RESEARCH ARTICLE

Abundance, distribution, and characteristics of microplastics in coastal surface waters of the Colombian Caribbean and Pacific

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Abstract

Microplastic pollution has become a global concern due to its distribution, high abundance, and negative impacts on aquatic ecosystems. These particles enter aquatic systems through the inadequate management of solid waste and wastewater generated from socioeconomic and domestic activities. In Colombia, about 65% of the solid waste generated in coastal populations is improperly managed and discharged into natural water bodies, contributing to microplastic pollution. The present study aimed to determine the abundances, distribution, and physical and chemical characteristics of microplastics in coastal surface waters of the Colombian Caribbean and Pacific. Samplings were carried out at 41 stations distributed across nine study areas during the rainy season of 2017, using a 500-μm mesh plankton net. The microplastic abundances ranged from 0.01 to 8.96 items m^{-3}, with the coastal waters of the Caribbean areas being the most polluted. Microplastics with shapes of fragments, filaments, and foams, composed of polyethylene, polypropylene, and polystyrene, were the most common. A baseline of microplastic pollution in Colombian coastal water was generated, which will serve to evaluate the effectiveness of the environmental measures implemented to significantly reduce this pollution type, within the sustainable development goals.

Keywords Marine litter · Plastic debris · Microplastic pollution · Polymer Characterization · Water contamination · Wastewater

Responsible Editor: Philippe Garrigues

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Introduction

Microplastic pollution (plastic particles smaller than 5 mm in diameter) has become a global concern, due to its wide distribution, high abundance, and the negative impacts it generates on aquatic ecosystems (Auta et al. 2017). Microplastics are classified according to their origin, in primary and secondary. Those of primary origin (with shapes of pellets, granules, and microspheres) are manufactured directly by the industry to be used as raw material for other products (Boucher and Friot 2017). Microplastics of secondary origin (with shapes of fragments, filaments, foams, and films) come from the fragmentation of larger plastic items, due to the action of environmental factors such as solar radiation, waves, oxidation, and biodegradation, among others (Auta et al. 2017).

Microplastics reach the marine environment through the inadequate disposal of solid waste and through wastewater discharges generated in industrial and domestic activities, which are improperly managed (Jambeck et al. 2015; Boucher and Friot 2017). Jambeck et al. (2015) estimated that in 2010, 192 coastal countries generated 275 million metric tons (MT) of plastic waste, and due to the deficiency in the

management of this waste, between 4.8 and 12.7 million MT of plastics entered to the ocean. On the other hand, Schmidt et al. (2017) estimated that rivers (receptors and transport routes of waste from the mainland to the sea) introduce between 0.41 and 4.0 million tons of plastics per year into the ocean. Once the plastics reach the marine environment, they are distributed on a global scale by oceanic currents, one part accumulates in ocean gyres, another sink on the seabed, and another part accumulates on beaches, mangroves, and other coastal marine ecosystems (Auta et al. 2017; Garcés-Ordóñez et al. 2019, 2020a).

Due to different sizes, shapes, and colors similar to some marine organisms, plastics are confused with natural foods and ingested by fish, birds, mammals, mollusks, and crustaceans, among others (Ory et al. 2017; Guzzetti et al. 2018). In addition, the temperate coral *Astrangia poculata* from urban areas selectively ingest microplastics rather than nutritious foods (Rotjan et al. 2019). The ingestion of microplastics by fish and other marine aquatic organisms represents a threat to biodiversity and fishery resources and a risk to human livelihoods (Lithner et al. 2011; Antão-Barboza et al. 2018). This is because microplastics correspond to different polymers from the families of polyurethanes, polyacrylonitriles, polyvinyl chloride, epoxy resins, and styrenic copolymers, among others, which are composed of monomers and corrosive, carcinogenic, mutagenic, and toxic for reproductive substances that can be released during the production, use, and disposal of the plastic product (Lithner et al. 2011).

In Colombia, most of the human settlements are in areas near rivers, swamps, and the sea. It is estimated that approximately 65% of solid waste and 100% of domestic wastewater generated in coastal populations are improperly managed and discharged into natural water bodies, contributing to plastic pollution in aquatic ecosystems (Garcés-Ordóñez et al. 2017; Superservicios 2017). Even though the accumulation of plastic in coastal marine ecosystems is evident in different areas of Colombia, studies on microplastics are scarce and only recently have been reported from mangrove soils (Garcés-Ordóñez et al. 2019; Garcés-Ordóñez and Bayona, 2019; Riascos et al. 2019), beach sands (Acosta-Coley and Olivero-Verbel 2015; Acosta-Coley et al. 2019a, b; Garcés-Ordóñez et al. 2020a, b), and from the digestive tracts of fishes (Ory et al. 2018; Calderon et al., 2019; Garcés-Ordóñez et al. 2020c). However, to date, microplastic pollution has not been evaluated in coastal marine waters.

In order to advance in the knowledge of the microplastic pollution problem from coastal areas of Colombia, this study aimed to determine the abundances, distribution, and the physical and chemical characteristics of microplastics in the coastal surface waters of the Colombian Caribbean and Pacific. This knowledge can help to understand the microplastic distribution, the main sources, and the risks that this pollution has on the aquatic ecosystems and livelihoods of coastal human communities. It furthermore represents useful information to establish environmental management strategies aimed at significantly reducing this type of pollution in the Colombian coastal marine environment, within the sustainable development goal number 14: conserve and sustainably use the oceans, seas, and marine resources (United Nations 2019).

## Materials and methods

Study areas

Colombia is a tropical country located in the northwestern part of South America (Fig. 1), with 1785 km of continental coastline and 146 km of insular coastline in the Caribbean region and 1545 km of continental coastline and 54 km insular coastline in the Pacific region (INVEMAR 2020). In the Caribbean region, average precipitation ranges between 500 and 4000 mm with a bimodal trend (rains during the last 6 months of the year), and average temperature fluctuates between 27 and 34 °C; while in the Pacific, average precipitation ranges between 3000 and 9000 mm, raining in all months of the year without a defined trend, and the average temperature fluctuates between 22 and 28 °C (Arango et al. 2012).

The tidal amplitude ranges from 0.22 to 0.25 m in the Caribbean and from 2.46 to 3.08 m in the Pacific (IDEAM 2017a, b). The surface currents in the Colombian Caribbean Sea are dominated by the Caribbean current that flows from east to west (Fig. 1) and is characterized by the high activity of mesoscale eddies (Ricaurte-Villota and Bastidas 2017). In the Pacific, the Colombian coastal current flows north (Fig. 1; Rodríguez-Rubio et al. 2007). Numerous rivers flow into the Colombian coasts; the most important rivers are the Magdalena, Sinú, and Atrato in the Caribbean and the San Juan, Micay, Guapi, Patía, and Mira rivers in the Pacific (Fig. 1) due to their high flow and pollution load (INVEMAR 2018).

The coastal marine ecosystems with the highest coverage in the Pacific are mangroves (72% of ~ 289,122 ha) and beaches (53% of ~ 865.5 km), and in the Caribbean, the largest coverage is coral reefs (99% of ~ 4405 km^2) and seagrasses (100% of ~ 148,171 ha) (Gómez-Cubillos et al. 2015). The Caribbean coast has the highest urban development, and the number of inhabitants triples in that reported in the municipalities of the Pacific coast; in addition, the intensity of coastal socioeconomic activities and sources of pollution (wastewater and solid waste) are higher in the Caribbean (INVEMAR 2018).

