Distribution of Plastic Debris in the Pacific and Caribbean Beaches of Panama

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ABSTRACT: Microplastics are a global ubiquitous problem, which is becoming a major issue of concern at scientific and political levels around the world. This study presents physical and chemical characterizations of microplastic debris and a comparison between the spatial distribution and anthropogenic activities in 4 Panamanian beaches located in both sides of the Isthmus. Two of them (Juan Diaz and San Carlos beaches) are located toward the Pacific Ocean, Panamá Province, whereas the others (Palenque and Punta Galeta beaches) are located at the Caribbean Sea, Colón Province. They were chosen to show different landscape management and environmental impacts: touristic and protected areas; coastal areas that receive pollutants and marine litter from urban rivers or are used for local fishing activities. Plastic debris samples were collected and visually analyzed following the protocol proposed by the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP). The physical characterization of the samples consisted in the determination of variables associated with the number of plastic particles, shape, color, and size. The characterization of the polymers was performed by the attenuated total reflectance-Fourier transform infrared spectroscopy technique. A high concentration of microplastics (353 items/m^2) were found at the studied sites at the Caribbean coast, whereas a lesser concentration with a greater diversity of shapes and polymer categories were found at the Pacific Coast (187 items/m^2). The results indicate that, in addition to anthropogenic activities, the proximity to Panama Canal installations, as well as seasonality, natural phenomena, winds, and ocean currents may be influencing the increase in microplastic contents and the types of polymers observed.

KEYWORDS: Microplastics, physical and chemical characterizations, density separation, ATR-FTIR, spatial distribution, anthropogenic activities

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Introduction

One of the main current environmental concerns is the increasing pollution of water resources (rivers, lakes, ground waters, and oceans) by plastic debris of various macro- and microscopic sizes; hence, the plastic materials have become a major emerging contaminant.[1-4] Due to the high production (with global average of about 335 million tons in 2016), usage, diversity of plastic materials, and the lack of a sound plastic waste management, an increasing plastic pollutant accumulation has been detected worldwide.[5] It has been estimated that between 42% and 96% of marine litter in the oceans and marine-coastal ecosystems are plastics.[6]

Plastic has become a ubiquitous problem as it leaches contaminants, adsorbs pollutants, and might act as a transport vector for living microorganisms such as bacteria[7,8] and microalgae.[9] Bacterial growth and biofilm formation are estimated to occur in the first week of exposure to the environment.[9,10] Currently, plastic can be found in form of particles even in remote inhabited regions of our planet. Winds and ocean currents can build up plastic islands or gyres, therefore influencing the distribution and concentration of microplastics in the oceans and shorelines.[4,11,12]

The Republic of Panama is in Central America, bordering both the Caribbean Sea and the Pacific Ocean, between Colombia and Costa Rica (between 7° and 10° N and 77° and 83° W). Panama is characterized by a tropical climate and precipitation between ~1300 and ~3000 mm per year.[13] Natural phenomena such as high tides and rough climate conditions in the tropics may contribute to dissemination and fragmentation of plastic debris. In the Pacific coast of Panama, during the rainy season, marine litter and plastic debris are often washed landward due to a phenomenon called *swell of the ocean*.[14]

During the action of wind currents, energy is transferred to surface water causing waves. A sustained action of wind produces deeper waves that will sweep over the bottom of the ocean[15,16] carrying both floating and sunken debris. This event is also known as eastern boundary upwelling systems and has been frequently observed at Panama's Pacific coasts and, according to Ory et al,[17] also at the southeast Pacific Ocean.

