

MICROPLASTICS IN THE BARRA NORTE AND MOCAMBO BEACH SEDIMENTS, GULF OF MEXICO, MEXICO

Bárbara Yaneth PÉREZ-ALVARADO¹ & John S. ARMSTRONG-ALTRIN^{2*}

¹*Posgrado en Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México, Ciudad Universitaria, Ciudad de México, 04510 CDMX., México*

²*Universidad Nacional Autónoma de México, Instituto de Ciencias del Mar y Limnología, Unidad de Procesos Oceánicos y Costeros, Ciudad Universitaria, Ciudad de México 04510, México*

**Corresponding author: armstrong@cmarl.unam.mx*

Abstract: The abundance and characteristics of microplastics (MPs) in the Barra Norte and Mocambo beach sediments in the Gulf of Mexico were investigated. The number of MPs was higher in the Barra Norte (5865 MPs · kg⁻¹) than in the Mocambo (4315 MPs · kg⁻¹) beach sediments. The size of MPs in the Barra Norte and Mocambo beaches was varied between 0.6 - 1.30 mm and 0.91 - 1.25 mm, respectively, and all MPs were fiber. In both beaches, the predominant color of fiber was transparent. The Scanning Electron Microscopy (SEM) images showed that the fibers were fragmented, with surface features such as fissures, cracks, holes, degradation and adhered particles, indicating polymer aging, mechanical weathering, chemical dissolution, and their exposure to UV radiation. Cellophane (CP) and polyethylene terephthalate (PET) were the polymer types detected by the Fourier-Transform infrared (FTIR) Spectroscopy, which were possibly sourced from the textile products and disposable plastic bags, respectively. It was inferred that the abundance of MPs in the Barra Norte beach was due to coastal industrial activities related to the Adolfo López Mateos Thermoelectric Plant. Similarly, MPs in the Mocambo beach was attributed to an inadequate management of urban solid waste in the coastal zone. This study provided an awareness to the scientific community on the threat of MPs contamination in the coastal sediments of the Gulf of Mexico.

Keywords: Coastal sediments, Degradation, Surface features, Polymer types, Fiber, Cellophane

1. INTRODUCTION

Plastic pollution has raised a great concern, because of its impact on the environment and health issues (Ismanto et al., 2024). Due to their versatility, low production cost, single use, durability, and resistance, plastics have become one of the main pollutants in the marine environment (Frias et al., 2018; Chen et al., 2024). In the marine environment, when plastics exposed to physical and chemical factors, they tend to degrade quickly, leading to the formation of MPs, which are generally in the range of 1 micron to 5 mm (Mathalon & Hill, 2014). MPs have been reported in marine and freshwater ecosystems, as well as in coastal sediments, lakes and from the deep-sea environments (Wang et al., 2019; Zhu et al., 2023; Luan & Wang, 2024). Based on their origin, MPs are classified into two types: 1) primary origin, which are intentionally manufactured as microbeads

and pellets and 2) secondary origin, which are plastic particles produced by the fragmentation of larger plastics that have been broken due to physical, chemical, and biological processes (Expósito et al., 2021; Charles & Rajaram, 2024).

The abundance of MPs in the coastal environment can be determined by land-based sources (litter, wastewater treatment plants, and urban and agricultural runoff) and maritime activities (marine aquaculture, shipping, and oil drilling) (Zhang, 2017). In general, the composition of MPs is related to the original parent materials and MPs can preserve their source characteristics, even though they are affected by the local environmental changes or climatic variations. Mariano et al. (2021) reported that the most common polymers in the coastal environment are polyethylene, polystyrene, polyvinyl chloride, cellulose acetate, and polyethylene terephthalate. MPs can be act as a transport vector for

chemical additives and are considered as an emerging contaminant. Instead of their characteristics such as greater surface area, hydrophobicity and lipophilicity, they can cause negative effects on the biotic and abiotic ecosystems (Xu et al., 2024).

A few studies have documented the abundance and characteristics of MPs in the coastal environment of Mexico. Wessel et al. (2016) examined the distribution of MPs in the estuarine sediments of the northern Gulf of Mexico. Flores-Cortés & Armstrong-Altrin (2022) described the association between grain size and MPs abundance in the Tecolutla beach sediments, Gulf of Mexico. Recently, Flores-Ocampo & Armstrong-Altrin (2023) investigated the characteristics, abundance, and types of MPs present in the Tampico Beach sediments, Gulf of Mexico. On the other hand, there are recent studies, which documented the abundance of MPs and polymer types in the Mexican Pacific coastal sediments (Páez-Osuna et al., 2023; Ruíz-Reyes et al., 2023; Ramos-Vázquez et al., 2024a). In fact, studies which integrated the distribution of MPs, their morphology, and polymer types in the Gulf of Mexico coastal sediments are not sufficient.

In this study, the Barra Norte and Mocambo beach sediments in the Gulf of Mexico are investigated. The Barra Norte beach is more dominated by industrial activities than tourism. On the other hand, the Mocambo beach is known as one of the tourist beaches in Mexico. The purpose of this study is to investigate the abundance of MPs in the beach sediments, as well as to analyze their physical characteristics, degradation, and polymer types. In addition, we attempt to deduce the possible source of these contaminants and provide suggestions to prevent further accumulation of MPs in the coastal environment. The results of this study will provide a new information on the contamination of beach sediments, which serve as a motivation to the public to reduce the accumulation of plastic particles in the coastal environment.

2. STUDY AREA

Based on the different coastal activities such as recreational, fishing, and industrial activities, two beaches in the Gulf of Mexico were selected, i.e. Mocambo and Barra Norte (Tuxpan), Veracruz State (Figure 1). Mocambo beach is one of the tourist beaches in Mexico, which is in the western part of the Gulf of Mexico, Veracruz State (between 19°08'05.1" N - 96°06'05.3" W and 19°07'79.0" N - 96°06' 52.4" W). The Barra Norte beach is in the northern part of the Gulf of Mexico, near Tuxpan, Veracruz State (between 20°58'59.15" N - 97°18'48.70" W and

20°58'36.57" N - 97°18'32.51" W). In the Barra Norte beach, thermal electric power plant, hotels and fishing activities are established, so the principal activity is more of towards industrial (Reyes-Ortiz et al., 2017; Ramos-Vázquez et al. 2024b).

The predominant climate in the Mocambo beach is warm and sub-humid (INEGI, 2020), with an average temperature of 23 °C with a maximum of 32 °C. The rain occurs in summer and in autumn with an annual precipitation of 1100 - 2000 mm (INEGI, 2020; Armstrong-Altrin, 2024). The Mocambo beach area is part of the Jamapa River basin, which has an area of approximately 3912 km² that originates from the slopes of the Pico de Orizaba peak (4700 m above mean sea level). Similarly, in the Barra Norte beach, the climate is warm sub-humid, with an average temperature of 24 - 26 °C and an annual precipitation of 1400 - 1600 mm (INEGI, 2010). This beach is located at the mouth of the Tuxpan River, which has a length of 150 km, an area of 5899 km², and an average natural surface runoff of 2072 hm³/year (Ramos-Sánchez, 2017).