Forty-one sampling stations distributed across nine administrative and geographical areas of Colombia were selected, six located on the Caribbean and three on the Pacific coasts (Fig. 1). The selection criteria for the stations were the location in urban and rural areas, with and without the influence of river discharges (Table 1). The samplings were carried out

Fig. 1 Study area map. The red dots correspond to the sampling stations distributed in the nine areas: (1) San Andrés Island, (2) Santa Marta, (3) Cartagena, (4) San Antero, (5) Antioquia, (6) Chocó Caribbean, (7) Chocó Pacific, (8) Buenaventura, and (9) Tumaco. The surface currents (blue arrows) in the Caribbean Sea and the Pacific Ocean were taken from Ricaurte-Villota and Bastidas ([2017](#)) and Rodríguez-Rubio et al. ([2007](#))
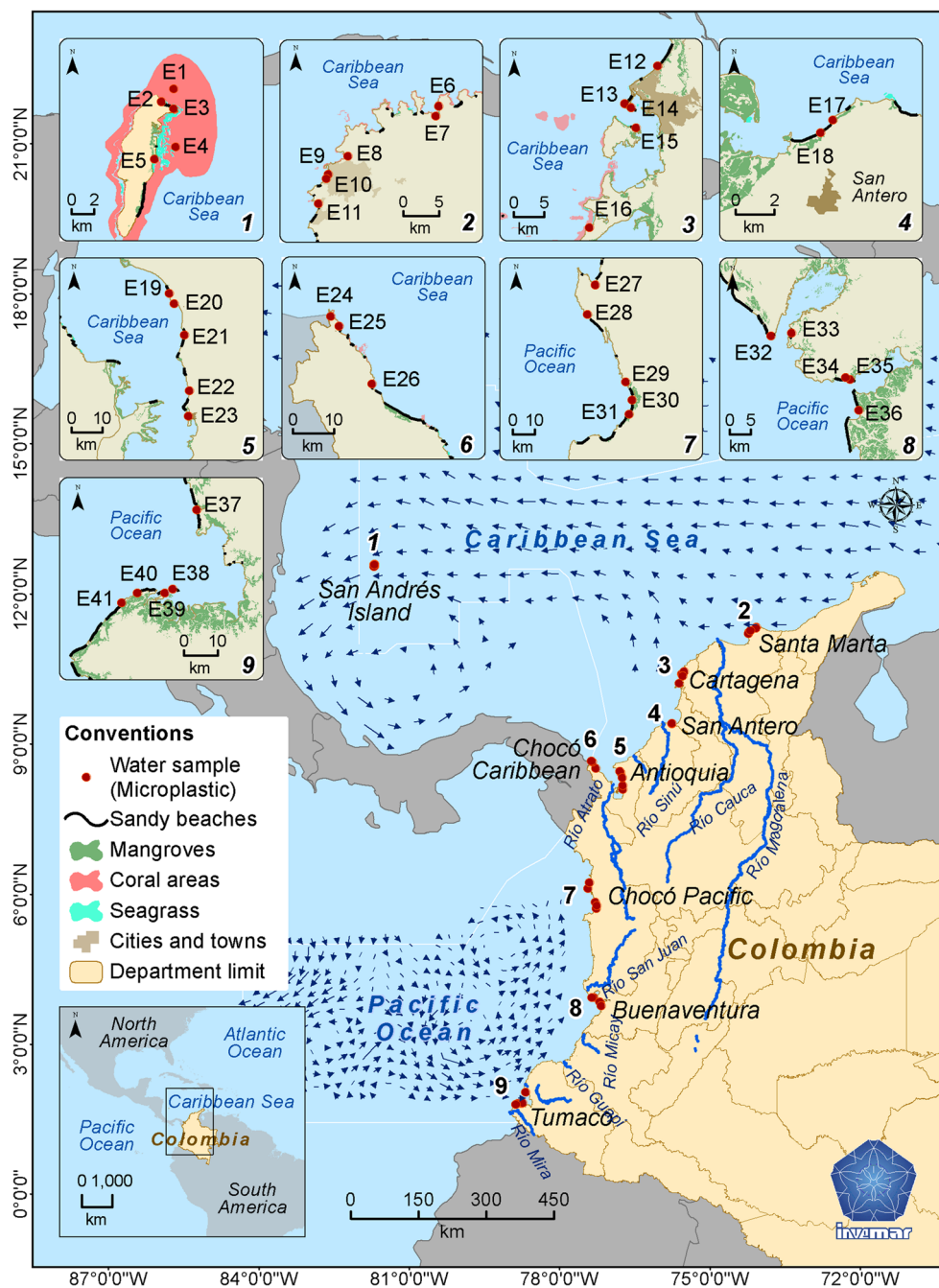
during the rainy season, between July and September 2017, within the Colombian Surveillance Network for Conservation and Protection of Marine and Coastal Water (REDCAM).

Sample collection and isolation of the microplastic

Microplastic sampling in coastal surface waters was performed aboard a 25-foot boat. Cotton clothing was used during the samplings. A plankton net with an aperture of 60 cm and 500-μm mesh was used, equipped with two buoys to keep it at the sea surface and with a Hydro-Bios Mechanical Flow Meter to estimate the volume of filtered water. The net was towed for 10 min at a constant speed of 2 knots in three parallel transects near the coast (~ 100 m), considering the recommendations of Kovač et al. ([2016](#)). The coordinates of the start and end points of each transect were georeferenced with a satellite geo-positioner (Garmin GPSMAP 78s). The samples were transferred to hermetic glass containers of 500 ml, and to degrade the organic matter to facilitate the analysis of the microplastics in the collected samples, between 30 and

Table 1 Description of the sampling stations in the nine study areas on the Colombian Caribbean and Pacific coasts. Urban and rural areas were defined according to concepts of the National Administrative Department of Statistics (DANE)

Region	Study areas	Station	Type	River discharge	Activities in the areas
Caribbean	San Andrés	E1	Rural	No	Tourism, conservation
		E2	Urban	No	Tourism, trade
		E3	Urban	No	Tourism, fishing
		E4	Rural	No	Tourism
		E5	Urban	No	Tourism, trade
	Santa Marta	E6	Rural	No	Tourism, conservation
		E7	Rural	No	Tourism, conservation
		E8	Urban	No	Tourism, fishing
		E9	Urban	No	Tourism, trade, port
		E10	Urban	Yes	Tourism, fishing
		E11	Urban	No	Tourism, trade
	Cartagena	E12	Urban	No	Fishing
		E13	Urban	No	Tourism, trade
		E14	Urban	Yes	Tourism, industry, port
		E15	Rural	Yes	Tourism, industry, port
		E16	Rural	No	Tourism, conservation
	San Antero	E17	Rural	No	Tourism
		E18	Rural	No	Tourism
	Antioquia	E19	Rural	Yes	Tourism, fishing
		E20	Urban	Yes	Tourism, fishing
		E21	Rural	Yes	Tourism, fishing
		E22	Rural	Yes	Tourism, fishing
		E23	Urban	Yes	Tourism, fishing
	Chocó-C	E24	Rural	No	Tourism, fishing
		E25	Rural	No	Tourism, fishing
		E26	Urban	Yes	Tourism, fishing
Pacific	Chocó-P	E27	Urban	Yes	Tourism, fishing, port
		E28	Rural	Yes	Tourism, fishing
		E29	Rural	Yes	Tourism, fishing
		E30	Rural	Yes	Tourism, conservation
		E31	Urban	Yes	Tourism, fishing
	Buenaventura	E32	Rural	Yes	Tourism, fishing
		E33	Rural	Yes	Tourism, fishing
		E34	Rural	Yes	Tourism, fishing
		E35	Rural	Yes	Tourism, fishing
		E36	Rural	Yes	Tourism, fishing
	Tumaco	E37	Rural	Yes	Fishing
		E38	Urban	Yes	Tourism
		E39	Urban	Yes	Tourism
		E40	Rural	Yes	Tourism, fishing
		E41	Rural	Yes	Fishing

50 ml of 10% sodium hypochlorite were added and left standing for 24 to 48 h at room temperature. Sodium hypochlorite digestion was used for its low cost, easy acquisition, and transport to remote areas of Colombia.

