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Litter Content of Colombian Beaches and Mangrove Forests: Results from the Caribbean and Pacific Coasts

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Abstract: Litter abundance and typology were investigated at different beaches and mangrove forests at nine sites on the Colombian Caribbean and Pacific coasts. Average litter abundance on the Caribbean Sea beaches (1.42 items/m^2–12.21 g/m^2) and in mangrove forests (1.29 items/m^2–28.72 g/m^2) were greater than that of the Pacific Ocean beaches (0 items/m^2–0 g/m^2) and mangrove forests (1.13 items/m^2–79.41 g/m^2). The most abundant litter material was plastic, which represented 93.61% of the total litter content. According to the Clean Coast Index, the sites analyzed in the Caribbean Sea were "Moderate" to "Extremely Dirty", while those in the Pacific Ocean were "Clean" to "Moderate Dirty". The Magdalena River is considered the main source of litter on the Caribbean Sea coast, while on the Pacific Ocean coast, litter is essentially associated with the mismanagement of solid wastes. This study constitutes a baseline on the litter content of beaches and mangrove forests, and is useful for establishing sound strategies for their protection, restoration and conservation.

Keywords: Clean Coast Index (CCI); 3S tourism; coastal contamination; plastic pollution; Magdalena River; department of Atlántico; Tumaco municipality

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1. Introduction

Marine litter is defined as any solid, man-made material deliberately or accidentally discharged into marine and coastal environments [1,2] and can be classified as small (1–40 mm), meso- (40.01–200 mm) and macro-litter (>200.01 mm) [3]. The origin of marine litter is mostly (80%) linked to land-based activities. Discharged items are mainly transported to marine and coastal environments through rivers and winds, or are directly abandoned on the beach by visitors. A lower percentage (20%) of litter is of marine origin and is mostly related to maritime transport, fishing, and off-shore oil extraction activities [4,5].

The transport and accumulation of litter depends on multiple factors such as oceanic and climatic conditions and beach geomorphological characteristics, among others [4,5]. Marine litter consists of different materials, including plastic, glass, wood, metal, rubber, textiles, and paper [4,6], with plastic items considered the main abundant and potential pollutants [2]. It is considered that from 6 to 10% of the annual global plastic production (ca. 315 million tons) ends up in marine environments [4,6].

It is estimated that, by 2050, 10 billion metric tons of plastic waste will be accumulated in landfills or in the natural environment, and there will be more plastic pieces (by weight) than fish in the ocean [2,5]. Overproduction, high use, and the great durability of plastics, along with inefficient waste management practices, are considered the most important reasons for the rapid increase of plastic marine litter over the last several decades [1].

The impact of marine litter on organisms is mainly related to entanglement, suffocation, and their ingestion and subsequent transfer to tissues and organs, a process that concerns the entire food chain, including humans [4,7,8]. Marine litter also favors non-native species dispersal, and the adsorption of persistent organic pollutants and heavy metals takes place on the surface of plastic items [4]. Marine litter may also affect the safety of bathers (because of cutting and sharp objects), and has serious social and economic impacts including aesthetic deterioration of coastal scenery (which produces rejective reactions of beach visitors), damages to recreational boats and fishing activities, and extra expenses needed to carry out beach clean-up operations, among others [2,6,8].

Mangrove forests constitute an ecosystem whose functions are of great ecological, aesthetic, recreational, scientific, social, economic, and cultural interest [9,10]. They are composed of unique plant species, i.e., halophytic trees and shrubs with morphological, physiological, and reproductive characteristics that allow them to survive in a critical interface among terrestrial, estuarine, and marine environments [11]. Presently, mangrove forests occupy ca. 14 million hectares worldwide, and more than two-thirds of them are found in 18 countries: Indonesia, Brazil, Australia, Mexico, Nigeria, Malaysia, Myanmar, Bangladesh, Cuba, India, Papua New Guinea, Colombia, Guinea Bissau, Mozambique, Madagascar, Philippines, Thailand, and Vietnam [11–13]. Colombia is the only country in South America with mangrove forests on both the Caribbean Sea and Pacific Ocean coasts. The forests cover an area of ca. 379,954 hectares, 87,230 of which are recorded along the Caribbean Sea coast where five mangrove species have been reported (i.e., *Avicennia germinans* and *Rhizophora mangle* (the two most abundant) and, secondarily, *Laguncularia racemosa*, *Conocarpus erectus* and *Pelliciera rhizophorae* [10]); and 292,724 ha are recorded along the Colombian Pacific coast [14,15], where nine mangrove species have been reported (i.e., those described from the Caribbean Sea coast plus *Rhizophora harrisonii*, *R. racemosa* and *Mora oleifera* [16]). Mangrove forests are considered a strategic ecosystem for adaptation to climate change [11,17]; however, presently most of the mangrove forests of the Colombian Caribbean Sea coast are under stress mainly due to anthropogenic activities such as: the construction of roads and tourist infrastructure; expansion of urban, agricultural and industrial frontiers; indiscriminate logging; and increased erosion linked to the emplacement of groins/breakwaters, among others [11,18]. The loss of mangrove cover on the Pacific Ocean coast is mainly related to illegal logging for energy-source purposes, and the construction of stilt houses [19,20].

Different studies have demonstrated the capacity of mangroves to act as marine litter traps due to their root structure [9,21,22], and how trapped litter affects mangrove development by undergoing degradation processes that generate microplastics able to enter the food chain, mainly at lower trophic levels, but with subsequent effects on organisms at higher trophic levels via bioaccumulation [23–25]. Microplastics and chemical additives used in the manufacture of plastic materials may be toxic to marine organisms [23,25]. In addition, because of their hydrophobic nature, microplastics may absorb persistent organic pollutants (e.g., polycyclic aromatic hydrocarbons and polychlorinated biphenyls), which can be released into an organism's tissues when ingested [23].

Despite the exosystemic importance of mangrove forests and the relevant environmental impacts on them of litter (especially of plastic materials), only four studies have been carried out to investigate the impact and origin of marine litter in Colombian mangrove forests: one in the islands of Providencia and Santa Catalina after Hurricane Iota, one in the Bay of Buenaventura (in the Pacific coast), and two in Ciénaga Grande de Santa Marta (in the department of Magdalena, on the Caribbean Sea coast) [26–29].

The aim of this paper is to determine the amount, typology, and sources of litter at nine sites including beaches and mangrove forests mainly located along the department of Atlántico (in the Caribbean Sea coast)—which contains ca. 613.3 ha of mangrove forest—and the Tumaco municipality in the department of Nariño (on the Pacific Ocean coast) [30], which contains ca. 24,570 ha of mangrove forest [31]. At each site, litter was determined at different beach zones and in homogeneous mangrove zones (i.e., areas characterized by the clear predominance of specific mangrove species). The objective of this paper is the establishment of a baseline amount and typology of litter stranded/trapped at each site and the determination of possible relationships between mangrove zone location and litter abundance/typology, keeping in mind that this is of paramount importance to establish sound management actions to protect mangrove forests and their associated ecosystem services.

2. Materials and Methods

2.1. Study Area

The coast of Colombia has a total length of 5548 km and includes the Caribbean Sea (2733 km) and Pacific Ocean (2815 km) coastlines [32], Figure 1. The Caribbean Sea coast borders with Panama to the southwest and Venezuela to the northeast, and constitutes a mixed, semi-diurnal microtidal (<2 m) environment, with a maximum tidal amplitude of 60 cm [33]. It is a tropical environment with seasonal variations in rainfall from the dry season (December–March) and the transitional seasonal (April–July) to the rainy season (August–November) [11]. Maximum precipitation reaches ca. 2500 mm/yr and mean annual temperature is ca. 27 °C [33]. Offshore waves essentially approach the coast from the first quadrant and are related to the trade winds (*Alisios*) recurrent during the December–March period [11]. Secondary refracted and diffracted wave fronts approach the coast from the fourth and third quadrants. Significant wave height, which is the average wave height of the highest one-third of the wave records, is ca. 2 m, and the average peak period is 7 s [34]. The net longshore drift has a dominant southwestward component, minor reversal to the northeast takes place during the rainy period when southerly winds dominate and set up short, high-frequency waves [35,36].