3. METHODOLOGY

3.1. Sampling

With the help of a stainless-steel shovel, 40 surface sediment samples (~2 kg each) were collected in the foreshore area (20 from the Mocambo beach and 20 in the Barra Norte beach). The samples were collected at an interval of 50 m between each sample and were subsequently dried in a Riosa brand oven for 24 h, at a temperature not higher than 50 °C.

3.2. Granulometric analysis

To determine the textural parameters of beach sediments, 40 g of each dried sediment samples were weighed and sieved in a Ro-Tap Sieve Shaker for 30 minutes (20 samples per beach, number of samples n = 40). The ASTM sieves were selected with an interval of ½ Φ. The sieved sediments were weighed separately, and the statistical parameters were calculated, i.e. mean size (Mz), standard deviation (σ), skewness (Ski), and kurtosis (KG) (Folk & Ward, 1957).

3.3. Extraction of microplastics

The separation of MPs in 20 sediment samples (10 samples from each beach, n = 20) was carried out by the density difference method (Schütze et al., 2022; Flores-Ocampo & Armstrong-Altrin, 2023). A saturated ZnCl₂ solution of 1:3 ratio was prepared (20 g of sediments per 60 mL of solution). The solution

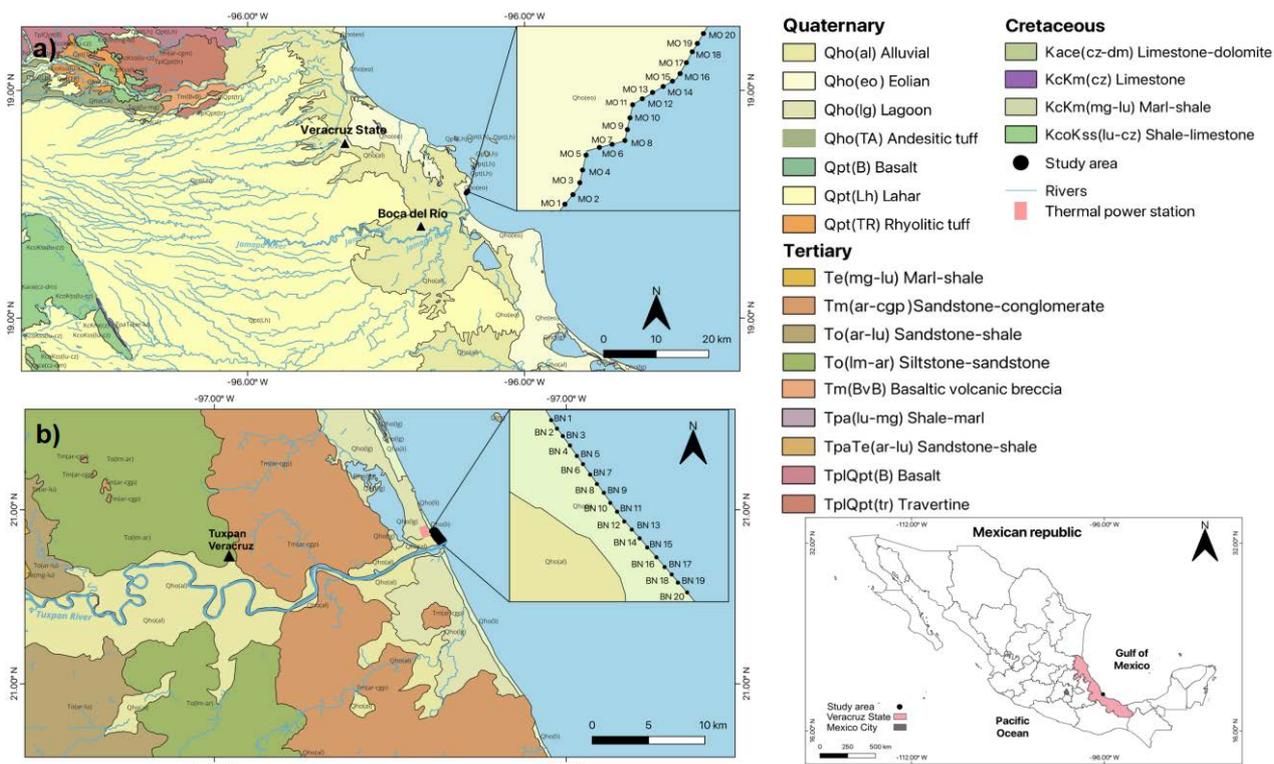


Figure 1. Geological Map showing the sample locations in the study area, Veracruz state, Gulf of Mexico: a) Mocambo beach, Veracruz; b) Barra Norte beach, near Tuxpan. Numbers from MO 1 to MO 20 and BN 1 to MN 20 represent sample locations.

was stirred for 20 minutes and left to deposition for 24 hours, where the thick sediment was deposited at the bottom, while the low-density particles remained in suspension and/or floated on the surface of the solution. These particles were extracted using a drum with a plunger adapted to a swinnex and a 0.022 μm MF-Millipore filter. The filters were rinsed with distilled water to avoid adherence of foreign particles on MPs and were subsequently stored in Petri dishes. In addition to the extraction of MPs, a blank sample was prepared in which less than 2 MPs were obtained.

3.4. Visual Identification

Once the MPs were extracted from the sediment samples, a visual identification was carried out using a stereoscopic microscope attached with a Nikon digital camera, which allowed the MPs to be classified according to their physical characteristics such as size, color, and shape (Falahudin et al., 2020). To determine the size of the MPs the images obtained were processed with the ImageJ software, subsequently the data obtained were classified based on the size scale proposed by Frias et al. (2018) (i.e. mesoplastics, long microplastics, small microplastics, and nanoplastics).

3.5. Scanning Electron Microscopy

To identify the morphological characteristics, surface features, and degradation, MPs from both beaches were randomly chosen, at least 25 MPs were selected per sample. MPs were analyzed using a JEOL JSM6360LV Scanning Electron Microscope at Institute of Marine Sciences and Limnology, UNAM.

3.6. Quality Control

To avoid external contamination of the analyzed sediment samples, quality control was carefully carried out when drying sediments, extraction, and further analysis. During the separation of MPs from sediments, the working area, filters, and petri dishes were cleaned with 70 % alcohol, cotton laboratory coats, and plastic-free materials were used.

3.7. Polymer identification

To identify the composition and type of polymers of MPs in the beach sediments, FTIR Spectroscopy (Fourier Transform Infrared Spectroscopy) analysis was performed. About 10 MPs per sample with different colors were selected for FTIR Spectroscopy analysis. Micro-FTIR with an Infrared spectrometer (μ -FTIR) imaging under

attenuated total reflection (ATR) mode (Thermo Nicolet iS50R Smart-iTX ATR with diamond glass and lens of ZnSe and optical window from 400 to 550 cm^{-1}), at Institute of Applied Sciences and Technology, UNAM. The comparison of the composition of MPs was carried out using the OMNIC version 7.2 program and the commercial library “Hummel Polymer Sample”.

