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Differential Presence of Microplastics and Mesoplastics in Coral Reef and Mangrove Fishes in Isla Grande, Colombia

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Abstract: This study aims to determine whether differences exist between the presence of microplastics and mesoplastics in fishes of coral reef and mangrove ecosystems, in Isla Grande, Colombian Caribbean. The collection of three species of coral reef (*Centropomus undecimalis*, *Caranx hippos*, and *Lutjanus synagris*) and three species of mangrove from coral reef (*Centropomus undecimalis*, *Eugerres plumieri*, and *Archosargus rhomboidalis*) were found to have ingested microplastics and mesoplastics, with a significantly higher in the mangrove species than in the coral reef species (1.9 vs. 1.6 items/individual). Furthermore, the average abundance and weight of microplastics and mesoplastics were significantly higher in females than in males ($p < 0.05$) and the abundance of microplastics and mesoplastics in the intestines was significantly higher than in the stomach ($p < 0.05$). PE, polyester, PVC, and PET were the most abundant polymers among common plastics found in species of the two habitats. Our findings highlight the importance of more rigorous plastic waste management strategies in areas nearby the coast and mangrove habitats.



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Keywords: mesoplastics; microplastics; pollution; fishes; coral reef; mangrove; contamination; Isla Grande, Colombia

1. Introduction

The usage and disposal of plastics have increased considerably in recent years, and they are currently considered the most extended form of anthropogenic waste in aquatic systems [1,2].

Characteristics of this material such as its widespread use, omnipresence, lightness, durability, and constant buoyancy [1] facilitate its large proportion accumulation in different worldwide ecosystems [1,3]. However, marine ecosystems have been the most affected since a vast part of the planet's garbage has been placed there for years [4].

Plastics can be differentiated by their size into macroplastics (>25 mm), mesoplastics (5–25 mm), microplastics (<5 mm), and nanoplastics (<1 μm) (Blair, 2017). It is worth highlighting that, currently, microplastics are numerically the most abundant waste present in the oceans [3,5,6]. The primary source of microplastics is human production, mainly from the manufacture of personal care products, such as toothpaste, scrubs, and cosmetics [2,6,7]. The secondary source of microplastics are environmental processes, such as the exposure to ultraviolet rays, oxidation, temperature, and microorganisms, which contribute to the degradation of large pieces of plastic such as bottles, bags, and fishing nets into smaller pieces [8,9].

One of the main environmental risks associated with these particles is their bioavailability as a food resource for different organisms [10,11]. Following to their degradation and transport by currents, microplastics mix on the surface and in water columns [12]; consequently, they are ingested by various marine organisms and accumulate at different trophic levels [5].

It has been evidenced through previous studies that the ingestion of microplastics has taken place in all types of organisms, causing internal injuries, blockages in the digestive tract, and death from starvation [10,11,13]. Additionally, microplastics pose risks to organisms within the trophic web by transferring toxic chemical elements that have the potential to bioaccumulate. This may represent a potential impact on human health through the consumption of aquatic species [3].

In marine fish, studies have reported a higher average occurrence of microplastics in pelagic fish (living near–medium Surface waters) is higher than in demersal fish (living near the bottom) [14]. Additionally, females, larger fish, omnivorous and carnivorous fish appear to accumulate higher quantities of microplastics [6,8,15]. Anthropogenic plastics can affect the subsistence of several marine organisms living in different ocean habitats, including coral reefs, estuaries, mangroves, shallow bays, open sea, and deep-sea [3,16].

However, despite all these research efforts, several studies evidence the lack of critical knowledge regarding the relationships between the presence of plastics, the different characteristics of marine organisms, and the ecosystems in which they inhabit [17]. Amplifying this knowledge will allow an evaluation of the real impact caused by the presence of these particles on marine ecosystems [6,18]. Moreover, this worldwide issue requires scientific work to support evidence of complex dynamics within dimensions and scope, leading to effective solutions adaptable to local cultural contexts [19,20].

Plastics can accumulate in coastal areas associated with restricted water flow [21], affecting widely mangrove ecosystems [20–23]. Furthermore, coral reefs are highly threatened mainly by the chemical pollutants present in plastics [1,24]. Although it is well known that the dynamics of marine currents and proximity to the coast is different between mangrove and coral ecosystems, comparative studies that establish how the phenomenon of plastic accumulation occurs in these ecosystems have not been carried out, which is highly important given the significant natural and touristic resource they represent [23,24].

This study aims to determine the difference between microplastics and mesoplastics in fish present in the coral reef and mangrove ecosystems of Isla Grande in the Colombian Caribbean. Approximately 65% of the solid waste generated by coastal populations in Colombia is improperly managed. Most are finally disposed of in open dumps or natural water bodies, such as rivers, that carry them to the sea [20]. Isla Grande, located in the Rosario Islands in the Colombian Caribbean, is constantly influenced by fresh water from the Dique channel, which contributes to the generation of a large amount of waste into the sea [25]. Additionally, as a highly appreciated touristic destination, it generates high amounts of waste that keep accumulating in the island because of limited waste management [26]. Likewise, a vast proportion of plastics can be carried by currents over large distances [1,7], which is why the marine ecosystems in this island are considered for this study.

With the local fishermen's participation, three species of coral reef were collected: common snook (*Centropomus undecimalis*), crevalle jack (*Caranx hippos*), and lane snapper (*Lutjanus synagris*), and three mangrove species: striped mojarra (*Eugerres plumieri*), common snook (*Centropomus undecimalis*), and Western Atlantic seabream (*Archosargus rhomboidalis*). It is critical to disentangle the dynamics on the relationship between plastic accumulation and many different characteristics of marine ichthyofauna, such as habitat, sex, size, and trophic guild. Hence, this study seeks to evaluate the possible impact that the presence of plastic particles may have on fishes that inhabit these ecosystems and, thus, in the future being able to propose assertive management strategies.

2. Materials and Methods

2.1. Study Area and Sample Collection

The Rosario Islands are a group of 27 small islands located in the Colombian Caribbean 45 km northwest of the city of Cartagena. The marine area surrounding these islands was declared Corales del Rosario y San Bernardo National Natural Park in 1977. It currently covers an area of 120,000 hectares. The largest part of the Rosario Islands is Isla Grande,

which has an area of 2277 km², and it is also the most populated and urbanized [26]. The increase in plastic waste on the island has grown significantly with the increase in the touristic visitors, becoming the main sector of its economy [27].

Between June and July 2019, during the rainy season [27], samples of three species of fish that inhabit the coral reef ecosystem [28,29]: common snook (*C. undecimalis*), crevalle jack (*C. hippos*), and lane snapper (*L. synagris*) and three species that inhabit the mangrove ecosystem [28–30], common snook (*C. undecimalis*), striped mojarra (*E. plumieri*), and Western Atlantic seabream (*A. rhomboidalis*), with an abundance of 10 individuals for each species, were collected by fishermen contacted at the local fishing market Bazurto, located in Cartagena. The fish were collected in the coral reef and mangrove ecosystems near Isla Grande in the Rosario Islands (Figure 1), during the early morning using the fishing line technique. The samples were transported in a Styrofoam cooler with refrigerating gels to the city of Bogotá. There, they were frozen at $-80\text{ }^{\circ}\text{C}$ until they were analyzed in the laboratory of the Facultad de Estudios Ambientales y Rurales, Pontificia Universidad Javeriana, Bogotá, Colombia.