Precautionary measures to prevent possible contamination by fibers during lab work were taken, such as the use of a clean and quiet work area (lab of limited access, with air extractors) and cotton clothes and the use of metal and glass tools to process the samples, previously washed with filtered water. The size of the microplastics analyzed was between 5 mm and 500 μm to minimize errors related to confusion with cellulose or animal materials in the visual identification

procedure. The microplastics were identified and separated by direct observations of the sample with the binocular stereomicroscope (Leica EZ4 Microsystems), taking into account basic criteria, such as (1) the absence of visible cellular or organic structures, (2) fibers with the same thickness along their entire length and without sharpening at the end, and (3) particles with light and homogeneous colors, not bright (Nor and Obbard 2014; Kovač et al. 2016). A total of 8960 microplastics with sizes between 5 mm and 500 μm were identified and separated, in an estimated total volume of 18,060 m^3 of filtered seawater in the net. The units were expressed in items m^{-3}.

Physical and chemical characterization of microplastics

The visually identified microplastics were physically characterized, taking into account shapes and colors. The shape of the microplastics was classified into fragment, filament, film, foam, pellet, and granule categories, to relate them to the primary or secondary origin (Kovač et al. 2016). Photographic records of the microplastics were taken using an AxioCam ERc5s camera (Zeiss).

For chemical characterization, a large number of microplastics (1400 microplastics) of different shapes and colors from seven studied areas were randomly selected, to corroborate and reduce the uncertainty due to the visual identification of microplastics. These microplastics were analyzed by attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR), using an ATR detector coupled to a Fourier tensor transform II spectrometer (Bruker Optik GmbH). Absorbance spectra were recorded in the mid-infrared range (4000 to 400 cm^{-1}), combining 16 individual scans at a resolution of 4 cm^{-1}. The acquisition mode was double forward-backward, and the Blackman-Harris-3 apodization function was used (Demyan et al., 2012; Harrison et al., 2012; Silva et al. 2019).

The absorption bands of the spectra were compared with the bands of known polymers available in Jung et al. (2018): polyethylene (PE, AB, 2915, 2845, 1462, 730, 717 cm^{-1}), polypropylene (PP, AB, 2950, 2915, 2838, 1455, 1377, 1166, 997, 972, 840, 808 cm^{-1}), polystyrene (PS-AB, 3024, 2847, 1601, 1451, 1027, 694 cm^{-1}), polyethylene terephthalate (PET, AB, 1713, 1241, 1094, 720 cm^{-1}), and polyvinyl chloride (PVC, AB, 1424, 1331, 1255, 1099, 966, 616 cm^{-1}).

Statistical analysis

To analyze the basic variables (minimum, maximum, median, and average) and their proportionality, descriptive statistics were used. To determine the separate or combined effect of the type of areas (factor 1, urban/rural) and river discharge (factor 2, yes/no) on microplastic concentration in coastal surface waters, a two-way ANOVA (Stahle and Wold 1989) was performed, after verifying the assumptions of normality and homoscedasticity of the data, using the Shapiro–Wilk test (Shapiro and Wilk 1965) and the F-test of homogeneity of variances (Erjavec 2011), respectively, applying a transformation of log 10 to normalize the data. Additionally, the Tukey post hoc test (Stahle and Wold 1989) was applied to compare the means of the data groups. The paired t-test (Hedberg and Ayers 2015) was used to separately analyze the difference in the percentages of the types of shapes, colors, and polymers of microplastics between the Caribbean and Pacific coasts, between urban and rural stations, as well as between stations with and without river discharges. The differences in the percentages of the types of shape, color, and polymer of the microplastics between the sampling areas were analyzed with the Friedman test. Statistical analyses were performed in the Infostat Professional® Software (version 2016p). All tests were performed with a 95% confidence level.

Results

Abundance and distribution of the microplastic

Microplastics were found in the surface waters of all sampling stations in the nine studied areas, reaching abundances that ranged from 0.01 to 8.96 items m^{-3} (Fig. 2), with medians of 0.16 items m^{-3} (ranges of 0.01–8.96 items m^{-3}) in the areas of the Caribbean coast and of 0.14 items m^{-3} (ranges of 0.01–1.35 items m^{-3}) in those of the Pacific coast, without presenting significant differences between both coasts (ANOVA, $F_{(1–40)} = 0.01$, P-value = 0.9244). The microplastic abundances in coastal surface waters at urban and rural stations did not show significant differences ($F_{(1–40)} = 0.23$, P = 0.6353), while the microplastic abundances at stations with and without river discharges were significantly different ($F_{(1–40)} = 7.10$, P = 0.0116). The microplastic abundances between sampling areas were significantly different ($F_{(1–40)} = 3.63$, P = 0.0042); Tukey's test showed that the average microplastic abundance in the coastal surface waters in the Cartagena, Antioquia, and Santa Marta areas on the Caribbean coast, Tumaco, and Buenaventura on the Pacific coast was significantly different from the San Antero, San Andrés Island, Chocó-C areas on the Caribbean and Chocó-P on the Pacific coast.

Physical and chemical characterization of microplastics

The most abundant microplastic shapes were fragments (71.4%), filaments (18.3%), and films (6.1%), followed by foams (3.2 %), granules (0.8%), and pellets (0.3%) (Fig. 3a). No significant differences were found between the

Fig. 2 Range of microplastics concentration in the coastal surface waters of the nine study areas in the Colombian Caribbean and Pacific: (1) San Andrés Island, (2) Santa Marta, (3) Cartagena, (4) San Antero, (5) Antioquia, (6) Chocó Caribbean, (7) Chocó Pacific, (8) Buenaventura, and (9) Tumaco
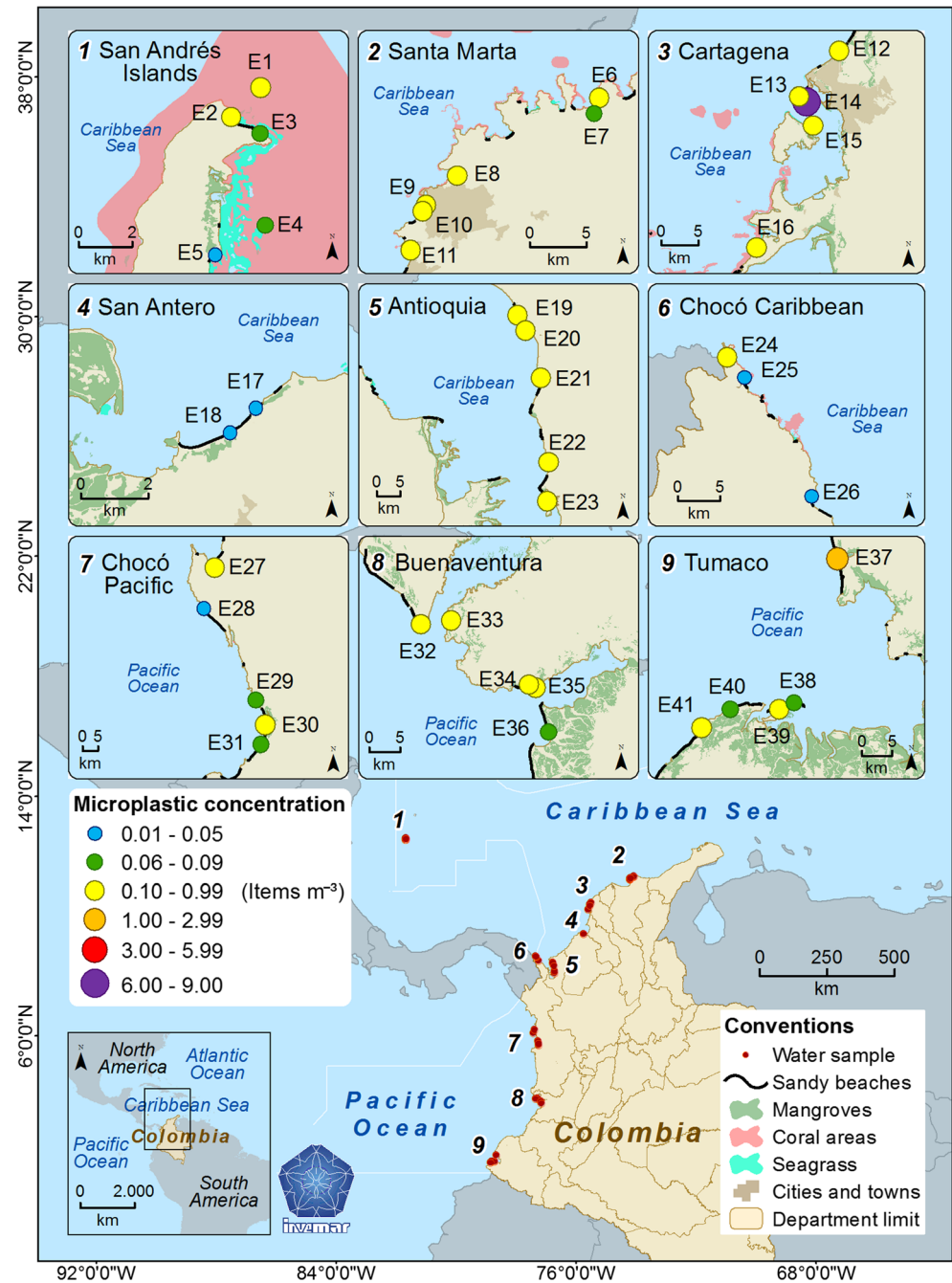