4. RESULTS AND DISCUSSION

4.1. Grain size

Grain size is an important attribute of sediments, because they can reflect the transport processes, level of weathering, and erosional features (Boggs, 2006). The textural parameters for the Mocambo and Barra Norte beaches are listed in Table 1. The mean grain size (Mz) ranges from $\sim 2.45 - 2.72 \phi$ to $\sim 2.53 - 2.83 \phi$ for the Mocambo and Barra Norte beach sediments, respectively. The sediments are classified as moderately well-sorted to well-sorted. The Mocambo beach sediments are very coarse skewed, and the kurtosis class range from mesokurtic to leptokurtic, while the Barra Norte

sediments are coarse skewed and classified as very leptokurtic (Table 1).

Numerous authors documented a significant correlation between MPs and fine fraction of sediments ($< 63 \mu\text{m}$), with an increase in the abundance of MPs when grain size decreases (Brown et al., 2011; Alomar et al., 2016; Mendes et al., 2021; Flores-Cortés & Armstrong-Altrin, 2022; Rodrigues et al., 2024). In contrast, in this study, a correlation between grain size and the abundance of MPs is not significant for the Mocambo ($r^2 = 0.0012$; $n = 10$) and Barra Norte ($r^2 = 0.1207$; $n = 10$) beaches. This correlation indicates that the distribution of MPs in beach sediments is depending on the density of plastic particles and the physical variations due to waves, coastal currents, river water input, and residence time. In addition, degradation and fragmentation due to UV radiation can also increase the number and abundance of MPs in beach sediments.

4.2. Abundance of MPs

In the Mocambo beach, an average of 86 particles are detected in 20 g of sediments ($n = 10$). In total, 863 MPs are identified in 10 samples (Table 2;

Table 1. Textural parameters for the Mocambo (MO) and Barra Norte (BN) beach sediments [mean (Mz), standard deviation (σ), skewness (Ski), and kurtosis (K_G)] (after Folk & Ward, 1957).

Sample	$Mz\phi$	$\sigma\phi$	Ski	K_G	$Mz\phi$ Class	$\sigma\phi$ Class	Ski Class	K_G Class
MO1	2.63	0.51	-0.25	1.07	Fine sand	Moderately sorted	Coarse-skewed	Mesokurtic
MO3	2.55	0.71	-0.54	0.99	Fine sand	Moderately sorted	Very coarse-skewed	Mesokurtic
MO5	2.47	0.8	-0.59	0.98	Fine sand	Moderately sorted	Very coarse-skewed	Mesokurtic
MO7	2.65	0.61	-0.39	1.36	Fine sand	Moderately well sorted	Very coarse-skewed	Leptokurtic
MO9	2.45	0.67	-0.35	1	Fine sand	Moderately well sorted	Very coarse-skewed	Mesokurtic
MO11	2.62	0.67	-0.48	1.29	Fine sand	Moderately well sorted	Very coarse-skewed	Leptokurtic
MO13	2.72	0.5	-0.35	1.2	Fine sand	Moderately well sorted	Very coarse-skewed	Leptokurtic
MO15	2.62	0.46	-0.34	1.35	Fine sand	Well sorted	Very coarse-skewed	Leptokurtic
MO17	2.7	0.6	-0.45	1.12	Fine sand	Moderately well sorted	Very coarse-skewed	Leptokurtic
MO19	2.55	0.65	-0.47	1.1	Fine sand	Moderately well sorted	Very coarse-skewed	Mesokurtic
BN1	2.83	0.28	0.1	1.37	Fine sand	Very well sorted	Nearly symmetrical	Leptokurtic
BN3	2.72	0.32	-0.04	1.64	Fine sand	Very well sorted	Nearly symmetrical	Very leptokurtic
BN5	2.73	0.37	-0.06	1.73	Fine sand	Well sorted	Nearly symmetrical	Very leptokurtic
BN7	2.7	0.34	-0.17	1.71	Fine sand	Very well sorted	Coarse-skewed	Very leptokurtic
BN9	2.7	0.35	-0.13	1.5	Fine sand	Well sorted	Coarse-skewed	Leptokurtic
BN11	2.53	0.4	-0.24	1.07	Fine sand	Well sorted	Coarse-skewed	Mesokurtic
BN13	2.67	0.36	-0.19	1.38	Fine sand	Well sorted	Coarse-skewed	Leptokurtic
BN15	2.53	0.41	-0.34	0.82	Fine sand	Well sorted	Very coarse-skewed	Mesokurtic
BN17	2.58	0.43	-0.4	1.19	Fine sand	Well sorted	Very coarse-skewed	Leptokurtic
BN19	2.62	0.36	-0.38	1.78	Fine sand	Well sorted	Very coarse-skewed	Very leptokurtic

Figure 2a). For the Barra Norte, an average of 117 MPs are identified in 20 g of sediment samples (n = 10). In total, 1173 MPs are detected in 10 samples (Table 3; Figure 2b). An extrapolation was carried out to quantify the number of plastic particles in 1 kg of sediment. An average of 4315 MPs · kg⁻¹ and 5865 MPs · kg⁻¹ is obtained for the Mocambo and Barra Norte beach sediments, respectively (Tables 2 and 3). The variations in the abundance of MPs between the two beaches could be due to the differences in the number of plastics carried by the rivers from the land to the Ocean. MPs are identified in both beach areas; however, Barra Norte consists of higher number of plastic particles. This can be attributed to its proximity to the Tuxpan River mouth. Tiwari et al. (2019) and Yaranal et al. (2021) reported that much of the plastics in the coastal environment were derived from the wastewater treatment plants. In addition, these authors documented that the MPs were transported by rivers to the coastal environment, where riparian vegetation acts as a trap for the accumulation, retention, and formation of MPs. In this study, the source of plastic contamination in the Barra Norte beach could be due to fishing and local industrial activities related to the Adolfo López Mateos Thermoelectric Power Plant (Figure 1). Similarly, MPs in the Mocambo beach sediments is attributed to the tourist activities and an inadequate management of urban solid waste in the coastal zones.