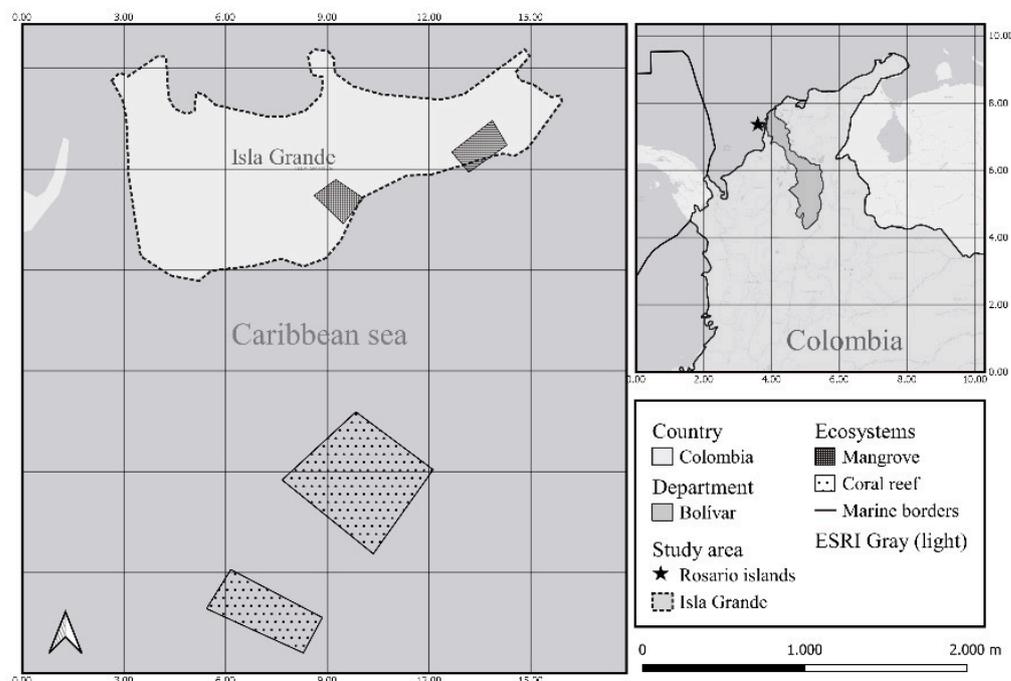


Figure 1. Map of the study area and sampling ecosystems, Isla Grande, department of Bolívar, Colombian Caribbean.

Data of fork length and standard length (to the nearest 0.1 cm, with the help of a calliper) and weight (to the nearest 0.1 g, with the help of a precision balance, Mettler Toledo® (model XP26PC, Tampa, FL, USA) were recorded for each of the individuals (Table 1) [15]. Ventral dissections of the fishes were performed to conduct the extraction of the gastrointestinal tract (cut from the anus to the mouth). Organs were stored in containers, separating the stomach from the intestines, for later analysis [6,31]. The weight of these organs was recorded (to the nearest 0.01 g, with the help of a precision balance, Mettler Toledo® (model XP26PC, Tampa, FL, USA)). Additionally, the sex of everyone was determined through gonad recognition [32,33].

Table 1. Abundance of microplastics and mesoplastics in fishes from Isla Grande, Colombian Caribbean, in coral reef, common snook (*C. undecimalis*), crevalle jack (*C. hippos*), and lane snapper (*L. synagris*), and in mangrove, common snook (*C. undecimalis*), striped mojarra (*E. plumieri*), and Western Atlantic seabream (*A. rhomboidalis*).

Fish Species	Feeding Features	Weight (g)	Fork Length (cm)	Microplastics		Mesoplastics	
				items/g	items/individual	items/g	items/individual
Coral reef							
<i>Caranx hippos</i> Crevalle jack	Carnivore	223.4 ± 37.0	20.5 ± 1.2	0.019 ± 0.02	0.9 ± 0.7	0.015 ± 0.02	1.05 ± 1.1
<i>Centropomus undecimalis</i> Common snook	Carnivore	198.6 ± 57.9	24.6 ± 3.1	0.015 ± 0.02	0.7 ± 0.6	0.014 ± 0.02	0.75 ± 0.8
<i>Lutjanus synagris</i> Lane snapper	Carnivore	181.7 ± 45.3	19.3 ± 2.1	0.020 ± 0.02	0.9 ± 0.9	0.019 ± 0.02	0.85 ± 1.3
Mangrove							
<i>Archosargus rhomboidalis</i> Western Atlantic seabream	Omnivore	137.8 ± 43.0	15.3 ± 1.8	0.018 ± 0.02	0.9 ± 1.3	0.020 ± 0.02	1.0 ± 1.2
<i>Eugerres plumieri</i> Striped mojarra	Omnivore	110.1 ± 28.1	15.4 ± 1.3	0.016 ± 0.02	0.7 ± 0.7	0.022 ± 0.03	1.05 ± 1.1
<i>Centropomus undecimalis</i> Common snook	Carnivore	155.2 ± 37.8	22.8 ± 1.7	0.022 ± 0.02	1.0 ± 0.9	0.017 ± 0.02	1.20 ± 1.2

2.2. Organic Digestion with Hydrogen Peroxide

The entire digestive tract was processed to facilitate the analysis of the plastics. The isolation of these pieces was carried out according to the methodology proposed by [34]. Based on the weight of the samples, 10% potassium hydroxide (KOH) was used, so that the volume of this reagent did not exceed 50% of the total volume of the container [35]. The containers were covered and placed in an incubator at 50 °C for 24 h or 72 h depending upon the digestion level [6].

2.3. Observation, Identification, and Validation of Microplastics and Mesoplastics

The result of the procedure above was subsequently observed under a stereomicroscope Leica M165 C (Wetzlar, Germany). Initially, the particles were described visually and classified according to their physical characteristics [7]. First, the images of the plastics were recorded to determine their length, using the ImageJ 1.52 imaging software (NIH, open source); the frequency of the pieces observed was also recorded by length categories [9]. Subsequently, types of plastic were recorded in different categories: fibers (elongated), fragments (small angular pieces), pellets (spherical pieces), films (thin and soft), and rounds with holes [6,15]. Both color and number of pieces found for each category and the weight were also recorded [14,15,18].

Following size categories described by [7], pieces of plastic <5 mm long were considered as microplastic [8,15], and those >5 mm as mesoplastic.

The most common plastic particles by species were selected and identified with the technique of Attenuated Total Reflectance-Fourier Transform Infrared (ATR-FTIR) spectroscopy Shimadzu, to identify the most frequent polymers [6,34].

