that illustrates the geographical distribution of publications

intestinal microbiome analysis, thereby limiting the investigation of plastic pollution in chondrichthyans.

A total of 54 chondrichthyan species were examined in the 48 publications considered in this review, including 41 shark species, which accounted for 75.9% of the overall analyzed species. Additionally, there were 12 Batoidei species (22.2%) and solely one Holocephali species (Fig. 2). Considering the total number of chondrichthyan species (approximately 1050) and the population dynamics (e.g., intraspecific variabilities in abundance, size, and migration patterns) (Weigmann 2016; Dulvy et al. 2017), the current state of research on plastic presence in chondrichthyans and its potential biological and ecological implications remains inadequate.

The 54 species can be taxonomically classified, based on their optimal habitat, as either pelagic or demersal. Pelagic chondrichthyans primarily consume plankton and/or organisms inhabiting shallow to moderate depths, such as the whale shark *Rhincodon typus* and blue shark *Prionace glauca*. In contrast, demersal chondrichthyans inhabit the seafloor or its vicinity and primarily feed on organisms or detritus available in the demersal environment (López-Martínez et al. 2021). The demersal species constituted the majority of the sampled chondrichthyans in these reviewed publications (57.4%). Specifically, the Mediterranean demersal sharks, namely lesser spotted dogfish *Scyliorhinus canicula* (17 publications, 34.7%), blackmouth catshark *Galeus melastomus* (13 publications, 26.5%), and velvet belly lanternshark *Etmopterus spinax* (8 publications, 16.3%), were the most extensively studied species. Meanwhile, *P. glauca* and *R. typus* emerged as the pelagic species that were most extensively studied with 6 and 4 publications respectively.

According to the evaluations conducted by the IUCN Red List, more than 50.0% of the studied chondrichthyans were categorized as threatened species (Fig. 4), specifically falling under categories of critically endangered (CR), endangered (EN), and vulnerable (VU). Among them, three species (great hammerhead shark *Sphyrna mokarran*, scalloped hammerhead shark *Sphyrna lewini*, and sand tiger shark *Carcharias taurus*), all of which are pelagic sharks, were classified as CR. Eight species were classified as EN, with six of them being pelagic sharks. Additionally, sixteen species were listed as VU, including ten pelagic and six demersal species. The remaining species were classified as near-threatened (NT), data deficient (DD), or of least concern (LC) based on their conservation status. The definitive status of these species in the context of conservation requires further efforts to be determined. Specifically, there is a high likelihood that DD species are at risk due to insufficient available information for assessing their status (Dulvy et al. 2014).

Isolation, observation, and identification of plastics

In previous studies, researchers have utilized nine different tissue types to evaluate the extent of macro- and microplastic pollution in chondrichthyans. The most commonly employed tissues include the stomach (48.1%) and gastrointestinal tract (31.5%). Other alternative tissues examined were the esophagus, gill,

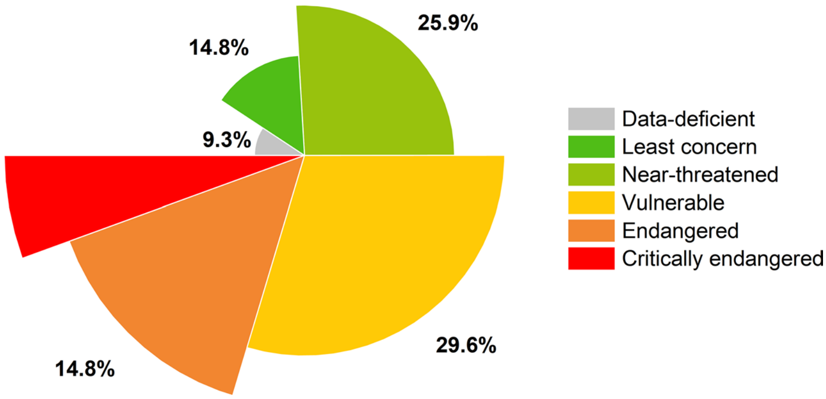

Fig. 4 The proportion of chondrichthyans in the reviewed publications was determined based on their International Union for Conservation of Nature Red List category

intestine, pylorus, scat/fecal matter, spiral valve, and vomit (Fig. 5). The practice of quantifying multiple tissues has become an accepted approach in the study of plastic pollution in chondrichthyans (Angelo et al. 2019; Capillo et al. 2020; Morgan et al. 2021; Janardhanam et al. 2022).

For macroplastic, visual inspection and microscope-assisted observation are widely used. These techniques rely on assessing physical characteristics such as the thickness and color of suspected plastic items (Bellas et al. 2016; Valente et al. 2020). For small-sized plastics (e.g., microplastic), however, visual inspection alone may result in misjudgments (Davidson and Dudas 2016). Therefore, it is necessary to combine additional methods to effectively separate and identify microplastics.

The selection of study objectives and tissue samples influences the choice of digestion procedures during the pretreatment process. Previous studies predominantly relied on visual inspection for the detection of macroplastic and microplastic, while only a limited number of studies (n = 19, 38.8%) employed