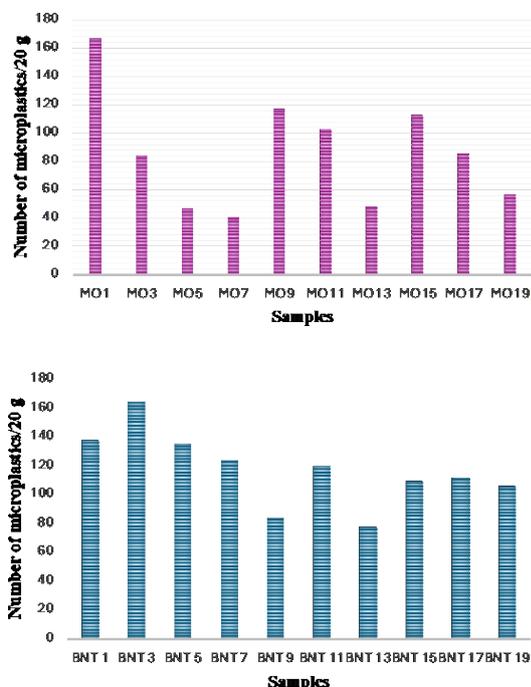


Figure 2. Abundance and distribution of fiber-type MPs in beach sediments of the study areas: a) abundance of MPs per 20 g in Mocambo beach sediments; b) abundance of MPs per 20 g in Barra Norte beach sediments.

4.3. Shape of MPs

Based on the shape, MPs are categorized into 5 major types, i.e. fibers, films, spheres/pellets, sponges, and fragments (Miller et al., 2021). The shape of MPs is related to their parent material and source, whether of primary or secondary origin, where basic forms such as pellets, spheres and granules are discharged directly as primary MPs. In this study, MPs identified in the Mocambo (Figure 3a-f), and Barra Norte (Figure 4a-f) beach sediments are only fibers. This kind of fiber-type MPs, indicating a secondary origin, which are subjected to weathering and degradation due to their exposure to the coastal environment, i.e. UV radiation. Numerous studies documented that fibers are originated from washing of synthetic textiles or generated from plastic products through fishing activities and are transported through atmospheric deposition, surface runoff, agricultural equipment, domestic sewers, and wastewater treatment plants (Brown et al., 2011; Hernández et al., 2017; Rodrigues et al., 2018; Ding et al., 2019; Jebashalomi et al., 2024).

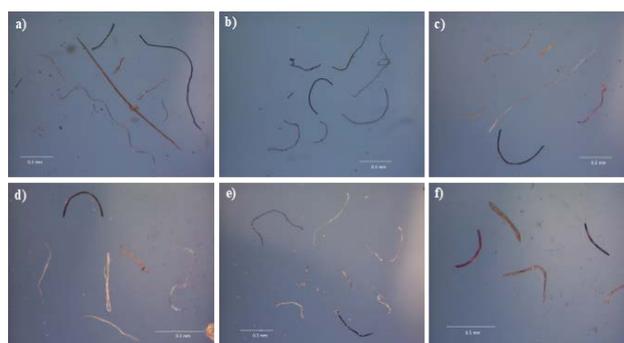


Figure 3. Fiber-type microplastics with different length and color are observed in the Mocambo beach.

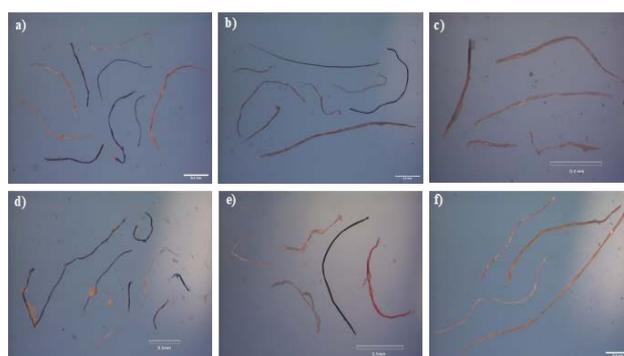


Figure 4. Small and large fibers with different colors observed in the Barra Norte beach sediments.

4.4. Size and color of MPs

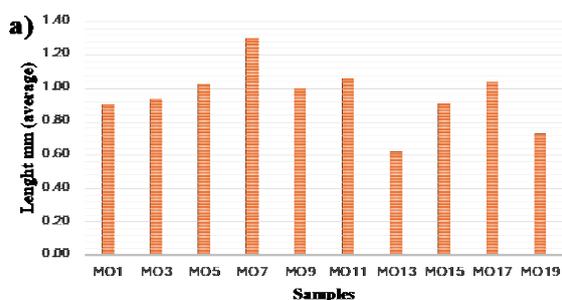
In the Mocambo beach, the size of the MPs varies from 0.6 to 1.30 mm, with an average of 0.95 ± 0.19 mm (Figure 5a).

Table 2. Number of microplastics found in 20 g of sediments from the Mocambo beach.

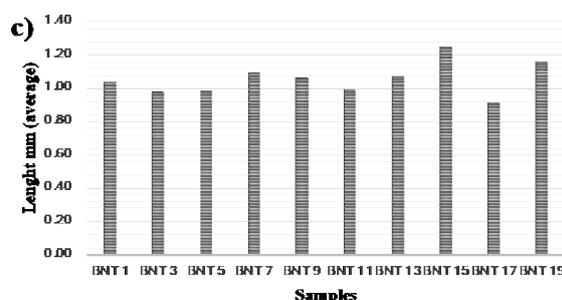
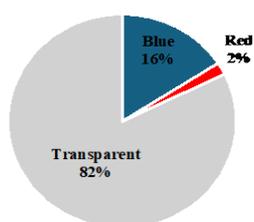
Sample no.	Number of microplastics in 20 g of sediment	Extrapolation of the number of microplastics in 1 kg of sediment
MO1	167	8350
MO3	84	4200
MO5	47	2350
MO7	41	2050
MO9	117	5850
MO11	103	5150
MO13	48	2400
MO15	113	5650
MO17	86	4300
MO19	57	2850
Total	863	43150
Average (n = 10)	86	4315

Table 3. Number of microplastics found in 20 g of sediments from the Barra Norte beach.

Sample no.	Number of microplastics in 20 g of sediment	Extrapolation of the number of microplastics in 1 kg of sediment
BNT 1	138	6900
BNT 3	165	8250
BNT 5	136	6800
BNT 7	124	6200
BNT 9	84	4200
BNT 11	120	6000
BNT 13	78	3900
BNT 15	110	5500
BNT 17	112	5600
BNT 19	106	5300
Total	1173	58650
Average (n = 10)	117	5865



b) Percentage by colours MO



d) Percentage by colours BN

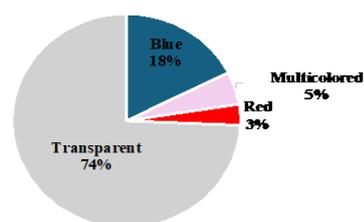


Figure 5. Abundance of fibers in percentage: a) size and b) color of fibers in the Mocambo beach; c) size and d) color of fibers in the Barra Norte beach.