The Colombian Pacific Ocean coast borders Panama to the north and Ecuador to the south [37]. This region is characterized by heavy rainfall, numerous rivers, and luxuriant vegetation [38]. The climate of the Pacific Ocean coast is humid tropical, dominated by the migration of the Intertropical Convergence Zone and its interaction with the high relief of the Western Ridge of the Colombian Andes. The average temperature is 26 °C with minimum values of about 14 °C. Rainfall reaches a maximum of ca. 10,000 mm/year in the central zone, and decreases towards the north and south to ca. 3000 mm/year [38]. The tide is mixed semi-diurnal with a mesotidal range, i.e., average amplitude between 2 and 4 m. Predominant winds come from the south and from the west to the southwest along the central and southern parts of the Pacific Ocean coast. Significant waves are 0.5–1.5 m high during calm weather and 2.5–3.5 m high during storm periods [38].

The Caribbean Sea of Colombia has ca. 87,230 ha of mangrove forests, with the largest extensions in the Ciénaga Grande de Santa Marta (department of Magdalena), El Canal del Dique, the Archipelagos of Nuestra Señora del Rosario and San Bernardo (Bolívar), the bay of Barbacoas, and the mouth of the Sinú River (department of Córdoba) [39]. The investigated sites are located in the departments of Atlántico and Magdalena, Figure 1.

Along the 64.5 km long coastline of the department of Atlántico [11,40], mangrove forests recorded important losses over recent decades, i.e., their cover decreased from 1184 ha in 1998 to 613 ha in 2005 because of the emplacement of human settlements linked to tourism and urban developments, illegal logging, the modification of fresh water supplies, and pollution problems [11,41]. Sites investigated in this paper are close to the Magdalena River mouth (Figure 1) that drains a basin of 257,430 km^2, corresponding to 724 municipalities representing 80% of the Colombian population [11]. The river transports to the coast large amounts of wastes and pollutants [42].

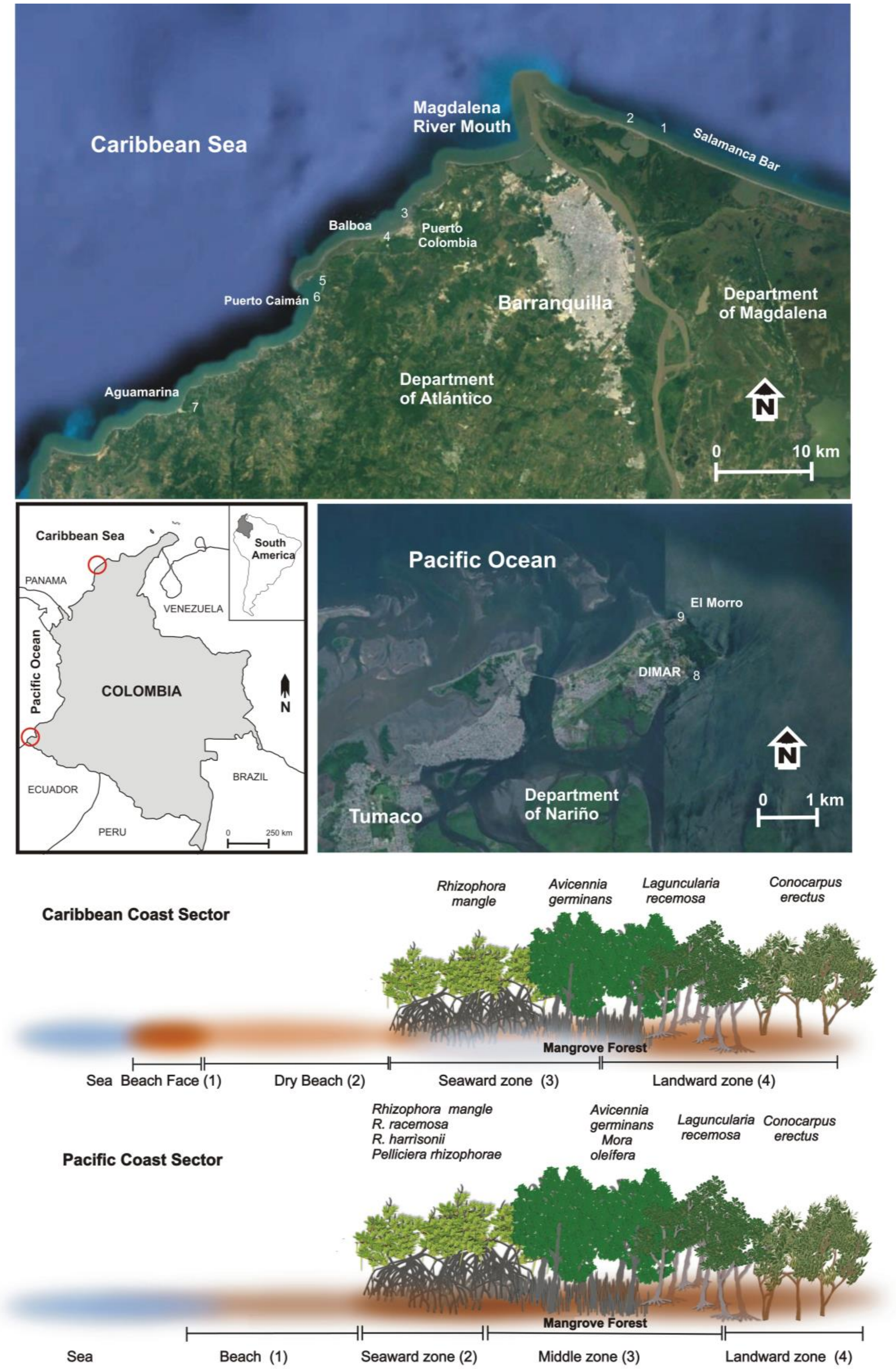

Figure 1. Location map showing the position of the nine studied sites. The investigated beaches and mangrove forest zones are also presented, as well as the typical zoning of mangrove species along the Caribbean Sea and the Pacific Ocean coasts.

The Pacific Ocean coast of Colombia has ca. 292,724 ha of mangrove forest, with the largest extensions found at the Jurado River mouth, in the Gulf of Tribugá, in the southern area of the department of Chocó, and, especially, at the departments of Valle del Cauca and Nariño, close to Ecuador [43]. In the Nariño department, where the investigated sites are located, 72,262 ha of mangrove forest has been recorded [44]. It is mainly affected by sewage and solid waste dumping, logging, and agricultural and livestock activities that generate an annual loss of 0.05% of coverage [44,45]. In Tumaco municipality, the main impacts on mangrove forests are related to urban growth, tourism, port traffic, the development of shrimp farming, and the discharge of urban and industrial wastewaters [31]. Unfortunately, Tumaco is an area where different illegal armed groups converge and has one of the highest rates of violence in the country [46]; for this reason it was not possible to investigate a large number of sites in this area.