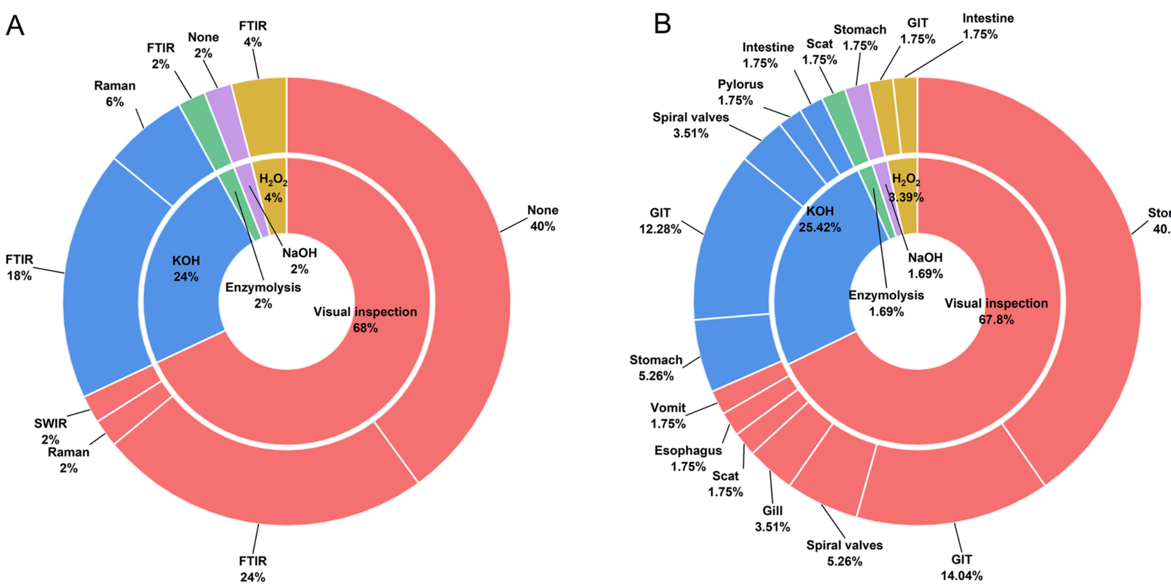

Fig. 5 The percentage of literature reviewed for chondrichthyans was analyzed based on **A** the technology used for polymer identification and digestion procedures, as well as **B** the organ of analysis and digestion procedures. FTIR, Fourier Transform Infrared spectrometer; GIT, gastrointestinal tract; H_2O_2, hydrogen peroxide; KOH, potassium hydroxide; NaOH, sodium hydroxide; None, none of the technologies described; Raman, Raman spectroscopy; SWIR, shortwave infrared spectroscopy

chemical digestion methods, e.g., alkaline solutions, H_2O_2, and enzymatic digestion. The KOH solution was widely used for alkaline digestion, although the concentration and digestion time varied across studies. For example, Maes et al. (2020) and Valente et al. (2019) used a 10% KOH solution for a 24-h digestion period to extract microplastics from the spiral valves of porbeagle shark *Lamna nasus* collected from the Northeast Atlantic Ocean and the gastrointestinal tracts of demersal sharks from the Tyrrhenian Sea, respectively. In contrast, Parton et al. (2020) increased the KOH concentration to 20% and extended the digestion time to 48 h when extracting microplastics from the gastrointestinal tracts of demersal sharks sampled from the Northeast Atlantic Ocean. Additionally, Pinho et al. (2022) employed a 30% KOH solution to digest the gastrointestinal tract of the Haller's round ray *Urobatis halleri*. The H_2O_2 was another commonly used solution in digestion procedures. For example, Avio et al. (2015) treated the stomachs of the spiny dogfish *Squalus acanthias* with a 15% H_2O_2 solution to facilitate digestion. Enzymatic digestion, employing proteinase K to break down organic matter, emerged as a reliable method for extracting microplastics, particularly in fecal samples. For instance, Yong et al. (2021) employed enzymatic detergent to isolate macro- and microplastic from fecal samples of *R. typus*. These differences in digestion procedures highlight the diverse approaches adopted in plastic pollution research, emphasizing the need for standardized protocols to ensure comparability and robustness across studies.

Fourier transform infrared (FTIR) and Raman spectroscopy have emerged as two common techniques for identifying the chemical composition of suspected microplastics in marine organisms (Metz et al. 2020). FTIR is considered reliable for microplastics larger than 20 µm and enables rapid identification of different polymer types. On the other hand, Raman spectroscopy is useful for further analyzing microplastics in the size range of 1–20 µm (Collard et al. 2015). Among the surveyed publications, a total of 28 studies (57.1%) used spectroscopic technologies to identify addition, combining FTIR and Raman spectroscopy has been suggested as a complementary approach for identifying microplastics in chondrichthyans (Capillo et al. 2020). However, it is worth noting that not all studies have taken pollution prevention and control measures into consideration during sample collection and pretreatment stages. Furthermore, the lack of information regarding the procedures involved in the digestion, extraction, and separation of microplastics raises concerns regarding potential biases in estimating quantities of macro- and microplastics in chondrichthyans. To address these concerns, future studies should adhere to standardized quality control protocols to prevent potential airborne, container-based, and tool-related contamination. These protocols are crucial for minimizing potential bias and ensuring the reliability of the results associated with assessing the characteristics of plastic pollution in different chondrichthyan species (Hermsen et al. 2018).

Global status of plastics in chondrichthyans

Plastic abundance and load

The mean values of plastic abundance and load in chondrichthyans, as reported in all reviewed publications, were 2.86 ± 7.71 items/individual and 4.91 ± 9.39 items/individual, respectively. The sharks purchased from local wet markets in Peninsular Malaysia exhibited significantly higher values of plastic abundance and load (Fig. 6, Kruskal–Wallis test, $p < 0.01$ and $p < 0.001$, respectively) (Matupang et al. 2023). Notably, this publication was excluded from the analyses of spatial variations in plastic abundance and load due to the unavailability of precise sampling location information. No significant difference was found in values of plastic abundance and load among the four regions (Kruskal–Wallis test, $p = 0.05$ and 0.548, respectively) (Fig. 6). However, the wide range of plastic abundance and load (range 0–46.00 items/individual) observed in all publications, along with the generally moderate inter-specific variability within each region, indicates a diverse level of plastic pollution both across and within regional chondrichthyans. The largest and lowest average value of plastic abundance and load occurred in the Pacific Ocean and Mediterranean, respectively. The ranges of plastic abundance and load in chondrichthyans from the three oceanic regions exhibited greater variability compared to that observed in the Mediterranean (Fig. 6). This phenomenon is likely attributable to the high levels of plastic abundance/load documented in specific chondrichthyan species sampled from oceanic regions. For example, Abreo et al. (2019)

