environments

Systematic Review

A Systematic Review of Microplastic Contamination in Commercially Important Bony Fish and Its Implications for Health

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Citation: de Souza, J.S.; de Pinho, J.V.; de Almeida Rodrigues, P.; de Melo, A.C.; Bergsten-Torralba, L.R.; Conte-Junior, C.A. A Systematic Review of Microplastic Contamination in Commercially Important Bony Fish and Its Implications for Health. *Environments* **2024**, *11*, 174. https://doi.org/10.3390/environments11080174

Academic Editor: Teresa A. P. Rocha-Santos

Received: 9 May 2024
Revised: 17 July 2024
Accepted: 30 July 2024
Published: 16 August 2024

Abstract: The increasing production of plastic products has raised concerns about environmental impacts related to microplastic formation, which harms ecosystems and human health. This systematic review aims to present the concentration of microplastics in commercially important bony fish and discuss the impacts on animal health and the possibility of these contaminants reaching the end consumer. The PICO methodology was used, and 517 articles were retrieved from four databases (PubMed, Embase, Web of Science, and Scopus); after selecting articles that complement the research objective, 70 articles were used to compose this review. According to the results, line-shaped microplastics, polypropylene, and polystyrene polymers were the most frequently identified in the articles. Additionally, the effects of microplastics on animal health, including false satiety and physical injuries, as well as risks to human health, such as epithelial inflammation, oxidative stress, and cell contamination, were discussed. Understanding the concentration of microplastics in commercially important bony fish is necessary for protecting human health and maintaining the health of marine ecosystems. It is necessary to adopt legislative measures for proper plastic disposal.

Keywords: plastic particle; plastic ingestion; polymers; human consumption; commercial fish; food habit

1. Introduction

The accumulation of solid waste has become increasingly alarming due to the impact of chemical substances and dispersed materials in the environment, ultimately leading to adverse effects on the biota. Among these residues, plastic is a material that has stood out in recent decades due to its low economic value, functionality, and wide range of possible worldwide applications [1].

Plastic has been produced from synthetic polymers with long chains of repeating macromolecules since the 1860s [2]. Its application was developed for industrial activities in the 1920s, and production increased in the 1940s, especially between the 1970s and 2012, with plastic production reaching approximately 300 million tons. Population growth has driven greater demand for plastics, especially for packaging, resulting in an increase in the production of these materials [3]. However, the lack of incentives for recycling and inadequate disposal contribute to the increase in plastic contamination in the environment, with this waste reaching water resources.

In aquatic ecosystems, these materials are also exposed to sunlight, wave action, and fluctuations in environmental conditions such as temperature, irradiation, and pH [4], promoting slow degradation that leads to the fragmentation of waste into microplastics (MPs). These plastic particles are defined by a size of less than 5 mm in diameter [5,6] and are capable of adsorbing substances, such as toxic metals and potentially toxic metals (Cr, Co, Ni, Cu, Zn, Cd, and Pb) on their surface [7,8], and adsorbing persistent organic pollutants, such as polycyclic aromatic hydrocarbons [9].

MP particles, such as fragments, thread, film, and pellets are commonly found in marine environments, causing damage to the organisms of aquatic food chains through direct consumption or trophic transfer [10,11]. Similarly, such contaminants can reach humans through the consumption of contaminated fish products [12].

The toxic effect that MPs can have on biota is mainly related to the characteristics of the chemical additives used during the manufacture of plastics to confer resistance to the action of light, ultraviolet radiation, and heat, resulting in damage to health, as in the case of Bisphenol A (BPA) [2,13,14]. In addition, MPs can leach into the environment, being found in substantial amounts in water [15–17], where they can interact with other compounds and increase their bioavailability [18–21]. These processes generate negative impacts on aquatic life.

Several studies have found the presence of MPs in the gastrointestinal tract of marine mammals, bivalves, and fish intended for human consumption [11,22–29] demonstrating the possible effects on the health of these animals, such as the ability of MPs to translocate to secondary tissues, causing damage to the immune system and cell health [14,30]. These organisms are constituents of fish products intended for human consumption, such as mussels, fish, and squid, therefore representing a significant route of exposure [29,31,32].

In recent decades, the volume of fish products has substantially increased, with global consumption growing at an average annual rate of 3.1% from 1961 to 2017. In 2017, fish consumption accounted for 17% of the animal protein intake of the world population, with bony fish responsible for 85% of total production. The global production of fish and fish products was estimated at approximately 179 million tonnes in 2018 [33].

Effects on human health depend on exposure concentrations [14], and it is necessary to determine the degree of contamination in commonly consumed animals. In this sense, this review aims to evaluate the behavior and distribution of MPs in bony fish of commercial interest in different fishing regions of the world and the possible effects on the environment and health. The abundance of different shapes and types of MP polymers present in animal tissues is assessed, emphasizing the food habits of each species and the impact of MP contamination on health.

2. Materials and Methods

2.1. Study Selection Criteria

This systematic review follows four sequential stages by the two authors (J.S.S. and A.C.M.). First, a search was performed across four databases: Embase, PubMed, Web of Science, and Scopus, using selected keywords as described in Section 2.3. The search was limited to English articles published between 2012 and 2024.

Subsequently, titles and abstracts of the retrieved documents were imported into the StArt 2.3.4.2 tool [34], where studies such as editorials, letters, reviews, mini-reviews, theses, and duplicate studies were excluded. Articles selected from titles and abstracts were then imported into Mendeley 1.1.9.8 software [35], fully read, and all relevant data were extracted and entered into a Microsoft Excel spreadsheet for evaluation. At each stage, studies that did not investigate associations between commercially important bony fish and the presence of microplastics were eliminated. Additionally, studies considered essential but not included in any of the research databases were added.

The results were reported following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [36] and registered in the Open Science Framework. From the data obtained, a map and graphics were produced using the R v. 4.0.4 ggplot2 package [37], and additional information on the identified fish species was obtained from the FishBase platform [38].

2.2. Focus Question

The central question: "What are the microplastic concentrations in bony fish of commercial interest and their implications for health?" was developed according to the problem, intervention, comparison, and outcome (PICO) method. To answer this question, the following sub-items were employed:

- What is the main animal's organ studied for microplastic extraction?
- What are the types of raw materials of microplastics, and what are the main forms found? How do these pollutants get into animals?
- Which habitats had the highest concentrations of MPs?

2.3. Information Sources and Data Curation

A literature search was performed using Medical Subject Headings (MeSH) to determine synonyms complementary to the established search terms. The research was conducted on the Embase, Pubmed, Web of Science, and Scopus platforms between April and May 2024, with the aim of carrying out a comprehensive bibliographical search. To direct the inquiry, four "Search Components" were defined:

- Search Component 1 (SC1)—Fish OR 'Bony Fish'.
- Search Component 2 (SC2)—Microplastic* OR 'Plastic Fragment'.
- Search Component 3 (SC3)—Behavior OR 'Plastic Transport' OR Dispersion.
- Search Component 4 (SC4)—'Marine Environment*' OR Ocean OR 'Coastal Water'.

