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Revealing microplastic and anthropogenic microparticles contamination in tidal blue carbon ecosystems from eastern Brazil☆

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A R T I C L E I N F O

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A B S T R A C T

We provide information about the accumulation of microplastic and other anthropogenic microparticles (AMP) in tidal blue carbon ecosystems from Eastern Brazil. This study analyzed the accumulation of AMP in 40 sediment samples extracted from tropical *Spartina* marsh (2 cores: CM1 and CM2) and mangrove (1 core: CAB) from Todos os Santos Bay (TSB, Bahia, Brazil). The main objective was to identify differences in AMP accumulation between mangrove and *Spartina* salt marsh cores in order to understand their different roles in AMP retention; and evaluate if *Spartina* marshes act as stronger AMP sinks than mangroves. The average AMP abundance was at least 38 % higher in saltmarshes compared to mangroves. Micro-Raman spectroscopy was applied to determine the chemical composition of the different collected samples, thereby enabling a detailed investigation of their structural and compositional features. Fibers represent the dominant category, likely due to the large widespread use of synthetic fibers, insufficient wastewater treatment and high levels of fishing activities in the area. The predominant color in all cores is blue (41.6 %) and transparent (20.0 %), the predominant particle size in all cores is between 0 and 1 mm. Organic matter (%OM) and mud content (%M) did not influence AMP concentration. This work improves the understanding of the distribution and consequences of AMP in South American mangrove and salt marsh ecosystems, highlighting the need for collective, comprehensive efforts to mitigate their effects, such as improving the efficiency of wastewater management and other human uses and mismanagement in TSB.

1. Introduction

Global plastic production exceeds 400 million tons per year (PlasticsEurope, 2023), and global fiber production exceeds 123 million tons per year (PFMMR, 2025), and together they constitute one of the most pervasive pollutants in coastal environments (Barrows et al.,

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2018). About 4.8 to 12.7 million tons of plastic debris enter the coastal and marine ecosystems annually, adding to the estimated 170 trillion plastic particles floating in the world's oceans (Jambeck et al., 2015; Eriksen et al., 2023). The small size and light weight of the microplastics (small solid fragments of plastic - up to 5 mm, produced in small size or originated from larger plastic fragmentation (Hartmann et al., 2019; Thompson et al., 2024; Thompson, 2015) and anthropogenic microparticles (synthetic (100 % plastic), semi-synthetic, dyed and modified natural particles with dimensions of less than 5 mm; Álvarez-Méndez et al., 2024) enable these materials to be easily transported by currents, rain, and winds (Rezaei et al., 2019). These emerging pollutants have been largely produced since the 1950s due to their low cost, high durability, ease of handling, and versatility (Derraik, 2002; Jambeck et al., 2015; Hale et al., 2020; Eriksen et al., 2023). Such characteristics drove their escalating global demand and a concomitant increase of AMP concentrations in global ecosystems, posing a significant hazard to ecological processes and marine carbon cycles (Galloway et al., 2017; Martin et al., 2020; Bom and Sá, 2022; Noman et al., 2024).

Blue carbon ecosystems (BCEs: mangroves, saltmarshes, and seagrass meadows) are recognized as key for climate change mitigation due to their capacity to sequester high amounts of organic carbon belowground while providing other essential ecosystem services, such as raw material and food production, coastal resilience, and pollutant sequestration. However, these ecosystems have been historically impacted by intense land use and cover changes (LUCC), such as deforestation, and urban sewage (Servino et al., 2018; Kauffman et al., 2018a; Creed et al., 2023; Muniz et al., 2024; Quevedo and Kohsaka, 2024; Adame et al., 2024). Simultaneously, plastic and solid waste mismanagement has emerged as a recognized problem over the last years (van Bijsterveldt et al., 2021; Pinheiro et al., 2021; Noman et al., 2024; Okoffo et al., 2024).

The Brazilian coast harbors the second-largest mangrove area in the world, as well as patches of saltmarshes, and seagrass along the coast. In general, the Brazilian mangroves and saltmarshes dominate the tidal influence zone (intertidal zone) while seagrass tends to colonize both intertidal and sublittoral zones (Isacch et al., 2006; Diniz et al., 2019; Creed et al., 2023). Besides the ongoing urban pollution in Brazilian BCEs (Egres et al., 2019; Hadlich et al., 2018; Muniz et al., 2024), the mangroves and saltmarshes are historically under similar pressures (e.g., forest and topsoil removal for shrimp farm production; Kauffman et al., 2018b; Muniz et al., 2024) while the impacts on seagrass meadows are related to shipping activities (such as anchoring and trawling; Creed et al., 2023). Given the pressure suffered by the intertidal mangroves and saltmarshes, these ecosystems could release massive amounts of AMP into the marine ecosystem, exacerbating the aforementioned problem (Pinheiro et al., 2021; Pinheiro et al., 2022; Noman et al., 2024).

The amount of AMP in BCEs is related to several factors, such as climate, latitude, hydrodynamics conditions, riverine flow, and also anthropogenic sources (Zhou et al., 2023; Zanetti et al., 2025). The largest anthropogenic sources of AMP inputs for BCEs are sewage treatment plants, tourism, fishing activities, urban and agricultural runoff, marine aquaculture, and shipping, in addition to the degradation of plastics already retained by BCEs ecosystems (Deng et al., 2021). In addition to factors linked to high regional population density, climatic factors influence higher abundance of AMPs, where Tropical BCEs have higher abundance of microplastics in sediments (Yu et al., 2022; da Silva Paes et al., 2022). Furthermore, higher temperatures can accelerate aging and decomposition of plastics, increasing AMP abundance, especially on the topsoil (Zhou et al., 2023), as well as to high precipitation, floods and storms also increase the input of terrestrial microplastics entering BCEs (Zhang et al., 2017). The same pattern is seen to higher river runoff, which increases the potential of AMP enrichment in the surface waters, but it does not appear to significantly change concentration of AMP in the sediment, especially since the presence of AMP in sediments may also be susceptible to current velocity, waves and tidal range, with sediments being both sources and sinks of microplastics (Zhou et al., 2023; Qi et al., 2025).

Biological, sedimentological and vegetation-related factors also influence the accumulation of AMP. Bioturbation mechanisms such as burrowing, feeding, defecation, and ventilation play an important role in nutrient cycling in BCEs (Krantzberg, 1985) as well as AMP burial (Wu et al., 2025). Bioturbation carried out by crabs, molluscs and worms has translocated AMP towards deeper sediment layers, participating in redistribution and retention of AMP (Näkki et al., 2017; Lloyd and Turner, 2026). Blue carbon vegetation contributes to greater accumulation of AMP, associated with the complex system of roots, leaves, aerial structures, and shoots, which results in significant wave attenuation, reduced water velocity and increased hydrodynamic retention time, acting to retain sediments and trap microparticles (Koch et al., 2009; Huang et al., 2021; Qi et al., 2025). AMP enrichment in vegetated BCE locations is 1.3 to 17.6 times greater than unvegetated BCE locations (Huang et al., 2021). Also, silt, clay, and particulate organic carbon (POC) content may also facilitate trapping and aggregate AMP due to their specific surface area and through electrostatic interactions (Huang et al., 2021; Qi et al., 2025). Saltmarshes have shown high concentrations of microplastics when compared to mangroves, mudflats and sandflats, mostly due to the vegetation structure, sediment characteristics, and hydrodynamic conditions (Paray et al., 2025). This highlights the role of vegetation in the dynamics of microplastics in coastal areas. However, the processes of AMP burial in blue carbon sediment cores remain poorly explored (Li et al., 2022a), especially in Brazil.

In Brazil, some studies have highlighted the presence of microplastics in mangrove and saltmarsh cores samples (Zamprogno et al., 2021; Paes et al., 2022; Rico et al., 2024; Pinheiro et al., 2022; Alves et al., 2023), with micro-FTIR spectroscopy to identify polymer composition (Rico et al., 2024; Pinheiro et al., 2022; Alves et al., 2023). However, even on a global scale, there are few studies that have compared the presence of microplastics in vegetative sediments (saltmarshes and mangroves). In this context, the main objective of this study is to quantify the abundance and composition of AMP in one of the most urbanized and industrialized areas of Eastern Brazil, assessing the difference in AMP accumulation between mangrove and saltmarsh cores in order to understand their different roles in AMP retention. Our results provide relevant data for further investigation of AMP presence and its ecological effects, which can direct to conservation policies to manage Brazilian coastal areas.

2. Material and methods

2.1. Study area

Our study area comprises the mangrove and tropical *Spartina* marshes (Caboto - Todos os Santos Bay: TSB; Fig. 1) along the tropical Eastern Brazilian coast. TSB (12°35′30″-13°07′30″S and 38°29′ 00″-038°48′00″W) is the Brazilian second largest bay (1233 km^2) with intense industrial (RLAM Landulpho Alves Refinery oil refinery, and the largest chemical complex in South America: Camaçari Industrial Center) and urban development (e.g. Salvador city and Aratu harbor), being the third largest metropolitan area in Brazil (population of ~2.9 million inhabitants (Egres et al., 2019; Reis and Barros, 2020; Santos et al., 2020). Three main tributaries flow into the bay: The Paraguaçu (56,300 km^2), the Jaguaripe (2200 km^2), and the Subaé (600 km^2) rivers. The hydrodynamic circulation is influenced by the meso-tidal regime, with tidal current velocities up to 1.20 m/s at the bay entrance, lowering towards the center of the bay to 0.5 m/s during spring tides (Lessa et al., 2009; Lessa et al., 2000). Saltmarshes in this region occur as patches, usually in front of the mangrove as pioneers (Reis et al., 2019), and are sparse and short when compared to temperate saltmarshes (Souza et al., 2022).