percentages of the microplastic shapes in the water of the stations on the Caribbean and Pacific coasts (paired t-test, $T_6 = -1.65$, $P = 0.1593$) nor between the stations with and without river discharges ($T_6 = -0.11$, $P = 0.9131$). On the other hand, the percentages of the microplastic shapes at urban stations differed significantly from those of rural stations ($T_6 = 2.75$, $P = 0.0404$). In the water of the urban and rural stations of the areas of Cartagena, Antioquia, Chocó-C on the Caribbean coast, Buenaventura, and Tumaco on the Pacific coast, the fragments were most common, but on the San Andrés Island and Santa Marta on the Caribbean coast and

Chocó-P on the Pacific coast, the filaments dominated. The pellets and granules had the lowest abundance, and pellets were observed mainly in the water samples from the Cartagena, Santa Marta, and Chocó-C areas, while granules were found in greater abundance in the Antioquia, Buenaventura, and Tumaco areas. Among these studied areas, the percentages of the microplastic shapes did not show significant differences (Friedman test, $T^2 = 1.00$, $P = 0.4537$).

Regarding the colors of microplastics, the most abundant were colorless, white, blue, and black (Fig. 3b). The percentages of the colors of the microplastics in the surface waters of

Fig. 3 Representation (%) of the physical characteristics (**a** shape, **b** color) and chemical (**c** polymers) of the microplastics sampled in coastal surface waters of the Colombian coast, according to the coasts (Caribbean and Pacific), the types of area (rural and urban), river discharge (yes and no), and studied areas. Figure 3c shows the results of the analysis of microplastics selected at random in seven of nine study areas
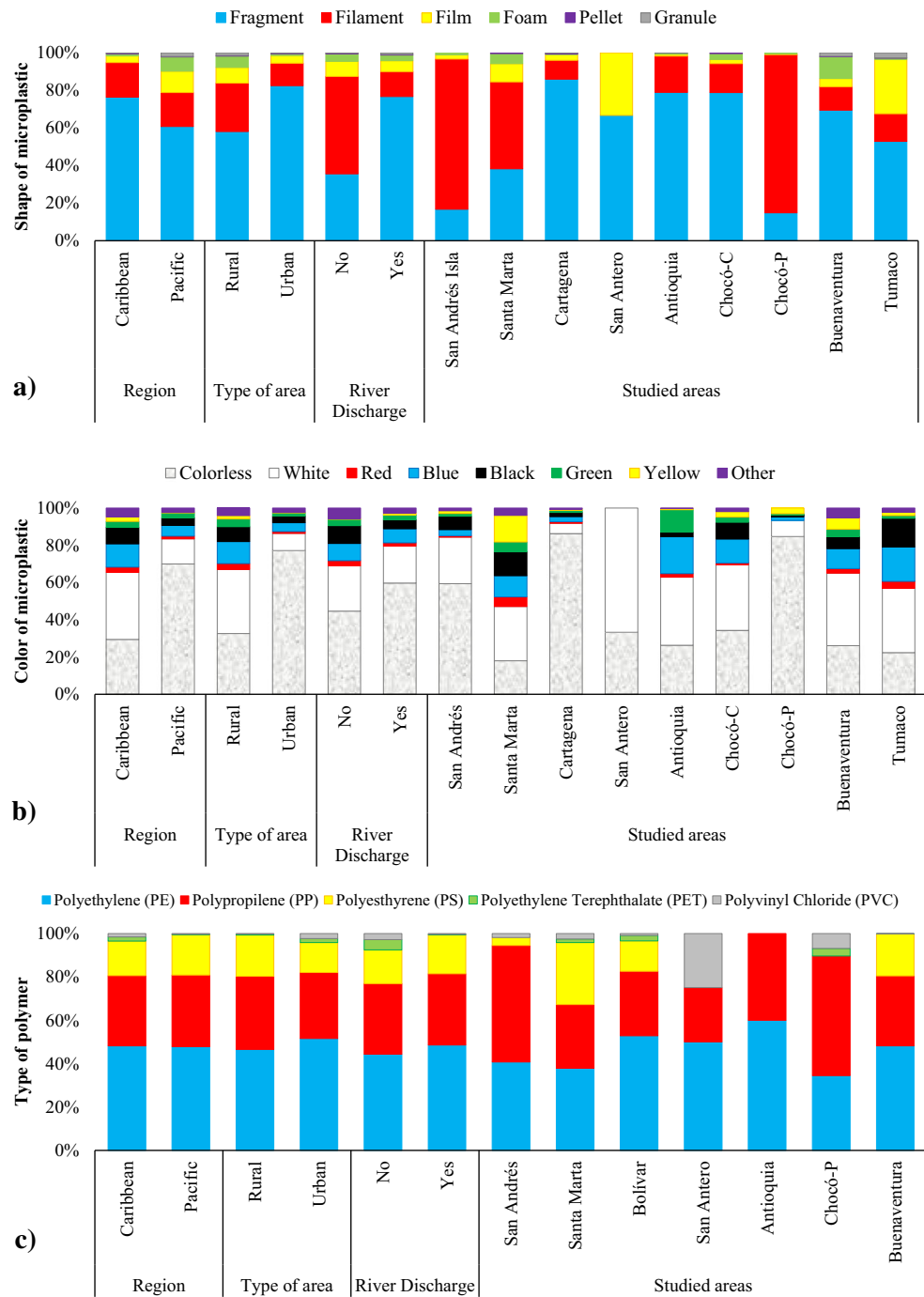
the stations between the Caribbean and Pacific coasts did not present significant differences ($T_8 = 2.12$, $P = 0.0716$) nor between the stations with and without river discharges ($T_8 = 1.13$, $P = 0.2955$). However, the proportions of microplastic colors differed significantly between the urban and rural stations ($T_8 = 2.82$, $P = 0.0258$). In the studied areas of Santa Marta and Chocó-C in the Caribbean coast, Buenaventura and Tumaco in the Pacific coast, greater diversity and proportionality of all the colors registered of microplastics were found, these proportions being statistically different ($T^2 = 3.13$, $P =$

0.0054) from the proportions of the colors registered in the areas of Cartagena and San Antero on the Caribbean and Chocó-P on the Pacific, where transparent and white microplastics represented more than 50% (Fig. 3b).