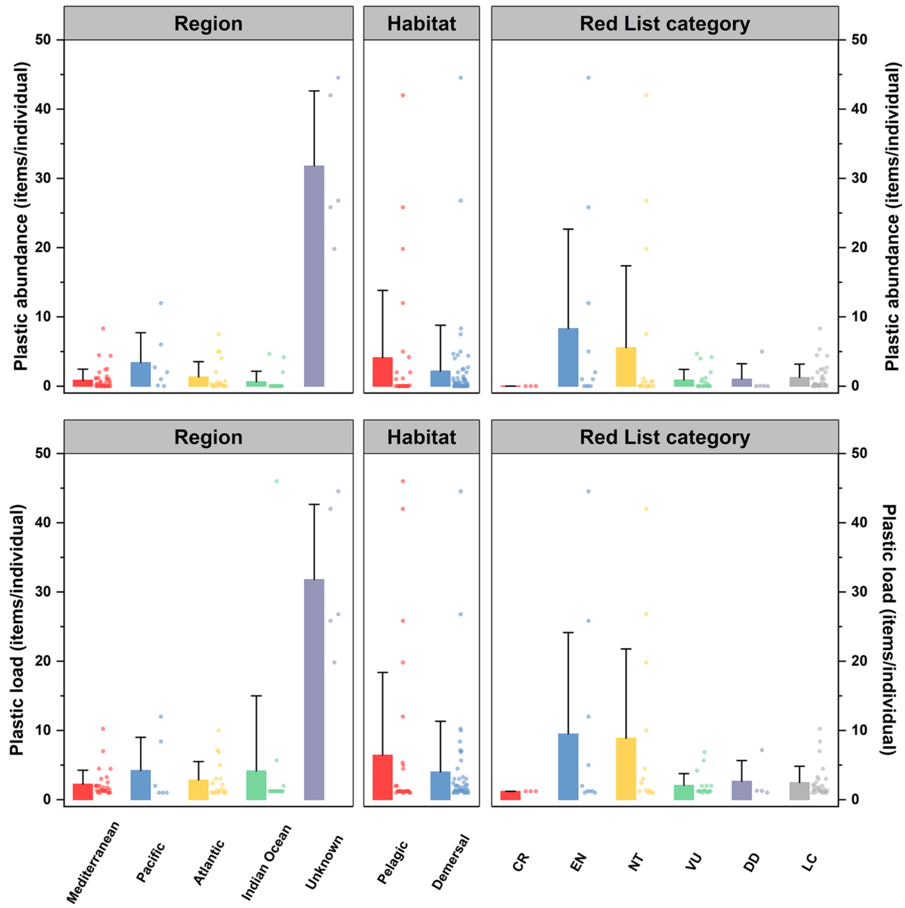

Fig. 6 Variation in macro- and microplastic abundance/load of chondrichthyans (items/individual) relative to region, habitat, and Red List category, respectively. Plastic abundance was calculated as the number of plastic items found in all individuals detected, while plastic load was the number of plastic items in the individual contained plastics. The box plot includes the mean value with error bars of standard deviations and datasets

reported a plastic abundance of 12 items/individual in a single *R. typus* from the Pacific Ocean. In the Atlantic Ocean, starry smooth-hound *Mustelus asterias* exhibited average plastic load of 10 items/individual (Parton et al. 2020). However, similar to studies conducted in the Mediterranean, the publications on three oceanic regions primarily focus on chondrichthyans sampled from coastal areas or continental shelves that are subject to land-based inputs (such as frequent industrial and agricultural activities) (Fig. 3), resulting in an increased incidence of macro- and microplastic ingestion by chondrichthyans. Indeed, the ingestion of macro- and microplastics was more evident in chondrichthyans inhabiting nearshore waters compared to oceanic species (Jabeen et al. 2017; Phaksopa et al. 2021).

In general, pelagic chondrichthyans (predominantly sharks) are characterized as high-trophic-level predators capable of undertaking extensive horizontal and vertical migrations to foraging (Weigmann 2016). Thus, compared to demersal chondrichthyans, pelagic species might be more prone to direct capture plastics or indirect ingestion of contaminated prey (Zhang et al. 2019). Unexpectedly, no significant difference was found in the plastic abundance and load between pelagic and demersal chondrichthyans (Kruskal–Wallis test, $p = 0.80$ and 0.23, respectively) (Fig. 6). The plastic abundance range for all studied pelagic chondrichthyans was 0.01–42.00 (4.11 ± 9.71) items/individual, while demersal chondrichthyans had a much wider range, from 0 to 44.54 (2.18 ± 6.62) items/individual. In terms of plastic load, pelagic chondrichthyans ranged from 1.00 to 46.00 (6.43 ± 11.94) items/individual, whereas demersal chondrichthyans showed a range of 1.00–44.54 (4.00 ± 7.32) items/individual (Fig. 6).

From the perspective of Red List Assessment category, there was no significant difference observed both plastic abundance and load (Kruskal–Wallis test, $p = 0.29$ and 0.57, respectively) (Fig. 6). The largest average value of plastic abundance occurred in the category EN, followed by NT, LC, DD, VU, and CR (8.31, 5.54, 1.26, 1.02, 0.89, and 0.01 items/individual, respectively). For plastic load, the EN also had largest average value, followed by NT, DD, LC, VU, and CR (9.50, 8.87, 2.68, 2.49, 2.06, and 1.22 items/individual, respectively). Apart from the CR species, which only have aggregated data of all specimens from one publication (Cliff et al. 2002), the wide range of plastic abundance and load observed in each Red List category (Fig. 6) indicates a considerable variability in plastic pollution levels within each Red List category.