After retrieving the Search Component results, the Boolean operator "AND" was used to make cross combinations between SC1, SC2, SC3, and SC4. It is worth noting that the research questions and inclusion criteria for the review were expressed in the terms of the PICO protocol.

2.4. Risk of Bias Assessment

Possible sources of bias include the inclusion/exclusion criteria, chosen database, date, language, number of articles, and types of articles selected for this study. Overall, these sources of bias cannot be considered negative for document quality. A prior search was carried out, generalizing the sources cited, that is, considering all languages, dates, types of articles, and in different databases, and from this search, we determined limits for each of these topics to obtain a better selection of documents that met the objective of the manuscript. The protocol for executing this article described above was carefully followed and the searches were carried out by two researchers, in order to avoid possible bias in the execution of the work.

Assessing the risk of bias for each study, Table 1 presents the main topics that can be considered fragile for obtaining reliable results regarding each experimental article used in this research.

Table 1. Risk of bias identified in the main experimental articles used in this review.

Reference	Risk of Bias
Al-Salem et al. [39]	Low sample number for each species and quality control to avoid external contamination during processing was not described, which may indicate that in the absence of this process, the particles described could come from contamination during processing and not from the animal's stomach contents.
Avio et al. [22]	The methodology for quality control was not described, and it was even described that textile fibers with irregular diameters were excluded from the analysis as they could be from contamination during sampling and processing.
Bour et al. [23]	The entire GIT was investigated, which could generate a bias related to different rates of digestion and feeding; however, this factor was not considered when investigating the difference in eating habits between species.
De Witte et al. [40]	Some data with potential relevance to the study were excluded due to inconsistency in species identification or because they were low-catch species. Low sample number for each species.
Klangnurak and Chunniyom et al. [28]	The entire GIT was investigated, which could generate a bias related to different rates of digestion and feeding; however, this factor was not considered when investigating the difference in eating habits between species.
Lopes et al. [41]	Excluded fibers based on visual identification and these could come from external contamination.
Lusher et al. [24]	The entire GIT was investigated, which could generate a bias related to different rates of digestion and feeding.
Morgana et al. 2018 [25]	The entire GIT was investigated, which could generate a bias related to different rates of digestion and feeding.
Miranda and Carvalho-Souza, [42]	Low sample number for each species and quality control to avoid external contamination during processing was not described, which may indicate that in the absence of this process, the particles described could come from contamination during processing and not from the animal's stomach contents.
Phaksopa et al. [27]	Low sample number for each species (pelagic).
Renzi et al. [31]	Sample number per species not defined; a lack of the counting and identification of very small particles (undetermined nature); aggressive extraction method that could affect the quality of the results obtained; and unrepresentative study area.
Robin et al. [43]	Low sample number for each species.
Tanaka and Takada, [44]	The entire GIT was investigated, which could generate a bias related to different rates of digestion and feeding; however, this factor was not considered when investigating the difference in eating habits between species.
Wang et al. [29]	The entire GIT was investigated, which could generate a bias related to different rates of digestion and feeding; however, this factor was not considered when investigating the difference in eating habits between species.
Zhang et al. [11]	Low sample number for some species. The entire GIT was investigated, which could generate a bias related to different rates of digestion and feeding; however, this factor was not considered when investigating the difference in eating habits between species.

The exclusion criteria selected were articles that did not study commercial bony fish (n = 127), articles without data on plastic quantification (n = 193), and articles that evaluated in vivo studies (n = 21). The inclusion criteria determined were articles that dealt with commercial marine fish, articles that identified and characterized microplastics and articles that investigated the relationship between the animal's habitat and the ingestion of microplastics. These criteria were also not limiting the quality of the research, and served to narrow the search so that the selected documents fit the research objective.

3. Results

A total of 517 scientific works were found: 146 articles were identified in the PubMed database, 103 in Embase, 178 in Web of Science, and 90 in Scopus. A total of 144 of those 517 were duplicates or triplicates, so they were excluded, resulting in 373 remaining papers. After reading the titles and abstracts, 341 articles were excluded, as they presented information on other animals and in vitro studies (Figure 1). The other 32 articles were fully evaluated, and only 20 of them were considered suitable for this review, as they reported MPs concentration in bony fish and discussed the circulation of MPs in the ocean. Thus, twelve articles were excluded, as they did not follow the inclusion criteria, eight studies were excluded due to the lack of data on the quantification of plastic, only two articles addressed MPs in the fish gills, and two articles were excluded for addressing plastic fragments larger than 5 mm in diameter, as this size did not align with the objective of this study.

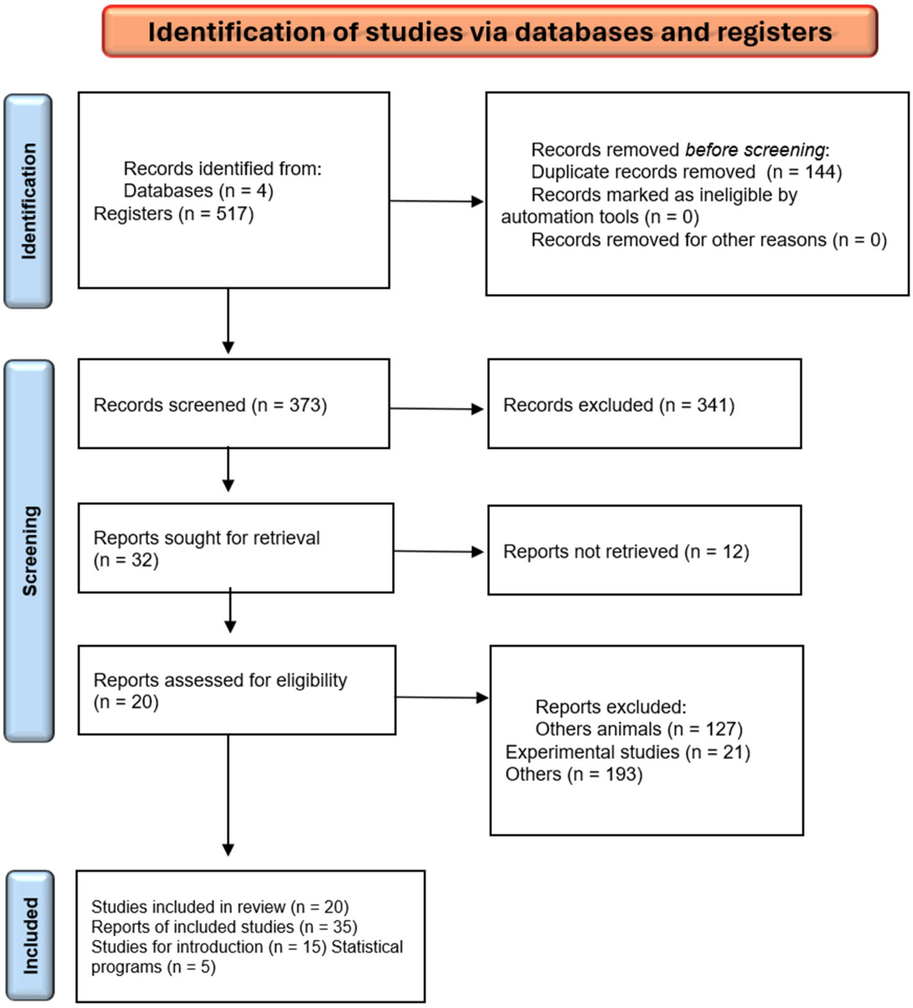

Figure 1. Flow diagram displaying the results of the literature search (PubMed, Embase, Web of Science, and Scopus).