2.2. Sampling Sites Description

We investigated seven sites along the departments of Magdalena and Atlántico (on the Caribbean Sea coast of Colombia) and two in the department of Nariño (on the Pacific Ocean coast of Colombia) in order to obtain a baseline on litter content and amount at each site and at the different zones of each site (Figures 1 and 2). In order to predominantly investigate litter related to marine inputs, i.e., not linked with bathers or other recreational beach activities—which can vary from place to place making the comparison among different sites unrealistic,—all sites but one (Puerto Colombia) were selected in rural and remote areas [47]. The site surveyed at Puerto Colombia, a village area, was in a coastal sector not frequented by beachgoers and can be considered as rural. In relation to the Pacific Ocean coast, the sampling included coastal sites close to the urban perimeter of Tumaco but far from direct anthropic disturbances, i.e., they were essentially influenced by the local dynamics of waves, currents and tides.

Each site investigated usually included the beach and different backing zones of mangrove forests (Figure 1). In places, the beach was nonexistent due to erosion by waves. Litter observation was carried out along transects 10 m in width (in the alongshore direction) [24,29] landward extended from the shoreline, according to the specific characteristics of each site, i.e., the cross-shore dimension investigated varied between sites (from 10 to 124 m). At each site, litter content was analyzed at different zones (i.e., parts of beach and mangrove environments): namely, at the beach face (that coincided in the Caribbean Sea coast with the strandline because it is a microtidal environment), on the dry beach, and in homogeneous zones of mangrove forests, i.e., zones characterized by the clear predominance of a specific mangrove species. Concerning the mangrove forests, at each sampled zone the following aspects/parameters were characterized: mangrove species, relative density of trees ("high"—tree coverage >75%; "moderate"—51–75%; and "low"—≤50%), presence/absence of pneumatophores and seedlings, and presence of other plant species (Table 1) [21,24,48].

2.3. Marine Littler Characterization

Surveys were carried out in December and January 2022 on the Caribbean Sea coast, and in August 2022 on the Pacific Ocean coast. At each site two observers covered the whole beach and mangrove forest zones by moving along 1 m separated transects parallel to the shoreline. All litter items larger than 2 cm in the longest linear dimension, ensuring the inclusion of bottle caps and cigarette butts as recommended by UNEP/MAP [49], were collected and brought to the laboratory. There, items were carefully washed to remove adhered sediments, dried under natural conditions, and weighed. Litter items were identified by assigning them to diverse categories according to their composition [50,51]. The amount of litter was expressed as number of items per linear meter (items/m) and square meter of beach/mangrove forest zone (items/m^2), and as weight of items per linear meter (g/m) and per square meter (g/m^2).

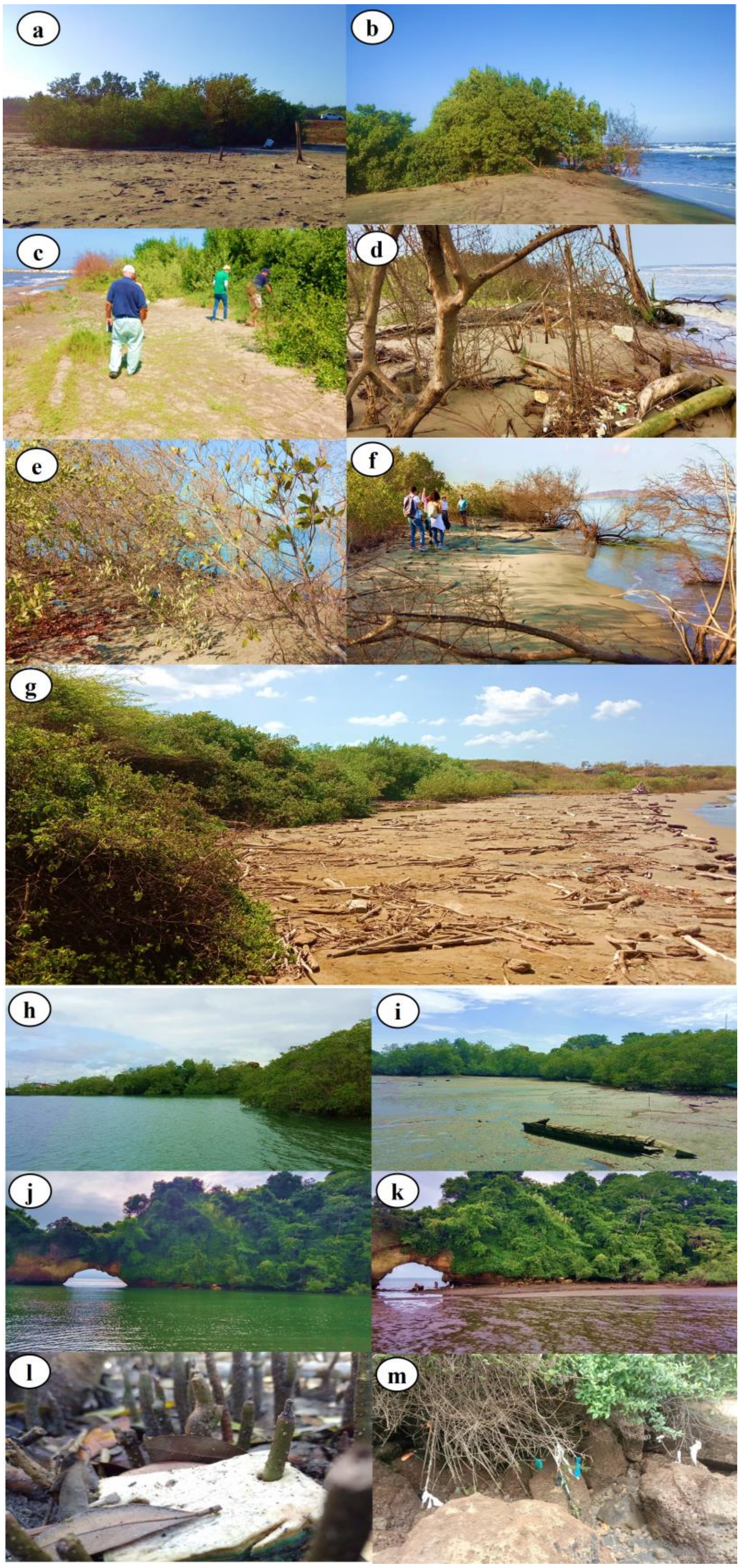

Figure 2. Images of the beaches/mangrove forests studied: (**a**) Salamanca A; (**b**) Salamanca B; (**c**) Puerto Colombia; (**d**) Balboa; (**e**) Puerto Caimán A; (**f**) Puerto Caimán B; (**g**) Aguamarina; (**h**) Complejo DIMAR (at high tide); (**i**) Complejo DIMAR (at low tide); (**j**) El Morro (at high tide); (**k**) El Morro (at low tide); (**l**) Litter trapped in a pneumatophore at Salamanca A; (**m**) The "Christmas tree" effect due to litter trapped in a plant of *Rhizophora* sp. at El Morro.

Table 1. Characteristics of beaches and mangrove forests at each sampled site.