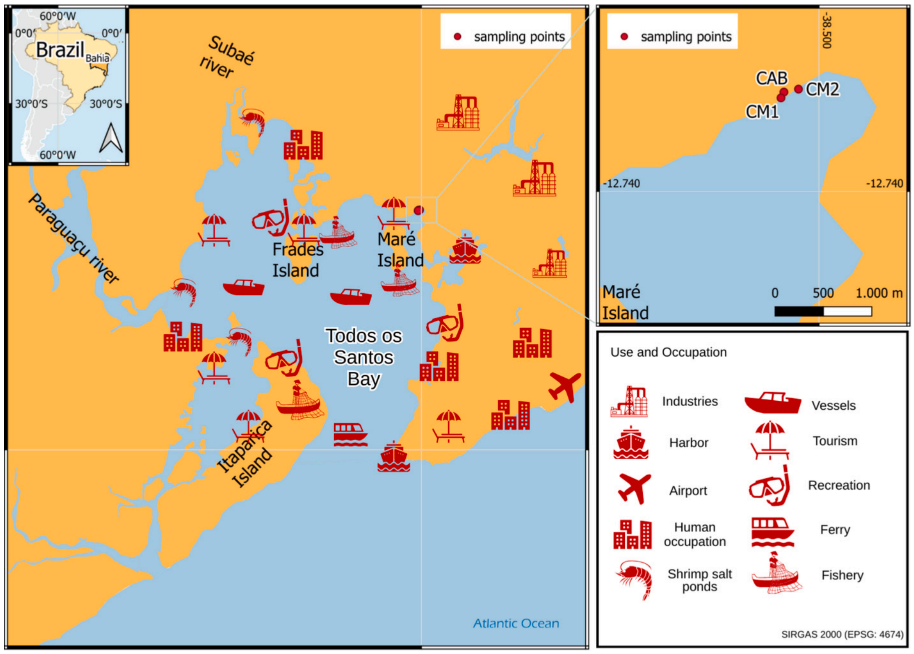

Fig. 1. Use, occupation, and location of the sampled cores at the mangrove (CAB) and saltmarshes (CM1 and CM2) in Todos os Santos Bay.

2.2. Sampling design

During low spring tides of February 2022, we sampled 3 sediment cores up to 24 cm depth using polyvinyl chloride tubes (PVC) of 10 cm in diameter, while the sediment-depth was measured using a 1 m deep millimeter ruler. At Caboto (Fig. 1 and Table S1) we sampled 1 core of 24 cm-depth from a mangrove forest dominated by *Rhizophora mangle* forest with isolated *Laguncularia racemosa* and *Avicennia schaueriana* trees (CAB); and 2 cores in saltmarshes of the genus *Spartina* located in front of the mangrove forest and between the forest and the mudflat (CM1 and CM2). All cores had a recovery of 24 cm-deep due to the shallow bedrock. For CAB, the sediment core was sampled in the mangrove forest basin (20 m distant from the fringe), while the sediment cores from the saltmarshes were sampled in the middle of the patch. Samples were extruded from the PVC tube in the field and sliced using a stainless steel knife in 1 cm intervals from the core top to 10 cm depth, and in 2 cm intervals from 10 cm to the bottom of the core. The samples were used for AMP extraction, organic matter content analysis (OM%) and mud content analysis (%M).

2.3. AMP extraction, organic matter (OM %) and mud content (M %) analysis

For AMP extraction, the freeze-dried samples were inserted (25 g per slice) in the Sediment-Microparticle Isolation (SMI: a small-scale, portable method for extracting microparticle from marine sediments; Coppock et al., 2017; Martin et al., 2020) to separate the AMP from the sediment by density flotation with saline solution (NaCl, 1.2 g/mL, 47 mm) followed by H_2O_2 supernatant digestion (30 %, 50 °C, 24 h). The supernatant was vacuum filtered through a 47 mm glass fiber mesh (1.2 μm); and the filters were analyzed under a microscope to sort, quantify, and characterize the AMP (size, color and shape), suspected AMP had no cellular/organic structures visible, with homogeneous color and texture (Zanetti et al., 2025).

We included key environmental variables (Organic Matter content: OM %; and mud content: M %) to test its influences over AMP types and content. The OM % was calculated by gravimetric variation using the ignition method for oven-dried sediments mass loss (~3 g dry sediment) in the muffle at 450 °C for 4 h, while M % was calculated by wet sieving (~2 g dry sediment), separating sand (50–2000 μm) from fine sediments (silt: 2–50 μm and clay: <2 μm).

2.4. Quality control

All steps were conducted following clean procedures to avoid contamination between sample analyses. To avoid airborne contamination and cross contamination, all glassware, SMI units and tweezers and laboratory benches were cleaned with filtered ultrapure water before every use. Glassware was stored covered in aluminum foil. Samples were extracted and visually inspected in an isolated room with no circulation of personnel, and all materials and samples were always covered with pre-cleaned aluminum foil. Procedural blanks were conducted by exposing petri dishes with filters, remaining by the side of the samples. Only cotton lab coats and latex (nitrile) gloves were used during sampling procedures. Negative controls (reagents without sample) were processed simultaneously with samples to assure quality of procedures (Zanetti et al., 2025). These rigorous practices ensure data reliability.

2.5. Polymeric identification

The polymers analysis was conducted using μ-Raman spectroscopy technique, using two spectrometers - Micro Raman - InVia Renishaw and LabRAM HR Evolution - HORIBA (Supplementary material), due to its low interference with water when compared with FTIR (Chen et al., 2023) and higher accuracy for characterization of polymers, and, particularly, for the identification and quantification of environmental AMP samples (e.g., marine sediments; Cabernard et al., 2018; Dąbrowska, 2021).

3. Statistical analyses

The Shapiro-Wilk and Levene tests were applied to assess normality and homoscedasticity of the data. After that, Kruskal-Wallis and Dunn tests were applied to evaluate differences in AMP distribution, mud and organic matter content across depth in each core and between cores. Chi-squared test and Bonferroni adjustment were applied to assess the size, color and shape distribution frequencies in cores. Spearman's rank tests were applied to assess correlation between mud content, organic matter content, and AMP concentration. All statistical tests were conducted using the R packages ggpubr, car and dunn test.

4. Results and discussion

4.1. Quality and contamination control

The average contamination in blank processual filters was 0.75 ± 0.87 items, and 25 items were removed from samples according to similarity of size, shape and color to the blank particles, as suggested by Munno et al. (2023). In the blank processual particles ($n = 24$), fibers represent 95.8 % ($n = 23$) of the total, while fragments ($n = 1$) represent 4.2 %. The AMP in the quality analyses was composed of four colors (transparent: 66.7 %, blue: 20.8 %, black: 8.3 % and red: 4.17 %). Blue, black and clear fibers are frequently observed in airborne AMP contamination (Liu et al., 2019). Thus, blanks are essential to ensure process quality, making possible to polish AMP estimation, since contamination can occur despite clean procedures.

4.2. Anthropogenic microparticles in blue carbon sediments

Mangroves and marshes accumulate distinct stocks of AMP globally. A total of 200 anthropogenic microparticles were found in the environmental samples (Table S1). The AMP stock of the three cores totals 8000 particles/kg dry sediment (Table 1; Table S2). Among cores, the CM1 core (Fig. 2a, Table 1) presents a total abundance of 1960 particles/kg dry sediment; the CM2 core (CM2 - Fig. 2b, Table 1) presents a total abundance of 4800 particles/kg dry sediment and the CAB core (CAB - Fig. 2c, Table 1) presents a total abundance of 1240 particles/kg dry sediment. The average AMP per sample is higher in the CM2 sample, as the standard deviation, highlighting the heterogeneity of particle distribution throughout the sample. The CM1 and CAB samples have lower average and maximum values, with greater homogeneity between extracts.

Once in the environment, plastics degrade into low molecular weight non-polymeric compounds, such as dissolved and gaseous products, and their presence in the environment impacts the decomposition of labile fractions of organic matter, promotes changes in the degradation of organic matter in sediments, and alters greenhouse gas emissions (GHG) (Stubbins et al., 2021), (Royer et al., 2018), (Sanz-Lázaro et al., 2021), (Chen et al., 2022). AMP during weathering processes can expose their functional groups (e.g., ketones), attracting microorganisms to use AMP as part of their biochemical cycles, as electron sinks or donors (Rillig et al., 2021). Because of their surface area, stability, and hydrophobicity, AMP can also interact with other macromolecules available in the environment (humic acids, proteins, extracellular substances), forming an organic capsule known as the eco-corona (Yang et al., 2025). The formation of eco-corona can affect AMP' toxicity, environmental fate, and bioavailability, but their extent of the biological effects and mechanisms is still limited (Yang et al., 2025).