The ATR-FTIR analysis identified five types of polymers, in order of the highest to the lowest abundance were polyethylene (PE, 47.9%), polypropylene (PP, 32.8%), polystyrene (PS, 17.7%), polyethylene terephthalate (PET, 0.9%), and polyvinylchloride (PVC, 0.8%) (Fig. 3c). No significant differences were found between the polymer composition of

microplastics in the Caribbean and Pacific stations ($T_5 = 1.47$, $P = 0.2145$), between the stations with and without river discharge ($T_5 = 1.43$, $P = 0.2264$), nor between urban and rural stations ($T_5 = -1.31$, $P = 0.2592$). The composition of polymers in the different studied areas did not show statistically significant differences either ($T^2 = 0.20$, $P = 0.9722$).

Discussion

Abundance and distribution of microplastics

This study is the first to quantify the abundance and physical and chemical characteristics of microplastics in the coastal surface waters of representative areas from the Caribbean and Pacific coast of Colombia, contributing to the knowledge of their distribution, sources, and the possible risk posed to marine aquatic ecosystems. Microplastics are considered emerging pollutants (unregulated) that remain in the environment because they do not degrade but rather fragment into smaller pieces and are considered ubiquitous since they have been found in all marine environmental compartments (waters, sediments, organisms) in studied places around the world actually (Hidalgo-Ruz et al. 2012; Alimba and Faggio 2019). In the surface waters of all the stations and studied areas along the Caribbean and Pacific coasts, the presence of different densities of microplastics (0.01–8.96 items m^{-3}) was evidenced, which are influenced significantly by the contributions of the many rivers that flow into the coastal waters of the country, including urban and rural areas.

The greatest microplastic abundances in coastal surface waters were registered in the areas where the largest populations of the Caribbean (Cartagena and Santa Marta) and the Pacific (Buenaventura and Tumaco) are located, which have the highest production of wastewater and solid waste (Fig. 4a and b). In the Cartagena area, there is a high industrial development, including the production of plastics, and part of its coast is influenced by the discharge of continental waters through the Canal del Dique, an artificial arm of the Magdalena River, which emits an estimated load of 16,700 tons of plastics per year into the Caribbean Sea (Lebreton et al. 2017). In the urban areas of Santa Marta, the Manzanares and Gaira rivers flow into it; these rivers receive wastewater and solid waste from the Santa Marta city regularly (INVEMAR 2018).

The Buenaventura and Tumaco areas receive wastewater and solid waste from the human settlements located on the banks of two and five rivers, respectively (INVEMAR 2018). It is important to mention that in the Colombian Pacific coast, the dynamics of the tides (with a tidal range close to 3 m; IDEAM, 2017) and river discharges (which generally have been increasing due to the high rainfall in the area; from 2000 to > 11,000 mm; IDEAM 2014) have an

essential role in the retention and export of floating marine litter (including microplastics) in coastal water. In Tumaco, it is observed in the tidal flow that the floating marine litter remains dammed in the water of the urban area, and in the ebb tide, the water appears "clean" or with a very little amount of floating marine litter, suggesting that this litter would be transported to rural areas, which requires further investigation.

In Colombia, the majority of human populations establish and develop on the banks of rivers and strategic water bodies, for greater ease of communication and connectivity between populations. Unfortunately, a large part of these populations have serious deficiencies in basic sanitation (Fig. 4a and b), so that wastewater is not adequately treated, and a high pollutant load is discharged into rivers and the sea (INVEMAR 2018). Likewise, solid waste is dumped into rivers, burned, buried, thrown into open dumps, or disposed of in landfills (Fig. 4c). The waste that reaches the rivers is transported to estuaries and coastal marine environments, affecting ecosystems such as beaches and mangroves, where large amounts of macrolitter (size > 5 mm) and high microplastics abundances are observed, from 3 to 1387 items m^{-2} of the beach (Garcés-Ordóñez et al. 2020a) and from 31 to 2863 items kg^{-1} of mangrove soil (Garcés-Ordóñez et al. 2019). Besides, microplastic litter probably reaches the marine environment through storm water runoff, storm drainage systems, and punctual sewage discharges directly into the sea, as has been reported in other studies (Ory et al. 2020; Piñon-Colin et al. 2020).

Physical characteristics and polymer composition of the microplastics

The microplastics' shapes most abundant (fragment, filament, film, and foam), which in total represented between 97 and 100% of the microplastics registered in the Colombian coastal surface waters, indicate that their origin is secondary. This plastic litter comes from the fragmentation of large plastic items (containers, packages, bags, disposable food containers, expanded polystyrene, textiles, and fishing nets, among others) that reach the marine environment through activities carried out in river basins or directly in the coastal areas, such as recreation, poor practices in municipal waste management, fishing, and aquaculture, among others (INVEMAR 2018; Garcés-Ordóñez et al. 2019, 2020a). The high proportion of secondary microplastics recorded in this study is similar to that reported in coastal water of France (Frère et al. 2017), Yellow Sea (Sun et al. 2018), and Jamaica (Rose and Webber 2019) where the fragments and filaments were the most abundant, and it differs from the dominance of primary microplastics (pellets), which were the most abundant (96.8%) in Hong Kong coastal water (Tsang et al. 2017).

Although in Colombia microplastic loads that are introduced into natural water bodies through wastewater

Fig. 4 Characteristics of the Colombian coastal populations in the nine studied areas: **a** the number of inhabitants and coverage of basic sanitation, **b** estimated production of wastewater and solid waste, and **c** forms of solid waste disposal. Sources: DANE (2005, 2018, 2019), INVEMAR (2018), Superservicios (2019)
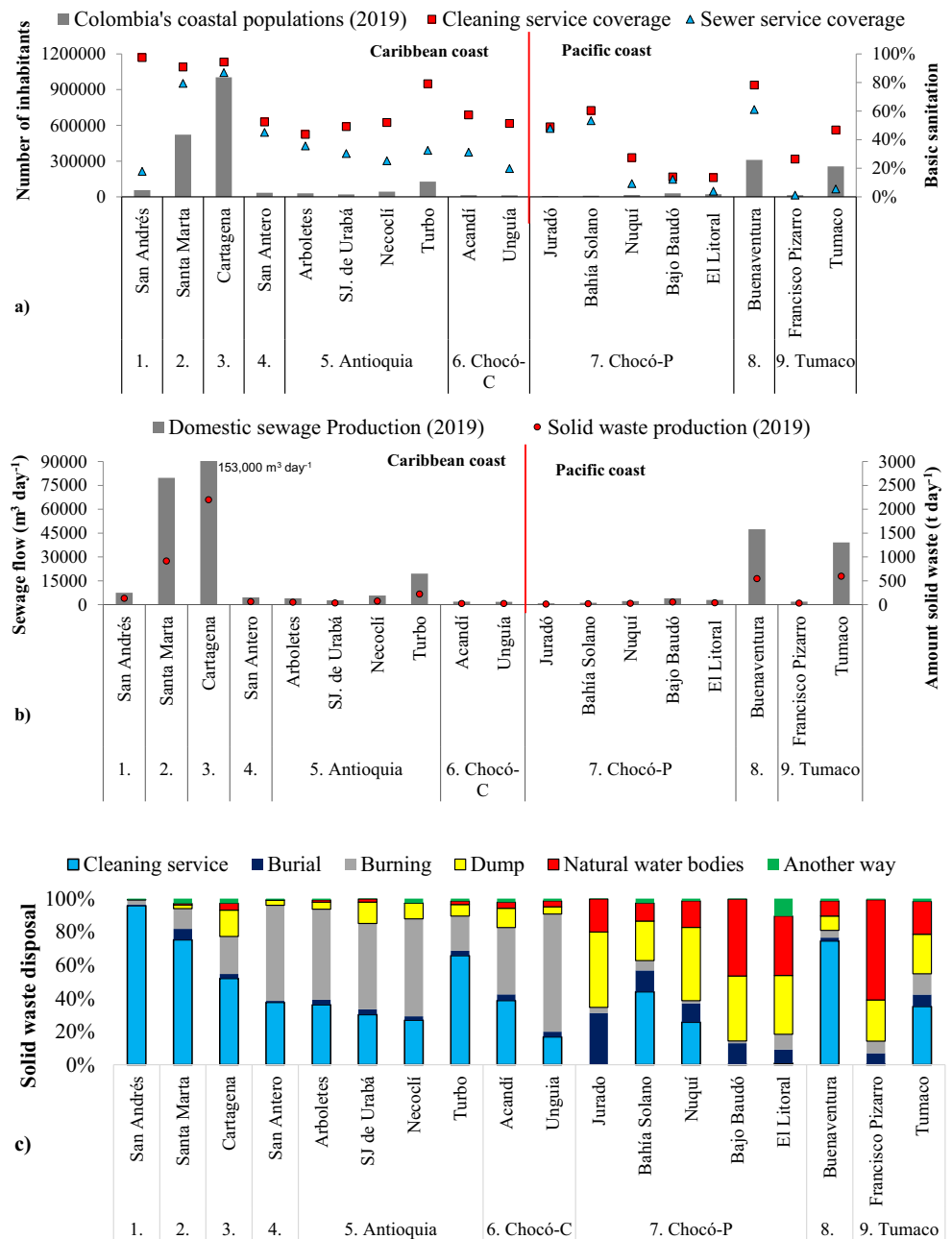
discharges has not been quantified, it is known that these residues are important sources of filaments and fibers, as well as pellets, granules, and microspheres (Browne et al. 2011; Correia-Prata 2018; Sun et al. 2019). In Colombia, wastewater is considered one of the pollution sources that most affects the quality of the country's marine water because it is not adequately treated to reduce the pollutant load, before disposing it in rivers and the sea (INVEMAR 2018).