Furthermore, the MPs are classified based on their size, among 863 MPs, 571 are classified as small microplastics (1 μm - 1000 μm), 285 are as long microplastics (1 - 5 mm), and only 7 are classified as mesoplastics (0.5 - 2.5 cm) (Frias et al., 2018). The predominant color is transparent (82%), which is followed by blue (16%) and red (2%) (Figure 5b). In contrast, the size of the MPs extracted from the Barra Norte beach ranges from 0.91 to 1.25 mm, with an average value of 1.06 ± 0.10 mm (Figure 5c). Similarly, small MPs are

dominant (number of MPs $n = 709$), which is followed by long MPs ($n = 457$) and mesoplastics ($n = 7$). The transparent color is most abundant (74%), which is followed by blue (18%), multicolor (5%), and red (3%) (Figure 5d). The MPs found in sediments from both beaches are mostly small and transparent in color, which suggests that most of the MPs have had a long residence time within the marine environment, being exposed to UV rays that caused discoloration (Brandon et al., 2016; Carvalho et al., 2021) and fragmented by

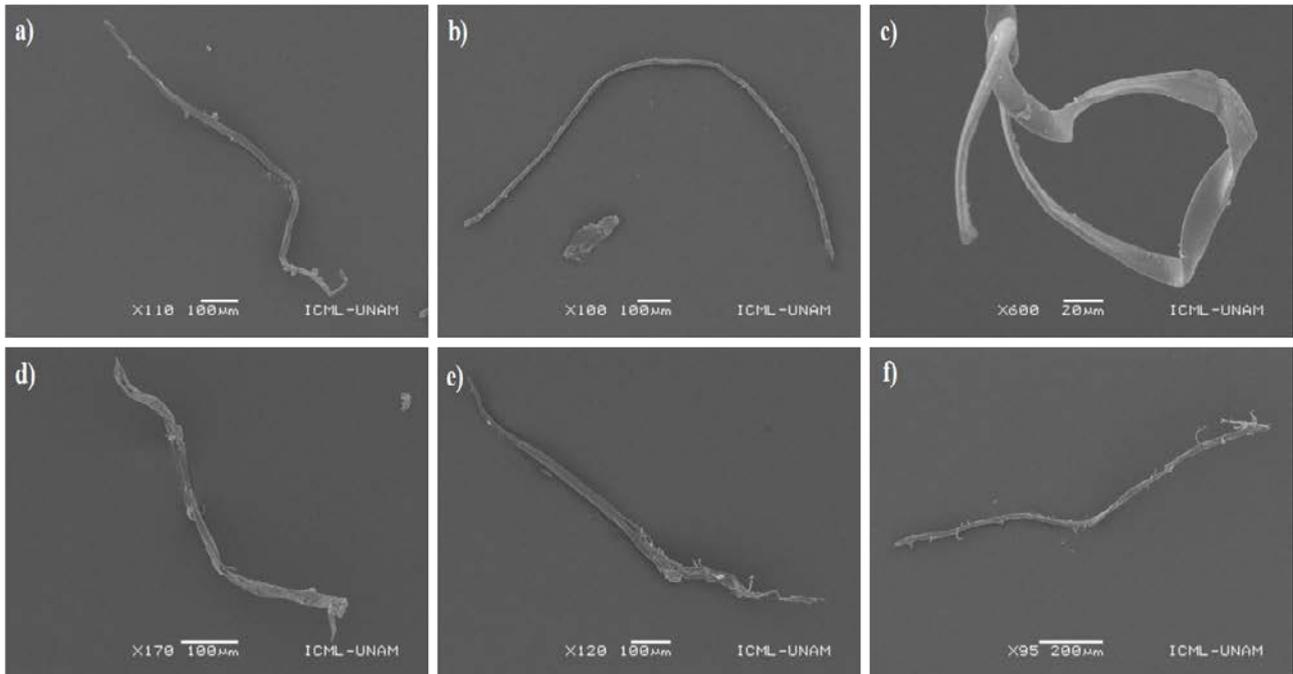


Figure 6. SEM images of fibers recovered in the Mocambo beach sediments.

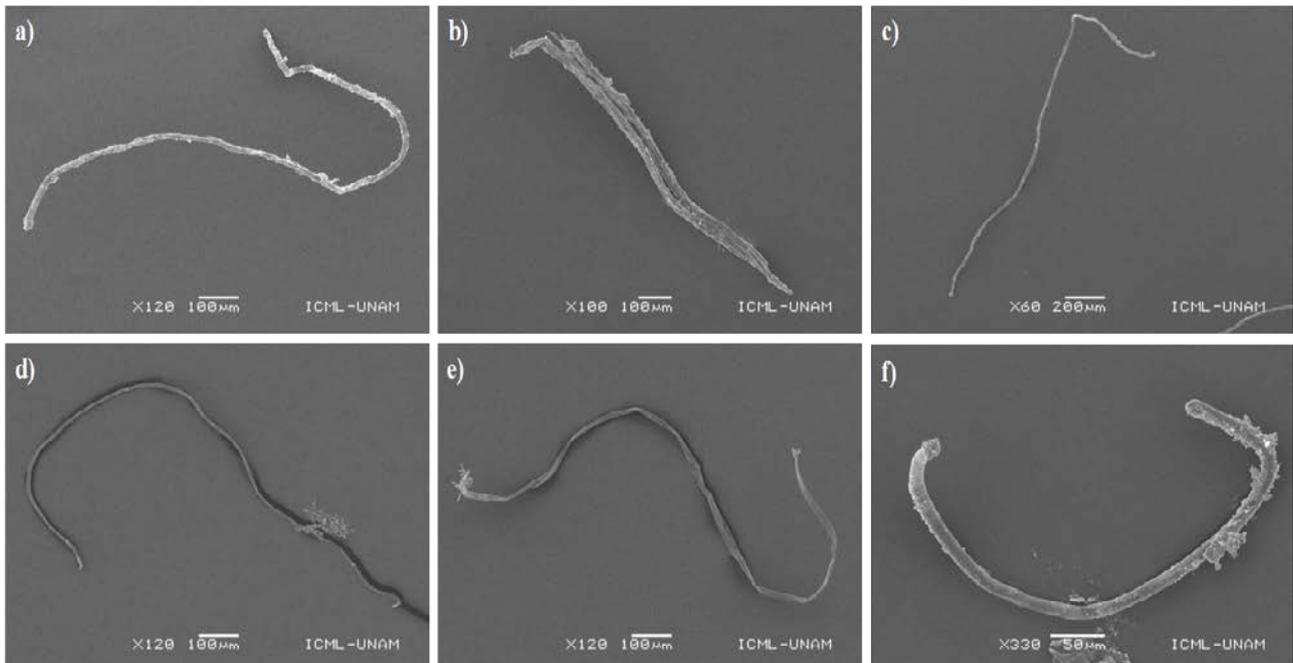


Figure 7. SEM images of fibers recovered in the Barra Norte beach sediments.

mechanical abrasion in swash and surf zones (Chubarenko et al., 2018; Ronda et al., 2023). The variations in MPs color also indicates the differences in their parent material (Sathish et al., 2019). On the other hand, transparent MPs are more harmful than colored MPs, because transparent plastic particles can be easily ingested by marine organisms. Similarly, small MPs can easily enter the sediment pore spaces, which is also harmful to the marine organisms like burrows, earthworms, and crabs.