The observed similarities in plastic abundance (load) among chondrichthyans across various regions, habitats, and Red List categories likely arise from interspecific diversity of biometric and ecological characteristics, such as ontogenic variations in feeding strategy and movement patterns, and behavior for eliminating indigestible item (e.g., plastics) from their body (Güven et al. 2017; Abidli et al. 2019; Bom and Sá 2021). Chondrichthyans may adopt a generalist/opportunistic foraging strategy during the juvenile stage, but undergo specialization in the adult stage (Cortés 1999; Estrada et al. 2006). Therefore, juvenile chondrichthyans might have a higher possibility of ingesting plastics through contaminated prey. For example, Alomar and Deudero (2017) and Bernardini et al. (2018) have reported that juvenile sharks are more likely to ingest plastics than adult individuals. However, the majority of the reviewed publications have not accounted for the variations in plastic ingestion resulting from dietary shifts across different life stages, which could lead to inaccuracies in assessing the level of plastic pollution in chondrichthyans. On the other hand, the ingestion of macroplastics by sharks might be underestimated due to their ability to eliminate indigestible items in stomach through gastric eversion (Brunnschweiler et al. 2005). Indeed, 33/40 (82.5%) sharks considered in the reviewed publications was assessed as endangered species by the IUCN due to anthropogenic threats, such as overfishing and discard-induced mortality (Dulvy et al. 2021; Zonn et al. 2021). Plastic pollution may introduce a novel potential threat to shark health (Huang et al. 2022). Notably, a portion of EN and NT species might indeed have experienced an ecological risk level due to the high plastic abundance (load) (Fig. 6).

Another possible explanation of such patterns in the abundance (load) of plastic among chondrichthyans might relates to differences in the methodologies as shown in Fig. 5. For example, 84.44% of the suspected microparticles identified by visual sorting were fibers; however, a small fraction (10%) of these particles were analyzed using Raman spectroscopy to validate the chemical composition (Matupang et al. 2023). This could lead to an overestimation of the amount of microplastics in these shark specimens. Indeed, fibers identification with Raman or FTIR spectroscopy is challenging due to their thinness (Käppler et al. 2016). In addition, it is important to be aware of the visual misjudgments, e.g., 78.5% of items initially identified using visual methods were rejected by FTIR spectroscopy (Pereira et al. 2020). In this context, an examination was conducted to assess potential differences in plastic abundance and load across different methodologies. The methodologies can be broadly classified into key processes of sample extraction and measurements, including chemical digestion, instrumental spectroscopy verification, and quality assurance/quality control (QA/QC). Results revealed significant differences in both plastic abundance and load in each specific methodology (Fig. 7). Therefore, the variations of plastic abundance and load between the region, habitat, and Red List category were reanalyzed at the methodology level, meaning that datasets were grouped by the same specific methodology. Similar plastic abundance and load were found across regions, habitats, and Red List categories when the datasets grouped by with or without instrumental spectroscopy verification and QA/QC (Table 1). While, the plastic abundance and load varied across habitats and Red List categories with chemical digestion. Nonetheless, these findings could be biased due to the limited and uneven distribution of publications in each comparison, they highlight the development of standardized sampling methods and quantification approaches for a more robust quantitative assessment of plastic abundance in chondrichthyans.

Size

There were 8 and 18 reviewed publications dedicated to the investigation of macroplastics and microplastics