AMP contributes to changes in sediment/soil aggregate size, soil porosity, and water holding capacity (Rillig et al., 2021). In addition, AMP can promote carbon release from sediments/soils and function as organic carbon substrates for microorganisms, affecting nitrogen cycling (Seeley et al., 2020). However, polymer type, plastic degradation stage, environmental conditions, and bacterial genes involved in nitrification processes can alter the effects of AMP on the environment (Seeley et al., 2020; Chen et al., 2022; Wang et al., 2023). There is also a large exchange of nutrients and aeration in BCEs, and the presence of AMP is capable of increasing mineralization, since they increase the porosity and aeration of sediments and reduce water retention, contributing to intensifying lateral losses (Guo et al., 2022).

Regarding accumulation patterns, the data distribution in all cores proved to be non-normal (p-value <0.05) and, therefore, non-parametric methods were applied. Furthermore, we recognized that our sample size of only three cores limits extrapolation of results within the TSB, and we caution against over-generalization of AMP variability across the entire TSB.

In general, the saltmarsh CM2 AMP accumulation was different from CAB (p-value <0.05; Table S3), while CM1 and CAB and CM1 and CM2 were similar (p-value >0.05; Fig. 2). The saltmarsh (CM1 and CM2) cores indicate uneven accumulation along the core. Additionally, as observed in our 3 cores, the superficial layer (at the air-sediment interface) is highly dynamic, and the constant removal and deposition of sediment can prevent the final accumulation of plastic particles, driving their migration to deeper layers. (Pinheiro et al., 2022).

In the CM1 core there is a higher concentration in the 3 cm top layers but also in the bottom, up to 18 cm and 24 cm. The concentration in the CM2 core increases in the first 6 cm and increases again at 14 cm; while for CAB core, the highest concentrations are in the 2 cm and 7 cm. The accumulated particle concentration indicates that in all cores there is a preferential deposition in the first 10 cm of the layers, although it is not statistically significant (p-value >0.05). The relationship between the concentration (AMP/kg of sediment) and depth was not significant (p-value >0.05) for all cores.

Factors related with depth accumulation are related to temporal deposition, vertical migration and release to the water column. Globally, there is a tendency of surface enrichment of AMP, indicating an accumulation in recent layers and decreasing from top to bottom, mostly related to increased production and use of AMP over time (Yu et al., 2023; Li et al., 2020). But cores with a trend of increasing AMP with depth have also been reported (Mohamed et al., 2023). These differences in patterns could be due to distinct local forces at each location, and dependent on biological, geomorphological, and hydrological processes in coastal regions (Pinheiro et al., 2022). AMP mobility can be directly influenced by pore water exchange, plant root growth and soil aeration, soil fauna activity (e.g., bioturbation), groundwater, and tidal dynamics (tidal level, velocity and range) (Wu et al., 2020; Duan et al., 2021; Sun et al., 2025). As pore water percolates downward, it promotes AMP migration. Also, mangrove vegetation can modulate pore water flow, interfering with AMP vertical distribution. Bioturbation controls material cycling in sedimentary environments, modifying sediment structure, porosity, and AMP bioavailability (Liu et al., 2025), influencing the accumulation observed in deeper layers. Bioturbation depends on animal feeding, behavior and burrowing strategies, and can promote AMPs transport in both up and downward directions (Gomes and Bernardino, 2020; You et al., 2023). For instance the presence of crab burrows may influence the dynamics of source/sink of AMP, either trapping or releasing AMP from deeper sediments into the water column (Wu et al., 2025). Other taxa, like polychets and bivalves could have similar influences through burrowing and vertical movement, which could introduce AMPs to deeper layers (Rillig et al., 2017).

Sedimentation rates in the TSB area region are around 1.5 ± 0.2 cm yr − 1 (Andrade et al., 2017). Using this estimate for our 24 cm cores, they would be between 14.1 and 18.5 years old, and the base of the cores would reflect the years between 2004 and 2007. This data can provide a basis for understanding that the cores collected still reflect recent events, and would still be much more recent than the beginning of the plastic era in 1930. These data also reflect two limitations of our study, the first one is the dating of our cores to estimate reliable data towards core age, while the second is related to the recovery of the core, to reach layers

Table 1
Range of AMP content (number of particle/kg of dry sediment) for each core (CM1, CM2 and CAB); 17 slices.

Core	AMP content (number of particle/kg of dry sediment)					
	Total	Min	Max	Mean	Median	SD
CM1	1960	0	400	115	40	153
CM2	4800	0	720	282	280	214
CAB	1240	0	240	73	80	69

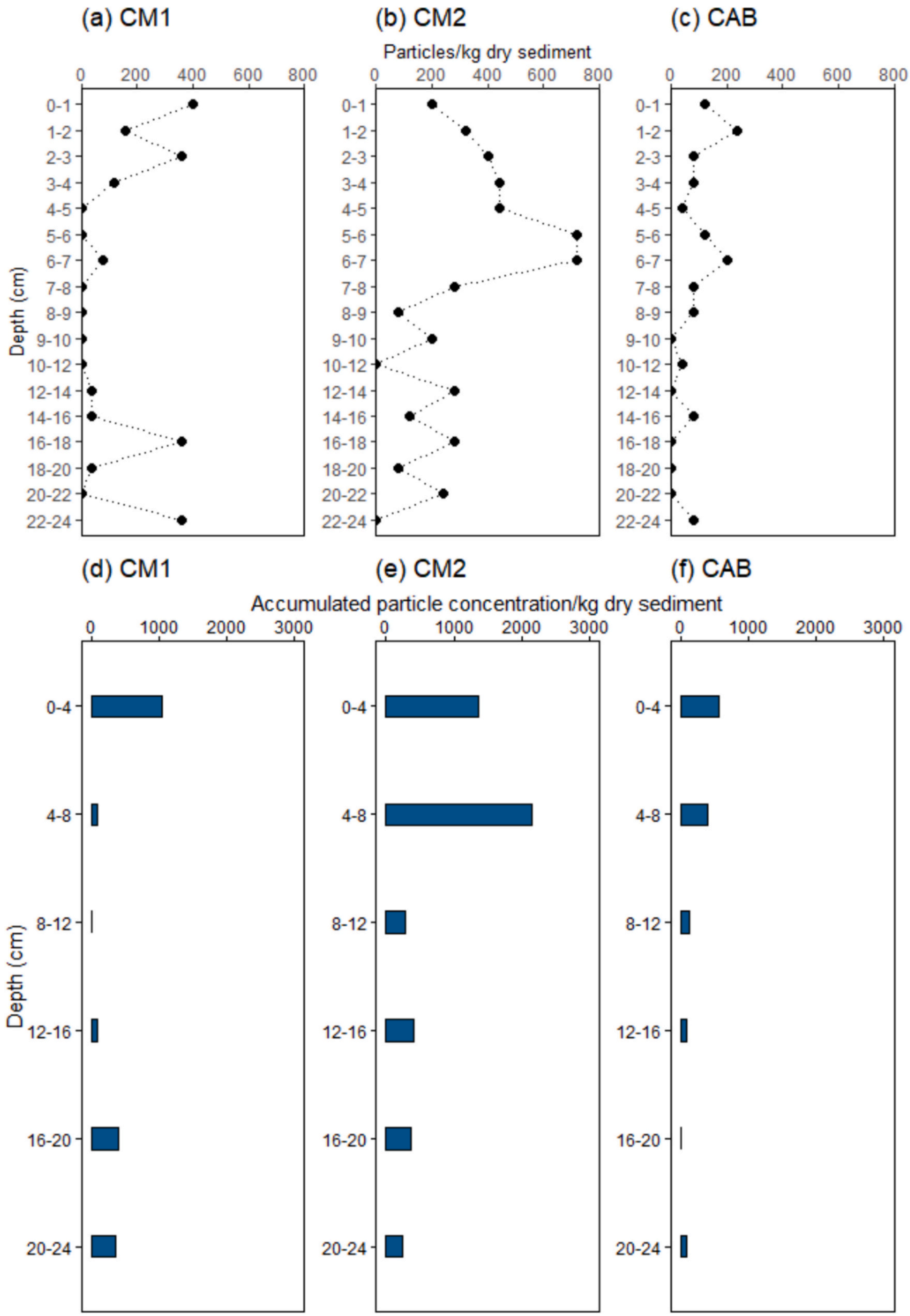

Fig. 2. Microparticle concentration along the sampled cores and related sum at each depth gradient for CM1 (a and d), CM2 (b and e) and CAB (c and f). The 0–4 cm and 4–8 cm layers have the highest accumulation of particles, regardless of the core analyzed.

prior to 1930, considering a constant sedimentation rate, the core would need to be 143 cm deep, which was not possible due to the shallow bedrock.