Colombian Caribbean Coast								
Site Number and Location	**Distance of the Mangrove Forest from the Shoreline**	**Zone 1 Cross-Shore Dimension/Surface of Beach Face**	**Zone 2 Cross-Shore Dimension/Surface of Dry Beach**	**Zone 3 Cross-Shore Dimension/Surface Seaward Mangrove Zone**	**Zone 4 Cross-Shore Dimension/Surface of Landward Mangrove Zone**	**Mangrove Specie/ Density**	**Pneumatophores and Seedlings**	**Other Plants**
1-Salamanca A	30 m	10 m/100 m^2	20 m/200 m^2	10 m/100 m^2	–	*A. germinans*, *R. mangle*/Low	Yes	–
2-Salamanca B	2 m	2 m/20 m^2	–	10 m/100 m^2	–	*L. racemosa*, *A. germinans*/High	Yes	*Batis marítima*
3-Puerto Colombia	13 m	3 m/30 m^2	10 m/100 m^2	15 m/150 m^2	8 m/80 m^2	*C. erectus*, *A. germinans*/High	Yes	*Prosopis juliflora* *Batis marítima*
4-Balboa	0 m	–	–	10 m/100 m^2	10 m/100 m^2	*A. germinans*/Low	Yes	*Batis marítima*
5-Puerto Caimán A	0 m	–	–	10 m/100 m^2	–	*C. erectus* *A. germinans*/Low	No	*Batis marítima* *Portulaca oleracea*
6-Puerto Caimán B	5 m	5 m/50 m^2	–	10 m/100 m^2	–	*C. erectus* *A. germinans*/Low	No	*Batis marítima*
7-Aguamarina	22 m	2 m/20 m^2	20 m/200 m^2	10 m/100 m^2	–	*Conocarpus erectus*/Low	No	–
Colombian Pacific Coast								
Site	**Distance of the Mangrove Forest from the Low Tide Position**	**Zone 1 Beach (Lower Foreshore)**	**Zone 2 Mangrove Seaward Zone (Middle Foreshore)**	**Zone 3 Mangrove Middle Zone (Middle Foreshore)**	**Zone 4 Mangrove Landward Zone (Upper Foreshore)**	**Mangrove Specie/ Density**	**Pneumatophores and Seedlings**	**Other Plants**
8-Complejo DIMAR	93 m	93 m/930 m^2	12 m/120 m^2	15 m/150 m^2	4 m/40 m^2	*Rhizophora racemosa* *R. mangle*, *A. germinans*, *L. Racemosa*/ High	Yes	*Acrosticum danaeifolium*
9-El Morro *	–	–	11 m/110 m^2	38 m/380 m^2 *	12/120 m^2	*R. Racemosa*, *R. Mangle*, *L. Racemosa*/ High	Yes	*Acrosticum danaeifolium*

* Mangrove forest site with no beach in front; the symbol "−" indicates that such zone does not exist in the site considered.

To determine the level of cleanliness of each zone, the Clean Coast Index (CCI), developed by Alkalay et al. [52] was calculated according to the following expression:

$$CCI = \frac{\text{Total litter on sampling unit}}{\text{Total area sampling unit}} \times k \quad (1)$$

The index reflects the total number of items/m^2, which is the result of the product of the width of each beach/mangrove zone (10 m in this case) and the zone length, i.e., the cross-shore dimension of each zone that varied between sites according to the specific geomorphological characteristics and vegetation cover typology and continuity. Consistent with the CCI index calculation [52], a coefficient K = 20 was used in equation (1) to make sure that the value of the resulting index did not fall between 0 and 1. CCI varies from "Very Clean" (0–2), "Clean" (2–5), "Moderate Dirty" (5–10) and "Dirty" (10–20) to "Extremely Dirty" (>20) [52–54].

2.4. Statistical Approach

To compare litter composition among coastal sites, a nonparametric multi-dimensional scaling analysis (nMDS) was performed. The objective of the nMDS analysis is to group data points into classes of similar points based on a series of variables, i.e., to represent the original position of data in multidimensional space as accurately as possible using a reduced number of dimensions (typically two) that can be easily plotted and visualized. The nMDS relies on rank orders (distances) for ordination, and this technique is based on a similarity and dissimilarity matrix. Previous to the analysis, the dataset was normalized, i.e., the number of items per zone was converted into items/m^2 and transformed to the square root. Analysis was made using the Bray–Curtis dissimilarity index [55]. In the nMDS plots, litter categories with a Pearson correlation > 0.7 (when item numbers were considered) and 0.8 (for item weights) were represented as vectors from a central point in a 2D space plot. Orientation of the vectors is related to the composition of the most important items. Analysis was conducted using PRIMER V.6 (Plymouth Marine Laboratory, UK). Very few coastal sites were removed from the nMDS analysis because they contained very few items or no litter. Cluster analysis was carried out as a complementary technique. This is a statistical method used with the goal of sorting different objects or data points into groups in such a manner that the degree of association between two objects is high if they belong to the same group and low if they belong to different groups. This helps to discover structures in data without explaining why those structures exist. The treatment of the data and the index for calculating dissimilarity were those used for the previous technique.

3. Results

Overall, beach litter was represented by small- and medium sized-fresh items that presented low abrasion and discoloration, whereas items in mangrove forests often presented larger sizes and showed poor conservation states. Considering all the zones investigated along the seven Caribbean Sea and two Pacific Ocean sites (Figures 1 and 2), a total of 2664 items (or 86 kg), belonging to 59 litter groups, were counted in an area of 3500 m^2, with an average abundance per zone of 0.761 items/m^2 (or 35.8 g/m^2) ranging from 0 to 6.9 items/m^2 (or 16 kg). On the Caribbean Sea coast, the average amount of litter was 1.3 items/m^2 (or 22.56 g/m^2), while on the Pacific Ocean coast this was 0.3 items/m^2 (68.1 g/m^2). A total amount of 36 kg of litter was collected at the seven Caribbean Sea sites, while 50 kg were collected at the two Pacific Ocean sites. Litter abundance and weight per zone and site surveyed are presented in Table 2.

Table 2. Abundance (items/m^2) and *weight* (g/m^2) per zone and site. The four zones investigated are reported in Figure 1. Total values were calculated per site, considering the total number of items per site and the total area of each site.

Site	Coast	Zone				TOTAL
		1	2	3	4	
1-Salamanca A	Caribbean	0.060 *0.21*	0.590 *3.26*	1.240 *29.28*	–	0.620 *9.00*
2-Salamanca B	Caribbean	0 *0*	–	0.570 *27.94*	–	0.475 *23.28*
3-Puerto Colombia	Caribbean	6.933 *76.04*	1.030 *2.54*	0.813 *35.19*	0.875 *17.48*	1.397 *25.59*
4-Balboa	Caribbean	–	–	1.230 *44.69*	2.890 *67.39*	2.060 *56.04*
5-Puerto Caimán A	Caribbean	–	–	1.640 *27.02*	–	1.640 *27.02*
6-Puerto Caimán B	Caribbean	0 *0*	–	0.990 *18.73*	–	0.660 *12.48*
7-Aguamarina	Caribbean	0 *0*	2.725 *15.59*	1.400 *18.17*	–	2.141 *15.42*
8-Complejo DIMAR	Pacific	0 *0*	0.083 *8.34*	1.067 *101.72*	4.775 *196.63*	0.291 *19.45*
9-El Morro	Pacific	–	0.773 *144.51*	0.132 *25.24*	0 *0*	0.221 *41.78*

The symbol "–" indicates that such a zone did not exist at the site considered.

3.1. Litter Abundance and Weight

Litter abundance (items/m^2) for the different zones of each site investigated on the **Caribbean Sea coast** is shown in detail in Figure 3a, and the mean and median values recorded at each site investigated and data dispersion (or distribution) are presented in Figure 3b. Litter amounts expressed as weight per square meter (g/m^2) are presented in Figure 3c,d. Beach face zones showed the lowest amount of litter (in number of items and weight), and the highest amount was generally recorded in mangrove forest zones (Figure 4a,b). Lastly, the beach face zone of site no. 3 recorded a huge accumulation of litter constituting an outlier in both plots of Figure 4.

Regarding litter abundance and weight for the different zones of each site investigated along the **Pacific Ocean coast** (Figure 1), values ranged from 0 to 4.77 items/m^2 (0−196.6 g/m^2). Considering all items and zones, the two Pacific sites presented lower abundance (0.2 and 0.3 items/m^2) than the Caribbean Sea sites (ranging from 0.4 to 2.1 items/m^2, Table 2). In the beach zone of site no. 8, no litter was observed and the mangrove seaward zone only presented 0.08 items/m^2 (or 8.3 g/m^2). The mangrove middle and landward zones of site no. 8 registered the highest abundance and weights: 1.1 and 4.8 items/m^2 (101.7 and 196.6 g/m^2), respectively (Table 2). However, at site no. 9, the highest values were recorded in the seaward mangrove zone (0.8 items/m^2 and 144.5 g/m^2), but litter items had also accumulated in the middle mangrove zone (0.1 items/m^2 and 25.2 g/m^2, Table 2).