2.4. Quality Control of Experiments

All implements used during the laboratory procedures were rinsed three times between each analysis with filtered distilled water to reduce the chances of contamination [34]. Gloves and cotton laboratory coats were worn throughout the time that a procedure was performed in the laboratory facilities. The samples were immediately covered when they were not in use to prevent contamination of microplastics provided by the environment and to avoid an overestimation of the data [9]. Additionally, three empty Petri dishes were placed as environmental contamination control at the beginning of each work session [6].

These blank controls followed the same process as used for the samples, control checking for potential contamination from the ambient air, and lastly the specific control during microplastic isolation into samples or onto filters; if any plastic piece resembled those found in the fish samples, it was discarded [9].

2.5. Statistical Analysis

Data were analyzed using the R[®] software (version 3.6.1, open source). Assumptions for parametric tests were checked by performing the normality test (Shapiro) and the variance homogeneity test (Bartlett) [36]. Subsequently, parametric tests were performed on the relationship between the habitat and abundances of plastics in the stomach and intestine (ANOVA and post hoc Tukey's tests). MANOVA and post hoc Tukey's tests were performed to evaluate the relationship between size, type, color and weight of plastics and the sex, trophic guild, and size of fishes [6,36].

Additionally, a principal component analysis (PCA) was performed, followed by a Pearson's correlation test [37], to evaluate the relationship between the weight of the fishes, standard length of the fishes, abundance of the plastics, and weight of the organ concerning the habitat.

3. Results

3.1. Abundance of Microplastics and Mesoplastics

Plastics were found in all studied species and in each of the individuals sampled, in different proportions (215 in total). Different types of both micro- (Figure 2a–c) and mesoplastics (Figure 2d–f) were found in the digestive tract of all the species studied. The most abundant category was fragments for the entire digestive tract, followed by fibers (Figure 3a).

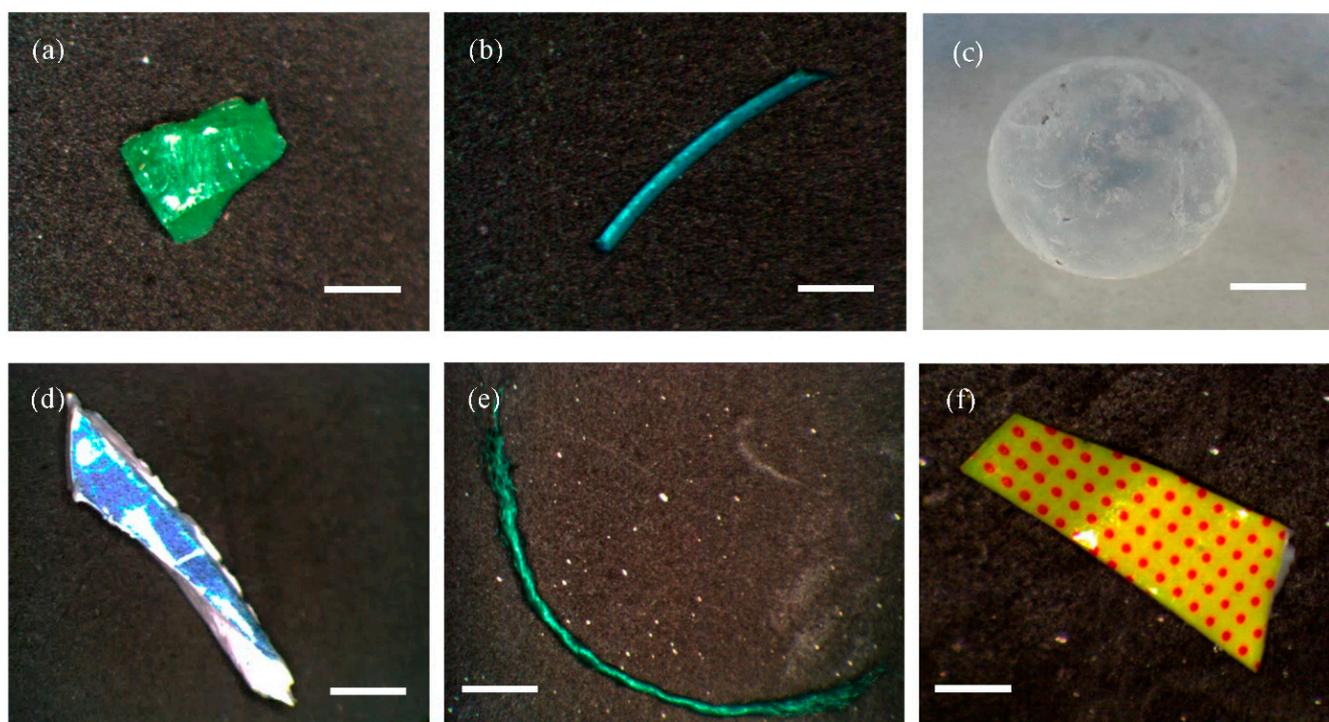


Figure 2. Pictures of microplastic and mesoplastics in fishes from Isla Grande. Types include fragments (a,d), fibers (b,e), pellets (c), and films (f). Scale bar = 0.8 mm (a–c) and 2.5 mm (d–f).