Plastic debris are particles that can be found in different shades of colors or even colorless. They can be classified according to their size range in: mega plastics (MG; >1 m), macroplastics (MA; 25-1000 mm), mesoplastics (ME; 5-25 mm), microplastics (MP; <5 mm), and nanoplastics (NP; <1 µm).[18-20] Recently, Hartmann et al[21] have highlighted the need of harmonizing definitions for size, shape, and polymer types for MP debris. They have recommended the MP size range between 1 µm and 5 mm. Although there are several definitions for MP sizes in the literature, in this work, MP are considered particles ranging between 1 and 5 mm due to methodological limitations: Our Fourier transform infrared spectrometer with attenuated total reflectance (ATR-FTIR) system can produce good analyses in this size range. In addition, MP can be classified as primary or secondary, depending on their origin. Primary MP is originated directly from industrial manufacturing activities and can be found in household cleaning items, toys, filling materials, industrial cleaning powders such as air-blasting media, and personal care and hygiene products (facial cleansers, toothpaste, exfoliating creams, makeup powders). In addition, petroleum derivates and resin beads (mermaid tears or nurdles) are widely used during manufacture of plastic products, usually presenting a pellet-like shape, which may vary depending on manufacturer (cylindrical, spherical, flattened, ovoidal). Secondary MP is generated from the fragmentation of larger plastic debris due to the action of external agents (photooxidation, physical abrasion, acidity, bacterial growth). They usually have the shape of fragments, films, broken edges, and granules.[18,22] Up to now, no harmonized morphological descriptors for marine plastic particles exist. Even an attempt to describe the origin might be a topic of discussion. For example, fibers and filaments are considered to be primary MP by some researchers.[23] MP can be mistaken for food and ingested accidentally by many marine species (marine mammals, seabirds, sea turtles, fish, shellfish), including simplest single-celled organisms (zooplankton and other benthic organisms).[17,24-26]

There are no previous studies on MP debris in the Republic of Panama. Among the few findings regarding composition and source of the macro debris in the Caribbean Sea south border, Garrity and Levings[27] highlighted in 1993 the presence of medical waste, composed mainly of plastic debris (56%), followed by polystyrene (31%) and glass (8%). Only about 10% of the materials had their source recognized, whereas 57% arise from foreign waste. This study aims to deepen the knowledge about presence and distribution of MP from 4 Panamanian beaches that are representative for anthropogenic activities at the Pacific and Caribbean coasts and might result in harm to Panama's coastal ecosystems. The information generated contributes to the understanding of the MP problem in marine-coastal ecosystems of Panama and will help support the necessary measures to prevent and significantly reduce this pollutant in the Caribbean and Pacific regions of Latin America.

Materials and Methods

Sampling areas

Four beaches were chosen according to the recommendations proposed by the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP).[28] This selection considers landscape management and anthropogenic environmental impacts (Figure 1). Embarcadero de Juan Diaz (JUD), a Pacific coastline beach (9° 00′ 55.5″ N, 79° 26′ 19.9″ W), which is located west of the Juan Diaz river mouth, a highly polluted river that receives massive urban plastic debris and discharge from the largest wastewater treatment plant in Panama City.[29] Consequently, JUD shows high levels of solid waste and organic matter from the Juan Diaz River. The structure of Juan Diaz Beach can be described as an open beach, with fine-grained sand that ends in mudflats surrounded by mangroves. San Carlos (SCA), a Pacific coastline beach (8° 28′ 36.2″ N, 79° 57′ 1.6″ W) with open structure and coarser sand, is a well-managed touristic area. SCA receives inland visitors, especially on weekends. It is also used for water leisure sports like surfing. The Juan Diaz and San Carlos beaches are in the Panamá Province. Punta Galeta Beach (GAL) is in a protected area used for scientific purposes, while Palenque beach (PAL) is in a typical rural fishermen township that has no garbage recollection services. The Punta Galeta (9° 24′ 15.4″ N, 79° 52′ 13.8″ W) and Palenque (9° 34′ 25.3″ N, 79° 21′ 33.4″ W) beaches are in the Caribbean coastline in the Colón Province.

Microplastic sampling

Beach sand samples were collected during the rainy season between May and November, 2018. For the MP sampling, the methodologies of the Guidance on Monitoring of Marine Litter in European Seas[30] and the GESAMP[28] were adapted for this study. Our sampling protocol consisted in tracing a 100-m parallel transect on the high-tide line in each one of the studied beaches. In each transect, 5 quadrants of 0.25 m^2 (using a 50 cm × 50 cm metal frame), 20 m apart, were delimited.[31] Inside each quadrant, the superficial layer of 1.0 cm thickness was collected using a stainless-steel spatula and stored in a wide-mouthed glass flask previously codified and the site georeferenced with a Garmin GPS (accuracy: ±2 m). Therefore, 5 sand samples were taken in each beach studied, totaling 20 samples.