Following this, articles were manually included, which contained pertinent information regarding the adverse effects of MPs on animal health, and studies investigating the toxicity of additives found in plastics. These articles were exclusively added to provide relevant information for the discussion in the present study. Consequently, a total of 70 articles were compiled for this review (Figure 1).

In order to summarize the studies retrieved, the focal questions of the work and their main answers obtained through the articles can be checked in Table 2.

Table 2. Questions of focus in this work, their main answers, and the number of articles obtained for each question.

Focus Question	Summary Answer	Number of Imported Articles
What is the main animal organ studied for microplastic extraction?	The gastrointestinal tract (GIT) was the most frequently analyzed organ, followed by gills and muscles.	14
What are the types of microplastic materials and the main forms found?	The most common types of microplastics found were polyethylene (PE), polypropylene (PP), and polystyrene (PS). The predominant shapes include fibers and fragments.	17
How do these pollutants enter the animals?	Microplastics enter animals mainly through the ingestion of contaminated water and food, and also through absorption by the gills during respiration.	20
Which habitats had the highest concentrations of MPs?	Coastal and estuarine habitats showed the highest concentrations of microplastics due to proximity to human pollution sources.	12

From the average MPs concentration found in the gastrointestinal tract of the animals studied in the search articles, a comparison was made with the reported global values (Figure 2A). A higher concentration of MPs in the gastrointestinal tract was observed in the study of Siddique et al. [32]. A total of 287 MPs were recovered from the specimens, with an average of 19.13 $\pm$ 10.77 particles per individual, ranging from seven to fifty-one particles per fish.

The data presented in this image did not include the articles by Al-Salem et al. [39], Hermsen et al. [45], Miranda and Carvalho-Souza [42], Morgana et al. [25], and Robin et al. [43], due to the low incidence of MPs in the captured animals. The values reported by Klangnurak and Chunniyom [28] were obtained by calculating the average of pelagic and demersal fish particles. The particle average in the Renzi et al. [31] study was calculated from the microplastic average found in the species *Sardinia pilchardus* and *Engraulis encrasicolus*. The particle average was based on the study site, stage, and particle average per species in the study by Pennino et al. [26]. In the study by Lopes et al. [41] and Valente et al. [46] the average number of microplastics was calculated from particles found in the gastrointestinal tract of the pelagic fish *Sardina pilchardus*, *Engraulis encrasicolus*, *Trachurus trachurus* and *Engraulis encrasicolus*, *Scomber scombrus*, and *Trachurus trachurus*, respectively. In the research conducted by De Witte et al. [40], the particle average was calculated as the mean value of the treatments used in polymer identification.

Although most studies show low amounts of particles that are not significant in terms of animal health, these particles can carry a considerable amount of contaminants, which can lead to significant impacts on animal health.

Furthermore, it is important to highlight that the greater quantity of particles in the animal's gastrointestinal tract is related to its eating habits and its ability to assimilate, digest, and excrete these residues. This pattern is presented in the species *Tenualosa illisha* in the study by Siddique et al. [32]. In this sense, it becomes even more important to analyze the transformation processes of these polymers within the organism, since the edible portion of the fish is its muscles. Therefore, it is indispensable to define the incidence of particles and whether they are present in different tissues, establishing a relationship with human health.

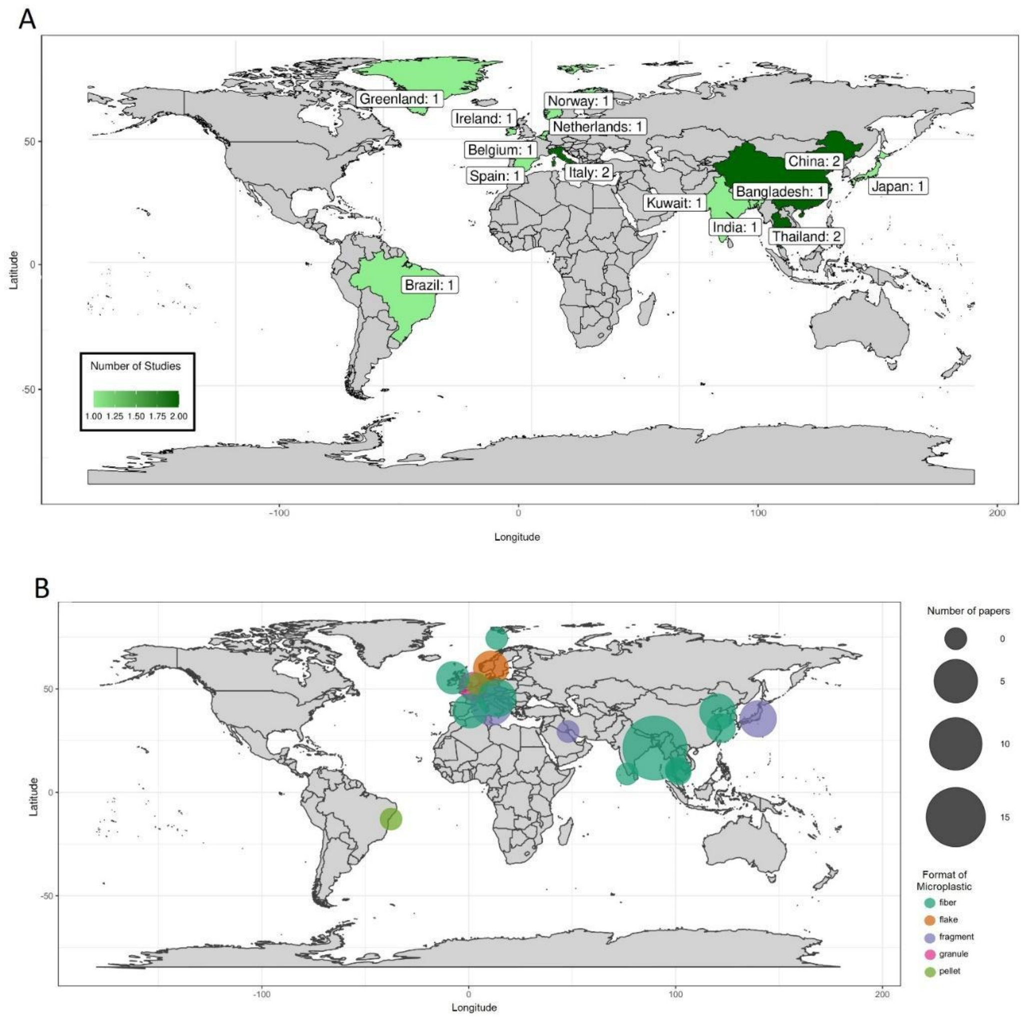

Figure 2. (**A**). Global average distribution of microplastics per individual. The map displays the concentration of microplastics found in the countries included in this review. The increasing size of the circle in each region represents the amount of microplastics. The circles' colors represent each country's most abundant particle type. Red indicates the line shape, the most frequent in the studies. Blue represents flakes, green represents fragments, purple represents granules, and orange represents pellets. (**B**). Geographic distribution of the works covered in this review.