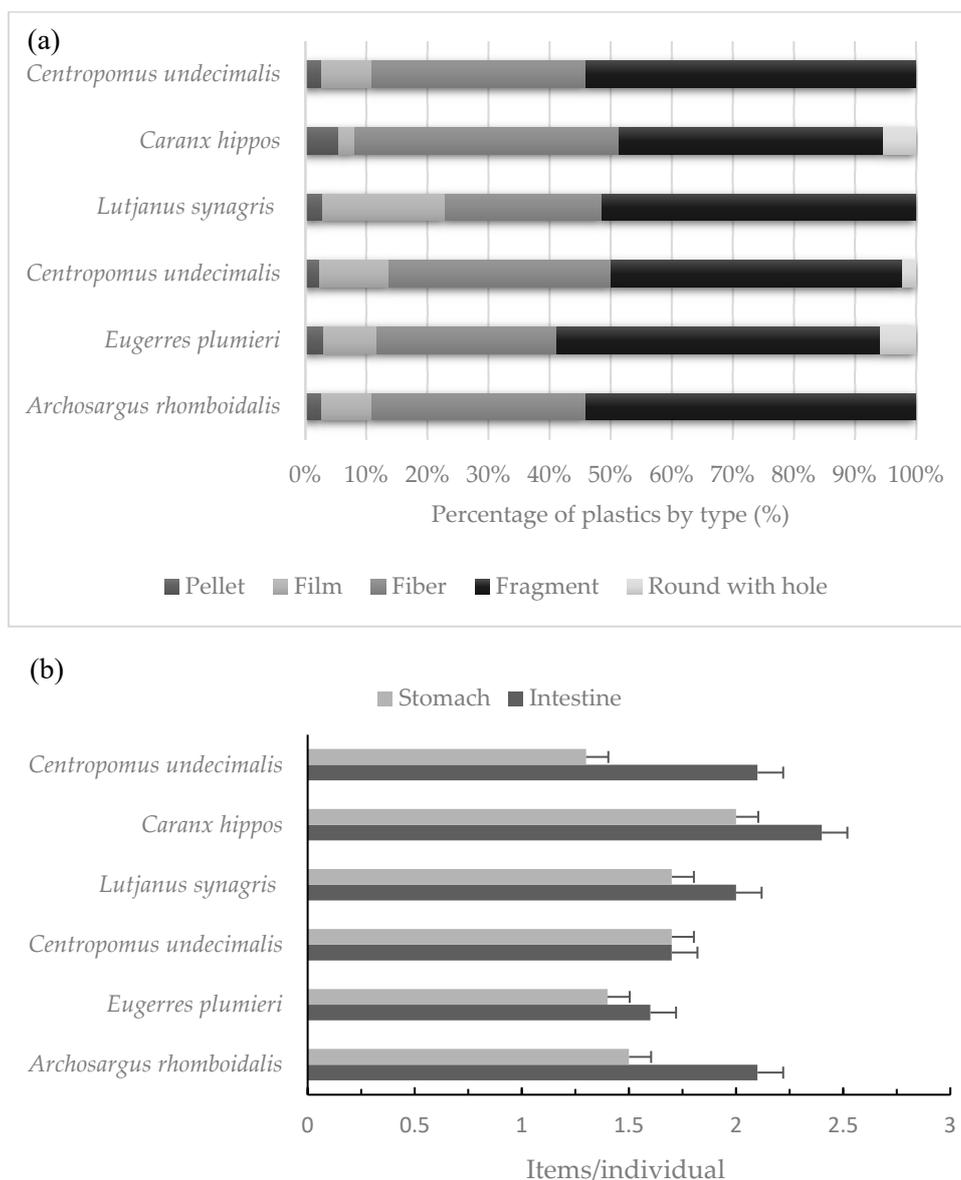


Figure 3. (a) Composition of microplastic and mesoplastic types. (b) Abundance of microplastic and mesoplastic types present in the stomach and intestine in fishes from Isla Grande, Colombian Caribbean, in coral reef, common snook (*C. undecimalis*), crevalle jack (*C. hippos*), and lane snapper (*L. synagris*), and in mangrove, common snook (*C. undecimalis*), striped mojarra (*E. plumieri*), and Western Atlantic seabream (*A. rhomboidalis*).

The abundance of microplastics ranged from 0.7 to 1.0 items/individual (0.015 to 0.022 items/g) and, of mesoplastics, it ranged from 0.75 to 1.2 items/individual (0.014 to 0.022 items/g) (Table 1). The average of microplastics per individual was significantly higher in the mangrove species *C. undecimalis*, for both abundance (1.0 ± 0.9 items/individual) and weight (0.022 ± 0.020 items/g) (Table 1). The average number of mesoplastics was significantly higher in the mangrove species *C. undecimalis* for abundance (1.2 ± 1.2 items/individual) and in *E. plumieri* for weight (0.022 ± 0.030 items/g) (Table 1).

Microplastics represented between 57.1 and 97.3% of the total plastic parts for the species (Table 2). The size of microplastics varied from 1 mm to 5 mm and mesoplastics from 5.1 mm to 14.3 mm. Therefore, plastics smaller than 5 mm were the most abundant (Table 2). In total, 13 colors were found in both mangrove and coral reef fish. Of the 215 plastic particles found in different proportions in all the individuals of the sampled

species, the black color dominated with 27.9%, followed by the green color with 26%. The least abundant color was “white with dots” with 0.46% of the total of pieces found (Figure 4).

Table 2. Types and sizes of microplastics and mesoplastics in fishes from Isla Grande, Colombian Caribbean, in coral reef, common snook (*C. undecimalis*), crevalle jack (*C. hippos*), and lane snapper (*L. synagris*), and in mangrove, common snook (*C. undecimalis*), striped mojarra (*E. plumieri*), and Western Atlantic seabream (*A. rhomboidalis*). np = number of pieces.

Fish Species	Microplastics (%)					Mesoplastics (%)					Sizes (%)		np
	Pellets	Films	Fibers	Fragments	Rounds with Hole	Pellet	Films	Fibers	Fragments	Rounds with Hole	<5 mm	>5.1 mm	
<i>C. undecimalis</i>	3.4	6.9	27.6	24.1	0	0	10.3	3.4	24.1	0	62.1	38	30
<i>C. hippos</i>	5.4	0	37.8	29.7	5.4	0	2.7	5.4	13.5	0	78.4	22	36
<i>L. synagris</i>	0	11.4	17.1	28.6	0	2.9	8.6	8.6	22.9	0	57	42.9	34
<i>C. undecimalis</i>	2.3	11.4	27.3	38.6	2.3	0	0	9.1	9.1	0	81.8	18	44
<i>E. plumieri</i>	2.9	5.9	26.5	44.1	5.9	0	2.9	2.9	8.8	0	85.3	15	34
<i>A. rhomboidalis</i>	2.7	8.1	35.1	51.4	0	0	0	0	2.7	0	97.3	3	37

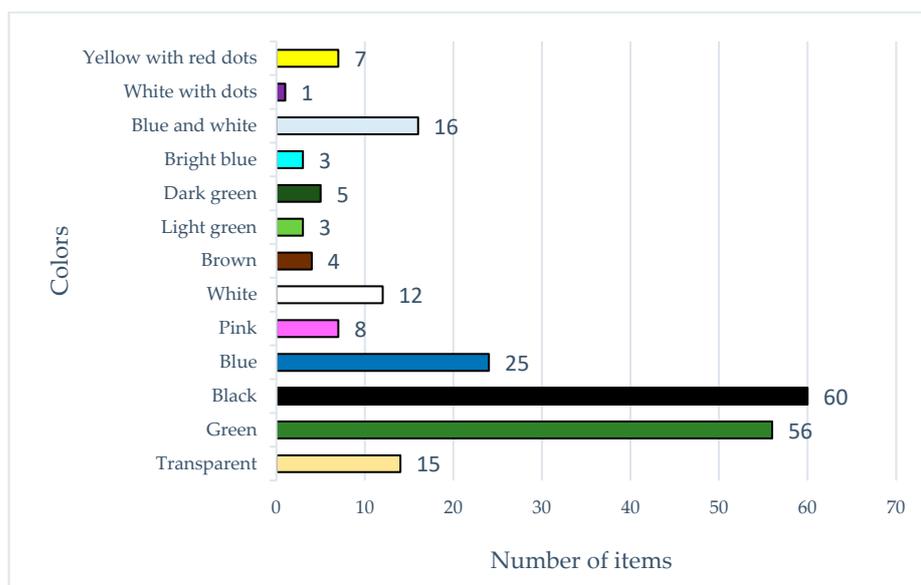


Figure 4. Colors of microplastics and mesoplastics present in the digestive tract in fishes from Isla Grande, Colombian Caribbean, in coral reef and mangrove.