Preventing cross-contamination

To prevent sample cross-contamination with airborne plastic particles, an air extraction device was connected to the sample preparation sector to ensure that air is being pulled away from

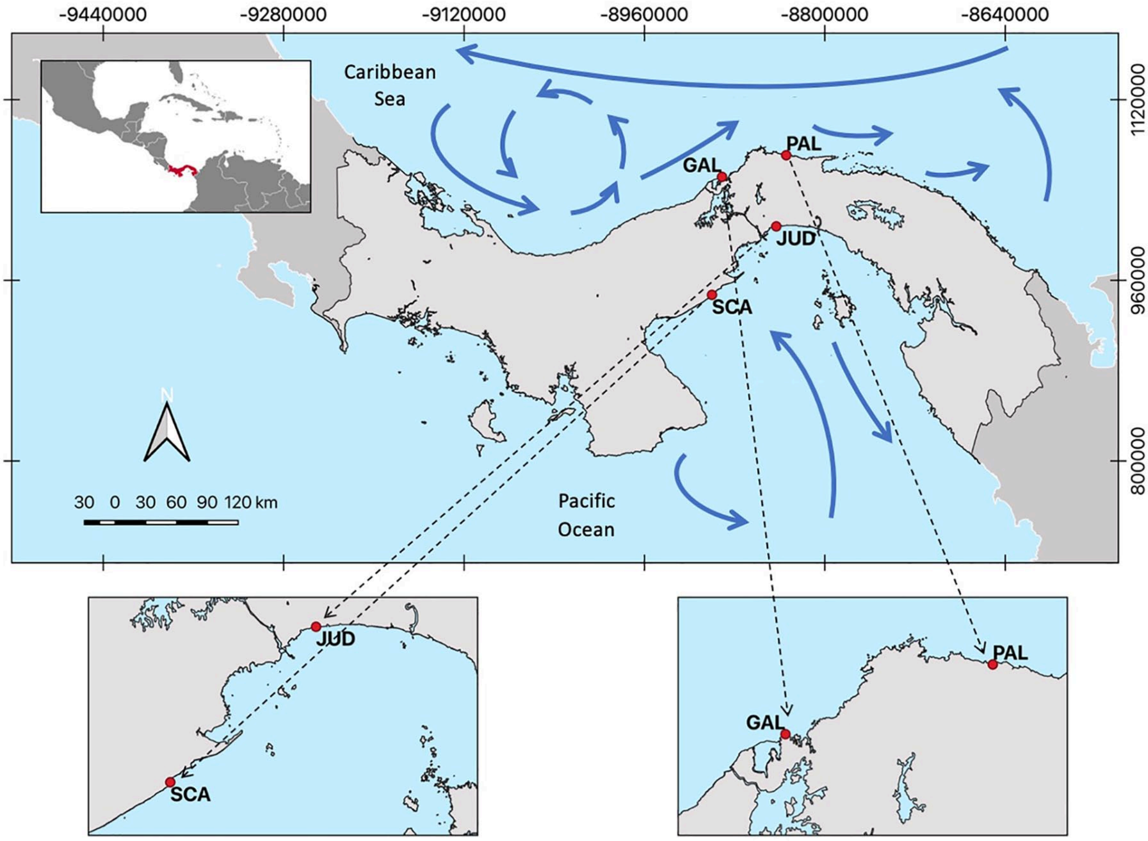

Figure 1. Sampling sites at the Caribbean and Pacific coasts of Panama. GAL is Punta Galeta Beach (located in a protected area), PAL is Palenque Beach (fishermen town), JUD is the Juan Diaz Beach (urban area), and SCA is San Carlos Beach (touristic area). The arrows indicate the direction of the main ocean currents at the Caribbean Sea and Pacific Ocean (data based on Scientific Visualization Studio—NASA).
Source: https://svs.gsfc.nasa.gov/3821.