4.5. Morphology

To identify the morphology and surface features, the fibers from the Mocambo and Barra Norte beach sediments are analyzed by SEM, and the images are shown in Figures 6a-f and 7a-f, respectively. Based on the variations in SEM images, the level of degradation (aging) and intensity of weathering of fibers are interpreted. The differences in surface features of fibers between the Mocambo and Barra Norte beaches are not significant (Figure 8a-f; Figure

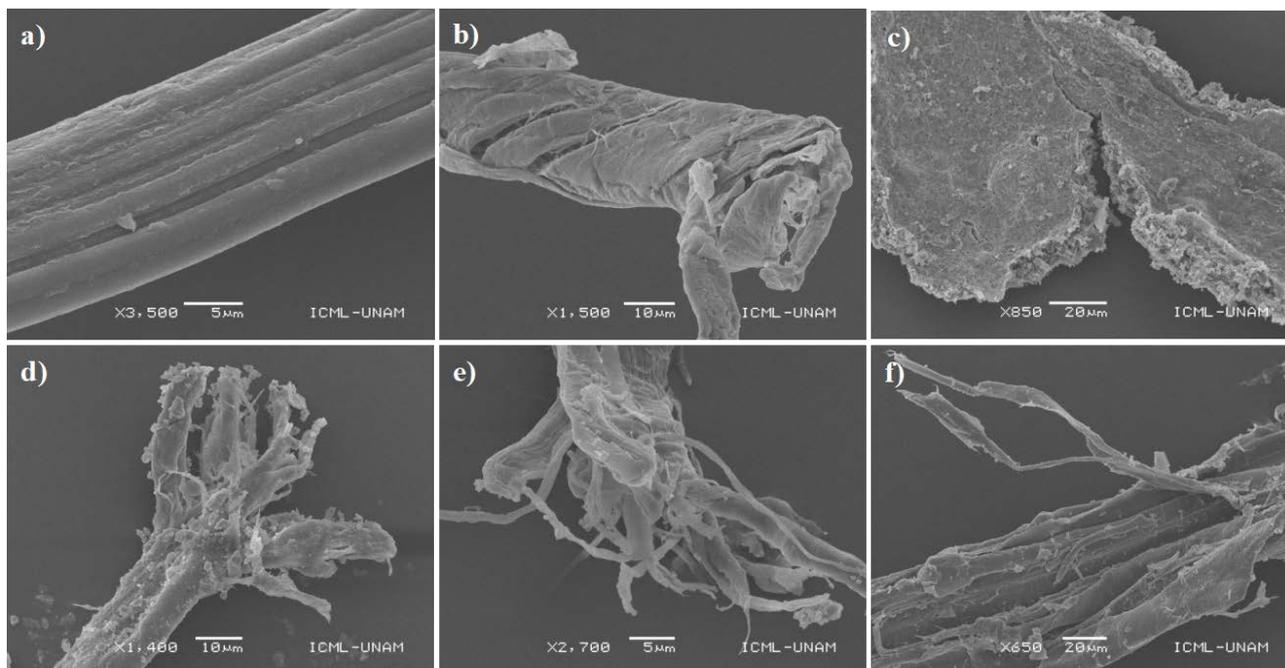


Figure 8. Surface features of fibers in the Mocambo beach: a) fissure; b) cracks and fractures with adhered particles; c) granular oxidation and fungal growth in the boarder; d, e, and f) stretched fibers with adhered particles.

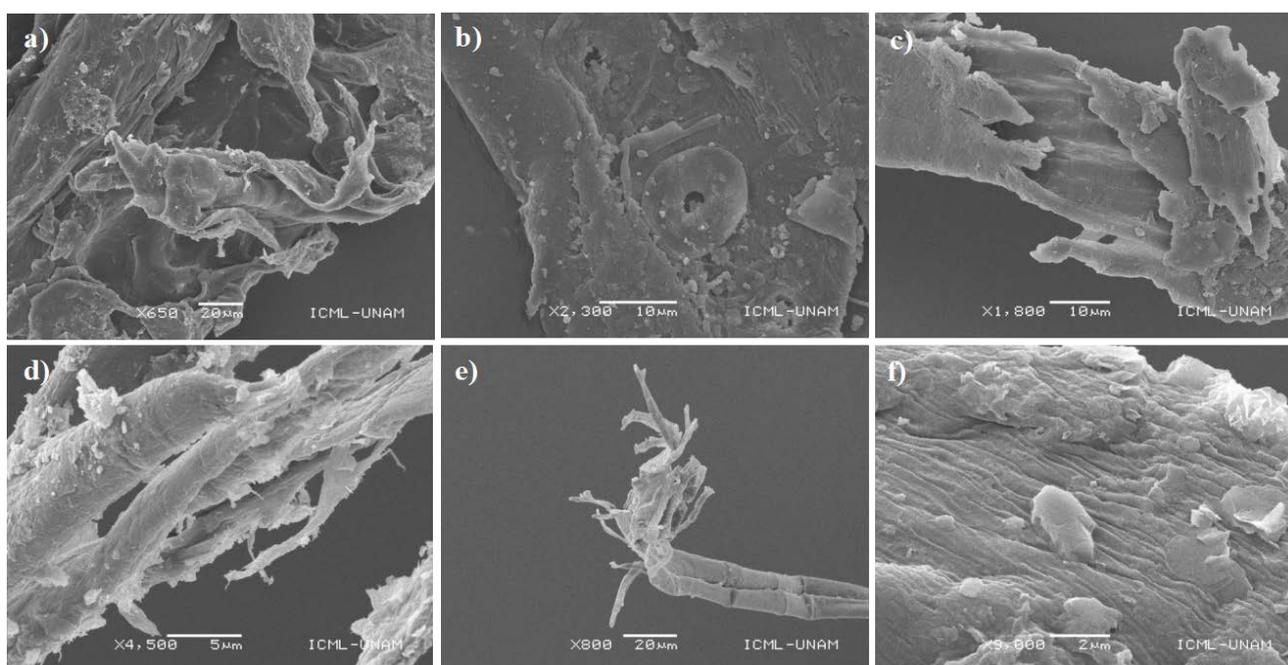


Figure 9. Surface features of fibers in the Barra Norte beach: a) detached fiber; b and c) fiber surfaces with adhered particles, solution pit, their surfaces are also indicating aging, oxidation, and precipitation of salt; d) degraded fiber with adhered particles; e) detached fiber due to tension; f) fiber surface with microbial colonization.