The CM1 together with CM2 showed higher concentrations than CAB. Although not statistically significant, the two marsh samples contain higher concentrations than the mangrove CAB core. The small sample size and single sampling event prevents consideration of local and seasonal varyability and limits the robustness of broader ecological conclusions. This preliminary sampling may indicate that the presence of saltmarshes in front of the mangrove forest may mitigate the entry of AMP into the mangrove forest, with the tide being the vector that brings microparticles inland. The study region is located in a low hydrodynamic energy location, and vegetation and flooding degree play a key role in AMP movement/entrapment (see Paray et al., 2025). Furthermore, there is a tendency of higher accumulation of MPs at the edges of mangroves than in the interior due to the influence of tides (Yu et al., 2022). Also, saltmarshes are known for sequestrating more AMP than other wetland systems (retention trends were identified as being higher in saltmarsh than mangrove, mudflat and sandflat) due to the high trapping efficiency of halophytes (Paray et al., 2025). However, confirmation of this hypothesis requires more studies that compare mangroves with and without *Spartina* in their fringe, to assess retention efficiency and compare effectiveness of vegetative areas in trapping AMP.

Furthermore, the concentrations found are related to anthropization of the TSB, linked to untreated wastewater discharged into rivers that flow into the bay, poor management of waste from dykes and landfills, and intensive use of plastic materials in fishing. The AMP concentrations found in this study are similar (Table 2) to those found in mangroves in Southern Thailand (Pradit et al., 2022) and the marshes of Molhe Oeste (Pinheiro et al., 2022), and higher than those found in the Malaysia (Mohamed et al., 2023) and Amazon River (Rico et al., 2024). They are also an order of magnitude lower than those found in Thames estuary (Trusler et al., 2025), Southeast coast of China (Yu et al., 2023) and Todos os Santos Bay (Paes et al., 2022). Among the largest stocks ever recorded are those in the same region, at TSB mangroves, with a mean concentration of 10.782 ± 7.671 MPs/kg (Paes et al., 2022, Table 1). In fact, for mangroves from TSB, the lowest concentrations in the study (2.776–10.825 items kg^{-1}) are still orders of magnitude higher than our results. It suggests that environmental influence (e.g., hydrodynamics and tides) play an important role over AMP accumulation within these ecosystems; and also the use of different methodological strategies to separate and analyse AMP polymers will directly influence the recovery and the related total amount. By this, it is important to follow the same strategy during monitoring programs to avoid over- and underestimation due to changing methodologies or calibrate the results accordingly.

4.3. AMP morphological characteristics

In CM1, 49 anthropogenic microparticles were found, only fibers (73.5 %, $n = 36$, adjusted p-value <0.001) and fragments (26.5 %, $n = 13$, adjusted p-value <0.001), mostly blue (44.9 %, $n = 22$) and black (22.4 %, $n = 11$). In the CM2 core, 120 anthropogenic microparticles were found, mostly fibers (82.5 %, $n = 99$; adjusted p-value <0.001), some fragments (16.7 %, $n = 20$; adjusted p-value <0.001) and one film (0.83 %, n = 1; adjusted p-value <0.001), predominant colors are blue (36.7 %, $n = 44$), transparent (20 %, $n = 24$) and black (18.3 %, $n = 22$). In the CAB mangrove core, 31 anthropogenic microparticles were found, composed by fibers (58.1 %, $n = 18$) fragments (29.0 %, n = 9) and films (12.9 %, n = 4), preferentially blue (54.3 %, $n = 17$), and transparent (25.8 %, $n = 8$). No statistical difference was observed between color distribution and depth for the three samples tested (p-value >0.05).

Considering all cores, the distribution of shape was significantly different ($\chi^2 = 177.97$; df = 2; p-value <0.001). Fibers (Fig. 3; $n = 153$: 76.0 %, adjusted p-value <0.001) were the most abundant shape of AMP along the vertical profile considering the three cores, followed by fragments ($n = 42$: 21.0 %, adjusted p-value <0.001) and films ($n = 5$: 2.50 %, adjusted p-value <0.001).

Fibers can be originated from effluents from domestic wastewater, fishing-related activities and aquaculture, and are usually the most prevalent form of AMP reported in environmental studies, including BCEs (Li et al., 2020; Rico et al., 2024; Mohamed et al., 2023). The TSB area is highly influenced by anthropic activities, fishing and aquaculture, with fourteen municipalities in its surroundings and a population of ~2.9 million inhabitants (IBGE, 2022), receiving treated and untreated industrial/domestic sewage (Andrade and Hatje, 2009) and with more than 173 fishing communities (Andrade and Hatje, 2009) which use equipment like ropes and lines composed of fibers. Furthermore, on a global scale, an annual emission of 5.69 million tons of fibers from domestic wastewater is estimated to flow from the continent into coastal ecosystems (Wang et al., 2024). Films likely originated from the breakdown of plastic bags, solid waste and agricultural films (Garcés-Ordóñez et al., 2019), while fragments originated from the degradation of larger plastic items, both also related to urban occupation, domestic wastewater (personal care products and cleaning products; Atugoda et al., 2021) and run-off from the land and river (Aquleema et al., 2024). These findings on shape abundance are aligned with global studies on AMP characterization in BCEs (Zhang et al., 2022; Zamprogno et al., 2021).

Considering all vertical profiles, color distribution was significantly different ($\chi^2 = 165.61$; df = 6; p-value <0.001), AMP exhibited 8 different colors (Fig. 3), predominantly blue (41.5 %; $n = 83$, adjusted p-value <0.001) and transparent (19.0 %, $n = 38$) followed by black (18.0 %, n = 36), white (13.0 %, $n = 26$), red (5.5 %, n = 11), pink (2.0 %, n = 4) and green (1.0 %, n = 2). Blue as a predominant color has also been previously reported in AMP studies (Li et al., 2020; Zamprogno et al., 2021), largely related to the common color of ropes and nets (Zhang et al., 2022), also related to their high visibility during visual inspection of filters, whereas other colors similar to the color of the matrix analyzed (example: brown or yellow fibers in mangrove sediments filters) may be underrepresented (Hartmann et al., 2019). No statistical difference was observed between color distribution and depth for the three samples tested (p-value>0.05).

Furthermore, the mean and median size of particles in CM1 (1.909 mm and 0.799 mm, Fig. 4d), CM2 (1.458 mm and 0.825 mm, Fig. 4e) and CAB core (1.143 mm and 0.663 mm, respectively, Fig. 4f) indicates a non-uniform distribution across size classes ($\chi^2 = 322.06$, df = 6, $p <$ 0.001) and a predominance of smaller size classes (between 0 and 1 mm) across the three cores samples (p-adjusted <0.001). The 0–1 mm class accounts for 56 % of AMP in CM1 (n = 22, adjusted p-value <0.05), 60 % for CM2 ($n = 69$, adjusted p-value <0.05) and 66 % for CAB ($n = 19$, adjusted p-value <0.05). Particle size is important for mangrove and saltmarshes due to its bioavailability, migration and accumulation (Moore, 2008; Besseling et al., 2017) as smaller sizes are predominant in sediments (Mohamed et al., 2023; Li et al., 2020) due to a tendency to aggregate with organic matter and form natural colloids, increasing their settling (Besseling et al., 2017). No significant differences in particle size across depth intervals were found, despite slight differences only in CM2 (depth 1–2 cm and 2–3 cm, p-value <0.05; Fig. 4). The trapping of smaller particles in salt marsh and mangrove sediments prevents their remobilization and isolates them from wave and tidal activity, so their sediment acts as a sink for smaller-particles.

Also, the predominance of smaller particles can indicate that these ecosystems might promote or accelerate plastic decomposition, which can lead to negative effects on the biota. Smaller plastic particles tend to cause greater potential damage to biota due to their strong adsorption by POPs and their easy transport to tissues (Huang et al., 2021; Batel et al., 2018), once the toxicity of AMPs is also dependent of particle size (Jeon et al., 2023; Zou et al., 2023). The prevalence of blue fibers and small particles (<1 mm) poses an ecological risk due to the fact that smaller particles are more probable to get ingested (Lehtiniemi et al., 2018) and the fact that AMPs could be potentially harmful to marine organisms

Table 2
Abundance of AMP in global mangrove and saltmarsh sediments. -: Lack of information; Polyethylene: PE; Polypropylene: PP; and Polyethylene Terephthalate: PET. *Area of the river basin or sub-basin **Estimated population of the city or province where the estuary is located, or number of inhabitants in the basin area reported in the study.