3.2. *Plastics in the Stomach and Intestine of Coral Reef and Mangrove Species*

Regardless of the habitat, significant differences ($p < 0.05$) were found in the total abundance of plastics present in the organs of the digestive tract. The intestine presented highest abundance in comparison to the stomach (2.0 items/individual in the intestine vs. 1.6 items/individual in the stomach (Figures 3b and 5a)). Regardless of the organ, there was a significant difference ($p < 0.05$) in the abundance of microplastics present in the species by habitat. Noteworthy, fish in the mangrove ecosystem showed significantly greater abundance than fish in the coral reef ecosystem (Figure 5b).

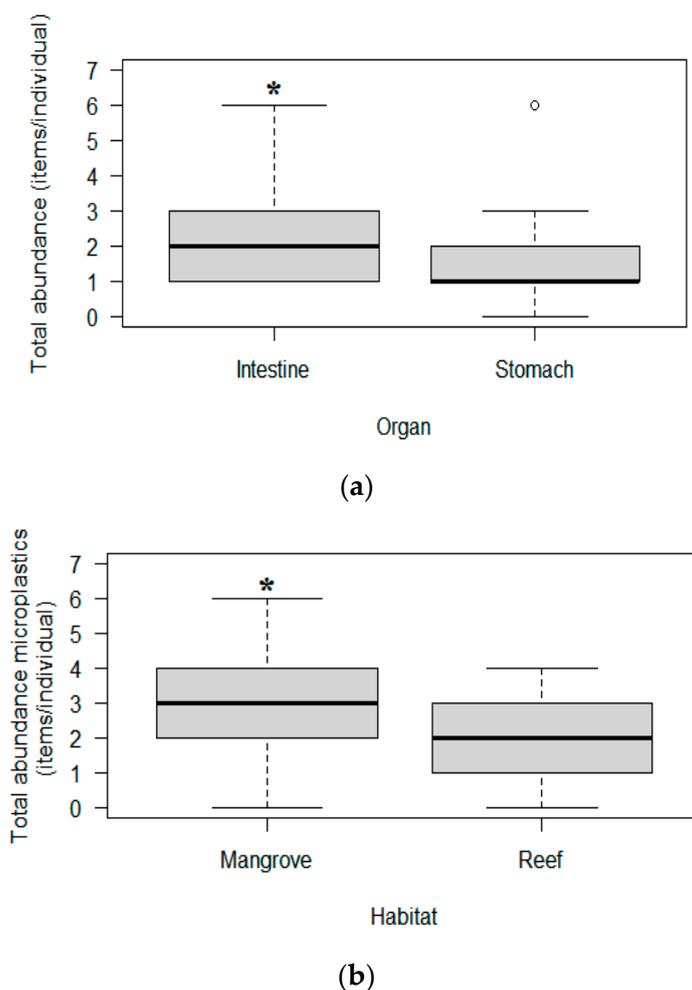


Figure 5. (a) Total abundance of plastics present in the stomach and intestine. (b) Abundance of microplastics present in fish from Isla Grande, Colombian Caribbean, in coral reef, common snook (*C. undecimalis*), crevalle jack (*C. hippos*), and lane snapper (*L. synagris*), and in mangrove, common snook (*C. undecimalis*), striped mojarra (*Eugerres plumieri*), and Western Atlantic seabream (*A. rhomboidalis*). * $p < 0.05$.

3.3. Accumulation of Plastics with Sex, Size, and Trophic Guild

There was a significant difference in the total abundance ($p < 0.01$) and weight of plastics ($p < 0.05$) by sex, females showing significantly higher values than males (Figure 6a,b). There was also a significant difference in the total abundance by fish size category: larger fish tended to have a higher abundance of plastics ($p < 0.1$) (data not shown). There was also a significant difference in the type of plastic related to sex, regardless of the trophic guild and the size of the fish. Females had a significantly more abundant category: fragments. Fibers were the second most abundant category, and the least abundant category was round pieces with a hole (data not shown). Regardless of fish size, carnivorous species (*C. hippos*, *C. undecimalis*, and *L. synagris*) recorded significantly higher data on plastic weight ($p < 0.1$), but not on abundance (data not shown).

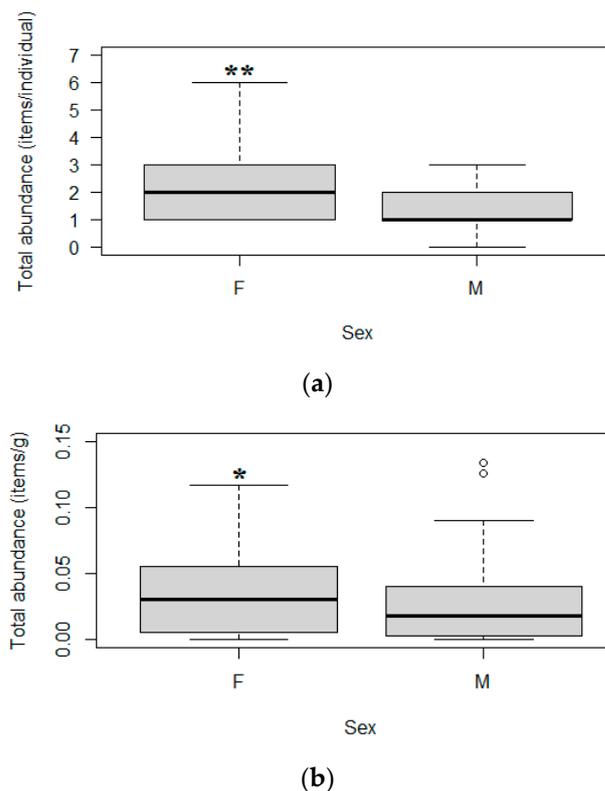


Figure 6. (a) Total abundance of plastics by sex. (b) Weight of plastics by sex present in the digestive tract of fishes from Isla Grande, Colombian Caribbean, in coral reef, common snook (*C. undecimalis*), crevalle jack (*C. hippos*), and lane snapper (*L. synagris*), and in mangrove, common snook (*C. undecimalis*), striped mojarra (*E. plumieri*), and Western Atlantic seabream (*A. rhomboidalis*). Females (F), males (M). ** $p < 0.01$, * $p < 0.05$.

PCA and Pearson's correlation analyses showed significant positive relationships ($p < 0.05$) between plastic abundance and weight ($p = 0.07$), on the one hand, and between standard fish length and fish weight ($p = 0.02$), on the other hand. However, there was no significant correlation between characteristics of plastics (abundance and weight) and features of fish (standard length, weight of organ, and weight of fish). This might indicate that the abundance of plastics does not necessarily increase with the size of the fish. PCA analysis also showed that larger fish were more related to coral reefs, in accordance with the fact that mangroves are known to be nursery areas for fish due to the presence of juvenile individuals [22]. As showed previously, the PCA analysis revealed a significantly great abundance of plastics in the mangrove ecosystem (Figure 7).