MPs have a variety of forms, and most authors classify them as filaments, fragments, films, and pellets. In addition to these four categories, some authors [11,31,32,43,46,47] also include foam as a classification shape. Among the 20 studies included in this review, 17 articles reported the presence of filamentous particles (Figure 3), which were the most abundant type of particle in 13 studies. These particles have mainly been identified in studies of pelagic fish species. The high concentration of filamentous MPs is associated with fishing activities, which contribute to the increase in these particles and favor their degradation process. These activities include the improper disposal of plastic waste, fishing activities, and the release of untreated sewage, including the washing of polyester or polyamide clothing.

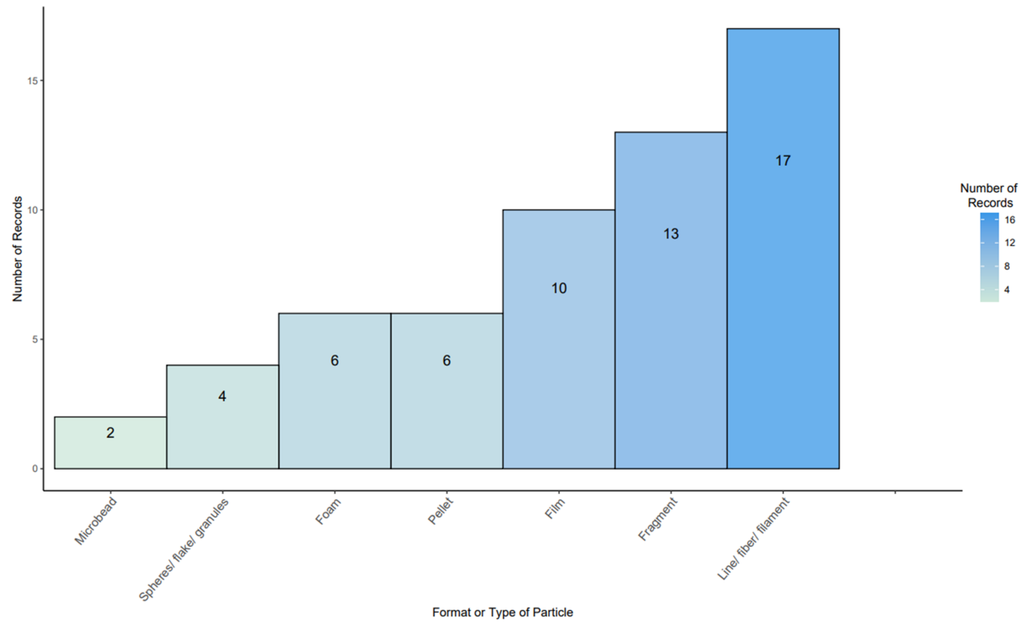

Figure 3. The frequency of microplastic shapes found in the 20 articles searched.

The articles evaluated by this study indicate that the microplastics found in aquatic environments are predominantly filamentous, as was the case with [23,39,43]. The authors also point out that filaments are often associated with secondary contamination due to their morphology and can originate from a variety of anthropogenic sources, including wear from synthetic textiles and waste from fishing activities and industrial processes, [24] suggesting that cross-contamination can occur at various stages of the sampling process, from collection to laboratory analysis. For this reason, [28,45] stress that studies with such polymers should employ strict quality control methods during sample collection and analysis, especially for handling, such as avoiding the use of equipment and laboratory clothing that release synthetic fibers.

Secondary contamination by filaments can even invalidate the results, masking the real concentrations and distributions of microplastics, affecting the interpretation of the data and the conclusions of the study [22]). One example is the occurrence of overestimates in the concentration of microplastics in the environments studied [25], demonstrating that the use of synthetic fiber-free laboratory clothing can significantly reduce secondary contamination, while [43] emphasizing the importance of detailed reporting of the quality control procedures adopted in each study, providing transparency and credibility to the results.

The majority of publications investigated the gastrointestinal tract of fish species (n = 14). Other authors analyzed the stomach, gills, and muscles of fish, as seen in Table 3. The study of these organs provides information about the diet and relationships in the trophic chain, being a good indicator of pollution associated with the animal's habits.

The frequency of polymers was estimated from the 20 search articles (Figure 4). Polyethylene (PE) was considered the most abundant polymer found in fish viscera in the articles by Avio et al. [22], Bour et al. [23], Morgana et al. [25], Robin et al. [43], Takana and Takada [44], and Fatema et al. [47].

Table 3. Organs studied in the search articles and the most abundant forms of microplastics found.

Reference	Organ	Abundant Shape
Al-Salem et al. [39]	GIT	Fragment
Avio et al. [22]	GIT	Fragment
Bour et al. [23]	GIT	Flakes
De Witte et al. [40]	GIT	Granules
Fatema et al. [47]	GIT	Fibers
Hermsen et al. [45]	GIT	Pellet
Klangnurak and Chunniyom et al. [28]	GIT	Fibers
Lopes et al. [41]	GIT, gills, and muscle	Fibers
Lusher et al. [24]	GIT	Fibers
Morgana et al. [25]	GIT	Fibers
Miranda and Carvalho-Souza. [42]	GIT	Pellet
Pennino et al. [26]	Stomach	Fibers
Phaksopa et al. [27]	GIT and gills	Fibers
Renzi et al. [31]	Stomach	Fibers
Robin et al. [41]	GIT	Fibers
Siddique et al. [32]	GIT	Fibers
Tanaka and Takada, [44]	GIT	Fragment
Valente et al. [46]	GIT	Fibers
Wang et al. [29]	GIT	Fibers
Zhang et al. [11]	GIT and gills	Fibers