9a-f). The surface features reveal the presence of irregular edges, fragmentation, cracks, oxidized surfaces, and adhered particles in MPs. This can be attributed to the degradation of fibers due to mechanical, chemical and biological factors, which are common in the coastal environment. The mechanical abrasion due to waves and exfoliation can produce microtextures such as holes and fractures (Wang et al., 2022). The presence of

various cracks and granular oxidation indicates that the fibers are subjected to polymer aging, mechanical weathering, and chemical dissolution (Figure 8a-c; Figure 9a-c) (Keerthika et al., 2022; Armstrong-Altrin et al., 2023). The adhering particles indicate a post depositional process in a low-energy environment, additionally, the external agents such as trace elements and organic matter can be able to adhere on the fiber surfaces due to

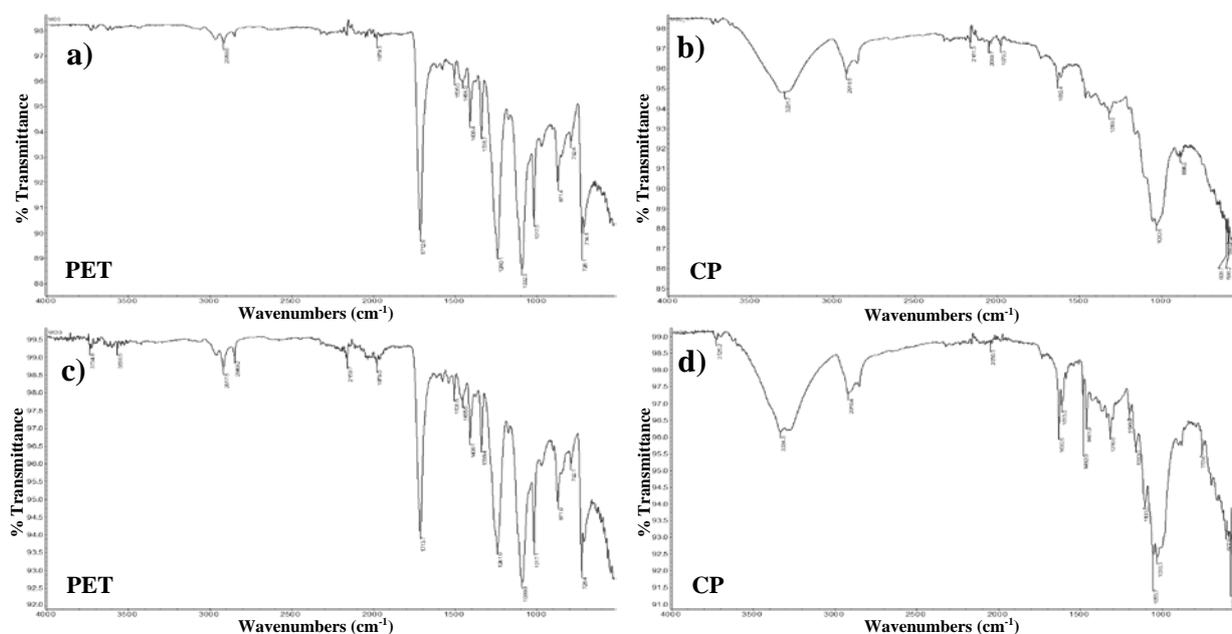


Figure 10. FTIR spectra of fibers in the Mocambo beach sediments. Polymers detected are: a) polyethylene terephthalate (PET); b) cellophane (CP); c) polyethylene terephthalate (PET); d) cellophane (CP).

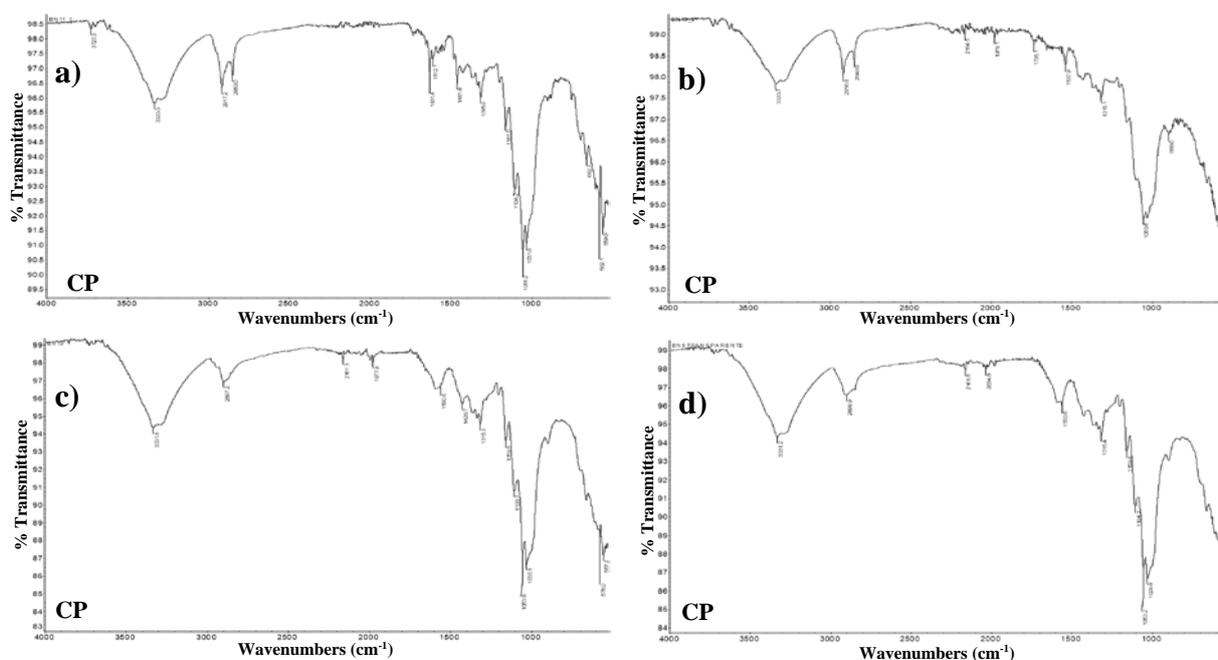


Figure 11. FTIR spectra of fibers in the Barra Norte beach sediments: a, b, c, and d) cellophane (CP).

fractures due to weathering on fibers surface can be caused by an abiotic (sea water temperature, salinity, winds, currents, and waves) and biotic erosional factors (microbial community composition) (Figures 8b,f; Figures 9a,e) (Armstrong-Altrin et al., 2022; Ranjani et al., 2022).

4.6. Polymeric identification of MPs

The identification of polymer types by FTIR-

ATR is an important tool to infer the source of MPs (Yaranal et al., 2021). Totally, 30 fibers are selected (15 from each beach), among them 50 % fibers obtained a good quality spectrum and only 2 polymer types were identified with a percentage greater than 70 % of match with the library spectra. In the Mocambo beach, cellophane (CP) and polyethylene terephthalate (PET) are identified, with CP being the most abundant polymer (Figure 10a-d). On the other hand, the polymer detected in the Barra Norte beach

Table 4. Comparison of microplastics abundance in beach sediments of this study with other studies of Mexico and around the world.