Ecosystem	Location	Watershed area (km^2)*	Population (hab)**	Core dimension	Extraction methods	Min and max	Mean concentration (MPs kg^{-1})	Shape	Color	Polymer	Size	Reference
Mangrove	Todos os Santos Bay, Brazil	1233	~2.9 million	100 cm	Flotation with $ZnCl_2$	555–31,087 particles kg $^{-1}$	10.782 ± 7.671 particles kg $^{-1}$	Fibers (72 %) and fragments (23.1 %)	White and transparent (57.5 % + 4.1 %)	–	196 μm (mean)	Paes et al., 2022
Saltmarsh	Molhe Oeste saltmarsh, Brazil	10,000	–	up to 66 cm	Flotation with NaCl	–	132.54 ± 252.26 particles kg $^{-1}$	Fibers (54.32 %) and fragment	White (38.55 %), clear (25.36 %), and blue (21.35 %)	HDPE (34.72 %), PE (25.92 %) and PP (23.15 %)	average of 1.73 ± 1.15 mm	Pinheiro et al., 2022
Mangrove	Songkhla lagoon and Pattani province, Southern Thailand	1040	2 million	5 cm diameter x 50 cm length	Flotation with NaCl	71–155 items and 106–413 particles kg $^{-1}$	–	Fibers	Black and blue	PE, rayon, rubber,styrene, paint, and poly (vinyl acetate)	<< 5.0 mm	Pradit et al., 2022
Mangrove	Kuala Gula Mangrove, Malaysia	–	7200	86 mm diameter	Flotation with NaCl and H_2SO_4 and H_2O_2	2.5–130 particles kg $^{-1}$	–	Fibers (88.0 %), fragments (~10.1 %) and others (1.9 %)	Blue and transparent	rayon, PET and azlon.	<500 μm and > 1 mm	Mohamed et al., 2023.
Mangrove	Mangrove in Southeast coast of China	–	–	7. 5 cm diameter x 120 cm length	Flotation with $ZnCl_2$	0 to 3123.3 particles kg $^{-1}$, highest abundance at 4–8 cm	–	Fiber and film	transparent and black	PP, PE, PS and	11,000–5000 μm	Yu et al., 2023
Mangrove	Amazon River delta, Brazil	–	–	22.74 cm^2 × 3 m	Flotation with $ZnCl_2$	0–167 particles kg $^{-1}$	–	Fibers (73 %) and fragments (24 %)	Back (33 %) and blue (30 %)	PE (34 %), viscose/rayon (16 %), PP (15 %) and PET (15 %)	1000–5000 μm (42 %)	Rico et al., 2024
Saltmarsh	Swanscombe marsh, Thames estuary, UK	–	–	20 to 70 cm depth	Flotation with $ZnCl_2$	44 ± 3.3 to 2671 ± 102 microplastic particles kg $^{-1}$	1014 particles kg $^{-1}$	Fibers (low and mid marsh zones) and fragments dominated high marsh zone	–	PE, PP and PS	10–1000 μm in size	Trusler et al., 2025
Saltmarsh	Rainham marsh, Thames estuary, UK	–	–	20 to 70 cm depth	Flotation with $ZnCl_2$	125 ± 7.5 to 3989 ± 231 particles kg $^{-1}$	988 particles kg $^{-1}$, with a spike in abundance at 20–30 cm	Fibers (low and mid marsh zones) and fragments dominated high marsh zone	–	PP, PE	10–1000 μm in size	Trusler et al., 2025
Mangrove and Saltmarsh	Todos os Santos Bay, Brazil	1233	~2.9 million	24 cm depth	Flotation with NaCl		156 particles kg $^{-1}$ or 43,564 particles m^{-3}	Fibers	Blue	Polyester, cellulose, indigo blue	< 5.0 mm	This study

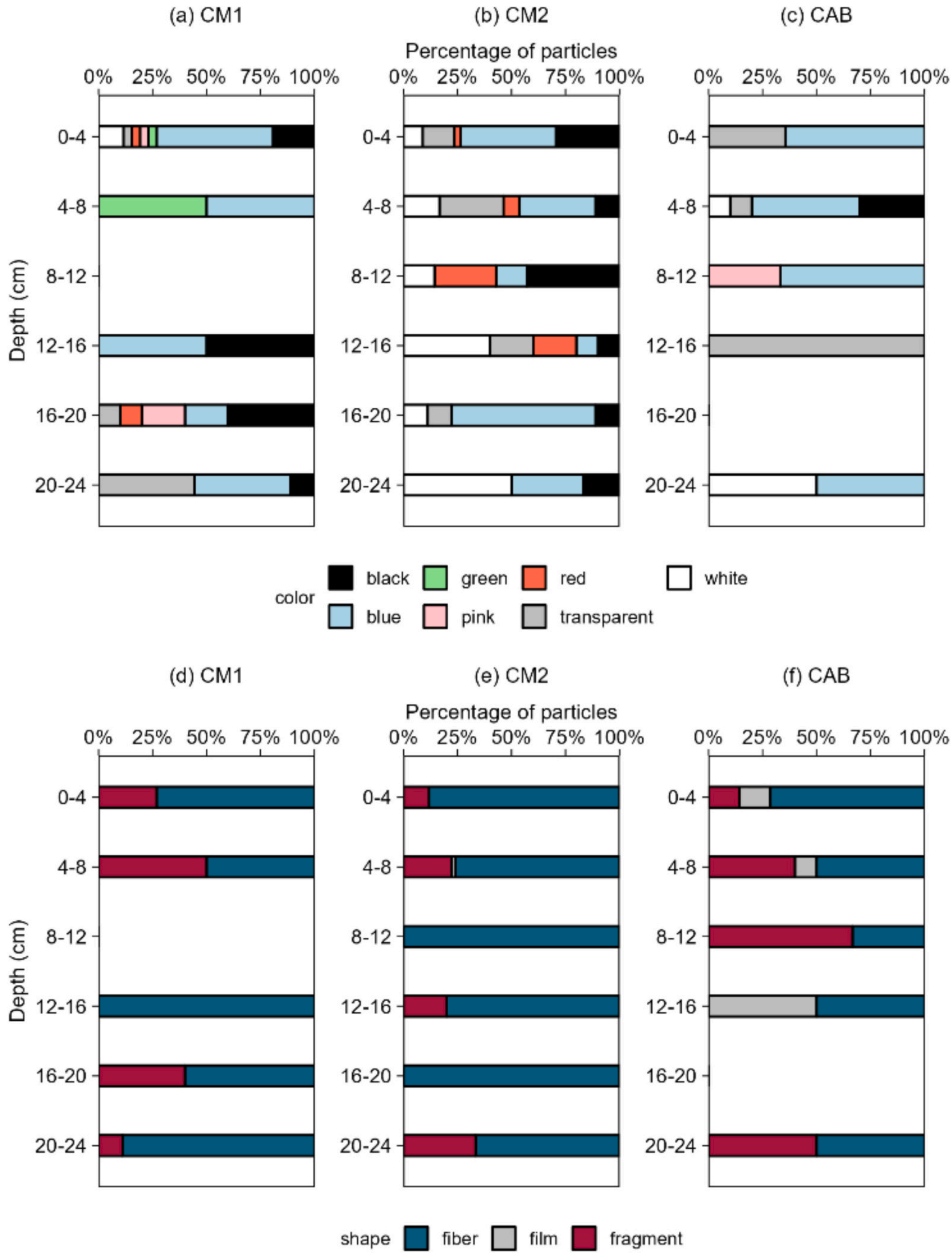

Fig. 3. Shape and color of the microparticles (AMP) sampled at CM1 (a and d); CM2 (b and e) and CAB (c and f). Blue ($n = 85$), transparent ($n = 41$) and black ($n = 35$) are the most outstanding colors, followed by white ($n = 26$), red ($n = 11$), pink (n = 4) and green (n = 2). Fiber ($n = 155$) and fragmented ($n = 44$) are the most outstanding classes, with films ($n = 5$) only appearing in (e) CM2 and in (f) CAB. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Savoca et al., 2019) through leaching of additives, such as antioxidants, dyes or fire retardants, and sorb/transfer a wide range of pollutants, such metals and organic compounds, amplifying their toxicity (Kinigopoulou et al., 2022; Lithner et al., 2011; Rochman et al., 2014). Textile dyes may increase biochemical and chemical oxygen demand, alter photosynthesis, bioaccumulate, biomagnificate, promote toxicity and carcinogenicity (Lellis et al., 2019; Sandhya, 2010). Plastic microparticles may cause multiple impacts on organisms like oxidative stress (Barboza et al., 2018; Li et al., 2022b), damaging cell membrane organelles, genotoxicity (He et al., 2023), changes in enzymatic activities (Wang et al., 2022), changing inflammatory response and immunological process (Hou et al., 2024), alteration of growth rate and fecundity (Jeong et al., 2022), translocation to circulatory system (Browne et al., 2008), gut blockage (Eom et al., 2020), as well as changes in perception of satiety (Manríquez-Guzmán et al., 2023), and changing in ecological processes (Galloway et al., 2017). Furthermore, AMP bioaccumulate (Watts et al., 2014), and are transferred through food webs (Manríquez-Guzmán et al., 2023).