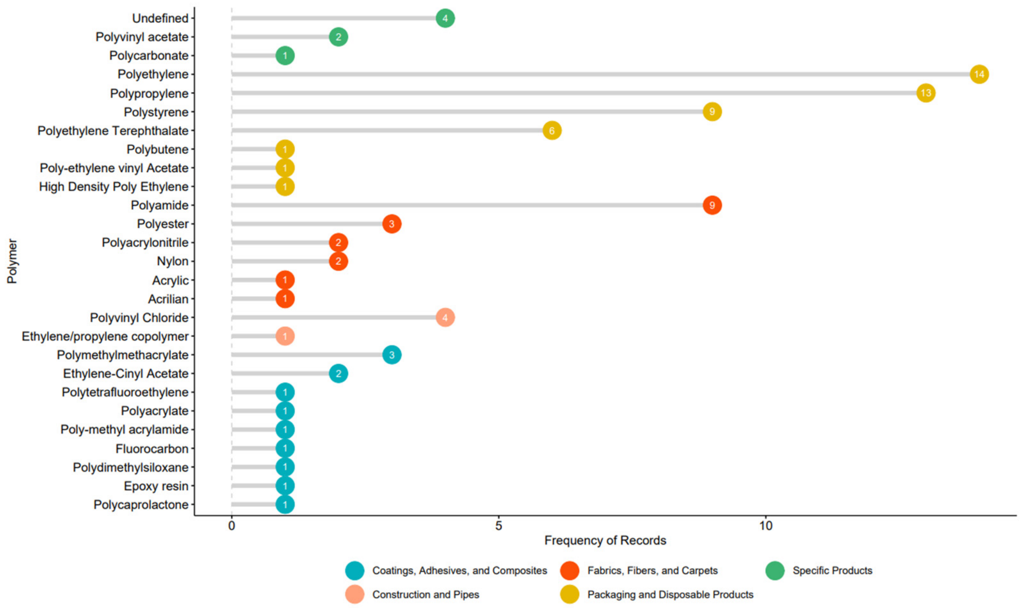

Figure 4. Frequency of polymers found in the 20 articles selected for this systematic review. The graph represents the frequency of studies using each mentioned type of polymer, where the *x*-axis represents the count (frequency) and the *y*-axis represents the type of polymer. The different colors indicate the various applications in the context of anthropogenic activities.

Fish can accidentally ingest microplastics when these particles are mistaken for food, especially when they resemble plankton, an important part of many fish species' diets.

Microplastics can also be ingested when they adhere to the food surface or when fish filter water for food. Therefore, it is necessary to understand fish feeding habits for a better comprehension of how they are affected by the presence of microplastics in their environments. In the reviewed studies, several fish species were analyzed, and it was observed that the majority had a demersal habit (41 species), followed by a pelagic habit (32 species), and then a benthopelagic habit (26 species), which comprised the highest number of individuals studied. On the other hand, benthic (three species) and mesopelagic (seven species) habits were the least studied (Figure 5). The high commercial value of pelagic and benthopelagic species, as they are the most captured, could explain the larger numbers of individuals analyzed with these habits [33].

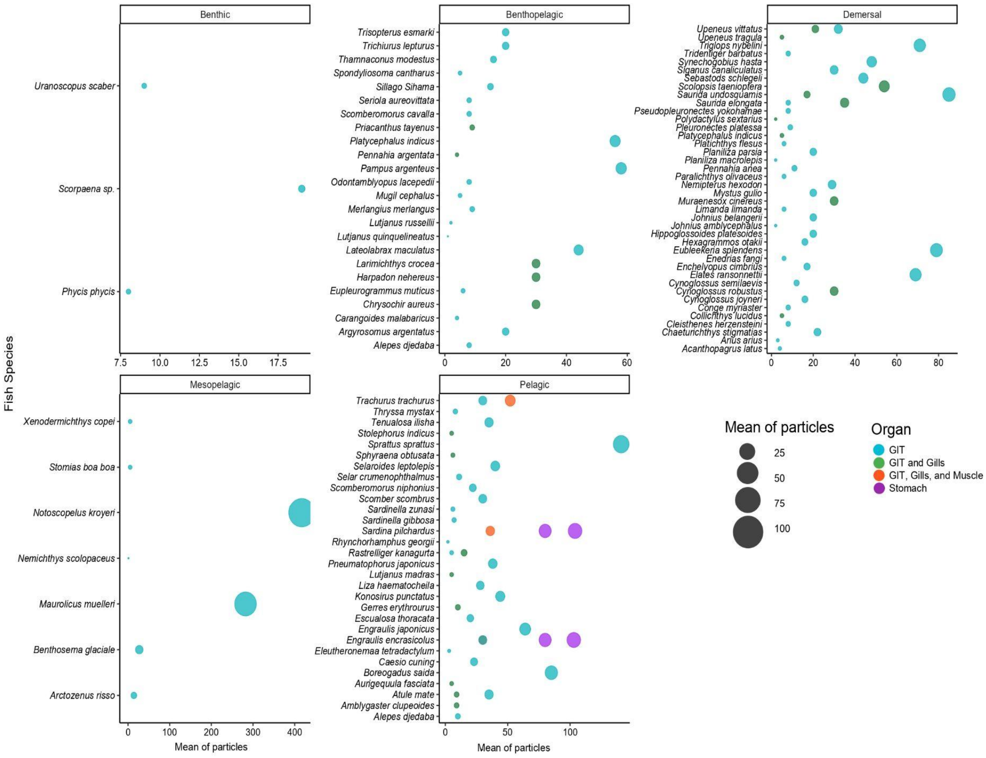

Figure 5. Number of individuals in relation to the analyzed habit and organ reported in the 20 articles selected for this systematic review. The diagram presents the habits of individuals in relation to the species analyzed in the studies. The circles represent the number of individuals per species, while the colors indicate the type of analyzed organ: blue represents the gastrointestinal tract (GIT); green the GIT and gills; orange the GIT, gills, and muscle; and purple the stomach.

4. Discussion

4.1. Characterization and Classification of Microplastic

The MPs characterization is described according to the source (primary or secondary), type (polymeric composition), shape (fibers, fragments, film, pellets, and spherical), size, and color. The physical characteristics are examined by visual analysis with or without an optical microscope and electron microscopy, while the chemical characteristics are analyzed through Fourier-transform infrared (FTIR) spectroscopy, Raman spectroscopy, and thermal analysis [48].

Different methods may not look that different when compared to the same fabrics, but sensitivity can vary between different fabrics. Therefore, it is important to opt for well-described and standardized methodologies. However, this has been a challenge, as there is no single guide that is applicable to all research, which in turn limits comparisons. The difficulty in standardizing the forms and methodologies used for identification, both visual and chemical, is evident in the reviewed works. Although the studies highlight the sensitivity of the analyses, the lack of standardization from the sampling process to the treatment and removal of samples can result in small variations that can overestimate the analyses when having a quantitative objective.

4.1.1. Sources of Microplastic

Depending on their origin, MPs can be classified as primary or secondary sources. Primary source MPs are plastic particles generated directly during the production of plastic products, while secondary source MPs are formed from the degradation of more extensive plastic materials. Thus, it is possible to estimate the emission sources of these particles by evaluating their properties, which can vary depending on the specific source and type of plastic [41,44].

The primary sources of MP pollution are primarily caused by the degradation of large plastic items such as bags and bottles and the release of MPs from consumer products [25,32]. These MPs can be released into the environment through human actions such as improper waste disposal or wastewater systems without adequate filtration. They are also a result of industrial processes, including the manufacture of polyester, acrylic, and nylon textiles.

Currently, it is highly challenging to establish a direct correlation between MPs and a specific source of pollution or to demonstrate how certain human activities affect their consumption by the biota [2–29]. The most abundant forms of MPs frequently cited in the literature as dominant in the marine environment are filaments and fibers. This contamination is directly related to the textile industry and domestic wastewater, where the abrasion of textiles during washing is a common source of particles. Studies indicate that a single laundry cycle can release over 1900 fibers [48]. Additionally, fishing activity can also play an influential role, as MPs resulting from the fragmentation of fishing gear are regularly observed [49,50].