3.4. Most Common Polymers Present in Plastics

Of the 215 plastic particles found in different proportions in all the individuals of the sampled species, FTIR was performed on 29% of these, since they were the most common found and representative for the analysis. The most abundant polymers found in this study in decreased order were polyester, PE, PVC, and PET. Of the 29% of pieces evaluated with the ATR-FTIR technique, 48.4% correspond to polyester, 29.0% to PE, 14.5% to PVC, and 8.1% to PET. The most abundant data records interpreted by ATR-FTIR showed peaks in the spectral range at 1093 cm^{-1} , which is consistent with polyester according to the standard categories of the FTIR spectrum (Figure 8a); PE (Figure 8b), according to the established categories, presented peaks in the spectral range at 2900 cm^{-1} and 1498 cm^{-1} ; PVC (Polyvinyl chloride) (Figure 8c) presented peaks in the spectral range at 750 cm^{-1} and 1200 cm^{-1} ; and PET (PE terephthalate) (Figure 8d) presented peaks in the spectral range at 1600 cm^{-1} and 1100 cm^{-1} similar to those established in the FTIR categories.

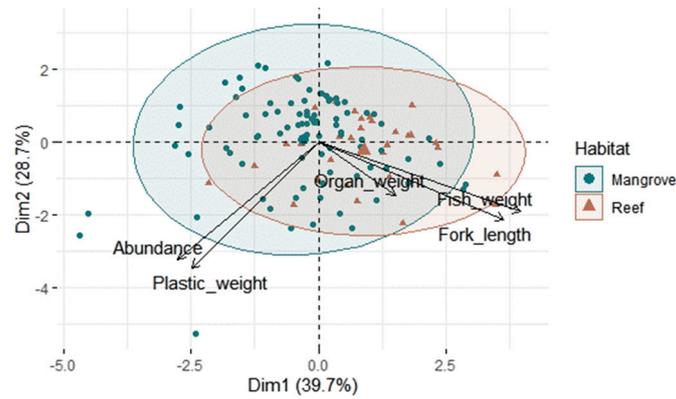


Figure 7. Principal component analysis by habitat for abundance (micro- and mesoplastics in stomach and intestine), plastic weight, fish weight, and fish standard length from Isla Grande, Colombian Caribbean, in coral reef, common snook (*C. undecimalis*), crevalle jack (*C. hippos*), and lane snapper (*L. synagris*), and in mangrove, common snook (*C. undecimalis*), striped mojarra (*E. plumieri*), and Western Atlantic seabream (*A. rhomboidalis*).

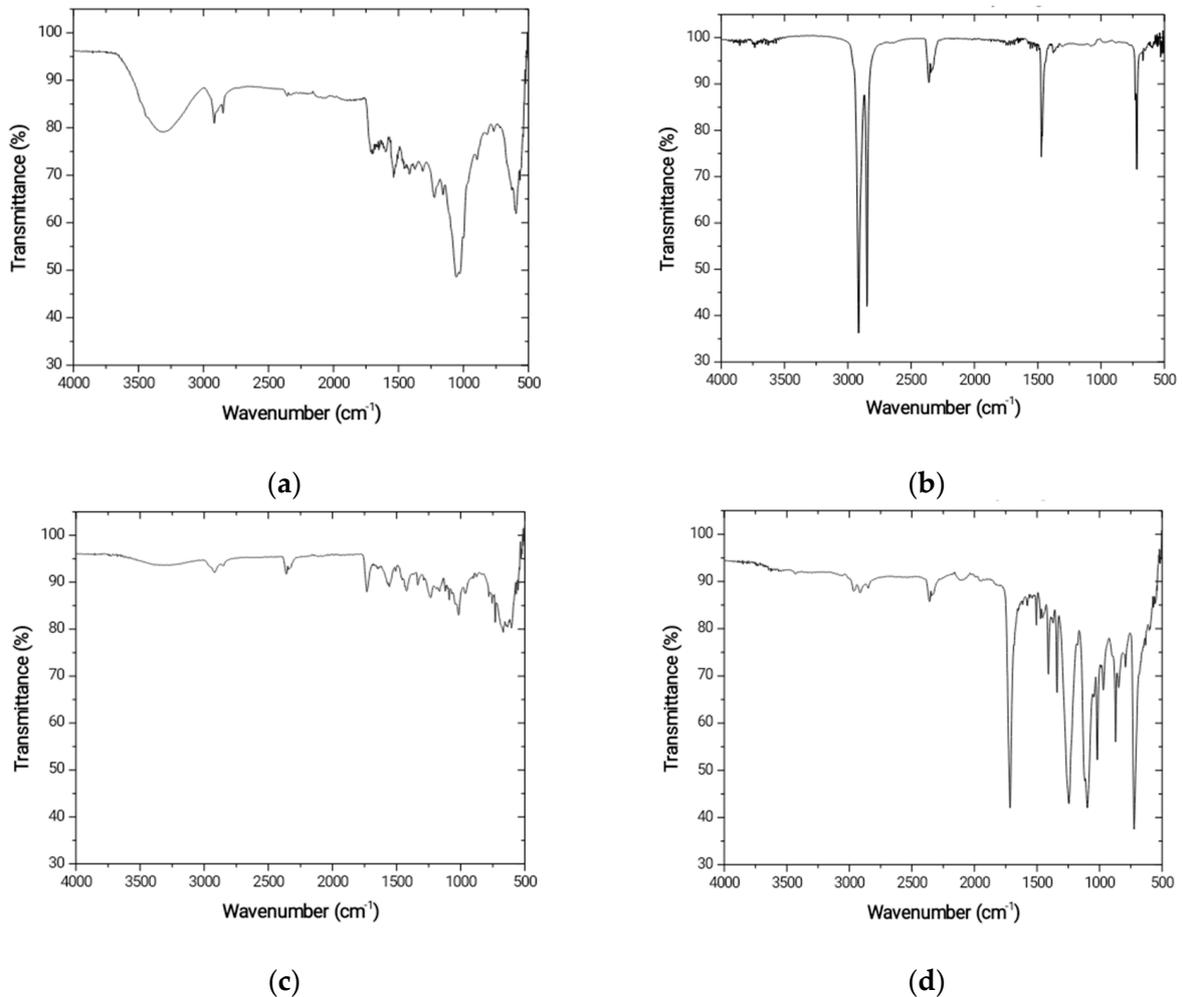


Figure 8. Significant ATR-FTIR spectrum for the most abundant polymers present in fishes from Isla Grande, Colombian Caribbean, in coral reef, common snook (*C. undecimalis*), crevalle jack (*C. hippos*), and lane snapper (*L. synagris*), and in mangrove, common snook (*C. undecimalis*), striped mojarra (*E. plumieri*), and Western Atlantic seabream (*A. rhomboidalis*). Polyester (Tencel) (a), PE (b), PVC (c), PET (d).

4. Discussion

4.1. Abundance of Microplastics and Mesoplastics in Mangrove and Coral Reef and Their Accumulation with Sex, Size, and Trophic Guild

Concerning habitats, the average accumulation of plastics in mangrove fishes was higher (1.9 items/individual) than that reported by [38] and the average accumulation by coral reef fishes (1.6 items/individual) was similar than that reported by [18], suggesting that higher abundances may be present in other mangrove ecosystems in the world, in comparison to nearby coral ecosystems.