4.4. Polymeric identification

From all samples, a total of 98 particles were analyzed through Raman spectroscopy, 86 particles from environmental samples and 12 from blank samples. A total of 71 particles were identified, including a

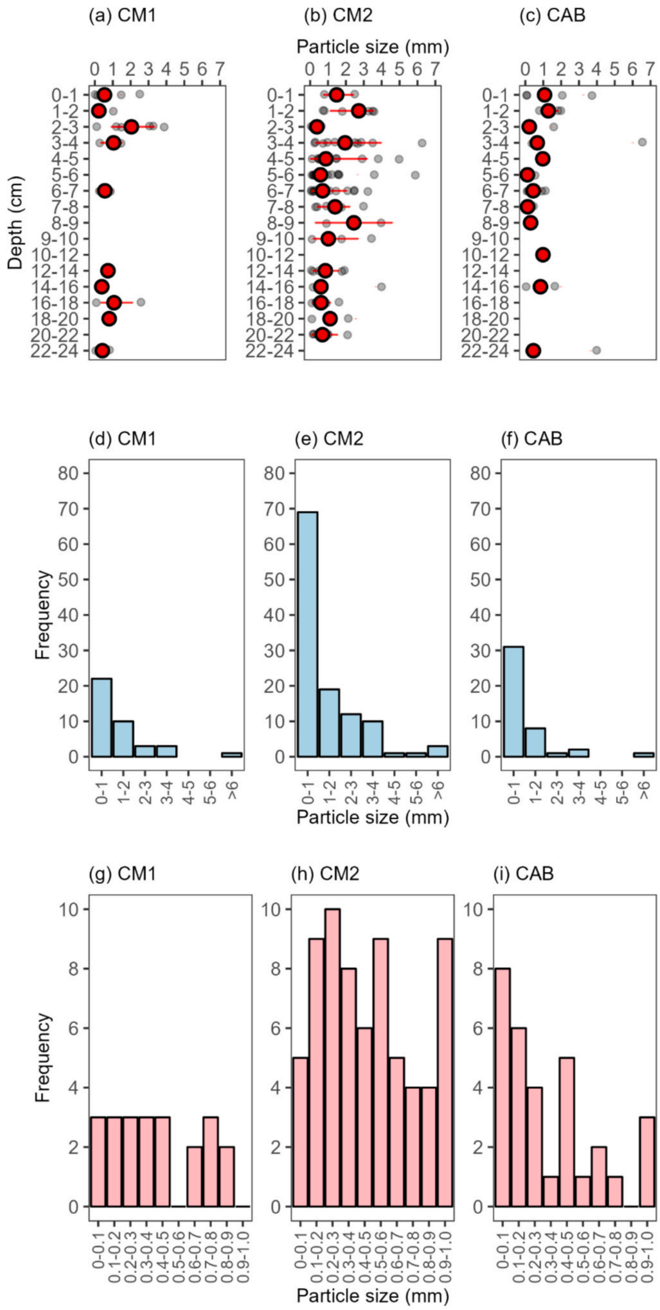

Fig. 4. Microplastic size (mm) per depth (a, b and c). The red dots on (a), (b) and (c) represent the median value. Related histogram (d, e and f) of sizes per class (0–1 mm; 1–2 mm; 2–3 mm; 3–4 mm; 4–5 mm, 5–6 mm and > 6 mm). The first class (0–1 mm) is the most abundant in all cores (56 %, *n* = 22 in CM1; 60 %, *n* = 69 in CM2 and 63 %, n = 22 in CAB). Subdivision of the first class (0–1 mm) from the samples of Todos os Santos bay (g, h and i). In (g) CM1 there is a similar distribution between class from 0 to 0.5 mm and 0.7–0.8 mm (n = 3, 14 % each). In (h) CM2 the most abundant small classes are 0.2–0.3 mm (*n* = 10, 14.5 %), 0.1–0.2 mm, 0.5–0.6 mm and 0.9–1.0 mm (*n* = 9, 13 %, each). In (i) CAB, the 0–0.1 mm (n = 8, 25 %) and 0.1–0.2 mm (n = 6, 19 %) are the most abundant small classes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

diverse pool of synthetic polymers, natural fibers, pigments, additives and mineral compounds. 27 particles could not be measured/identified mostly because they were under a high stage of degradation.

For environmental samples, a total of 60 particles were identified (Figs. 5 and 6). The most frequent polymers are polyester (*n* = 7, 12.7 %), cellulose (n = 7, 12.7 %), PP (*n* = 5, 9.1 %), acrylic (*n* = 4, 7.3 %) and PE (*n* = 3, 5.5 %). The two most frequent dyes identified are Indigo (*n* = 11, 20 %) and copper phthalocyanine (n = 3, 5.5 %), both blue. Single occurrences (n = 1, 1.6 % each) were observed for cotton, polyethylene co-vinyl acetate, 1,3-Diaminopropane dihydroiodide (additive), Direct Yellow 62 (yellow dye), Levafix brown (brown dye), PAR, PB63 (Indigoid, blue dye), PVP (Poly(N-vinylpyrrolidone), rutile (white dye), p-(N-vinyl pyrrolidone), poly(1-butene) (PB-1). In 14 samples, we identified more than one compound, for instance Cellulose/Carbon black; PET/Levafix brown (brown dye) e-2R; PET/PAR; Polyester/1,3-Diaminopropane dihydroiodide (which can be used to change some properties of polyester, such as thermal stability and mechanical strength); Polypropylene/Direct Yellow 62 (yellow dye); poly(1-butene)/Plasdone k29/32 (PVP); polystyrene/rutile (white dye).

For blank samples, a total of 11 particles were identified, the most frequent polymers are cellulose (n = 3, 27.3 %) and polyester (n = 1, 9.1 %). Dyes identified are all blue, amido black 10B (n = 3, 27.3 %), indigo (*n* = 2, 18.2 %), copper phthalocyanine (n = 1, 9.1 %) and naphthol blue black (n = 1, 9.1 %).

The polymers found (Figs. 5 and 6) are in line with massive global production; polyester is the most produced type of fiber plastic worldwide (54 % of the global 113 million metric tonnes of textile production in 2021; Smelik, 2023). Massive production influences its high concentration within marine sediments and related damages to coastal ecosystems functioning (Castelvetro et al., 2020; Hope et al., 2020; Piccardo et al., 2020). Man-made cellulose represented ~6.4 % of fiber production in 2022, (TextileExchange, 2022). Also, PE and PP represent the most widely produced plastics worldwide and, together, account for 40 % of global production (OECD, 2022), estimated at 400 million tons annually (PlasticsEurope, 2023). Also, the polymers are similar to other studies conducted in mangroves and salt marshes in Latin America, with a high abundance of polyester, cellulose, PE and PP (Rico et al., 2024; Pinheiro et al., 2022; Alves et al., 2023). The occurrence of Indigo and triphenylmethane dye in fibers is also indicative of textile sources that are chemically produced and widespread in multiple ecosystems (Athey et al., 2020; Buteler et al., 2023; Pirani et al., 2024; Ronda et al., 2025). Furthermore, for pigment-positive samples, the high fluorescence associated with the pigment hinders the identification of the Raman peaks coming from the base fiber in Raman spectroscopy (Pirani et al., 2024; Käppler et al., 2016).

Some dyes and additives can be classified as carcinogenic, mutagenic, or toxic to reproduction to organisms. For instance, indigo blue, under laboratory conditions, was toxic to the invertebrates *Parhyale hawaiensis* and inhibited the reproduction of *Enchytraeus crypticus*, and the leuco form of indigo was acutely toxic to *Daphnia similis* (de Farias et al., 2025). Additionally, the ability of terrestrial and marine invertebrates to digest and degrade cellulose, can release the dyes and additives in their digestive tracts (Zimmer et al., 2002). However, the impact of coloring agents for invertebrates digestive tracts currently remains little investigated (Remy et al., 2015).

4.5. Abiotic factors

Regarding mud and organic matter content, in general, the organic matter content (OM%) was similar along the sampled cores (CM1: 3.00 to 6.26 %, CM2: 3.57 to 9.98 %, and CAB: 4.30 to 7.68 %; Fig. 7, Table 3). OM% content is relatively constant with depth in all cores with the highest values at CM2 14–16 cm (9.03 %) and CM2 20–22 cm (9.98 %). CM1 had the lowest percentage of organic matter (*p*-value >0.05), with an increase of 32.9 % from 0 to 4 cm to 4–8 cm and significant decreases between 4 and 8 cm and 8–12 cm (33.2 %) and between 8 and 12 cm and 12–16 cm (12.8 %). CM2 core showed a 51.5 % increase from 0 to 4 cm to 4–8 cm and a 20.6 % increase from 8 to 12 cm to 12–16 cm, creating a shaped decay in OM from past to recent records. CAB core showed a gradual growth from 0 to 4 cm to 12–16 cm, sharp decline between 12 and 16 cm and 16–20 cm (13.8 %) and increase at the bottom at 20–24 cm (8.94 %).