contamination sources (eg, clothing) and remained on for at least 30 minutes before starting the laboratory activities. Additional measures, such as using cotton clothing during sampling activities and wearing a lab cotton coat, were mandatory while processing sand samples. Cleaning of work benches, equipment (Leica stereoscope S9i and Agilent FTIR-ATR) and its surroundings was performed carefully after each analysis of sample sets. References to measures adopted can be obtained in Koelmans et al.[32]

Sample preparation and physical characterization of microplastics

The information in this section was gathered through the collection, isolation, and physical (size, shape, color, and concentration) and chemical (types of polymers) characterization of MP. Once in the laboratory, the wet weight of each of the 20 sand samples was determined. Subsequently, the samples were placed in the oven in trays and dried at 60°C for 24 hours. With moisture ranging between 1% and 2%, the dried samples were homogenized on a mechanical sifting machine (Minor 200; Endecotts Ltd.), containing a sieve stack with 1- and 5-mm mesh (Gylson, ISO-certified sieves) to obtain the MP debris fraction. According to the European Marine Observation and Data Network (EMODnet),[33] the physical characterization of MP debris can be easily performed using a magnifying glass or stereoscope for this size fraction. After sieving, the samples containing the MP (20) fractions were weighed to obtain their total weight. Each set of 5 MP samples ($MP_{i,1}$-$MP_{i,5}$) from each beach *i* was subjected to an initial visual inspection to obtain the MP particles and reduce the volume of material. Once separated, the obtained plastics are classified by shapes. Based on our experiences, at this stage of the analysis, it is possible to obtain plastic materials such as polyethylene terephthalate (PET), polyurethane (PUR), and acrylonitrile butadiene styrene that do not float in the saturated NaCl solution. However, additional methodology tests should be conducted to validate this observation.

The remaining sifted material (composed of residual plastic materials, wood fragments, shells, sand, dust, dried algae, leaves, dry flowers, and seeds) was then subjected to a density separation step using an NaCl saturated solution (358 g/L; 1.21 g/cm^3) to separate plastics that are less dense than the saline solution and hard-to-identify plastics (such as weathered and flattened polystyrene and translucent or colorless plastics). These are hard to pick out during the initial visual inspection. The composition of the floating debris is variable and consists of organic, plastic, and mineral fragments.

Less-dense debris floats in saltwater, easily separating from the denser debris contained in the mixture.[34] To accelerate the plastic particle separation, the solution was introduced into a centrifuge (Corning LSG, 3000 r/min) for 10 minutes, instead of waiting for a one-night time, usually proposed for natural settling of the solution.[19]

At the end of the MP separation process, 673 MP debris from the 4 beaches were obtained and washed. An ultrasound bath (Branson 1800, 5 minutes in distilled water) was used to obtain a cleaner MP. This cleaning procedure was applied only in cases where the MP samples showed visible surface contaminations such as sand particles or iron splinters, common materials on Panamanian beaches, or even bacterial growth. This step is recommended after quantification of the particles due to the extreme brittleness of a few polymers.[18]

The physical characterization of the MP size range (1-5 mm) was performed, considering the shape and color categories. The density (MP items per m^2) was calculated for each quadrant obtained in each one of the 4 beaches studied. Therefore, the mean and standard deviation from the 5 quadrants was reported as a beach MP density. Statistical analysis and plot visualization were performed using the Seaborn plugin for python (Python Software Foundation).[35] Subsequently, the cleaned MP debris were stored for the ATR-FTIR analysis to determine the chemical nature of the plastic particles.

ATR-FTIR Analysis

The polymer characterization of the MP debris was performed by the ATR-FTIR spectroscopy technique, using an ATR detector in a Cary 660 Fourier Transform Spectrometer (Agilent Technologies). The analysis was performed at the Experimental Center for Engineering (CEI-LABAICA), Technological University of Panama. Absorbance spectra were recorded in the mid-infrared range (4000-400 cm^{-1}) by 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 to record the absorbance of each sample.[36-38] Plastic characterizations were performed by comparing the absorption bands (AB) of the samples with those in the published literature.[18,38-40] Absorption bands stand for specific wavelengths in the electromagnetic spectrum that are characteristic for a given substance and can be therefore used to identify it.