The colors of the microplastics in the coastal waters in studied areas were variable, predominantly colorless and white, followed by blue and black. These colors correspond

to the original plastic products; although the coloration of microplastics can change when exposed to environmental conditions (solar radiation, oxidation) (Acosta-Coley et al. 2019a), and their identification can be subjective, which reduces the reliability and comparability of this characteristic (Cadiou et al. 2020). However, in the marine environment, the colors of microplastics are important due to the similarities with planktonic organisms, which is considered one of the main causes of microplastic ingestion by fish and other organisms of different trophic levels (Ory et al. 2017; Sun et al. 2017; Botterell et al. 2019). Studies on the ingestion of

microplastics by fish in Colombia have found transparent, white, blue, red, and black particles in the digestive tract of commercially important species, so this contamination in the water represents a risk for the local fishing resource (Garcés - Ordóñez et al., 2017, 2020c; Ory et al. 2018).

In the microplastics of this study, five types of polymer were identified (PE, PP, PS, PET, and PVC), with PE, PP, and PS being the most abundant in coastal surface waters, which could come from bags, packaging, and short lifetime product containers, for which they are widely used (Geyer et al. 2017) and are the most common marine plastic litter on Colombian beaches (Garcés-Ordóñez et al. 2020a, b). These three types of polymers (PE, PP, and PS) have low specific densities compared to seawater and were reported in high percentages in coastal water of Slovenia (Gajšt et al. 2016), Brest Bay, France (Frère et al. 2017), and Kingston, Jamaica (Rose and Webber 2019). Although PVC is rare in surface waters, as it has a higher specific density than seawater, it has also been found in low percentages in marine surface waters in Slovenia (Gajšt et al. 2016) and Fiji (Ferreira et al. 2020) and in the zooplankton of coastal surface waters of the Yellow Sea (Sun et al. 2018).

The presence of PVC, PS, PET, and PP polymers in the Colombian coastal water represents an environmental and health hazard, according to the classification model developed by Lithner et al. (2011), which is based on the chemical substances used to produce each polymer; PVC is considered highly dangerous because it contains vinyl-chloride (50–100% by weight) and benzyl-butyl-phthalate (0–50% by weight), substances that are carcinogenic and toxic for reproduction, respectively. The expanded PS, which was also found in the seawater of the studied areas, contains styrene (93% by weight) and pentane (7% by weight), substances of acute toxicity (oral, dermal, inhalation) and toxic to the aquatic environment, respectively (Lithner et al. 2011). PET contains ethylene glycol (37–39% by weight), which is of acute toxicity (oral, dermal, inhalation), in addition, contains zinc oxide which is highly toxic to aquatic life; lastly, PP is composed of propylene (100% by weight), and n-heptane is used in its polymerization, which is highly toxic to aquatic life (Lithner et al. 2011). However, it is necessary to corroborate the negative effects of these polymers on aquatic organisms in the coastal areas of Colombia, which shows the urgent need for new studies aimed at filling these information gaps.

Conclusions

This study presents the first results on the abundance and physical and chemical characteristics of microplastic litter in 41 stations on the coastal surface waters of the Colombian Caribbean and Pacific. These results provide information about the distribution of pollution and possible source of microplastic on coastal marine water and help to understand the litter that arrives at the beaches and other coastal ecosystem of Colombia. The large number of rivers that flow into the Colombian coasts, including urban and rural areas of both the Caribbean and the Pacific, significantly influence microplastic pollution. Different microplastic types indicate that the majority of microplastics are of secondary origin and probably come from rivers in the vicinity of the sampling stations, which are receivers of municipal wastewater and solid waste of Colombia. The chemical characterization identified types of polymers to be very common in household waste, showing the presence of this material as a source. Additionally, polymers with toxic and carcinogenic potential are present in the coastal waters.

The presence of these microplastics in the surface waters leads us to believe that they will be sources for the accumulation of plastics on the beaches, and their presence represents a risk to the Colombian coastal marine ecosystems. These data are of fundamentally important for a better evaluation of local microplastic pollution. They will provide a basis for the identification of possible accumulation hotspots, in addition to serving to infer the search for the main sources of pollution.

Author contributions OGO conceived and designed the experiments, analyzed the data, and wrote the first draft of the manuscript. OGO, LFE, MCM, LSP, and RMA made critical revisions and contributed to the writing of the manuscript. OGO, MCM, and LSP contributed to the laboratory analysis. OGO, LFE, MCM, LSP, and RMA agree with manuscript results and conclusions. All authors reviewed and approved the final manuscript.

Data availability The data that support the findings of this study are available from the Information Services Laboratory of the Instituto de Investigaciones Marinas y Costera José Benito Vives de Andréis - INVEMAR, Colombia, but restrictions apply to the availability of these data, which were used under license for the current study and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of the director general of INVEMAR.

Declarations

Ethics approval and consent to participate   Not applicable.

Consent for publication   Not applicable.

Competing interests   The authors declare no competing interests.