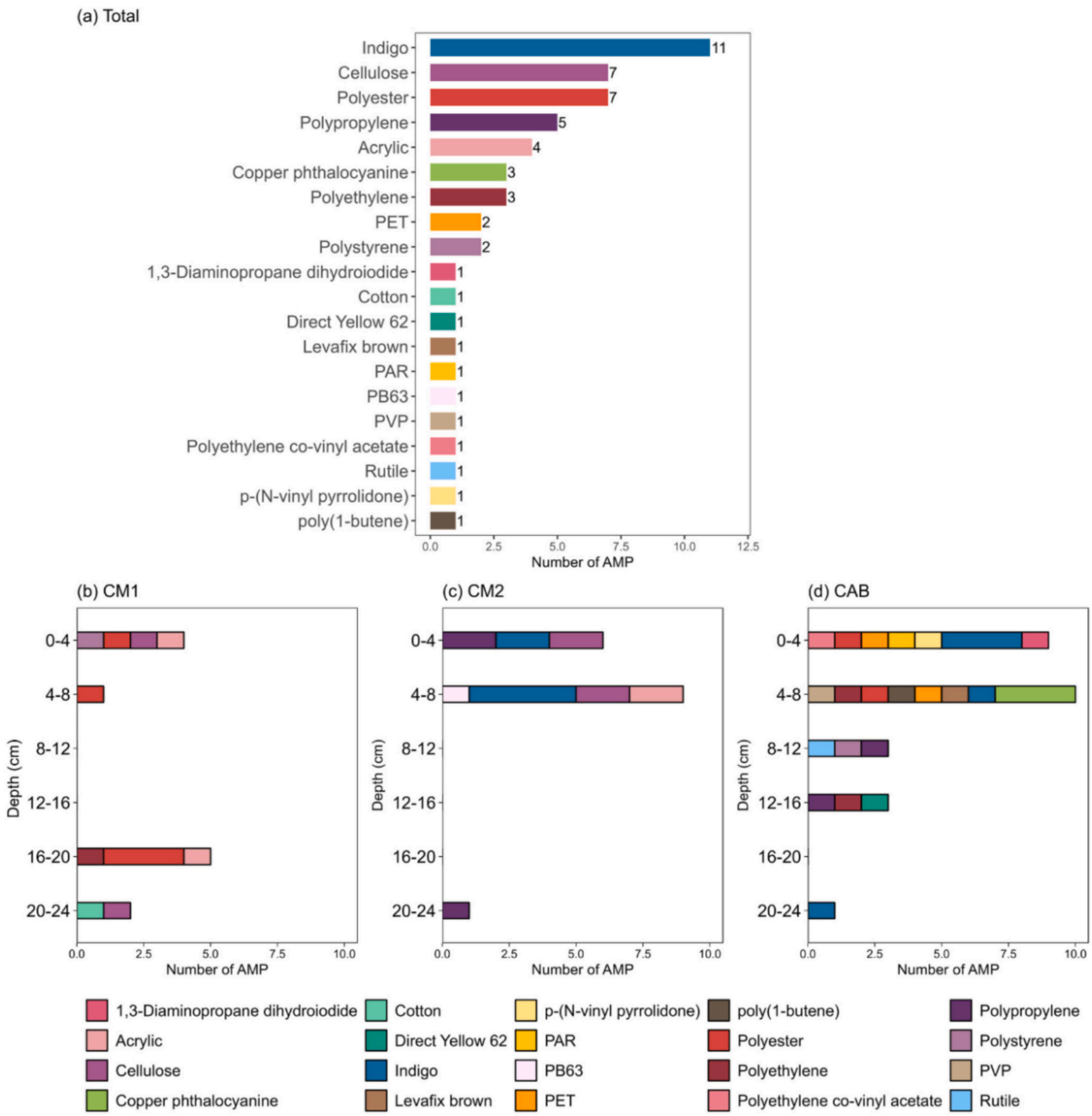

Fig. 5. Environmental samples analyzed by Micro Raman - InVia Renishaw and LabRAM HR Evolution (HORIBA) equipment. Indigo is the most abundant dye (n = 11, 20 %), and polyester (n = 7, 12.7 %) and cellulose (n = 7, 12.7 %) are the most abundant polymers, followed by PP (n = 5, 9.1 %). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Furthermore, mud content (%M) increased from recent to past records for all the sampled cores (CM1: 30.32 to 62.5 %, CM2: 31.28 to 67.98 %, and CAB: 48.44 to 63.54 %) (Table 3). In general, the saltmarshes cores were sand-dominated from 10 cm depth to the top of the core, while the mangrove core was sand-dominated in the top-soil (0–1 cm depth; Fig. 7). Mud content differed among cores ($p < 0.05$), specifically between CM1 and CAB and between CM1 and CM2 (adjusted $p < 0.05$). Neither organic matter (%OM) nor mud content (%M) influences AMP concentration (p-value>0.05; Table S4 and S5) in all cores, as also reported by other authors, emphasizing the role of local anthropogenic pressures and hydrodynamical process in AMP accumulation (Deng et al., 2020).

5. Management and monitoring of AMP

The efficient management of plastics, microplastics and anthropogenic microparticles should follow two priorities. The first is combating land-based sources, ensuring better waste management on land, guaranteeing selective collection, reducing losses during transport, establishing a circular economy, and valuing waste pickers and recycling cooperatives, installing physical floating barriers in rivers, optimize washing parameters to reduce microfibers release, install microfiber filters in washing machines, add a final filtering step to wastewater facilities (Campos, 2014; Sasahara et al., 2024; Periyasamy, 2023; Elliff et al., 2025). This front is relevant as many plastics leak into the environment due to improper waste management, enhancing its distribution while experiencing a slow degradation (Jambeck et al., 2015; Beaumont et al., 2019). It is very important in Global South scenarios (e.g., Brazil) which faces difficulties due to the heterogeneity of waste sorting and processing infrastructure across the country (Campos, 2014); like Latin America and the Caribbean (LAC), where 40 million people still lack access to proper waste collection (UN, n.d.). The second front is the monitoring of sources of plastic, microplastics and anthropogenic microparticles. LAC countries still have scarce long-term studies and several understudied ecosystems regarding AMP contamination and such as estuaries, mangroves, tidal flats, seagrass, saltmarshes, coastal

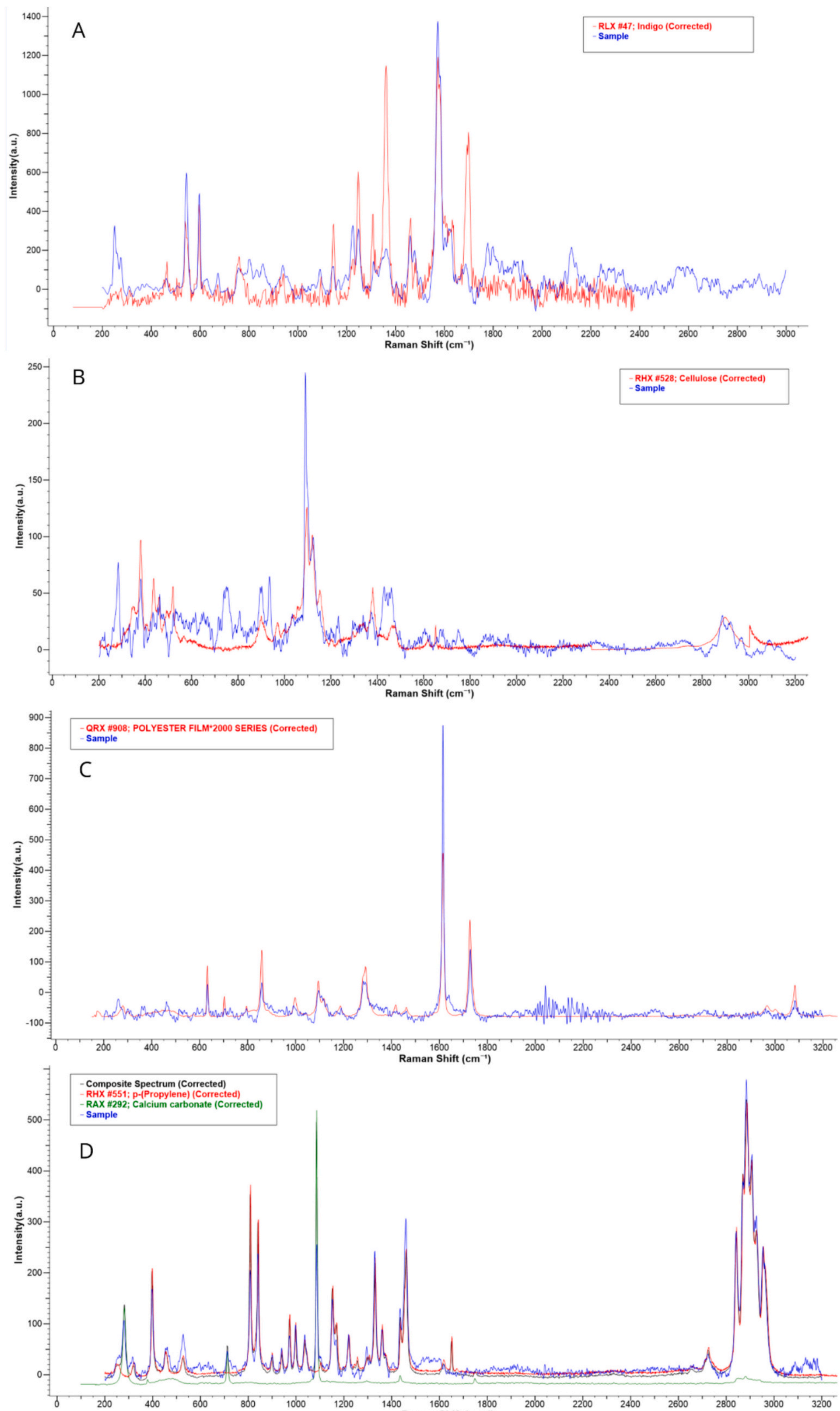

Fig. 6. Polymer comparison and compatibility between sampled polymers and known databases RamanMP R package (Nava et al., 2021) and SLoPP and SLoPP-E (Munno et al., 2020). A) Indigo, B) Cellulose, C) Polyester and D) Polypropylene. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