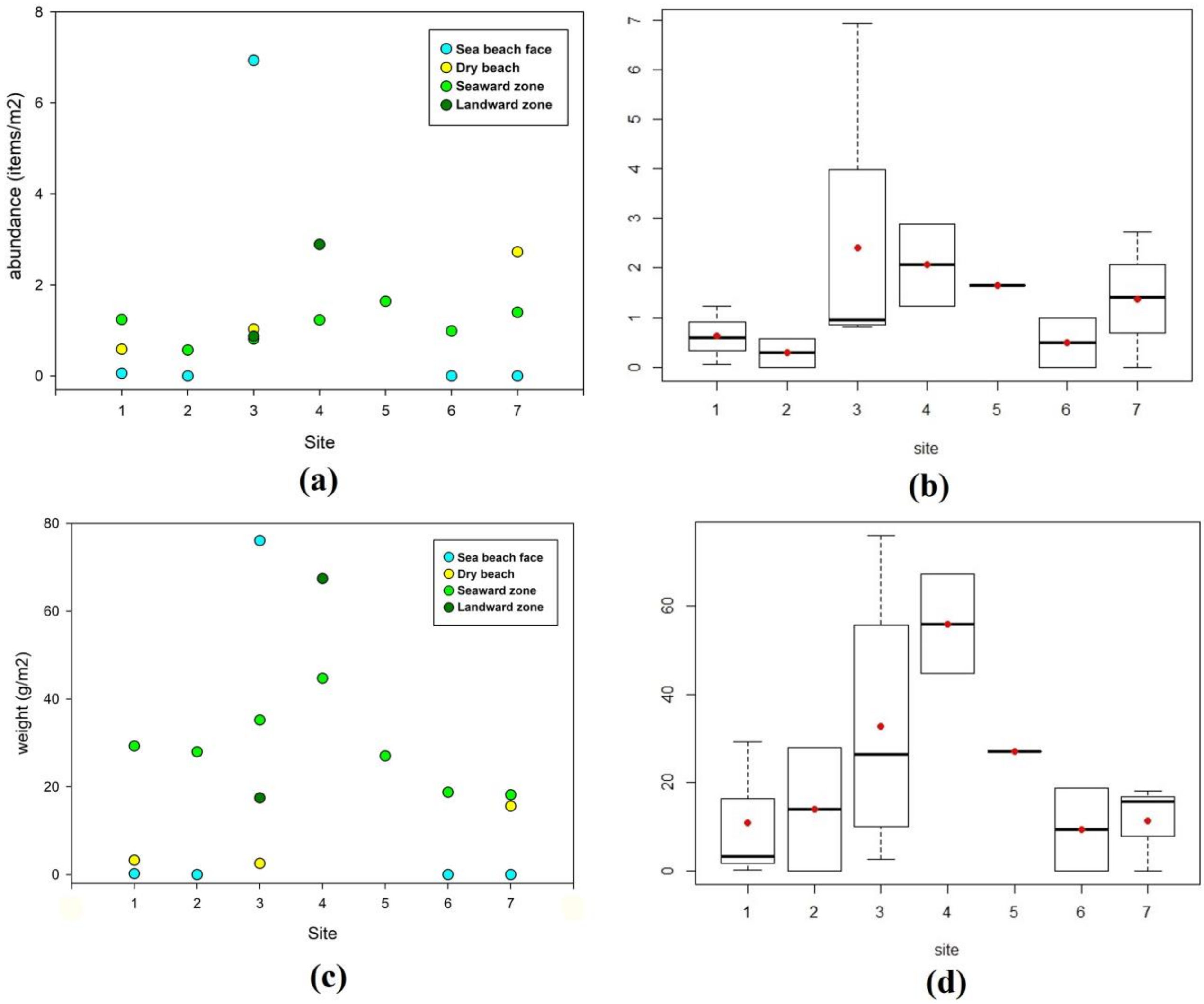

Figure 3. Caribbean Sea coast. (**a**) Litter abundance (items/m^2) at all beach/mangrove zones per site. (**b**) Box plots concerning litter abundance values (items/m^2) per each site investigated; red dots represent mean values and black lines median values. (**c**) Weight of recollected litter items (g/m^2) at all beach/mangrove zones per site. (**d**) Box plots concern weights of litter items (g/m^2) per site.

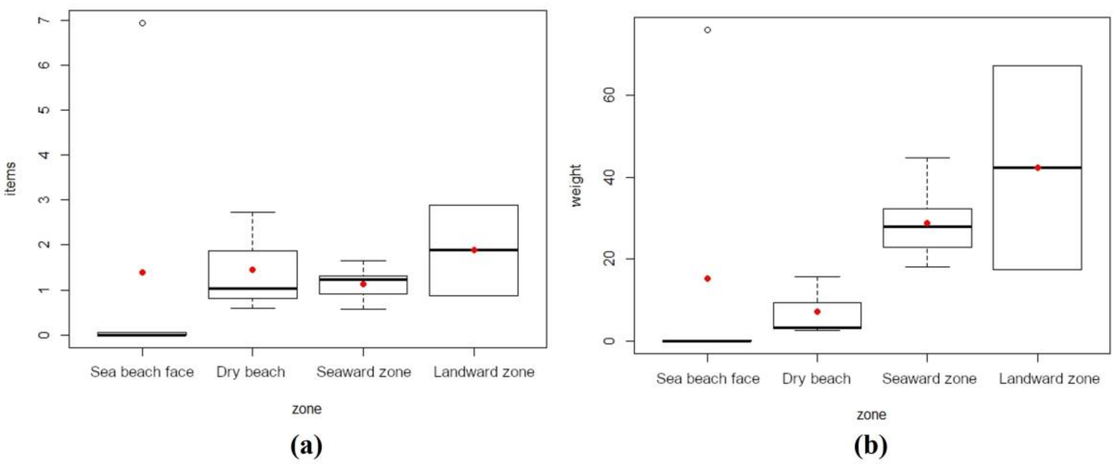

Figure 4. Box plots concerning Caribbean Sea beach/mangrove zones. (**a**) Litter abundance (items/m^2). (**b**) Weight of litter items (g/m^2). Red dots represent mean values and black lines median values.

3.2. Litter Composition

Concerning litter composition across all whole Caribbean Sea and Pacific Ocean investigated sites, most litter items were composed of plastic materials that represented 93.61% of the total litter composition, followed by rubber (2.50%), glass (1.67%), metal (0.96%), cloth (0.96%), paper and cardboard (0.17%), unidentified materials (0.09%), and processed wood (0.03%, Table 3). Despite small differences in the percentage of materials observed between the Caribbean Sea and Pacific Ocean sites, plastic was always the predominant material (Table 3).

Table 3. Litter proportion (%) per type of material in the Caribbean and Pacific coasts of Colombia.

Material	Caribbean Sea Sites (%)	Pacific Ocean Sites (%)	Total (%)
Cloth	0.51	2.46	0.97
Glass	0.99	3.85	1.67
Metal	0.25	3.30	0.97
Paper and cardboard	0.22	0.00	0.17
Plastic	94.72	89.51	93.61
Rubber	3.15	0.36	2.50
Processed wood	0.04	0.15	0.03
Other	0.11	0.36	0.09

Regarding plastic materials, foamed and hard plastic pieces were the most common litter groups accounting for 1039 items, i.e., 39% of the total. Other very abundant plastic litter groups included caps/lids and drinks (<2 L) that accounted for 8% in both the Caribbean Sea and Pacific Ocean coasts. Table 4 shows the 10 litter groups with the highest number of items recorded. Some litter groups such as hard plastic pieces (2.5−50 cm), drinks (<2 L), hard plastic cups, and food wrappers were common to both the Caribbean Sea and Pacific Ocean coasts (Table 4).