A total of 400 MP items (about 60% of the collected samples) were randomly chosen, analyzed, and their chemical nature was identified. Although the samples were chosen randomly, the prevalence criterium was followed and a ratio of 1:1 assumed for the particles of each coast. Six main polymer types were identified (Figure 2): 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, 1492, 1451, 1027, 694, 537 cm^{-1}), polyethylene terephthalate (PET-AB: 1713, 1241, 1094, 720 cm^{-1}), high-impact polystyrene (HIPS-AB: 2923, 2855, 1597, 1492, 1448, 1027, 909, 760, 697 cm^{-1}), and polyurethane (PUR-AB: 2865, 1731, 1531, 1451, 1223 cm^{-1}).

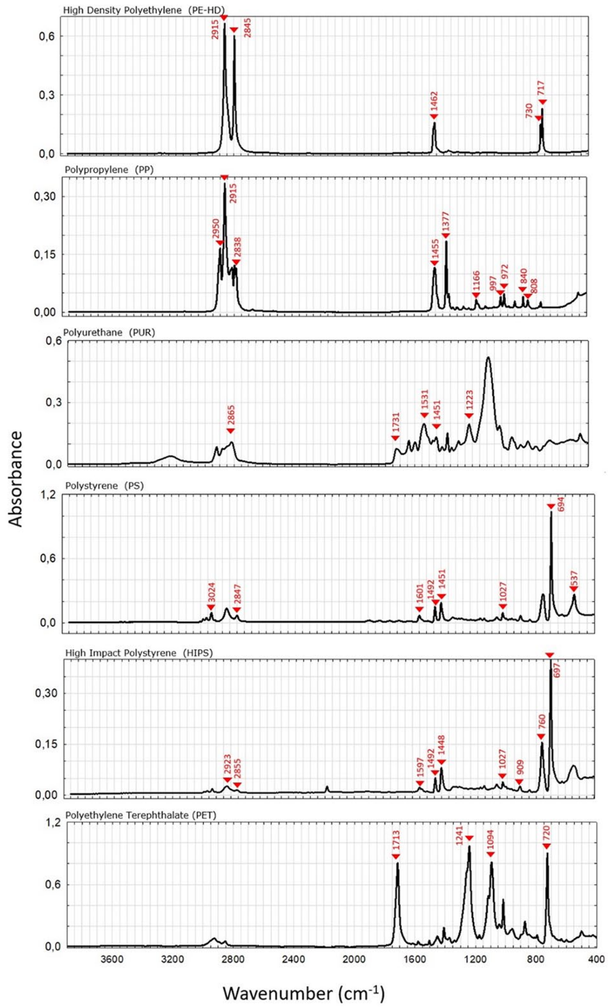

Figure 2. Typical absorbance spectra of the main polymers found in the sand beach samples in Panama.

Results

For the Punta Galeta Beach, the physical characterization of MP debris shows a normalized amount ranging between 56 and 420 items/m^2. The mean value was of 294 ± 316 items/m^2. The results for the Palenque beach show a normalized amount ranging between 28 and 84 items/m^2 with a mean value of 62 ± 76 items/m^2. For the Juan Diaz Beach, a normalized amount ranging between 72 and 168 items/m^2 was found, with a mean value of 105 ± 96 items/m^2. Finally, a normalized amount ranging between 16 and 56 items/m^2, with a mean value of 34 ± 28 items/m^2, was determined for the San Carlos Beach. Regarding MP colors, our findings for the main colors observed in all 4 beaches are as follows: colorless (42.78%), blue (22.07%), and white (16.08%) for Punta Galeta (GAL); white (32.05%), colorless (26.92%), and green (12.82%) for Palenque (PAL); white (46.09%), green (12.50%), and others (10.16%)

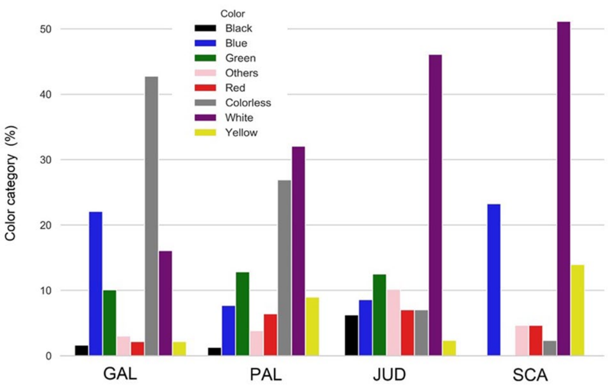

Figure 3. Color distributions of the microplastics at the Caribbean and Pacific coasts in Panama.