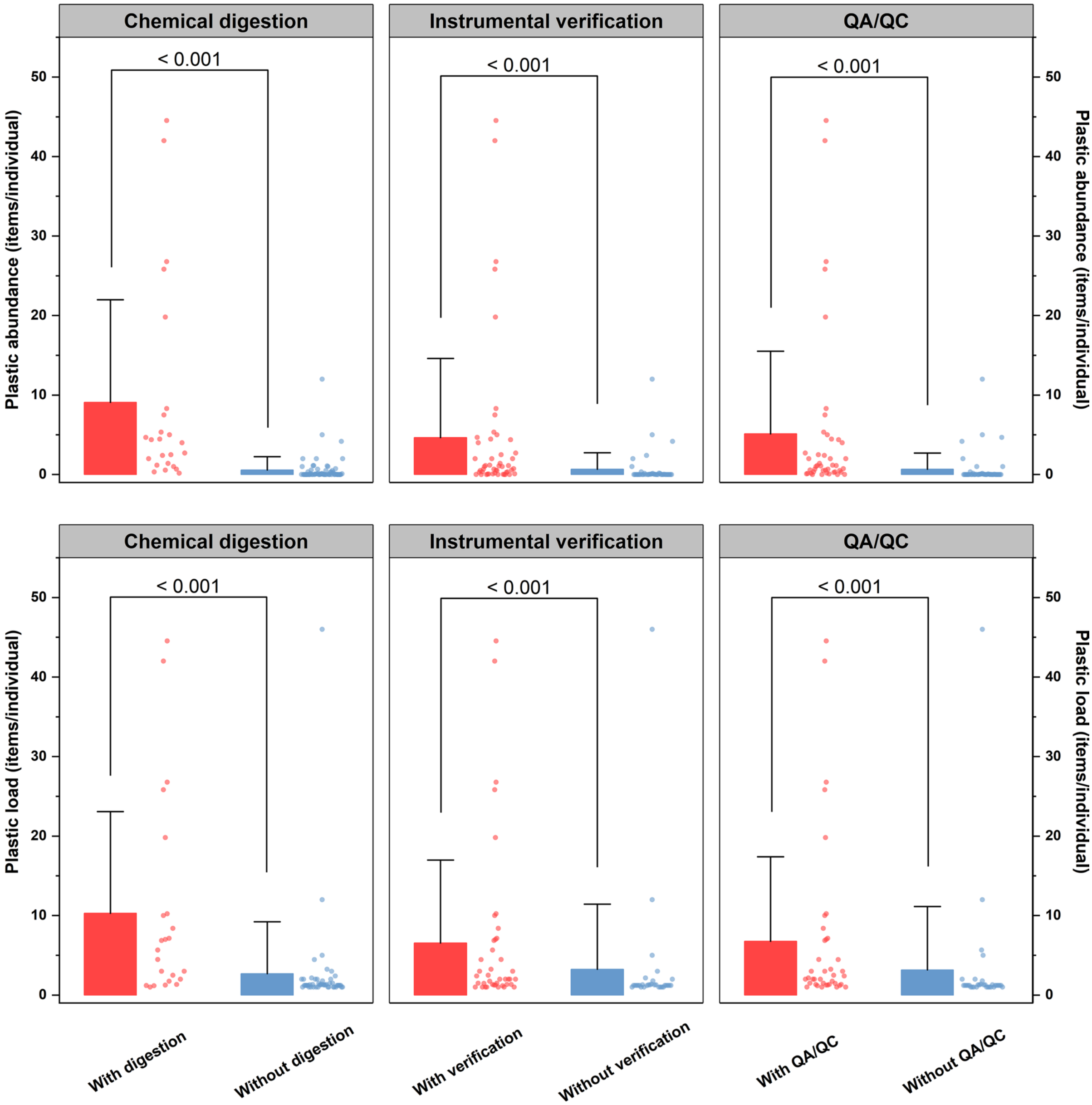

Fig. 7 Plastic abundance/load of specific methodologies employed in the literature of chondrichthyans

pollution, respectively; while 22 publications examined both types simultaneously (Table S1). According to these publications, variations were observed in the sizes of plastics ingested by chondrichthyans inhabiting pelagic or benthic environments. Due to body size and feeding behavior, high-trophic-level pelagic sharks, such as *R. typus* (Haetrakul et al. 2009; Sampaio et al. 2018; Abreo et al. 2019) and *P. glauca* (Barreto et al. 2019; Fernández and Anastasopoulou 2019), have demonstrated a greater propensity for macroplastic ingestion, with a ratio of microplastic to macroplastic records being 10:17. Previous studies have reported the severe adverse impacts of macroplastics on the internal organs of sharks, and even fatality in certain instances (Haetrakul et al. 2009). These macroplastic are often utilized in fisheries, tourism, and transportation (Mendoza et al. 2018). Therefore, there is a need to adopt standardized

Table 1 Results of the analysis of variance in plastic abundance and load across the region, habitat, and Red List category at the methodology level

		Number of publications	Plastic abundance Kruskal–Wallis test *p* value	Number of publications	Plastic load Kruskal–Wallis test *p* value	Number of publications	Plastic abundance Kruskal–Wallis test *p* value	Number of publications	Plastic load Kruskal–Wallis test *p* value
		With digestion				Without digestion			
Region	Mediterranean	11	0.32	11	0.31	29	0.06	28	0.67
	Pacific	2		1		5		5	
	Atlantic	5		5		15		15	
	Indian Ocean	1		1		16		16	
Habitat	Pelagic	4	0.01	3	0.02	25	0.63	25	0.43
	Demersal	20		20		40		39	
Red List category	CR	0	0.01	0	0.01	3	0.39	3	0.83
	EN	2		2		9		9	
	VU	5		5		15		15	
	NT	4		4		14		14	
	LC	12		11		20		19	
	DD	1		1		4		4	
		With verification				Without verification			
Region	Mediterranean	30	0.13	30	0.05	10	0.11	9	0.67
	Pacific	5		4		2		2	
	Atlantic	8		8		12		12	
	Indian Ocean	1		1		16		16	
Habitat	Pelagic	8	0.09	7	0.18	21	0.40	21	0.22
	Demersal	41		41		19		18	
Red List category	CR	0	0.43	0	0.43	3	0.83	3	0.81
	EN	4		4		7		7	
	VU	9		9		11		11	
	NT	13		13		5		5	
	LC	22		21		10		9	
	DD	1		1		4		4	
		With QA/QC				Without QA/QC			
Region	Mediterranean	24	0.84	23	0.21	16	0.16	16	0.26
	Pacific	5		4		2		2	
	Atlantic	10		10		10		10	
	Indian Ocean	0		0		17		17	
Habitat	Pelagic	8	0.18	7	0.33	21	0.31	21	0.09
	Demersal	36		35		24		24	

Table 1 (continued)

		Number of publications	Plastic abundance Kruskal–Wallis test *p* value	Number of publications	Plastic load Kruskal–Wallis test *p* value	Number of publications	Plastic abundance Kruskal–Wallis test *p* value	Number of publications	Plastic load Kruskal–Wallis test *p* value
Red List category	CR	0	0.29	0	0.13	3	0.36	3	0.27
	EN	4		4		7		7	
	VU	6		6		14		14	
	NT	10		10		8		8	
	LC	23		21		9		9	
	DD	1		1		4		4	

management of fisheries production to reduce wear and tear on plastic fishing tools (e.g., fishing nets and ropes), and minimize plastic waste at sea (e.g., plastic gloves and bags), thereby minimizing threats to pelagic chondrichthyans (MacLeod et al. 2021).