Table 4. Most numerous litter items in the Caribbean Sea and Pacific Ocean coasts of Colombia.

Caribbean Sea Sites	%	Pacific Ocean Sites	%
Foamed plastic pieces (2.5–50 cm)	24.4	Film plastic pieces (2.5–50 cm)	26.6
Hard plastic pieces (2.5–50 cm)	20.2	Hard plastic pieces (2.5–50 cm)	13.9
Caps/lids	10.1	Bags (e.g., shopping)	13.5
Drinks (bottles, containers, drums) < 2 L	9.1	Hard plastic cups	13.1
Crisp/sweet packets and lolly sticks	4.8	Glass fragments (2.5–50 cm)	5.6
Hard plastic cups	4.7	Metal fragments (2–50 cm)	5.0
Food wrappers	3.8	Food wrappers	4.4
Drinks (bottles, containers and drums) > 2 L	3.6	Clothing	4.2
Footwear (flip-flops)	2.6	Drinks (bottles, containers, drums) < 2 L	3.4
Foam (insulation & packaging)	2.5	Tubes	2.2

3.3. Litter Distribution

According to the Clean Coast Index (CCI) proposed by Alkalay et al. [52] the least polluted areas ("Very Clean") corresponded to beach face zones, as observed at the Caribbean Sea sites nos. 1, 2, 6 and 7 (Table 5). On the Pacific Ocean coast, the "Very clean" grade was also recorded, e.g., at beach and mangrove middle and seaward zones of site no. 8 and at mangrove landward zone of site no. 9. The "Clean" grade was recorded at the remaining mangrove zones of sites nos. 8 and 9 (Table 5). The remaining mangrove zones and beach face zone of site no. 3 were in very poor condition and classified as “Dirty” or “Extremely Dirty” (Table 5).

Table 5. Clean Coast Index (CCI) proposed by Alkalay et al. [53].

Site	Coast	Zone 1	Zone 2	Zone 3	Zone 4	TOTAL
1-Salamanca A	Caribbean	Very Clean	Dirty	Extremely Dirty	–	Dirty
2-Salamanca B	Caribbean	Very Clean	–	Dirty	–	Moderate
3-Puerto Colombia	Caribbean	Extremely Dirty	Extremely Dirty	Dirty	Dirty	Extremely Dirty
4-Balboa	Caribbean	–	–	Extremely Dirty	Extremely Dirty	Extremely Dirty
5-Puerto Caimán A	Caribbean	–	–	Extremely Dirty	–	Extremely Dirty
6-Puerto Caimán B	Caribbean	Very Clean	–	Dirty	–	Dirty
7-Acuamarina	Caribbean	Very Clean	Extremely Dirty	Extremely Dirty	–	Extremely Dirty
8-Complejo DIMAR	Pacific	Very Clean	Very Clean	Very Clean	Clean	Moderate
9-El Morro	Pacific	–	Dirty	Clean	Very Clean	Clean

The symbol “−” indicates that such a zone does not exist at the site considered.

Because of the differences in tidal range between the Caribbean Sea and the Pacific Ocean coasts—i.e., sites investigated in the Pacific Ocean coast are daily flooded by the tide and this is not the case for the Caribbean Sea coast—comparison between the two coastal environments is unviable. Additionally, each type of coastline is characterized by the presence of specific plant species that can affect litter dynamics and accumulation (Figure 1 and Table 1). Therefore, statistical analyses carried out in this study only concerned the Caribbean Sea data. Considering the results of the statistical analyses, an interesting grouping among the sampled sites was observed. In terms of litter abundance and typology, yellow points (corresponding to dry beach zones) are located in a different part of the graph with respect to the green points (corresponding to zones in mangrove forests). However, dry beach zones at sites nos. 1, 3 and 7 are more similar to the nearby mangrove zones (i.e., mangroves zones of the same site) than to the corresponding mangrove zones of other sites, suggesting that there is a direct litter transfer from the dry beach zone to the adjacent mangrove zone (Figure 5).

There is also a clear difference among major litter groups. Vectors oriented towards beaches correspond to litter groups that are mostly found on dry beach zones and are related to beach users (spoons, stirrers and caps/lids, Figure 5). Other items are essentially observed in the mangrove forest zones, e.g., drinks (<2 L), foam, film pieces (>50 cm), etc. and are generally light, floating items. Seaward mangrove zones generally registered low amounts of litter. In order to have a better interpretation of the results, sites with no litter were not considered in the statistical analysis. The most dissimilar zone was the beach face of site no. 1, which only recorded six items. Litter composition and abundance at the beach face zone of site no. 3 were similar to values recorded in mangrove zones (Figure 5).

In terms of weight of litter items, dry beach zones are located on the right side of the graph, while mangrove zones are located on the left side (Figure 5). In mangrove zones, litter content in weight is greater than in beach zones, as shown in Figure 5. Some litter items are essentially related to beach users such as cloths, cigarette lighters, spoons and stirrers while others are especially observed in mangrove areas, such as plastic bag ends, footwear, foamed pieces, hard plastic pieces, medical containers and drinks (Figure 5).

In order to better understand the results obtained from the Caribbean Sea sites, cluster analysis was performed to highlight similarities/dissimilarities between zones. In general, mangrove forest zones presented greater similarity with respect to beach zones, in terms of litter composition and weight (Figure 6).

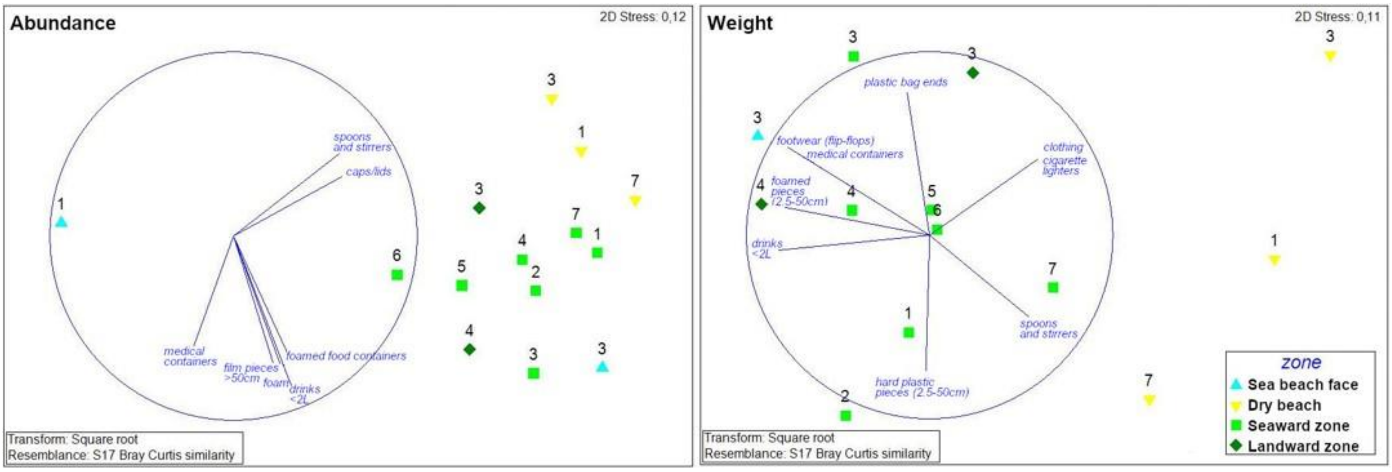

Figure 5. Caribbean Sea coast. Nonparametric multi-dimensional scaling ordination for litter abundance and weight based on litter categories recorded at each coastal zone. Colors (cyan, yellow, light and dark green) correspond to the four zones investigated (beach face, dry beach, seaward and landward mangrove zones, respectively), while labels from 1 to 7 correspond to the sites investigated. Vector labels refer to litter categories that showed a Pearson correlation > 0.7 and 0.8 (for litter abundance expressed in number of items and weight, respectively).