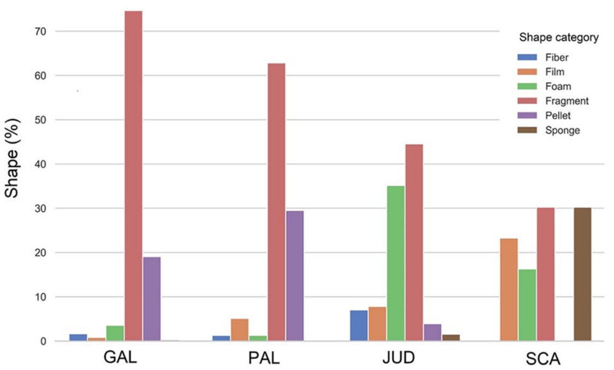

Figure 4. Shape distributions of the microplastics at the Caribbean and Pacific coasts in Panama. GAL indicates Punta Galeta Beach; JUD, Juan Diaz Beach; PAL, Palenque Beach; SCA, San Carlos Beach.

for Juan Diaz (JUD); white (51.16%), blue (23.26%), and yellow (13.95%) for San Carlos (SCA) (Figure 3).

The GAL and PAL beaches (at the Caribbean coast) are mainly characterized by fragments (74.7% and 62.8%, respectively), pellets for PAL were 29.5%, and GAL 19.1%. The percentage of fibers was 1.63% for GAL and 1.28% for PAL (Figure 4). On the contrary, the Juan Diaz and San Carlos beaches (at the Pacific coast) are characterized by an equally balanced shape types of MP debris, such as fibers, films, sponges, and polystyrene foams. Mainly fragments (44.5%), foamed debris (35.2%), and fibers (7.03%) were found in the Juan Diaz Beach. San Carlos shows a homogeneous distribution of MP debris shapes, being 30.2% of fragments, 30.2% of polystyrene (Styrofoam), 23.3% of films, and 16.3% sponge of PUR type. Although fibers were not found in the San Carlos Beach, we can generally conclude that a diversity of shapes exist in all 4 beaches, San Carlos being the less diverse.

Regarding the chemical characterization of MP debris (Figure 5), Punta Galeta, Palenque, Juan Diaz, and San Carlos beaches show similar distributions of polyethylene (PE), polypropylene (PP), and polystyrene (PS). Only Juan Diaz showed additional contributions (low amounts) of PET, HIPS, and PUR.

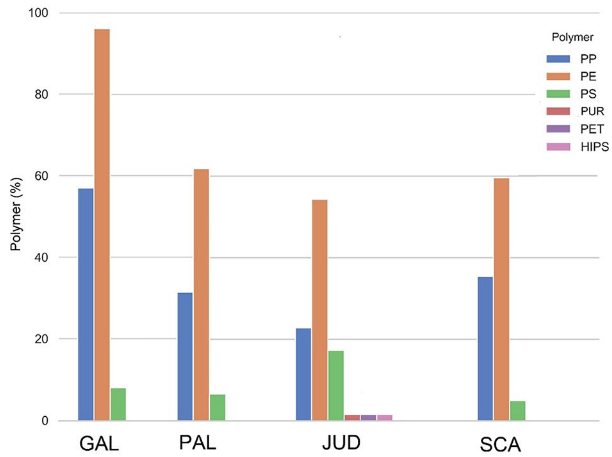

Figure 5. Polymer distributions of the microplastics at the Caribbean and Pacific coasts in Panama. GAL indicates Punta Galeta Beach; HIPS, high impact polystyrene; JUD, Juan Diaz Beach; PAL, Palenque Beach; PE, polyethylene; PP, polypropylene; PS, polystyrene; PUR, polyurethane; PET, polyethylene terephthalate; SCA, San Carlos Beach.