Therefore, determining the exact source of MP contamination is still challenging for the scientific community, as a specific type of polymer can originate in different objects. However, combining the characteristics of the MPs, such as the color, shape, and type of polymers, can provide clues to its emission source.

4.1.2. Type of Plastic Polymer

Plastic packaging currently in widespread use is made up of high-density (HDPE,) or low-density (LDPE) polyethylene, in addition to utensils made of polypropylene (PP), polystyrene (PS), polyamide (PA), polyester (PES), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) such as plastic bottles [51]. Despite the high applicability, as these materials are quickly discarded and are normally not degradable, they tend to remain in nature for decades [1,52].

In a study conducted by Klangnurak and Chunniyom [28] analyzing fish in Thailand, it was observed that fibers were the most predominant shape of MPs found in demersal fish, with 17% fragments and 82% fibers. The average ingestion of MPs per individual was 0.08 ± 0.03 particles. Pelagic fish showed a higher average concentration of fibers and fragments, with 0.17 ± 0.05 particles per individual. After the FTIR analysis, the polymers were polyamide (PA), polyethylene (PE), and polypropylene (PP), which can be commonly used in the manufacture of clothing and fishing items. The higher concentration rate of MPs found in pelagic fish can be explained by the type of polymer's density; since PA, PE, and PP are considered less dense polymers, they float on the water's surface, thus increasing the probability of ingestion by pelagic fish.

Another study conducted in Thailand reported that 64% of pelagic and demersal fish had polyethylene terephthalate (PET) in their tissues [27], while polyamide (nylon) was present in two out of eleven demersal fish. This occurrence should be explained because of its density, which causes it to sink into the sea. Polyethylene (PE) was found in only 8.33% of pelagic species and 3.70% of demersal species [27]. This result suggests that pelagic fish are more likely to be exposed to MPs, as was also observed in [28]. In another study by Wang et al. [29] in the Bohai Sea, China, a higher rate of MP concentration in the fiber shape was also observed. The FTIR analysis showed 10 types of polymers, with the highest rates of synthetic polymers being polyethylene terephthalate (PET, 16.9%) and polypropylene (PP, 2.5%).

The supplementary analysis involves checking the type of polymer found, as it helps identify potential sources of contamination [44]. To this end, 16 authors used Fourier-transform infrared (FTIR) spectroscopy to identify the polymer present in the MPs and understand the nature of the MPs. Polyethylene (PE) was the predominant polymer identified in the studies (Figure 4) [11,22,23,25–29,38,42,43,46]; PE is commonly used in packaging and fishing nets [23,31].

4.1.3. Shape of Microplastics

The characterization of the MPs, concerning their shape, was observed in all studies. The most frequent shapes were line, film, pellet, and fragment. In the study by Avio et al. [22], the lines were described as having a regular diameter along the particle and non-frayed ends. These fibers had an irregular diameter along the particle and frayed tips. Particles similar to films were irregular, flexible, and thin. While the pellets were spherical. Meanwhile, particles classified as fragments were irregular with sharp edges and thicker than the film-type MPs [22].

In the work by Bour et al. [23], they classified the particles into four categories, flakes, fragments, textile fibers, and lines. Thus, dividing the filament into two new categories: textile fibers, which are non-regular along the particles and frayed ends, and lines, filaments with a regular shape and without frayed ends, as proposed by Avio et al. [22]. In comparison, other authors classified only the fiber category [11,19,25,27,28,32,42,45,47], leaving open whether they consider textile fibers as a thread since they did not describe the classification method [11,24,25,32]. Other authors classified fine or elongated particles as fibers, without differentiating whether the ends were frayed [28]. In contrast, Avio et al. [22], for example, disregarded the fibers in the study since they could represent air contamination from clothing during the sampling.

Likewise, particles of the same type are described by different terms, such as spheres, flakes, and granules, but all refer to spherical particles [23,32,43,45]. On the other hand, although pellets are also classified as spherical particles, they were not included in this group, as they have a primary origin and are used in industry to produce larger plastics. Thus, due to the similarity of the particles described by the authors, we identified these three groups as the same type of particle in this study (Figure 3).

Because of this, the works followed similar descriptions for particle shapes but did not specify the criteria each author used to define these shapes. Therefore, it becomes necessary for authors to adopt a standardized methodology to provide greater clarity in the classification methods used to define each particle shape. Thus, the use of terminology and chemical composition specific to the type of polymer can be used as a keyword in future systematic review searches, highlighting a greater frequency of forms and polymers described in this context.

4.1.4. Color and Size of Microplastics

The color of MPs can be influenced by various factors, such as the type of plastic, additives, and pigments used during manufacturing [13]. MPs can undergo color changes over time due to physical and chemical degradation processes and exposure to environmental factors [53].

Characterization by color was performed in 14 studies [11,23–25,27,28,31,32,42–44,46]. The predominant color was blue in five articles [11,23,25,41,46], followed by black (n = 4) [24,27,31,46], white (n = 4) [32,41,42,44], and red (n = 1) [28]. Some studies showed the selectivity of fish regarding the color of MPs, as it resembles the natural pigmentation of their prey. Thus, preference for certain colors is directly related to the feeding of the fish [46,54].

In several studies by Lusher et al. [24], Phaksopa et al. [27], Renzi et al. [31], and Fatema et al. [47], black was the predominant color. In the study by Renzi et al. [31], *Engraulis encrasicolus* ingested mostly black-colored MPs (20.5–60.0%) followed by blue MPs (18.8–50.0%). It was observed that this species preferred darker prey, so darker MPs increased the ingestion rate [31].

The size of plastic waste can be divided into three categories: macroplastics, which have dimensions above 5 mm; MPs, with dimensions between 1 µm and 5 mm; and nanoplastics (NPs), with dimensions below 1 µm [55]. The size of MPs was taken into consideration in 19 articles [11,22–25,27–29,31,32,39–46]. A total of seven studies [11,22,23, 29,32,39,42] observed MPs of smaller sizes, ranging from 1 µm to 0.1 mm, while all articles observed MPs larger than 0.1 mm.

MPs smaller than 0.1 mm were identified in the study conducted by Siddique et al. [32]. This finding may be attributed to the feeding habits of the analyzed fish species, *Tenualosa ilisha* (Figure 5), which feeds through filtration and can ingest smaller MPs during feeding. This result is consistent with the study by Renzi et al. [31], which investigated the presence of MPs in two different species, *Sardina pilchardus* and *Engraulis encrasicolus*. The results revealed that *Sardina pilchardus* had a greater quantity of MPs characterized by smaller size compared to *Engraulis encrasicolus*.

4.2. MP Distribution in Water Environments

The MP circulation, concentration, and distribution throughout the environment occurs in several ways and must be well elucidated. In the atmosphere, MPs can be transported for long distances by wind and settle on land and water. The circulation in water is influenced by some factors (sources of plastic pollution, the location, hydrodynamics of water, physical, and chemical MP properties). MPs have been found in all oceans, including remote areas [56].