Compared with pelagic chondrichthyans, demersal species ingest more small-sized plastics, Valente et al. (2019) reported that 90% of the plastics in the gastrointestinal tract of demersal shark species (*G. melastomus*, *S. canicula*, and *E. spinax*) from the Tyrrhenian Sea were smaller than 330 µm. In addition, the majority of plastics in the Mediterranean *S. canicula* (Mancia et al. 2020) and *U. halleri* from the Gulf of California (Pinho et al. 2022) are below 1 mm. In general, through the adsorption of organic pollutants and microorganisms, microplastic can sink into deeper water layers or sediments, making themselves available to demersal organisms (Kooi et al. 2017). In most demersal chondrichthyans, especially juveniles and species that feed on other benthic/demersal organisms, microplastics can easily accumulate in their bodies through trophic transfer. In addition, demersal rays and skates can whirl up the seawater during feeding, causing the bottom microplastics to float and increasing the bioavailability of microplastics to these chondrichthyans (Fossi et al. 2018). Considering the size-dependent toxicity of microplastic (Von Moos et al. 2012; Lusher et al. 2015), more attention should be given to the adverse effects of these small-sized plastics on demersal chondrichthyans.

From the perspective of Red List Assessment category, macroplastics were found in 17 threatened chondrichthyans, predominantly comprising pelagic species (2 CR species, 6 EN species, and 9 VU species). These findings are particularly relevant to researchers focused on biological conservation, especially considering the potential harm inflicted upon the internal organs of chondrichthyans due to prolonged retention of macroplastics within their bodies (Haetrakul et al. 2009; Barreto et al. 2019). In contrast, a smaller subset of threatened species demonstrated indications of microplastic presence, comprising 4 EN species and 6 VU species. These findings may be attributed to various factors, such as the methodology used to identify the suspected microparticles and the objectives of different studies. For example, (Cliff et al. 2002) reported a much lower percentage of sharks, including 2 CR species, that contained plastic items (15,666 specimens, 0.38% using the visual analysis of stomach contents); however, the occurrence of microparticles was not explicitly evaluated.

Shape

To streamline the statistical analysis of plastic shapes, we followed the definitions and standards by the Group of Experts on the Scientific Aspects of Marine Environmental Protection and the European Marine Strategy Framework Directive regarding diverse terminologies employed for various microplastic shapes mentioned in previous publications. The classification has been standardized into fiber (including line, filament, and strand), fragment (including granule and flake), film (including sheet), pellet (including sphere, resin bead and microbead), and foam [including expanded polystyrene (EPS) and polyurethane (PUR)]. The plastic items in chondrichthyans are predominantly composed of fibers, constituting 71.3% of the total number of studies analyzed in reviewed publications, followed by the fragment (19.8%) and pellet (6.7%) types and film and foam accounting for less than 2% (Fig. 7).

The observed distribution pattern is consistent with the findings presented in (Ugwu et al. 2021) review of global marine biota, as well as with the studies investigating the occurrence of plastic pollution in seawater. Generally, fibrous plastics are mainly originated from the discharge of laundry washing water and domestic sewage, while pellets are primarily associated with microbeads incorporated into industrial plastic products or personal care items. The formation of fragments and other types of microplastics is primarily attributed to the gradual fragmentation of larger plastic pieces through physical and chemical processes, such as wind force, ultraviolet radiation, and biodegradation. The shape distribution of macro- and microplastics ingested by chondrichthyans were similar across different marine regions, with the predominant shape was fiber, followed by fragment (except for Pacific Ocean, with the second shape being pellet) (Fig. 8). This distribution pattern may be associated with publications of Pacific Ocean primarily focused on the study of pelagic shark species (e.g., *P. glauca* and *R. typus*). These species are considered highly migratory, undertake diel vertical migrations of several hundred meters and seasonal migrations between the shelf and open ocean, thereby increasing the potential for ingestion of pellet-shaped plastics through both neritic and oceanic food webs.