Discussion

Protocols applied in European countries for MP analysis on beach sands have proved to be appropriate for studies in Latin American countries.[41-45] These protocols are based on categories such as abundance, size, shape, color, and polymer type. Particle size distributions have not been assessed in this article. Our aim was to study the fraction between 1 and 5 mm. However, when the plastic materials remain in the environment for a long time, they are exposed to strong solar radiation, wind erosion, and friction against the sand, so that they become fragile and fragment easily. Therefore, it is difficult to prevent that a few samples break during preparation, thus leading to results that do not reflect reality. A second complication occurred in the mechanical sieving step. We observed that, in some cases, when the original sample contained large amounts of sand and organic residues, sieving is more difficult. Consequently, under such conditions, the process for obtaining plastic debris can be less efficient. To manage this difficulty, the maximum amount per sample to be prepared was standardized to not exceed the value of 1.0 kg of dry sand.

First, a mechanical sieving step was performed. Subsequently, a visual separation of the MP in the sand sample was done. Afterward, density separation was performed in the saline solution. In our experience, this sequence of steps proved to be more efficient in terms of time for extracting MP in the 1 to 5 mm size range (see section "Sample preparation and physical characterization of microplastics" on Methodology). After visually counting the particles (items/m^2), we found that reporting the data by weight of the isolated and clean plastic shape in relation to the original sample dry weight (W/W) could be more suitable. This applies particularly, if the polymer type is easily identifiable but fragile (eg, Styrofoam). In addition, counting the exact number of fibers could be difficult and error-prone because they are entangled and may form fiber clusters. Also, in this case, the value could be reported in W/W units. As depicted in Figures 4 and 5, Pacific beaches show a higher diversity of shapes and polymer categories than the Caribbean ones. Figure 4 shows that the Juan Diaz (JUD) and San Carlos (SCA) beaches (at the Pacific coast) proved to be mainly characterized by secondary MP (fibers, films, sponges, and foams). Primary MP such as pellets occurred in very low amounts. The results found in the literature[46] suggest that the high presence of secondary MP in debris may be related to an increase in anthropogenic activities. The Pacific area is highly populated, with extensive human activity (eg, recreational usage, tourism, fishing, sailing, and surfing). Panama City (with almost 1 million inhabitants) has a mixed sewage water system. Solid waste management is poorly organized. This situation corroborates the results observed for MP shape distributions on the Pacific coast. A similar finding was observed for the distribution of polymers (Figure 5), as the lack of adequate waste management and the increase in anthropogenic activities favor the presence of typical household waste polymers.[47] Polyethylene is used for single-use bags, plastic bottles, and fishing lines and nets. Polypropylene is found mainly in bottle caps, ropes, textiles, drinking straws, food packaging, and car spare parts. Polystyrene is widely used for food packaging, single-use articles, and insulating construction material. These polymers, once in the waterways and oceans, will generate secondary MP (irregular, broken edges, granules, and filaments/fibers) negatively affecting marine-coastal environments. These findings are consistent with similar studies conducted on sandy beaches in the region, where PE, PP, and PS are the most reported chemical classes.[43,45,48,49]

When comparing the number of plastic particles found in Pacific beaches with the GAL beach on the Caribbean coast, plastic particle numbers were lower. However, there is a greater variability in the shape of the plastic particles found in the Pacific beaches. We interpret this as being driven by the high anthropogenic activity along the Pacific coast. In terms of MP concentration, it was determined that while the Juan Diaz (JUD) beach (in Panama City) has 105 ± 96 items/m^2, the San Carlos Beach (SCA) has 34 ± 28 items/m^2. One reason for this difference is that San Carlos Beach is a leisure and tourism area with better waste management, which is organized by the local community to attract investors and tourism.