In a study with Japanese anchovy (*Engraulis japonicus*) (Figure 5) collected in Tokyo Bay, Japan, Tanaka and Takada [44] detected the presence of MPs in 49 of the 76 fish examined. The composition of microplastics consisted mainly of polyethylene (PE) (52.0%) and polypropylene (PP) (43.3%) and among the formats analyzed, 7.3% were plastic spheres. By comparing the size and shape of the spheres to those contained in four popular facial cleansers in the Japanese market, the authors determined that the MP particles likely originated from these products.

Siddique et al. [32] investigated the presence of MPs in *Tenualosa ilisha* (Hilsa shad) (Figure 5). High concentrations of MPs were found, which can be attributed to the influx of domestic sewage from the combined Ganges, Brahmaputra, and Meghna rivers in the Bay of Bengal, Bangladesh.

Translocation of MPs and Biota

Commercial fishing is a significant global economic activity, with a production of 96.4 million tons in 2018, with small pelagics being the main group of this production [57]. The world's annual per capita fish consumption is approximately 20 kg [58]. Depending on the polymer, MPs can accumulate at the surface and in various water column strata due to their density and environmental conditions [24]. This irregular distribution of plastic particles can be used to assess the health of the food web and the exposure of pelagic fish to the risk [24,27,45].

Hermsen et al. [45] highlighted the risks of contact with MPs for organisms occupying a range of niches, such as diets, feeding behaviors, and positions in the water column. Phaksopa et al. [27] comparatively assessed the ingestion of MPs by pelagic and demersal fish species, finding that pelagic fish species were more likely to be exposed to MPs due to their lower density and buoyancy, which allows them to remain longer in the water column compared to particles that sink to the bottom. Lusher et al. [24] demonstrated that mesopelagic fish are more likely to come into contact with MPs, particularly during feeding in surface waters, through vertical migration.

In studies by Phaksopa et al. [27] and Zhang et al. [11] they evaluated MPs in two tissues, the gastrointestinal tract and the gills, both of which present MPs. Phaksopa et al. [27] observed a higher presence of MPs in the gastrointestinal tract of fish than the gills. However, Zhang et al. [11] observed a higher abundance of MPs in the gills compared to the gastrointestinal tract. This difference can be attributed to the larger contact surface area of the gills, allowing more MPs to adhere to this tissue during respiration.

MPs are distributed throughout the water column [27,28]. However, the behavior of MPs in the marine environment is related to factors such as particle density, size, shape, and environmental conditions such as temperature and salinity. Thus, depending on the shape and type of polymer, they tend to persist for extended periods due to their physical characteristics, such as buoyancy [24].

The contamination by MPs affects all marine animals. Among contaminated fish, bony fish are the most consumed worldwide [57], making it essential to study and understand the contamination rate of these animals. Fish is a high-quality source of protein and nutrients, including vitamins, minerals, and omega-3 fatty acids, that are essential in the human diet for maintaining a healthy body [33]. However, the consumption of contaminated fish can adversely affect human health.

Among the studies obtained in the search, only four [25,27,46,47] described the processes and factors involved in the dispersion of microplastics in the marine environment. This can be attributed to knowledge about these properties being incipient or to the complexity of marine environments [59]. Fish inhabiting coastal areas, such as estuaries [32], showed a higher MP contamination rate than fish inhabiting more distant coastal areas [2]. This difference in contamination between coastal fish and fish from more remote areas is associated with human activities, where coastal areas are more prone to receiving plastic waste.

Furthermore, the rate of MP contamination in bony fish may vary depending on the animal's habitat. Two studies evaluated the concentration of MPs in two fish species, one with a pelagic habit and the other with a demersal habit [25,27]. In the study by Morgana et al. [25], higher concentrations of MPs were observed in demersal fish, while Phaksopa et al. [27] showed higher concentrations of MPs in pelagic fish. The specific behavior of MPs in the water column tends to vary, which makes it difficult to understand which groups of animals will be the most exposed.

Furthermore, MPs can be distributed throughout the water column and transported over long distances, as seen in the study by Morgana et al. [25], highlighting the vulnerability of the Arctic Ocean. Although far from direct sources of pollution, the ingestion and concentration of MPs have been recorded.

The study by Valente et al. [46] investigated the translocation of MPs in marine food chains using the stable isotope analysis (SIA) technique. Their results indicated that the ingestion and accumulation of MPs in marine fish vary considerably between different areas, with species at higher trophic levels, such as *T. trachurus* and *S. scombrus*, presenting higher concentrations of microplastics. Fatema et al. [46] analyzed the frequency of MPs in different fish species based on their feeding habits. The study found that planktivorous fish, such as *E. thoracata* and *T. ilisha*, were more contaminated than carnivorous and omnivorous fish. Therefore, different trophic levels of marine biota are impacted by MPs suspended in the water column or by different fish microhabitats.

Studies describe complex modeling attempts to understand and anticipate the flow of particles in environmental compartments [60–63]. Hydrodynamic models, which assess water column transformations based on parameters like wind, currents, drag coefficient, and turbulence, are one of the tools used to track particles [60]. On the other hand, statistical models such as Markov chain analysis, rely on probabilistic data of particle locations to predict their future whereabouts [61]. Mass balance models, meanwhile, consider the variation between the input and output mass of residues [62]. Among all of these models, this study highlights the importance of process-based models [63] such as the "one health" approach, as they consider the biological and physical effects on microplastic behavior, like biofilm development, biofouling, fragmentation, degradation, half-life, and sedimentation, among others, which play a crucial role in the fate of microplastics and transport mechanisms.

The frequency of PE (Figure 4) found in the studies in this review suggests that the density of this MP and its position in the water column has a significant impact on the exposure of aquatic organisms (Figure 6). Pelagic fish are more susceptible to ingesting PE MPs due to their lower density characteristics than seawater, allowing them to remain floating for longer. As aforementioned, PE is the most commonly found polymer in the studies (Figure 4). Its abundance and physical characteristics increase the risk of pelagic fish directly or indirectly ingesting this type of MP. This becomes a concern, as much of wild commercial fishing is focused on pelagic fish [57].