References

Acosta-Coley I, Olivero-Verbel J (2015) Microplastic resin pellets on an urban tropical beach in Colombia. Environ Monit Assess 187:435. https://doi.org/10.1007/s10661-015-4602-7

Acosta-Coley I, Duran-Izquierdo M, Rodriguez-Cavallo E, Mercado-Camargo J, Mendez-Cuadro D, Olivero-Verbel J (2019a) Quantification of microplastics along the Caribbean Coastline of Colombia: pollution profile and biological effects on Caenorhabditis elegans. Mar Pollut Bull 146:574–583. https://doi.org/10.1016/j.marpolbul.2019.06.084

Acosta-Coley I, Mendez-Cuadro D, Rodríguez-Cavallo E, De la Rosa J, Olivero-Verbel J (2019b) Trace elements in microplastics in Cartagena: a hotspot for plastic pollution at the Caribbean. Mar Pollut Bull 139:402–411. https://doi.org/10.1016/j.marpolbul.2018.12.016

Alimba C, Faggio C (2019) Microplastics in the marine environment: current trends in environmental pollution and mechanisms of toxicological profile. Environ Toxicol Pharmacol 68:61–74. https://doi.org/10.1016/j.etap.2019.03.001

Antão-Barboza L, Vethaak AD, Lavorante B, Lundebye A, Guilhermino L (2018) Marine microplastic debris: an emerging issue for food security, food safety and human health. Mar Pollut Bull 133:336–348. https://doi.org/10.1016/j.marpolbul.2018.05.047

Arango C, Dorado J, Guzmán D, Ruiz JF (2012) Climatología trimestral de Colombia. Grupo de Modelamiento de Tiempo. Clima y Escenarios de Cambio Climático Subdirección de Meteorología – IDEAM, Bogotá 19 p

Auta HS, Emenike CU, Fauziah SH (2017) Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions. Environ Int 102:165–176. https://doi.org/10.1016/j.envint.2017.02.013

Botterell Z, Beaumont N, Dorrington T, Steinke M, Thompson R, Lindeque P (2019) Bioavailability and effects of microplastics on marine zooplankton: a review. Environ Pollut 245:98–110. https://doi.org/10.1016/j.envpol.2018.10.065

Boucher J, Friot D (2017) Primary microplastics in the oceans: a global evaluation of sources. IUCN. 43p. ISBN: 978-2-8317-1827-9, Gland, Switzerland. https://doi.org/10.2305/IUCN.CH.2017.01.en

Browne M, Crump P, Niven SJ, Teuten EL, Tonkin A, Galloway T, Thompson RC (2011) Accumulation of microplastic on shorelines worldwide: sources and sinks. Environ Sci Technol 45:9175–9179. https://doi.org/10.1021/es201811s

Cadiou JF, Gerigny O, Koren Š, Zeri C, Kaberi H, Alomar C, Panti C, Fossi MC, Adamopoulou A, Digka N, Deudero S, Concato M, Carbonell A, Baini M, Galli M, Galgani F (2020) Lessons learned from an intercalibration exercise on the quantification and characterisation of microplastic particles in sediment and water samples. Mar Pollut Bull 154:111097. https://doi.org/10.1016/j.marpolbul.2020.111097

Correia-Prata J (2018) Microplastics in wastewater: state of the knowledge on sources, fate and solutions. Mar Pollut Bull 129(1):262–265. https://doi.org/10.1016/j.marpolbul.2018.02.046

DANE (2005) CENSO 2005. Variables de Vivienda. Eliminación de basura. Departamento Nacional de Estadísticas. https://www.dane.gov.co/index.php/estadisticas-por-tema/demografia-ypoblacion/censo-general-2005-1

DANE (2018). Proyección nacional y departamental de la población para los años desde 2018 al 2020. Departamento Nacional de Estadísticas. https://www.dane.gov.co/index.php/estadisticas-por-tema/demografia-y-poblacion/proyecciones-de-poblacion

DANE (2019). Servicios Públicos en Colombia. Departamento Nacional de Estadísticas. https://dane.maps.arcgis.com/apps/MapSeries/index.html?appid=2749922ca5f8469db9990986c02b1b93

Erjavec N (2011) Tests for homogeneity of variance. In: Lovric M (ed) International Encyclopedia of Statistical Science. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-04898-2_590

Ferreira M, Thompson J, Paris A, Rohindra D, Rico C (2020) Presence of microplastics in water, sediments and fish species in an urban coastal environment of Fiji, a Pacific small island developing state. Mar Pollut Bull 153:110991. https://doi.org/10.1016/j.marpolbul.2020.110991

Frère L, Paul-Pont I, Rinnert E, Petton S, Jaffré J, Bihannic I, Soudant P, Lambert C, Huvet A (2017) Influence of environmental and anthropogenic factors on the composition, concentration and spatial distribution of microplastics: a case study of the Bay of Brest (Brittany, France). Environ Pollut 225:211–222. https://doi.org/10.1016/j.envpol.2017.03.023

Gajšt T, Bizjak T, Palatinus A, Liubartseva S, Kržan A (2016) Sea surface microplastics in Slovenian part of the Northern Adriatic. Mar Pollut Bull 113(1–2):392–399. https://doi.org/10.1016/j.marpolbul.2016.10.031

Garcés-Ordóñez O, Castillo V, Rueda R, Ríos M, Bayona M, Molina F, Escobar M (2017) Diagnóstico de residuos microplásticos en las zonas marinas de Colombia. 108-166. In INVEMAR and MinAmbiente, 2017. Resolución No. 646 de 2017. Formulación de lineamientos, medidas de conservación, manejo y uso de ecosistemas marinos y costeros, con la intención de apoyar acciones de fortalecimiento en la gestión ambiental de las zonas costeras de Colombia. Santa Marta, 239 p

Garcés-Ordóñez O, Castillo-Olaya V, Granados-Briceño A, Blandón L, Espinosa L (2019) Marine litter and microplastic pollution on mangrove soils of the Ciénaga Grande de Santa Marta, Colombian Caribbean. Mar Pollut Bull 145:455–462. https://doi.org/10.1016/j.marpolbul.2019.06.058

Garcés-Ordóñez O, Espinosa L, Pereira R, Issa B, Meigikos R (2020a) Plastic litter pollution along sandy beaches in the Caribbean and Pacific coast of Colombia. Environ Pollut 267:115495. https://doi.org/10.1016/j.envpol.2020.115495

Garcés-Ordóñez O, Espinosa L, Pereira R, Muniz M (2020b) The impact of tourism on marine litter pollution on Santa Marta beaches, Colombian Caribbean. Mar Pollut Bull 160:111558. https://doi.org/10.1016/j.marpolbul.2020.111558

Garcés-Ordóñez O, Mejía-Esquivia K, Sierra-Labastidas T, Patiño A, Blandón L, Espinosa-Díaz L (2020c) Prevalence of microplastic contamination in the digestive tract of fishes from mangrove ecosystem in Cispata, Colombian Caribbean. Mar Pollut Bull 154:111085. https://doi.org/10.1016/j.marpolbul.2020.111085

Geyer R, Jambeck J, Lavender K (2017) Production, use, and fate of all plastics ever made. Sci Adv 3(7):e1700782. https://doi.org/10.1126/sciadv.1700782

Gómez-Cubillos C, Licero L, Perdomo L, Rodríguez A, Romero D, Ballesteros-Contreras D, Gómez-López D, Melo A, Chasqui L, Ocampo M, Alonso D, García J, Peña C, Bastidas M, Ricaurte C, (2015) Portafolio "Áreas de arrecifes de coral, pastos marinos, playas de arena y manglares con potencial de restauración en Colombia". Serie de Publicaciones Generales del INVEMAR No. 79, Santa Marta. 69 p

Guzzetti E, Sureda A, Tejada S, Faggio C (2018) Microplastic in marine organism: environmental and toxicological effects. Environ Toxicol Pharmacol 64:164–171. https://doi.org/10.1016/j.etap.2018.10.009

Hedberg E, Ayers S (2015) The power of a paired t-test with a covariate. Soc Sci Res 50:277–291. https://doi.org/10.1016/j.ssresearch.2014.12.004

Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M (2012) Microplastics in the marine environment: a review of the methods used for

identification and quantification. Environ Sci Technol 46(6):3060–3075. https://doi.org/10.1021/es2031505

IDEAM (2014). Plataforma del Atlas climatológico de Colombia. Instituto de Hidrología, Meteorología y Estudios Ambientales. http://atlas.ideam.gov.co/visorAtlasClimatologico.html

IDEAM (2017a). Pronósticos de pleamares y bajamares en la costa Pacífico colombiana, año 2017. Instituto de Hidrología, Meteorología y estudios Ambientales. Bogota, 132 p. ISBN 958-95850-6-X

IDEAM (2017b). Pronósticos de pleamares y bajamares en la costa Caribe colombiana, año 2017. Instituto de Hidrología, Meteorología y estudios Ambientales. Bogotá, 168 p. SBN 958-95850-6-X