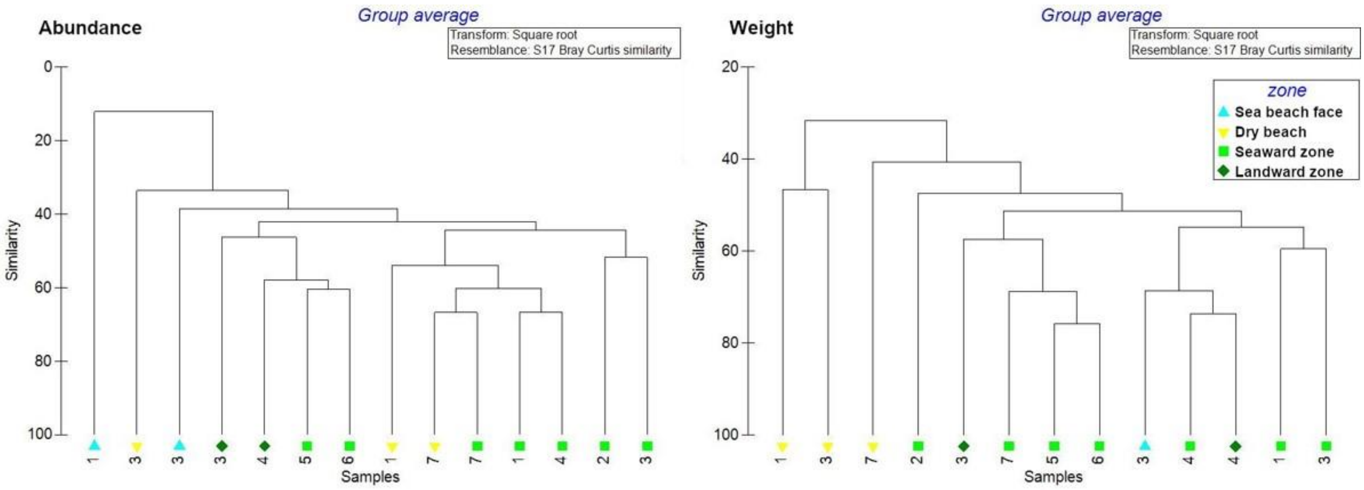

Figure 6. Cluster analysis for abundance and weight of litter items at the Caribbean Sea sites.

On the Pacific Ocean coast, litter items mostly consisted of plastic bags, film plastic pieces (2.5–50 cm), metal fragments (2.5–50 cm), and clothing. Concerning similarities among the different zones sampled along the Pacific Ocean coast, the two sites investigated are not comparable in terms of litter composition, with site no. 8 essentially containing hard plastic pieces (2.5–50 cm), film pieces (2.5–50 cm), drinks (<2 L) and food wrappers, while site no. 9 clothing, bags and glass fragments (2.5–50 cm).

4. Discussion

The presence of litter on Colombian beaches has been extensively studied [56–62] and is mainly associated with tourism/recreational activities (particularly on the Caribbean Sea coast) and poor waste management practices (in the Pacific Ocean coast) [63,64], i.e., deficient beach management programs, a lack of environmental education on the part of beach users, and deficiencies in solid waste treatment and disposal services [62,63,65]. Unlike beaches, which are very dynamic due to being directly and daily exposed to wave impacts, mangrove ecosystems are usually observed in sheltered environments and present a complex network of trees, shrubs and aerial root systems (e.g., pneumatophores and prop roots) that greatly favor litter retention [21,48,66]. Therefore, the findings and lessons learnt from beaches cannot be extrapolated to strategic coastal marine ecosystems such as mangrove forests [48]. In Colombia, only a few studies exist on the impact and distribution of litter in mangrove forests (e.g., in the Ciénaga Grande de Santa Marta and Buenaventura bay, respectively on the Caribbean Sea and Pacific Ocean coasts) [26–29]. This paper is the first to deal with litter assessment and characterization corresponding to different beach zones and homogeneous mangrove forest zones.

4.1. Distribution of Litter in Beach Environments

Average litter abundance on Caribbean Sea beaches (1.42 items/m^2—12.21 g/m^2) and mangrove forests (1.29 items/m^2–28.72 g/m^2) was greater than on the Pacific Ocean coast beaches (0 items/m^2–0 g/m^2) and mangrove forests (1.13 items/m^2–79.41 g/m^2) (Table 2). This is related to the specific location of the sites studied in the Caribbean Sea, since they are very close to the Magdalena River mouth. The Magdalena is the largest river system in Colombia with a length of 1612 km and a drainage basin covering 257,438 km^2 [67,68]. From an administrative point of view, this area, which hosts 80% of the total population of Colombia, belongs to 724 municipalities, 46% of which have no solid waste disposal system [65,68]. It is estimated that the Magdalena River annually deposits 16,700 tons of plastic materials into the Caribbean Sea, which eventually accumulate in the coastal and marine ecosystems of the departments of Atlántico and Magdalena [26,69]. Regarding beach litter pollution along the Department of Atlántico, Rangel-Buitrago et al. [65] confirmed the importance of the Magdalena River inputs as well as highlighting the significance of human activities related to beach tourist use. The relevance of the Magdalena River as the main source of litter items for the sites located in the Caribbean Sea coast was confirmed in this paper, since most of the items encountered i) showed a poor conservation state, i.e., abrasion, discoloration and/or other evidences of a long transport, and ii) were not commercialized in the department of Atlántico (e.g., large-sized Ron bottles, some plastic medical jars, etc.).

In dry beach zones (zone 2) observed items were often related to beach users, as spoons, stirrers and caps/lids. They were probably abandoned on nearby beaches and, then, stranded on the beaches studied in this paper by waves and currents [70]. These litter items are among the most abundant in Europe [71,72] and are also observed on Moroccan beaches frequented by beach users [73].

Beaches analyzed in this study along the Caribbean Sea coast showed an abundance of litter in accordance with Rangel-Buitrago et al. [65] and Williams et al. [60], who reported a high presence of beach litter along the coastline of the department of Atlántico. Litter abundance in this study was higher than that reported on the coast of Cádiz by Asensio-Montesinos et al. [74], with an average of 0.06 items/m^2, and Nachite et al. [75] on the Mediterranean beaches of Morocco, with an average of 0.054 $\pm$ 0.036 items/m^2, but was lower than the amount observed by Lavers et al. [76], who reported an average of 21.68 $\pm$ 19.01 items/m^2 on the Cocos Islands (Australia).

Specifically, the zone 1 of Puerto Colombia (Figure 2c and Table 2) was the site with the highest abundance of litter, mainly plastic items (e.g., foamed plastic pieces, drinks bottles and caps), which coincides with the observations of Williams et al. [60] who reported on such a beach huge amounts of litter along with the presence of many common items plus nappies and condoms. In addition, Rangel-Buitrago et al. in several studies carried out along the Department of Atlántico [77,78], determined that Puerto Colombia was one of the sites with the highest density of plastic items. In other countries, plastic litter also accounted for more than 80% of the total beach litter amount as evidenced in Turkey [79], Italy [80], South Africa [81], Israel [82], and Morocco [75], and different authors have stated that plastics are the most common items in all coastal marine ecosystems [8,83,84]. Lastly, no litter was observed on the beaches investigated on the Pacific Ocean coast, which could be related to the mesotidal range of this coastal environment: flooding tide carries litter items landward accumulating them in correspondence of the landward limit of the tidal area, as observed in similar tidal environments by Convey et al. [85] and Asensio-Montesinos et al. [74].