Location	Concentration	Size	Polymer type	References
Xiangshan Bay, southeastern China	1739 ± 2153 items/kg	1.54 ± 1.53 mm	PE, PP, PS, PET, and synthetic cellulose	Chen et al. (2018)
Balearic Islands, Spain	0.90 ± 0.10 items/g	NR	--	Alomar et al. (2016)
Lima, Peru	2089 items/m ²	2.8 - 4.75 mm	HDPE, PS, and PP	De-la-Torre et al. (2020)
Banten Bay, Indonesia	267 ± 98 items/kg	500 - 1000 µm	PS, CP, cellulose, PET, PP, and PE	Falahudin et al. (2020)
Lake Huron, North America	47,398 items/kg	500 µm - 1.2 mm	PP, PS, and PET	Belontz et al. (2022)
Tamil Nadu, India	439±172 items/kg	0.5 - 3 mm	PE, PP, NY, PES, and PS	Sathish et al. (2019)
Can Gio, Vietnam	6.58 items/kg	0.5 mm - 5 mm	PP, PS, and PE	Nhon et al. (2022)
Fernando de Noronha archipelago, Brazil	1059.3 ± 1385.6 items/m ²	2.9 ± 1.0 mm	--	Carvalho et al. (2021)
Dubai UAE	59.71 items/kg	NR	PE and PP	Aslam et al. (2020)
Slovenia	155.6 items /kg	1 mm - 0.25 mm	NY, PES, PP, PE, PVC, PVA, PS, PUR, PAN, and PA	Laglbauer et al. (2014)
Phuket, Thailand	188.3 ± 34.48 items/kg	>300 µm - 20-300 µm	PET, PS, PP, and PVC	Akkajit et al. (2021)
Todos Santos Bay, Baja California, Mexico	2494 items/m ²	<250 µm	PP, PE, PE-PDM, NY, CP, PET, PVC, and PAN	Ramírez-Álvarez et al. (2020)
Tecolutla, Mexico	2387 items/kg	NR	--	Flores-Cortés & Armstrong-Altrin (2022)
Campeche, Mexico	16.46 ± 17.76 items/kg	NR	--	Osten et al. (2023)
Tecolutla estuary, Mexico	121 items/kg	411 ± 408 µm	LDPE, PES, PP, PE, PC, SF, PVC, PAN, PA, NY, and PET	Sánchez-Hernández et al. (2021)
Baja California Peninsula, Mexico	135 ± 92 items/kg	NR	PAM, NY, PC, and PET	Piñon-Colin et al., (2018).
Chiapas, Mexico	53.6 ± 37.9 items/kg	NR	PE, PP, and PS	López-Velázquez et al. (2024)
Tampico, Mexico	12,800 to 14,150 items/kg	1.76 mm - 3.92 mm	PES, PEA, CP, PAN, SAN, and PVAE	Flores-Ocampo & Armstrong-Altrin (2023)
Barra Norte and Tuxpan, Mexico	4315 and 5865 items/kg	0.95 mm - 1.05 mm	CP and PET	This study

Polymer types: polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), cellophane (CP), high density polyethylene (HDPE), nylon (NY), polyurethane (PUR), polyvinyl chloride (PVC), polyether sulphone (PES), polyvinyl alcohol (PVA), polyacrylonitrile (PAN), polyamide = nylon (PA), polyethylene-propylene-diene (PE-PDM), polyethylene (LDPE), polycarbonate (PC), rayon (SF), polyacrylamide (PAM), polyethylacrylate (PEA), polystyrene acrylonitrile (SAN), and polyvinyl acetate ethylene (PVAE). Sample type: beach sediments; Extraction method: in these studies, microplastics were separated from sediments by density separation method, mostly using NaCl and/or ZnCl₂; NR = Not Reported. Common microplastics shape reported by the authors: fiber, fragment, filament, foam, pellet and films.

is only CP (Figure 11a-d). The high density of these polymers (cellophane = 1.50 - 1.52 g·cm⁻³ and PET = 1.38 g·cm⁻³) allows them easier to deposit quickly in sediments (Gu et al., 2024). Cellophane is the predominant polymer identified in sediments from both beaches. The higher abundance of Cellophane than PET can be explained by its widespread use in food packaging applications, as well as its use as a release agent to produce fiberglass rubber coatings for paper, cigarettes, and clothing (Shruti et al., 2022). Similarly, PET is commonly used in textile products, disposable plastics, bags and beverage bottles. The abundance of this polymer in beach sediments is due to the result of large production and consumption of PET products in Mexico. In fact, Mexico is the number one nation in the world in per capita consumption of bottled water (Eaton & Roberts,

2014; Silva, 2024). In Mexico more than 7 million tons of plastic products are produced per year of which only 6 % are recycled (Greenpeace Mexico, 2019).

The abundance of MPs of this study (Barra Norte and Mocambo beaches) is compared with other similar studies in Mexico as well as around the world (Table 4). For comparison, the number of MPs in this study (4315 to 5865 items/kg) is higher than in other beaches, except Tampico (12,800 to 14,150 items/kg) and North America (47,398 items/kg). Furthermore, it is identified that PET, PP, and PVC are common in beach sediments of the world, it is due to the reason that these polymers are the product of commonly used materials like toys, plastic bags, food packaging materials etc. Hence, simultaneously an increase in the disposal of these plastic materials into the coastal

environment can increase the number of PET, PP, and PVC in sediments. Also, the shape of MPs reported in Mexico as well as in other countries are dominated by fibers and fragments, suggesting that they can be able to withstand in the coastal environment for a long span of time. It seems that fibers and fragments are highly adjustable to the wave energy condition and are also resistant against degradation process, a further study is necessary to prove this assumption.

This comparison reveals that the number of MPs in the Mocambo and Barra Norte beaches of this study is higher than in other beach areas, suggesting a major treat to the Gulf of Mexico marine environment.

5. CONCLUSIONS

This study analyzed the abundance and characteristics of MPs in sediments from the Mocambo and Barra Norte beaches in the Gulf of Mexico. The abundance of MPs is identified in all samples from the Mocambo and Barra Norte beaches. The number of MPs is higher in the Barra Norte (5865 MPs · kg⁻¹) than in the Mocambo (4315 MPs · kg⁻¹) beach. Fiber is the only type of MP identified in both beaches. Small MPs are abundant both in the Mocambo (avg. 0.95 mm) and Barra Norte (avg. 1.06 mm) beach sediments and are mostly transparent in color. Two types of polymers are identified, i.e. cellophane and PET, in which cellophane is more abundant than PET. Textile production, cloth washing, fishing activities, and daily waste produced from plastic products are considered as the main source of these polymers. SEM images reveal that the MPs are weathered and degraded due to UV radiation, oxidation, and polymer aging. Mechanical abrasion by waves and wind activity, as well as the adhering particles produced by the chemical and biological agents intensified the degree of degradation.

The abundance of MPs in the beach sediments is largely influenced by environmental factors, anthropogenic activities, and the amount of plastic waste released into the coastal environment. The MPs are transported to the beaches by rivers and are distributed in sediments by coastal currents and waves. This study identifies that the industrial activity in the Barra Norte coastal area is responsible for the higher abundance of MPs than in the Mocambo beach sediments.

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