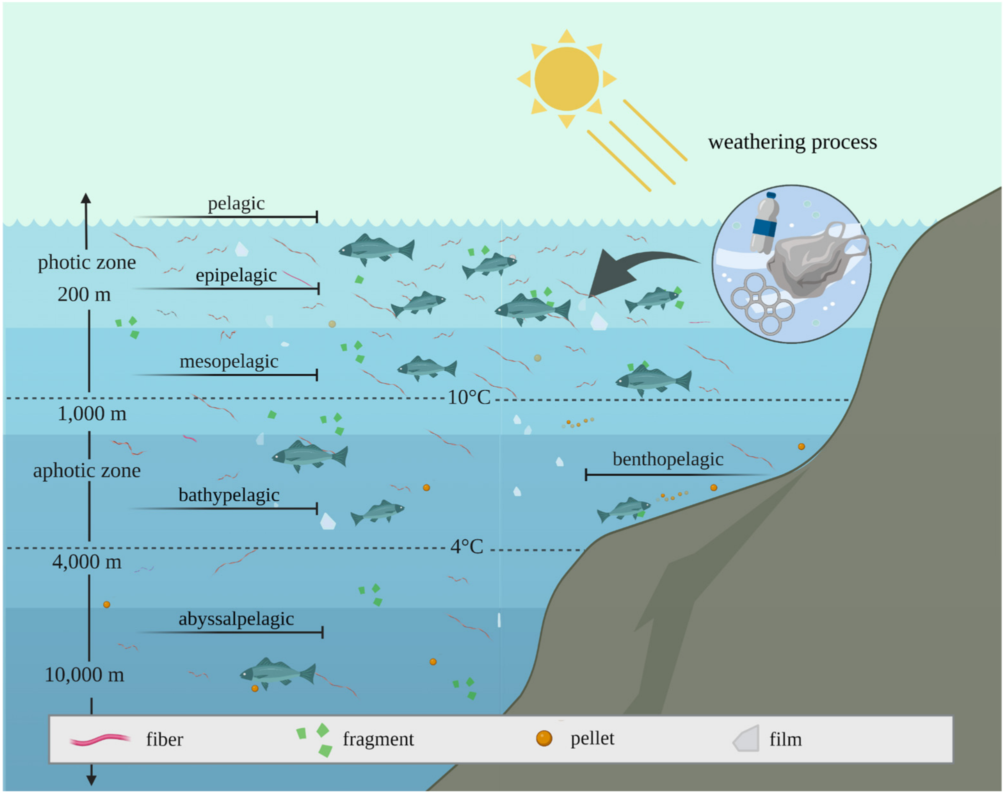

Figure 6. Distribution of microplastics in different zones of the ocean. The fibers are predominantly found in the epipelagic zones, and due to vertical transport, they are also present in the mesopelagic and bathypelagic zones. Fragments are found in all zones, including the abyssalpelagic. Films in the epipelagic zone may occur in deeper zones due to transport currents. Pellets are found in all zones but are less common in deeper areas, such as bathypelagic and abyssalpelagic. The distribution of polymers also varies in each zone due to density. Polymers such as polyethylene (PE) and polypropylene (PP) are commonly found in the epipelagic zone. The mesopelagic zone has a more significant presence of low-density polymers, such as polyester (PET) and polyamide (PA). The bathypelagic zone may contain polymethylmethacrylate (PMMA). In the abyssalpelagic zone, microplastics are less common, while in the benthopelagic zone, polymers, such as PE, PP, PA, and PET, can be observed. Therefore, these particles can float or sink depending on their shape and composition, reaching different water column layers and marine habitats.

4.3. Side Effects of Microplastics on Biota

Other substances may be associated with MPs in their dispersion process in the environment, such as chemicals and toxic metals that are adsorbed and accumulated on the surface of the particles and that, when ingested together with plastic, can bioaccumulate and biomagnify in marine biota, causing damage to health [32,64]. Physical effects associated with the size, shape, and concentration of the particle in the organism are identified [64]. Siddique et al. [32] identified high-risk chemical pollutants adsorbed on MPs, including oil compounds, pharmaceuticals, pesticides, persistent organic pollutants, detergents, and toxic metals, namely Cd and Pb. They increase the health risk of animals that accidentally ingest MPs [41]. Barborsa et al. [65] conducted an evaluation of the combination of MPs and Hg. They observed that mercury bioaccumulation in fish tissues was associated with adsorption by MPs. The combination of these two contaminants led to neurotoxicity, lipid peroxidation in the brain and muscles, and an alteration in the activity of energy-related enzymes. The effect of the two contaminants can be enhanced when ingested together, compared to when they are ingested alone [66,67].

It is necessary to understand how MPs affect the animal organism and what these impacts are. The authors Tanaka and Takada [44], Browne et al. [49], and Wright et al. [68] identified that ingesting MPs is related to false satiety, leading to malnutrition, since natural prey can easily be confused with plastic particles. Other authors have observed physical injuries, including intestinal and internal or external ulcers [69,70]. In addition, the ingestion of MPs can cause a decrease in fecundity, reducing reproductive success [10,71–73].

Additives are added to plastics during production and can separate when discarded, generating toxic compounds. They can dissociate from the plastic and enter the environment. The transfer of chemical compounds between solids and liquids is known as sorption, which can occur in two forms: adsorption and absorption. In adsorption, the molecules are at the boundary between the phases and are linked by interactions such as van der Waals, ionic, steric, or covalent bonds. In absorption, the molecules penetrate the solid matrix and are held by weak van der Waals forces. High additive concentration favors absorption, while low concentration favors adsorption. Thus, MPs more susceptible to adsorption pose a higher risk to the ecosystem, given the presence of more vital interaction forces on the surface. The use of additives in plastics represents a danger to the entire ecosystem [74]. It is also believed that MPs can go to other animal tissues, such as musculature, representing a potential risk to human health [75].

5. Conclusions

This review reveals that contamination by microplastics in commercially important bony fish is present in various fishing regions worldwide, posing a potential risk to consumers and marine biota. The abundance of microplastics in fish depends on habitat and particle dispersion in the ocean. Fibers/lines, as well as polypropylene and polyethylene polymers, were the most frequently found types of microplastics in reviewed articles, possibly originating from the textile industry or abandoned fishing gear at sea. However, the precise identification of emission sources remains a challenge, and standardization and clearer identification of particles by authors are needed. Further studies are needed to explore the consumption of fish products as a route for the acquisition of microplastics by the human population, as there are few studies on this relationship, particularly conducting a risk analysis. However, there is already ample evidence of the presence of microplastics in commercially important species. It is essential to monitor the presence of these particles and develop solutions to reduce contamination in coastal areas and the ocean, to protect the health of fish and ensure the food safety of consumers.

Author Contributions: J.S.d.S.: Investigation, Formal analysis, Data curation, Writing—original draft and editing; J.V.d.P.: Formal analysis, Data curation, Writing—review and editing; P.d.A.R.: Investigation, Formal analysis, Data curation, Writing—review and editing; A.C.d.M.: Writing: review and editing; L.R.B.-T.: Investigation, Formal analysis, Data curation, Writing—review and editing; C.A.C.-J.: Supervision, Conceptualization, Resources, Data curation, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are thankful for the financial support provided by the Fundação de Amparo À Pesquisa do Estado do Rio de Janeiro (FAPERJ) Brazil grant number [E-26/200.891/2021 (C.A.C.J.); E-26/200.077/2022 (P.A.R.); E-26/204.731/2022 (J.S.S.)], the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) grant number [313119/2020-1], and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) Brazil—Finance Code 001, for the granted scholarship to J.V. de P. The APC was funded by Fundação de Amparo À Pesquisa do Estado do Rio de Janeiro (FAPERJ).

Data Availability Statement: Data will be made available upon request to the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

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