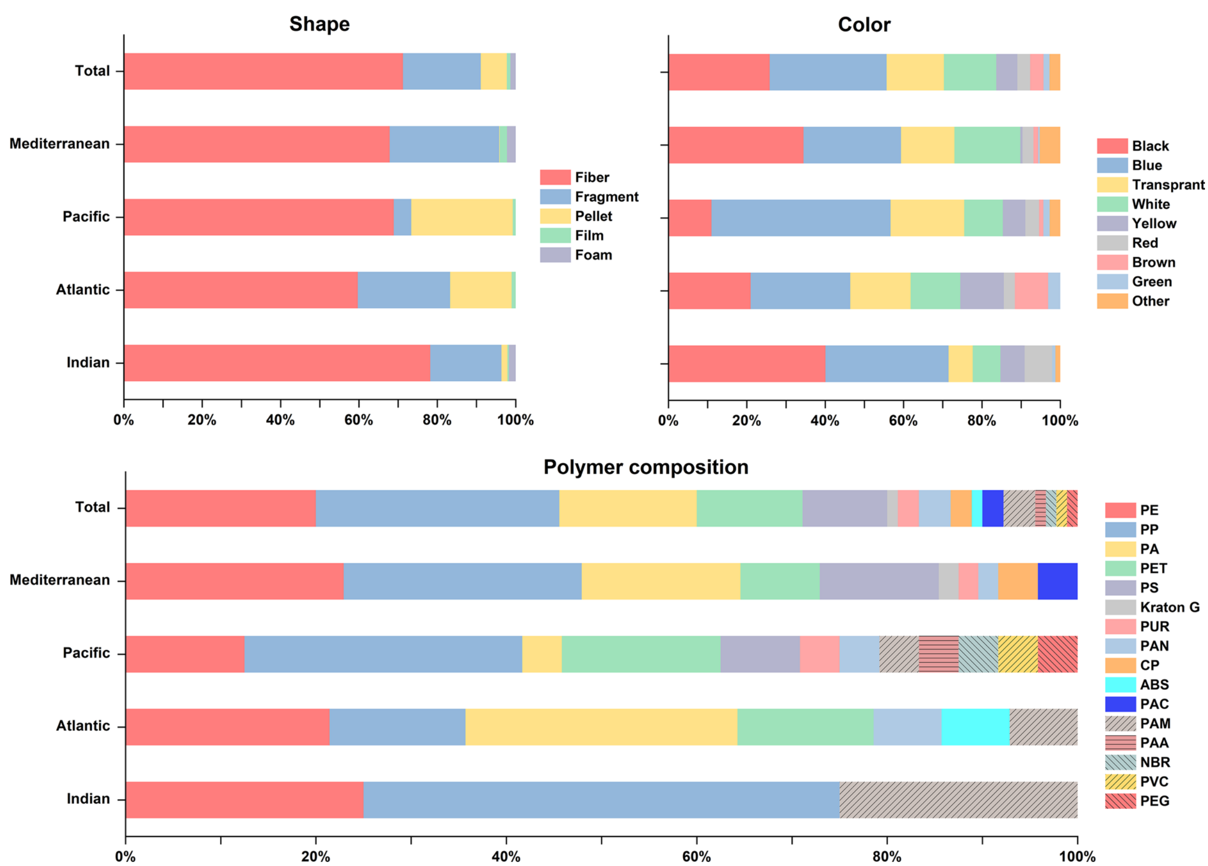

Fig. 8 Distribution of macro- and microplastics in chondrichthyans: insights into shape, color, and polymer composition. The histograms depict the relative percentages across global and four studied regions. PE, polyethylene; PP, polypropylene; PA, polyamide; PET, polyethylene terephthalate; PS, polystyrene; Kraton G, triblock copolymer; PUR, polyurethane; PAN, polyacrylonitrile; CP, cellophane; ABS, acrylonitrile butadiene styrene; PAC, polyacrylate; PAM, polyacrylamide; PAA, polyacrylic; NBR, nitrile rubber; PVC, polyvinylchloride; PEG, polyethylene glycol

Color

The analysis of the reviewed publications revealed a total of 11 color types, with blue (29.8%) and black (25.8%) comprising the majority, followed by transparent (14.7%) and white (13.3%). The remaining colors accounted for less than 5.4% (Fig. 8). The observed color patterns in chondrichthyans corresponds to the color compositions of plastics in marine environment, as summarized by Rezania et al. (2018). The predominant colors of microplastics in the marine mammals, seabirds, and turtles were also observed to be blue, black, and transparent (Ugwu et al. 2021). However, color distribution of plastics in chondrichthyans varies among studied regions. The chondrichthyans from the Mediterranean region was primarily characterized by the black (34.4%) and blue (24.9%). In contrast, the Pacific and Atlantic oceans exhibited dominant colors of blue (45.7%) and transparent (18.8%), and blue (25.4%) and black (21.0%), respectively. When comparing the same species found in different regions, the color of plastics in its body was also different. For example, (Capillo et al. 2020) found that plastics in the gastrointestinal tracts of *S. canicula* from the central Mediterranean was characterized by black (85%) and red (15%) colors. Conversely, plastics in the gastrointestinal tracts of *S. canicula* from the Northeast Atlantic Ocean consisted mainly of blue (88%) and black (8.8%) colors (Parton et al. 2020). These findings suggest that different marine regions exhibit distinct sources of plastic pollution.

The color of plastics frequently induces marine organisms to mistake them as prey or plankton species. This misidentification initiates a chain of events that results in the transfer of plastics across the marine food web (Ory et al. 2017; Rios-Fuster et al. 2019). Specifically, filter-feeding chondrichthyans might accumulate large amounts of plastics. With a substantial volume of seawater ingested, there is no doubt that plastics are directly or indirectly ingested. For example, the microplastics in the fecal of *R. typus* from the Philippine Sea is 2.48 ± 3.96 items/g (1.12 ± 0.7 mm) and mainly transparent in color (Yong et al. 2021).

Polymer type

A total of 16 polymer types were mentioned in the 48 publications (Fig. 8), with polypropylene (PP) and polyethylene (PE) accounting for the higher proportions with 25.6% and 20.0%, respectively; followed by polyamide (PA, 14.4%), and polyethylene terephthalate (PET, 11.1%), and the remaining polymers ranging from 1.1 to 8.9%. These findings were consistent with the global statistics of polymer compositions of plastic products (Geyer et al. 2017). PP, PE, and PA were three major raw materials used in the packaging, textiles, agricultural and construction. Although direct investigation for traceability of origins of these plastics has not explicitly evaluated in the previous publications, the majority of the sampling locations covered were in semi-closed seas (Mediterranean) and the coastal waters (Fig. 3), which were characterized by urbanization, industrialization, and other anthropogenic activity. Compared with offshore waters, higher plastic abundance is associated with a high level of anthropogenic activities (Murphy et al. 2017; Chan et al. 2019). Our results from the reviewed publications indeed supported this hypothesis, and provide further evidence of a correlation between the proportions of polymer types in chondrichthyans and the ranking of plastic production.

In terms of number of polymer types, more complex composition of polymers (9 types) was identified in the Mediterranean Sea and Pacific Ocean, while there were fewer polymer types observed in the Indian Ocean (3 types). These differences are probably due to regional sources of plastics. Evidence has shown that Europe, North America, and countries in the Western Pacific Rim have dominated global plastics production as well as plastic polymer diversity, while India and countries in the Indian Ocean Rim account for only about 15% of global plastics production (UNEP 2021).