INVEMAR (2018) Diagnóstico y evaluación de la calidad de las aguas marinas y costeras en el Caribe y Pacífico colombianos. Red de vigilancia para la conservación y protección de las aguas marinas y costeras de Colombia – REDCAM. Serie de Publicaciones Periódicas No. 4 del INVEMAR, Santa Marta. 336 p. ISSN: 2389-8615

INVEMAR (2020) Informe del estado de los ambientes y recursos marinos y costeros en Colombia, 2019. Serie de Publicaciones Periódicas No. 3. Santa Marta. 183 p. http://www.invemar.org.co/documents/10182/0/IER-2019_Informe_del_estado_de_los_ambientes_y_recursos_marinos/b7520e57-5cdc-4558-a3d4-bea36f767a98

Jambeck J, Geyer R, Wilcox C, Siegler T, Perryman M, Andrady A, Narayan R, Lavender Law K (2015) Plastic waste inputs from land into the ocean. Science 347(6223):768–771. https://doi.org/10.1126/science.1260352

Jung MR, Horgen FD, Orski SV, Rodriguez CV, Beers KL, Balazs GH, Jones TT, Work TM, Brignac KC, Royer SJ, Hyrenbach KD, Jensen BA, Lynch JM (2018) Validation of ATR FT-IR to identify polymers of plastic marine debris, including those ingested by marine organism. Mar Pollut Bull 127:704–716. https://doi.org/10.1016/j.marpolbul.2017.12.061

Kovač M, Palatinus A, Koren Š, Peterlin M, Horvat P, Kržan A (2016) Protocol for microplastics sampling on the sea surface and sample analysis. JoVE. 118:55161. https://doi.org/10.3791/55161

Lebreton L, van der Zwet J, Damsteeg J, Slat B, Andrady A, Reisser J (2017) River plastic emissions to the world´s oceans. Nat Commun 8:15611. https://doi.org/10.1038/ncomms15611

Lithner D, Larsson Å, Dave G (2011) Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition. Sci Total Environ 409(18):3309–3324. https://doi.org/10.1016/j.scitotenv.2011.04.038

Nor N, Obbard J (2014) Microplástics in Singapore's coastal mangrove ecosystem. Mar Pollut Bull 79(1-2):278–283. https://doi.org/10.1016/j.marpolbul.2013.11.025

Ory N, Sobral P, Ferreira J, Thiel M (2017) Amberstripe scad Decapterus muroadsi (Carangidae) fish ingest blue microplastics resembling their copepod prey along the coast of Rapa Nui (Easter Island) in the South Pacific subtropical gyre. Sci Total Environ 586:430–437. https://doi.org/10.1016/j.scitotenv.2017.01.175

Ory N, Chagnon C, Felix F, Fernández C, Ferreira J, Gallardo C, Garcés-Ordóñez O, Henostroza A, Laaz E, Mizraji R, Mojica H, Murillo V, Ossa Medina L, Preciado M, Sobral P, Urbina MA, Thiel M (2018) Low prevalence of microplastic contamination in planktivorous fish species from the southeast Pacific Ocean. Mar Pollut Bull 127:211–216. https://doi.org/10.1016/j.marpolbul.2017.12.016

Ory N, Lehmann A, Javidpour J, Stöhr R, Walls GL, Clemmesen C (2020) Factors influencing the spatial and temporal distribution of microplastics at the sea surface – a year-long monitoring case study from the urban Kiel Fjord, southwest Baltic Sea. Sci Total Environ 736:139493. https://doi.org/10.1016/j.scitotenv.2020.139493

Piñon-Colin T, Rodriguez-Jimenez R, Rogel-Hernandez E, Alvarez-Andrade A, Toyohiko F (2020) Microplastics in stormwater runoff

in a semiarid region, Tijuana, Mexico. Sci Total Environ 704:135411. https://doi.org/10.1016/j.scitotenv.2019.135411

Riascos J, Valencia N, Peña E, Cantera J (2019) Inhabiting the technosphere: the encroachment of anthropogenic marine litter in Neotropical mangrove forests and its use as habitat by macrobenthic biota. Mar Pollut Bull 142:559–568. https://doi.org/10.1016/j.marpolbul.2019.04.010

Ricaurte-Villota C, Bastidas M (2017) Regionalización oceanográfica: una visión dinámica del Caribe. INVEMAR. Serie de Publicaciones Especiales de INVEMAR No 14. Santa Marta, Colombia 180 p. http://www.invemar.org.co/documents/10182/14479/regionalizacion_oceanografica_baja.pdf

Rodríguez-Rubio F, Bastidas M, Zorrilla D (2007) The Colombia current: an eastern tropical Pacific coastal current, early oceanographic characteristics. Dirección General Marítima, Tumaco. 1 p

Rose D, Webber M (2019) Characterization of microplastics in the surface waters of Kingston Harbour. Sci Total Environ 664:753–760. https://doi.org/10.1016/j.scitotenv.2019.01.319

Rotjan R, Sharp K, Gauthier A, Yelton R, Baron Lopez E, Carilli J, Kagan J, Urban-Rich J (2019) Patterns, dynamics and consequences of microplastic ingestion by the temperate coral, Astrangia poculata. Proc R Soc B 28620190726:20190726. https://doi.org/10.1098/rspb.2019.0726

Schmidt C, Krauth T, Wagner S (2017) Export of plastic debris by rivers into the sea. Environ Sci Technol 51(21):12246–12253. https://doi.org/10.1021/acs.est.7b02368

Shapiro S, Wilk M (1965) An analysis of variance for normality (complete samples). Biometrika 52:591–611. https://doi.org/10.2307/2333709

Silva MM, Maldonado GC, Castro RO, Felizardo JS, Cardoso RP, Anjos RM, Araújo FV (2019) Dispersal of potentially pathogenic bacteria by plastic debris in Guanabara Bay, RJ, Brazil. Mar Pollut Bull 141:561–568. https://doi.org/10.1016/j.marpolbul.2019.02.064

Stahle L, Wold S (1989) Analysis of variance (ANOVA). Chemom Intell Lab Syst 6(4):259–272. https://doi.org/10.1016/0169-7439(89)80095-4

Sun X, Li Q, Zhu M, Liang J, Zheng S, Zhao Y (2017) Ingestion of microplastic by natural groups in the northern South China sea. Mar Pollut Bull 115(1-2):217–224. https://doi.org/10.1016/j.marpolbul.2016.12.004

Sun X, Liang J, Zhu M, Zhao Y, Zhang B (2018) Microplastics in seawater and zooplankton from the Yellow Sea. Environ Pollut 242 Part A:585–595. https://doi.org/10.1016/j.envpol.2018.07.014

Sun J, Dai X, Wang Q, van Loosdrecht M, Ni BJ (2019) Microplastics in wastewater treatment plants: Detection, occurrence and removal. Water Res 152:21–37. https://doi.org/10.1016/j.watres.2018.12.050

Superservicios (2017) Estudio Sectorial de los servicios públicos domiciliarios de Acueducto y Alcantarillado – 2016. Superintendencia de Servicios Públicos Domiciliarios, Bogotá. 64 p. https://www.superservicios.gov.co/sites/default/archivos/SSPD%20Publicaciones/Publicaciones/2018/Oct/estudio_sectorial-compilado-26-12-2017-vbibiana.pdf

Superservicios (2019) Disposición final de residuos sólidos informe Nacional 2018. Superintendencia de Servicios Públicos Domiciliarios, Bogotá 97 p

Tsang Y, Mak CW, Liebich C, Lam SW, Sze E, Chan K (2017) Microplastic pollution in the marine waters and sediments of Hong Kong. Mar Pollut Bull 115(1-2):20–28. https://doi.org/10.1016/j.marpolbul.2016.11.003

United Nations (2019). Sustainable development knowledge platform. https://sustainabledevelopment.un.org/

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