Given the continuous fragmentation, the concentration of plastics tends to increase with decreasing size [11]. Furthermore, accumulation in different marine ecosystems is largely determined by the currents and hydrodynamic characteristics of these systems [23]. In this study, the abundance of plastics was higher in mangrove than in coral reef. Mangrove ecosystems have low currents that may cause storage, resulting in greater potential for intake by wildlife [1,9,11,15]. Mangroves are intertidal transition zones, so they act as a filter for different anthropogenic debris, which can remain longer in time before reaching open sea [15]. Mangrove ecosystems in tropical countries such as Colombia have been affected by inadequate solid waste management, resulting in a large accumulation of solid waste [20,39]. Our findings can be related to other regional trends in the Caribbean Sea, concerning accumulations on beaches, mangroves, and other marine ecosystems [20], as the estimated emissions of the Magdalena River up to 16,700 tons of plastic each year [40]. The presence of plastics in these ecosystems could be related to different sources. The Dique channel, a tributary of the Magdalena River, strongly contributes to contamination of freshwater ecosystems by carrying large amounts of sediments and waste to the open sea. This pollution notably increases during the rainy season because of different industrial activities present in the city of Cartagena, the Mamonal industrial complex, and the inland regions of the country [25]. Across the country, different types of plastics are disposed of into numerous affluents of the Magdalena River, and they end up reaching the Caribbean Sea. Moreover, the release of plastics into the marine environment also occurs from other sources, such as river and atmospheric transport activities [40]. Moreover, Cartagena's geographical closeness may also have an impact on the presence of plastics in the offshore and the islands, as it is known as "the South American capital of plastics" [41]. Another socio-economic factor influencing plastic pollution in Isla Grande is touristic activity because it generates large daily amounts waste that is not well managed and generates more accumulation spots [26]. However, it is important to recognize that, given the marine dynamics, the presence of plastics on Isla Grande may also be the result of different circumstances specific to geographic areas near the Caribbean. The buoyancy of these materials allows them to move widely in the ocean [1], being carried through the ocean by marine currents. The Caribbean current leads the waters pattern in this area, along with the influence of trade winds and counter current of Panama, intensely different, depending on the climatic season [42]. Microplastics can cause a deterioration in environmental quality and can directly impact the species living in these ecological niches [20]. Mangrove ecosystems are the nurseries for many juvenile fishes. Therefore, the accumulation of plastics may affect them from very early stages of development, potentially impacting characteristics of life history [43,44]. Therefore, more studies should be carried out to identify sources of microplastic pollution in mangrove ecosystems.

Since coral reefs are popular tourist places, tourism activities generate the presence of different types of plastics in these areas [24]. During low tide, floating plastics are very likely to meet coral surfaces [24]. Because of the deposition on the coral bed, coral reef species are threatened as they mistakenly ingest these particles as food [18]. Because of that coral reef ecosystems are widely threatened, mainly by toxic chemicals in plastics, such as heavy metals and persistent organic pollutants [1,24]. Therefore, more studies on microplastic pollution sources and effects should be carried out in coral ecosystems.

The most abundant color in the coral ecosystem was black; it is the second most abundant category after transparent, in the study by [6] on microplastics and mesoplastics in

fish from China and by [15] in fish from the Thames and Clyde estuaries, Scotland. Similarly, black was the most abundant color for the study by [8,14]. It has been observed that the most common plastics on the surface of the water are black, such as those found in the digestive tract of fish [45]. Another study suggests that the high concentration of black particles indicates the dominance of these colors in near-shore ecosystems [46]. For mangroves, the most abundant color was green differing from other mangroves ecosystems where the most abundant color was transparent, such as reported by [21] on the abundance of microplastics in mangroves in Malaysia, in which the most abundant color was transparent.

The difference in colors affects plastic disposition in the marine ecosystems because of the similarity they may have with natural prey [11,14]. This may explain the difference in abundant plastic color per habitat due to a choice based on the mechanism of selective consumption [15]. Some commercially important fishes and their larvae are visual predators feeding on small zooplankton. They are thus susceptible of feeding on microplastics that closely resemble their prey [11]. This can have negative consequences on these species because of the abundance in their gastrointestinal cavities, such as internal injury, reduced food uptake, starvation, and exposure to pollutants [11].

In relation to sex, the average accumulation of females had a lower record (2.08 items/individual) than that reported by [15] (6.00 items/individual) and [14] (8 items/individual). The abundance of plastics in males (1.48 items/individual) was also lower than that reported by [15] (2.9 items/individual) and by [14] (5 items/individual). Although the abundances were lower, females accumulated more plastics than males in our study.

The average weight of plastics in this study (2.8 mg) was lower than that reported by [5] (4.6 mg), but higher than that reported by [47] (0.47 mg). Although weights were lower than in other studies, the same was observed as for abundance; females not only accumulate more plastics than males but also have the highest weight of plastics.

The greater abundance in females could be explained by the energy cost of producing healthy eggs, meaning higher reproductive success, also associated with feeding [16]. This could reflect that females have higher energy requirements, thus increasing the consumption of nutritional particles and, therefore, increasing exposure to the consumption of plastics [15]. In addition, in several species, females take a year longer to become sexually mature, and in others, they hatch before the males. This could cause them to forage for a longer period, which may also lead to greater exposure to plastic consumption [15].

Chemical elements composing plastic structure vary depending on its elaboration, and many of them are highly polluting [1]. Many of these chemical contaminants such as BTs (butyltin compounds) are endocrine disruptors, causing ovarian spermatogenesis [48], delayed ovulation, reproductive failure, and nutritional problems, resulting in decreased populations [11,49]. Additionally, these particles can absorb pollutants present in the water, representing a potential route for the transfer of chemicals to fish [14]. Our results, by abundance and weight in females, suggest that these risks of exposure to toxic chemicals may be greater in females than in males.

Although there was also a significant difference in total abundance by fish size category: larger fish tended to have a higher abundance of plastics, and our results show lower records of pieces of plastic in larger fish (1.87 items/individual) and smaller fish (1.72 items/individual). In contrast with the results reported by [15] where larger fish ingested more plastic pieces (2.9 items/individual for small fish and 3.2 items/individual for large fish), our results show lower records of pieces of plastic in larger fish (1.87 items/individual) and smaller fish (1.72 items/individual). Our results are consistent with quantities reported in freshwater fish by [50] (1.8 items/individual).

Larger fishes' preys are visually more as plastic pieces, so these pieces could be more frequently consumed by larger than smaller organisms [51]. Additionally, larger fish tend to occupy higher trophic levels, causing more bioaccumulation and biomagnification processes of plastics in the food chain [8]. In addition, larger animals are expected to have higher energy requirements and need higher feed intake increasing the probability of consuming plastics [15]. This result also suggests that, with the same exposure, smaller fish

are less likely to reach the maximum plastic intake than larger fish [50] and suggests that life stages can also influence the intake of particles due to feeding habits [52].

This study highlights that the increased risk associated with the consumption of plastics for large fish may be related to a reduction in nutrient particle intake, which may have long-term consequences for their fitness and offspring. However, more studies need to be carried out to evaluate these effects.