These plastic products pose potential harm due to their production methods and the additives used during processing. Therefore, in this review, we employed the chemical toxicity ranking and hazard classification based on the monomer hazards identified by (Lithner et al. 2011). The results indicated that several high-toxicity polymers [polyacrylonitrile (PAN), polyurethane (PUR), acrylonitrile butadiene styrene (ABS), polyacrylic (PAA), polyamide (PA)] were observed in eight demersal species, and PA being the main polymer type in *S. canicula* and *G. melastomus*. In contrast, only PA was detected in *L. nasus* from the Northeast Atlantic Ocean for pelagic chondrichthyans (Maes et al. 2020). In terms of Red List category, high-toxicity polymers were not found in the CR and EN species. However, PA was detected in two VU species, i.e., *L. nasus* and milk shark *Rhizoprionodon acutus*. Furthermore, PAN, PUR, ABS, and other high-toxicity polymers were all found in the demersal chondrichthyans (starry ray *Raja asterias*, *S. canicula,* thornback ray *Raja clavata,* and Brazilian electric ray *Narcine brasiliensis*).

Compared to pelagic chondrichthyans, demersal species including *G. melastomus* (Alomar and Deudero 2017), longnose stingray *Hypanus guttatus* (Pegado et al. 2021), and *U. halleri* (Pinho et al. 2022), displayed a higher ingestion rate of high-density polymers, e.g., PET (1.34 g/cm^3) and PA (1.14 g/cm^3). These polymers possess higher density than seawater (1.025 g/cm^3), causing them to sink into deeper water layers or sediments, making themselves available to organisms living in these areas, e.g., demersal chondrichthyans. Due to biofouling and subsequent vertical transport, low-density polymers can also exhibit a propensity to sink. Although there is no evidence at present that microplastics have toxic effects on chondrichthyans, research has validated their capacity to inflict diverse detriments upon various marine organisms. These ramifications encompass conditions like endocrine disorders, oxidative stress, neurotransmission dysfunction, and even genotoxic effects (Wright et al. 2013; Avio et al. 2015; Barboza et al. 2018). Given the elevated hazard potentials intrinsic to these polymer components, further efforts are required to assess the effects of microplastic on chondrichthyans, particularly those endangered species.

Conclusion and future prospects

This review presents a comprehensive analysis of the dispersion and characteristics of plastic pollution in marine chondrichthyans across distinct regions, habitats, and Red List categories. The findings provide valuable insights into the current presence of plastics in chondrichthyans, offering a significant perspective for further biodiversity conservation within this group. However, it is worth noting that the vast majority of the reviewed studies are observational rather than empirical, which makes it difficult to isolate the impact of intra- and inter-specific variations in biometric and ecological characteristics and provides insufficient information to substantiate the contamination dynamics of plastics among chondrichthyans. Therefore, the following issues could be addressed in future studies.

Compared to teleosts, research on plastic pollution in chondrichthyans is still in its early stages. More than 1200 species of chondrichthyans have been described worldwide; however, only less than 5% of these species were analyzed in the reviewed publications. Moreover, most of these publications focused on coastal demersal chondrichthyans, plastic contamination levels in oceanic chondrichthyans have not yet been studied extensively. The available datasets are insufficient to fully comprehend a taxon that not only plays a crucial role in oceanic ecosystems but also faces multiple threats (Serena et al. 2020). Future research should address knowledge gaps concerning chondrichthyans by implementing effective monitoring strategies in these regions. There is a need to intensify in-situ investigations of plastic pollution in their inhabiting seawater and prey across a broader range of species and spatial extents. Based on the environmental plastic collected simultaneously with the chondrichthyans, it is possible to verify potential relationships between the different matrices and thus provide more robust data for implementing a scientific and systematic system for ecological risk assessment. This integrated approach will facilitate the comprehensive quantitative assessment of the origin, distribution pattern, and trophic transfer of plastic pollution in chondrichthyans.

The development of standardized sampling methods and quantification approaches for assessing plastic pollution in chondrichthyans remains lacking. The majority of publications lacks quantitative records of specific characteristics of plastics (e.g., shape and polymer type), and the datasets have not been consistently and uniformly described. Future studies could quantify the abundance, shape, size, and polymer composition of plastics, and coupled with the adoption of an established standardized terminology, e.g., the classification system for microplastic proposed by GESAMP. In addition, we recommend provide information regarding the biological and ecological characteristics (e.g., life stage, body size, feeding strategy, and sex ratio) of the studied specimens, as well as precise spatial information (latitude and longitude coordinates), sample size (e.g., all specimens and the number of specimens that contained plastics) and number of items found in the different organs/tissues. This will facilitate the acquisition of data that closely reflect natural environment conditions and enhance the comparability between studies (Wootton et al. 2021). Furthermore, in order to prevent potential errors in the results caused by indoor cross-contamination or airborne pollutants, it is essential to strictly adhere to quality assurance/quality control (QA/QC) standards throughout the entire experimentation process (Hermsen et al. 2018).

The effects (e.g., biological, physical, ecological) of plastics on chondrichthyan populations and communities need further investigation. Unlike teleosts, most chondrichthyans have spiraling folds in their intestines, and the length of their intestines is shorter compared to that of teleosts (Klimley 2013). The anatomy of the intestine differs among sharks, rays, and chimaeras, including spiral valve, scrolled valve, and funnel valve structures. This life history trait is one of the factors responsible for the evolutionary success of chondrichthyans. Considering the gastrointestinal system is extensively utilized for plastic detection in chondrichthyans and teleosts (Fig. 4; Santos de Moura and Vianna 2020; Wootton et al. 2021; Barboza et al. 2023), it is recommended to compare the variations in retention and characteristics of plastics among different intestinal structures. The evaluation of the presence of plastics in chondrichthyans should not be restricted only to the gastrointestinal system. For instance, it is imperative to investigate the presence of microplastics in the reproductive system, specifically focusing on chondrichthyans with viviparous embryonic development, as several studies have documented the toxic effects on fish embryos (Zhang et al. 2021). Such investigations are essential for the comprehensive understanding of bioavailability and ecological risks of plastics for endangered chondrichthyans.

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Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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