By analyzing the beaches at the Caribbean Sea, it was found out that although Punta Galeta Beach (GAL) is in an environmentally protected area, it has a higher MP concentration (294 ± 316 items/m^2) than the fishermen town Palenque (PAL: 62 ± 76 items/m^2). Punta Galeta Beach is managed by the Smithsonian Research Institute, consisting of a natural laboratory for mangroves and marine species, so that only specialized scientists and technicians are allowed to be in the area. Nevertheless, despite all the protective measures, the concentration of plastic debris is significant.[50] In addition, Figure 4 depicts that Caribbean beaches have higher concentrations of pellets than those in the Pacific, which point to the existence of primary MP. Its origin may be associated with the disposal or unintentional loss of packaging materials or raw materials during port activities. The proximity to the Panama Canal, the Port Manzanillo, and Port Cristobal can be affecting negatively both the Punta Galeta and Palenque beaches. Considering that PE is the main polymer used in the manufacture of microspheres or pellets (cylinders, disks, spherules, flat, ovoid), this corroborates the fact PE are greatly predominant as shown in Figure 5. In turn, white and colorless MP are predominant in the 4 beaches, as indicated in other studies.[51]

Finally, the large amounts of polymer particles observed on the Caribbean side suggest that they may be subject to the effects of the coastal dynamics (intricately linked to winds, waves, and land formations) (see Figure 1). The results also suggest that the coastal currents may influence the distribution of plastic debris originating in the Caribbean area, being in some cases more important than the influence of local human activities or the number of inhabitants on the coastal-marine environment.

Conclusions

This article reports the first study on the distribution of MP debris on the Pacific and Caribbean beaches of Panama that will help to understand the environmental and socioeconomic impacts of these pollutants. Suggestions are proposed to improve a few steps of the procedure for collecting and analyzing beach sand samples, to provide effective protocols for the extraction and classification of MP debris. They are important for the scientific research of MP pollution in the region. In addition, the data obtained are of great importance for the effective sustainable environmental management of coastal-marine ecosystems in Latin America, which can be achieved through regulations and monitoring based on scientific knowledge. The relevance of having MP inventories lies in the fact that this tool reveals the potential risks that high concentrations of MP debris might have for economy, tourism, public health, and environment.[22,52-54]

Our results indicate that the concentration of plastic particles found in Pacific beaches is lower compared with the Caribbean coast. In contrast, we found a greater variability of shapes in the Pacific beaches. We conclude that this is due to the high anthropogenic activity along the Pacific coast. In general, MP debris pollution in the Pacific and Caribbean beaches of Panama is influenced by anthropogenic activities (household and industrial wastes) and coastal dynamics. On the Caribbean coast, winds, waves, and land formations seem to play an outstanding role in the MP pollution process, as these are environmentally protected areas. This means that there is low anthropogenic intervention and land-based sources of plastic pollution can be rather ruled out. The occurrence of higher concentrations of MP debris observed in the GAL beach in comparison with the PAL beach is consistent with the coastal current model proposed by Zhang et al.[55] These authors concluded that the Caribbean coast (with their complex hydrodynamic structures, interactions with tides, river plumes, and currents) is the main factor influencing the transport of the marine litter. Therefore, the deposition of debris in beaches is strongly affected by the profile of the relief and the energy profile of the waves (beach morphodynamics). A similar conclusion can be drawn for the movement of plastic debris on the Pacific coast, justifying why JUD beach has a higher concentration of MP than the SCA beach. These findings emphasize the importance of studies on coastal ocean dynamics and its role in the transport of suspended and floating MP from the North Atlantic Gyre, through the Caribbean Current and Antilles Current to the Isthmus of Panama.

Certainly, additional studies should be conducted in other coastal regions of Panama to confirm this trend, especially in the areas of touristic attractions, water sport activities, fish and seafood farms, as well as sea salt production. A multidisciplinary approach including oceanographic experts will be of great importance to properly explain the coastal dynamics that influences the deposition of plastics and another marine litter. However, it is already possible to warn about the extreme need to create sustainable plastic waste management actions to prevent/mitigate the entry of plastic waste from the land to waterways and oceans and the subsequent generation of MP debris.

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Author Contributions

DDdB conceived and designed the experiments, analyzed the data, and wrote the first draft of the manuscript. DDdB, JFD, OG-O, JPdSF, and RMdA contributed to the writing of the manuscript. DDdB and JO contributing to the laboratory analysis. DDdB, JFD, JO, OG-O, SGA, MV, JPdSF, and RMdA agree with manuscript results and conclusions. DDdB, JFD, and RMdA jointly developed the structure and arguments for the paper. DDdB and JFD made critical revisions and approved final version. All authors reviewed and approved the final manuscript.

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