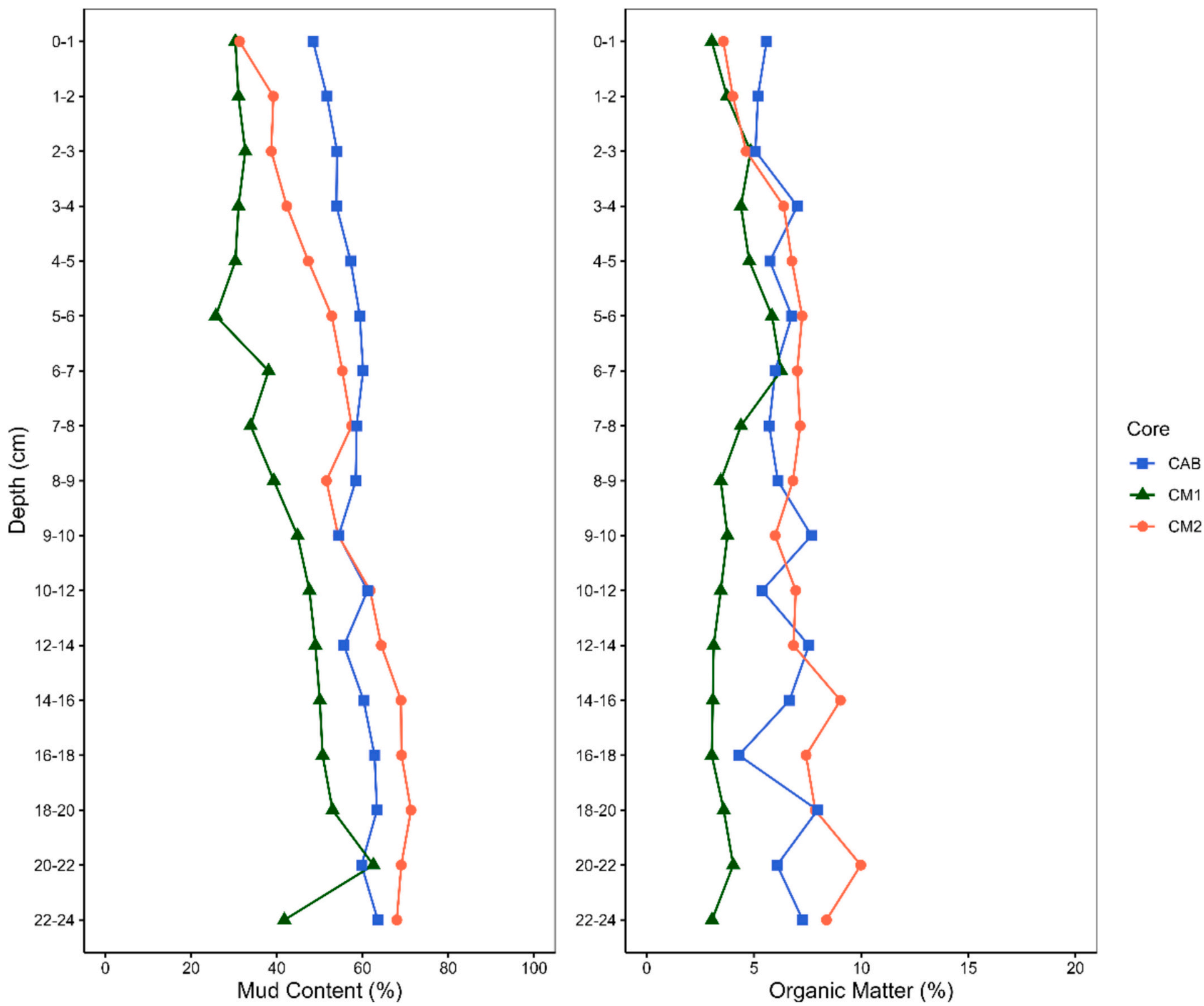

Fig. 7. Concentrations of organic matter and mud content for CAB (%, blue line), CM1 (%, green line) and CM2 (%, red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Organic Matter (OM %) and Mud (%) content from saltmarshes (CM1 and CM2) and mangrove (CAB) cores.

Core	OM (%) content					Mud (%) content				
	Min	Max	Mean	Median	SD	Min	Max	Mean	Median	SD
CM1 (n = 17)	3.00	6.26	3.99	3.74	0.982	25.8	62.5	40.7	39.3	10.3
CM2 (n = 17)	3.57	9.98	6.83	6.95	1.64	31.3	71.3	55.5	55.3	12.4
CAB (n = 17)	4.30	7.68	6.24	6.08	1.03	48.4	63.5	57.8	58.6	4.25

lagoons, sand dunes, continental shelf, freshwater ecosystems and biota (Cordeiro et al., 2022; Mesquita et al., 2022; Fernandes et al., 2022; Zanetti et al., 2025). Monitoring and assessment programs are essential to guide decision-making and evaluate management actions. Monitoring involves sediment, water, and biota data to assess hotspots and understand the main sources and pathways. To ensure efficient monitoring, standardized protocols, quality control measures, and appropriate techniques must be used. Furthermore, non-destructive techniques like FTIR and Raman spectroscopy, and including reference material utilization to measure recovery rates, are also crucial to reach best practices (Zanetti et al., 2025).

Brazil recently approved the National Plastic Free Ocean Strategy (ENOP) decree, which creates guidelines for public policies with the coordinated participation of civil society actors. In addition, several states have developed their regional plans (e.g. PEMALM, 2021) to combat marine litter in conjunction with the regional Clean Ocean Network (Rede Oceano Limpo) coalition, including strategies focused on monitoring and raising awareness among civil society about plastic and microplastics. Furthermore, from 2025 to 2034, the National Circular Economy Plan (ENEC) will be established, which will reduce the use of resources and the generation of waste (Brasil, 2024). The ENEC aims to preserve the value of materials and minimize waste, by encouraging recycling plants, reducing waste generation through circular practices linked to various industries and promoting articulation between waste management policies and the Circular Economy (Brasil, 2024). Aligned with the United Nations 2030 Agenda for Sustainable Development, the implementation of this and other public policies, as well as collaborative work between society, academia, and government, is essential to ensure the tackling of plastic and AMPs in terrestrial, coastal, and marine environments.

6. Limitations and future directions

The study represents an important contribution to understanding AMP contamination in tropical estuarine environments in South America. Beside this, we recognize some limitations, like the shallow bedrock limiting the recovery of deeper sediment cores within saltmarshes. There is also a limitation regarding spatial representation, the data particularly represent the Caboto region but not the entire TSB, which could overestimate or underestimate AMP contamination for the full TSB. In addition, the punctual sampling (February 2022) provides a detailed assessment of AMP contamination but cannot distinguish between stable AMP pollution and short-term variations, especially in superficial depth, since these are more susceptible to seasonal variability and climate events. Our future recommendations are related to expanding sampling efforts for sampling deeper cores and upper layers of the sediment. It will provide a detailed distribution of AMP in multiple spatial and temporal scales. Furthermore, working with both cores and surface sediment samples can provide interesting insights into the dynamics of more recent deposition. In addition, we suggest the investigation of AMP contamination through different tidal cycles to understand its migration in the sediment profile, considering that the tide influences the abundance and shape of sampled microplastics (Alves et al., 2025).

7. Conclusion

Our preliminary results indicate that AMPs are widespread in tropical saltmarsh and mangrove with higher variability in salt marshes related to abundance and compositional characteristics. The accumulation pattern appears influenced by factors like vegetation and hydrodynamic conditions. AMP in the Caboto area were mostly composed of fibers, with a predominance of blue color, and size under 1 mm. micro-Raman analysis shows the presence of cellulose, polyester, acrylic, PP, PE, PS, pigment indigo blue and pigment triphenylmethane, which indicate that domestic wastewaters, textile materials and packaging were possible sources of AMP This study provides invaluable baseline insights in AMP distribution across BCE and focuses on the importance of considering the particularities of habitat factors in the management of plastic pollution. Our results also emphasize the need for management of polluting sources, with a focus on the release of domestic effluents and management of river pollution.

CRediT authorship contribution statement

Daniela Gadens Zanetti: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Luiz Eduardo de Oliveira Gomes:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mitchael Micael Silva Gomes:** Writing – review & editing, Methodology, Data curation. **Eduardo Nery Duarte de Araújo:** Writing – review & editing, Methodology, Data curation. **Ana Carolina de Lima Barizão:** Writing – review & editing, Funding acquisition. **Anderson Antônio Batista:** Writing – review & editing, Funding acquisition. **Jessica Dipold:** Writing – review & editing, Methodology, Data curation. **Niklaus Ursus Wetter:** Writing – review & editing, Methodology, Data curation. **Anderson Zanardi de Freitas:** Writing – review & editing, Methodology, Data curation. **Fabio Cavalca Bom:** Writing – review & editing. **Fabian Sá:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2026.119221.

Data availability

Data will be made available on request.

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