Regarding plastic types, as in the study by [14], females had a greater diversity of plastics closely linked to the prey they consumed. In other studies [8,15,16,18,50], fibers were second in abundance, while in this study, they were the most abundant. In studies by [5,43,53,54], fragments were the first category. In most categories, females had the greatest abundance, which may be due to a higher volume of food consumed by the females for reproduction, and thus a higher intake of microplastics in various forms [55,56].

In contrast to [8], where omnivores had the greatest abundance, in this study it was carnivores. The intake of microplastics is closely related to different feeding strategies [57,58]. It has been found that higher trophic levels tend to accumulate more particles, due to biomagnification processes, through a transfer by trophic levels [8]. However, the factors that influence the intake of heavier plastics by top predators still need to be clarified [11,54].

As accumulation of plastics increases towards higher positions in the food chain, plastics can generate not only risks for marine species, but because they are, for the most part, species of commercial interest [28,42], they can represent risks to human health through the transmission of contaminants [18] and more studies should be also carried out in this context.

4.2. Plastics in the Stomach and Intestine of Coral Reef and Mangrove Species

The accumulation of plastics in fish intestines can be reported in addition to measures performed on the stomach, as shown by [6]. Our study reports a lower average of plastics (2.0 items/individual) than those reported by [6] (2.7 items/individual) in fish from coastal and fresh waters of China, and those reported in [5] (5.8 items/individual) in the North Pacific Central Gyre.

The average abundance of plastic in fish stomach (1.6 items/individual) was lower than that reported by [6,8,14,43]. However, our results are consistent with those reported by [15,18]. In this study, the significantly higher abundance of microplastics found in the intestine in relation to the stomach might be since, although the food is mainly crushed in the stomach, the digestive enzymes in the fishes do not degrade the plastics, so they reach the intestine where the cycle of nutrient absorption is completed [10].

The accumulation of plastics in different parts of the digestive tract may have several negative consequences on fishes, which is why the comparison between stomach and intestine was conducted. First, these small pieces can accumulate in the gastrointestinal cavities, compromising the foraging activity. Secondly, some pieces can be further degraded in nanoplastics, entering the tissues and cells, and compromising chemical signals [11]. The retention of plastics can remain for many weeks due to the size of the intestines [11]. The accumulation of non-nutritive elements can lead to malnutrition, physical deterioration, and eventual starvation [1,5,11]. Additionally, microplastic accumulation can decrease nutrient dilution, and reduce growth rates from exposure to toxic substances [11]. Although the effects were not analyzed in this study, these possible effects should be analyzed in the future.

Some types of plastics can be more harmful than others. For example, pellets and fragments can block the digestive path internally. In one of the individuals, a pellet was found as a stopper in the beginning of the intestines, and it looked very similar to a fish egg. Additionally, it was observed that the fragments had sharp edges that could potentially cause lesions in the digestive tract, as suggested by several authors [13,53,59,60]. Moreover, the type of plastic, according to the components that give it structure, can play a determining role in the toxicity of ingested microplastics. Long, round plastic particles are considered the most toxic, followed by pellets [11].

4.3. Most Common Polymers Present in Plastics

The most abundant type of plastic found was fragment. The most abundant polymers found in this study in decreasing order were polyester, PE, PVC, and PET. This contrasts with other findings in the region of the Santa Marta mangrove [20], where the most abundant pollutants were synthetic copolymers NBR (nitrile butadiene rubber) and materials derived from pyridine. However, fragments were also the most abundant category reported by [5,43,53,54].

Polyester (Tencel), the most abundant polymer, was found in the black fragments, as well as in the study by [15] and contrary to what was found by [6]. In the study by [14], it was found that, for one of the species, PVC was the most abundant polymer category, contrary to what was found in the present study where this was the third most abundant category. Unlike [21,41], PE was the second most abundant category of the polymer. As in the study by [61], polyester was the most abundant polymer.

Knowing the chemical composition of plastics found in the digestive tract of fish allows us to come closer to the sources of their disposal and, eventually, to be able to generate adequate management strategies. Polyester is known to be used as laminated fiberglass resin (for example, in boats) [54]; specifically, Tencel was found to be widely used in garment factories [7]. PVC is needed in plastic sheets used to package products during transport to ships [14]. PET is usually used in the manufacture of plastic bottles [14]. PE is usually used in plastic packaging and bags [21]. Therefore, these potential sources should be further explored in the future.

The chemical composition varies with the type of plastic, so fish are exposed to a wide range of chemical pollutants that can affect their development [18,23,41,43] and, therefore, the human that consumes these [7,62]. Antimony trioxide, a substance that may cause human cancer, is added to PET manufacture as a catalyst in addition to its usage as a flame retardant and a smoke suppressant [7]. There is a possibility that, in contact with water, PET can filter out small amounts of the metalloid antimony, which will be potentially added to aquatic systems, generating a possible risk of bioaccumulation of this pollutant by marine biota. It has also been found that PE and PVC show a higher absorption capacity of dichloro-diphenyl-trichloroethane (DDT) [7]. However, there is insufficient information to establish with certainty the consequences of the presence of these compounds in the environment and their effects on marine biota [7]. On the other hand, in a study conducted in Portugal, black microplastics, collected from two Portuguese beaches (Fonte da Telha and Cresmina), appeared to have a higher polluting concentration, while of white microplastics, the concentrations were lower [63]. Although the number of yellow plastics found in this study was not the most abundant, it has been suggested that the yellow color of the microplastics indicates the presence of quinoid-based structures, produced by the oxidation of antioxidant additives, added to the plastics during manufacturing [64]. Additionally, the yellow color suggests that microplastics have been in the aquatic environment for a prolonged period with an increased possibility of contamination with substances present in the water [65]. Thus, both the potential of contaminated microplastics that can generate toxic effects on aquatic organisms and their incorporation into the food chain represent very worrying risks, which require rigorous studies that quantify and qualify the true potential of these threats to marine fauna and human health.

5. Conclusions

The present study found a greater accumulation of microplastics in fish that inhabit the mangrove ecosystem when compared to the coral reef ecosystem. In addition, the accumulation of microplastics and mesoplastics by organ was significantly different. The largest amount of these particles was accumulated in the intestines. Significant differences were also observed by sex since females had significantly higher abundances of microplastic and mesoplastics particles than males. Furthermore, plastic fragments were the most abundant category found in fishes, with different accumulation abundances depending on size and trophic guilds. Larger fishes belonging to a higher guild presented the greatest

abundances of plastic. Black was the most abundant color of plastic followed by green. In addition to fragments, fibers were one of the most abundant categories of plastic. PE, polyester, PVC, and PET were the most abundant polymers among the common plastics found in species of the two habitats. The accumulation of plastics represents a major threat to marine ecosystem and ocean ecological functions. Our findings highlight the importance of more rigorous plastic waste management strategies in areas nearby the coast and mangrove habitats. Pollution and health risks are critical ongoing and future challenges that require increasing awareness of both stakeholders and the scientific community, especially in tropical developing countries.

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