4.2. Distribution of Litter in Mangrove Forests

Concerning mangrove forests, the results obtained in this paper showed that litter is observed in all zones of mangrove forests (Tables 2 and 5).

In the Caribbean Sea mangrove forests, zone 3 generally presented the highest abundance and weight of items, followed by zones 4 and 2 (Figure 4 and Table 5). Mangrove forests studied in the Caribbean Sea were essentially located in remote places and/or close to beaches not used for bathing, and had no clean-up operations (Figure 2). In this regard, Riascos et al. [28] established that, at sites where there are no beach clean-up operations, the spatial distribution observed in marine litter likely reflects long-term spatial patterns of entanglement on mangrove roots and wrapping on the forest ground. In addition, mangrove forests studied on the Caribbean Sea coast were fronted by beaches showing a smooth slope, where the wave run-up is often able to penetrate tens of meters allowing the arrival of litter into the backing mangrove forest, as reported by Cordeiro and Costa [24] in the São Vicente Estuary (Brazil). Results obtained in this paper along the Caribbean Sea coast show that, once litter enters the mangrove from the sea, it tends to move landward (i.e., towards zone 4) during storms, whereas litter at the seaward edge of a mangrove forest (zone 3) eventually re-enters into a nearby beach zone [86]. The most abundant litter items in the Caribbean Sea mangrove forests were those with positive buoyant capacity (e.g., foamed plastic pieces, hard plastic pieces and caps/lids, Table 4). In mangrove forests, due to the low recorded hydrodynamic conditions linked to different factors such as the presence of pneumatophores and seedlings that attenuate wave energy and current turbulence, litter is retained for long periods of time and then buried (Table 1 and Figure 2l) [21,87–90]. Similar results were found in the Ciénaga Grande de Santa Marta by Garcés-Ordóñez et al. [26] who reported that many of the plastic items were found covering pneumatophores of *A. germinans* and *L. racemosa.* Along the study area, litter degradation was especially evident at Puerto Caimán B (Figure 1); this site was, until ca. 20 years ago, directly exposed to waves and currents [91]. Presently, the sampling site, which has a low canopy density which allows sunlight penetration, is located in a sheltered area protected by Puerto Velero sand spit which has been migrating southwestward during the past several decades [91]. Therefore, litter presently observed there was probably stranded ca. 20 years ago and showed evident deterioration due to the transport experienced and fragmentation caused by UV light [92].

At Tumaco municipality, on the Pacific Ocean coast of Colombia, sites investigated (Figure 2h–k) are located on an alluvial area showing rivers, canals, tidal creeks and coastal lagoons [93]. At places in such riverine and swamp environments, local inhabitants constructed stilt houses with poor or no solid waste management programs.

Waste materials are often discharged in riverbanks or directly in wetlands, rivers, and tidal creeks, and then transported away and dispersed along coastal environments by rivers and tidal action, which achieves certain relevance since it is a mesotidal environment.

In the case of Complejo DIMAR (site no. 8), the greatest abundance and weight of litter was observed in zone 4, followed by zones 3 and 2 (Table 2). Such behavior and trends in litter distribution are influenced by tidal processes [94]. As an example, in zone 4 (Table 2), a high presence of film plastic pieces was recorded (especially single-used plastics, Table 4) in the roots of *Rhizophora* sp. resulting in a ‘Christmas tree’ effect (Figure 2m). In this regard, Ivar do Sul et al. [87] established in the Goiana Estuary (Brazil) that the tide is apparently the main driving force controlling litter movement patterns in mangrove forests, while Yin et al. [48] determined in Penang Island (Malaysia) that lighter and more buoyant materials (e.g., plastic bottles and film plastic pieces) have a greater tendency to accumulate during rising tide in the mangrove forest landward edge.

Concerning litter content in mangrove forests, the results of this study report that most litter items are composed of plastic materials, representing 93.61% of the total litter composition (Tables 3 and 4). Such results are consistent with other studies, e.g., in São Vicente Estuary (Brazil), Cordeiro et al. [24] reported high plastic content (62.81% of total amount), with bags and food wrappers being the most numerous items. Abreo et al. [95], in Pujada Bay (Philippines), reported plastic amounts of 66.79%; Luo et al. [86] in Hong Kong, values of 70.31%; Kesavan et al. [96], in Mumbai (India), reported 62.4%; and Yin et al. [48], in Penang Island (Malaysa), observed 87.2% of plastic materials. In Colombia, Garcés-Ordóñez et al. [26] in Ciénaga Grande de Santa Marta, and Riascos et al. [28], in Buenaventura bay, recorded 84.5% and 85% of plastic content. The high abundance of film and hard plastic pieces and bags observed in the studied area coincides with those reported in the mangrove forests of Ambon Island, Indonesia, by Suyadi et al. [97] who identified plastic films and bags as the most abundant items and the landward edge of the forest as the most polluted. Kesavan et al. [96] in a mangrove forest of Mumbai, found that plastic bags were the most abundant trapped litter because they are easily carried by tidal action and wind. In turn, in Tumaco, site no. 9 is located behind a rocky arch called "El Morro" (Figure 2j,k) [98], and seawater enters through this arch during the flooding tide. In this mangrove forest, the greatest abundance of litter was recorded in zone 2 (Table 2), where a large number of plastic bags and glass fragments are observed. In contrast to the "Complejo DIMAR" (site 8), tourists are present at the "El Morro" site and probably represent the main source of litter, especially of heavy glass fragments since their accumulation occurs close to the point of discharge because such items are not very susceptible to rolling [99,100]. The 'Christmas tree' effect was also observed in this mangrove forest [94].

The effect of plastic litter on the mangrove soil includes different aspects linked to both the impact of items on the propagules and seedlings and the physical changes in the soil layers due to litter incorporation in first horizons, which can affect natural soil aeration, water movement and regeneration [21,27]. Other common issues observed are: (a) the formation of a barrier that can hinder the development of propagules and seedlings and limits natural root growth [27], and can alter photosynthesis, causing mortality [31,32]; (b) plastic items smothering young saplings by covering and burying smaller mangrove seedlings and, due to their weight, can be transported by waves and tide where they impact on and break young branches [95]; (c) litter preventing propagules from properly landing on the water or on the soil beneath the canopy [95]; (d) litter contamination promoting microbial colonization by pathogens and generating disease outbreaks; (e) negative effects on some species that subsist in such habitats within mangroves roots (e.g., mollusks and crustaceans) [26]; and (f) plastic fragmenting due to physical and chemical factors (e.g., high temperatures and solar ultraviolet light), generating microplastics that can be ingested by species living in the mangrove forest [23,29,101].

Finally, concerning litter abundance, results observed in this study report 1.29 items/m^2 (28.72 g/m^2) and 1.13 items/m^2 (79.41 g/m^2) for the mangrove forests of the Caribbean Sea and Pacific Ocean coasts, respectively. Although such values are close to the observations of Luo et al. [86] (who reported an average amount of 1.45 items/m^2 in Hong Kong), in general, results reported in this paper showed lower values than other places around the World, e.g., Riascos et al. [28] reported in Buenaventura mangrove forests an average amount of 15.03 and 3.81 items/m^2 of litter in internal and external areas, respectively; in Mumbai (India), Kesavan et al. [96] estimated average values of 8.8 items/m^2; and in Ambon Island (Indonesia), Suyadi [97] estimated average values of 92 items/m^2.

5. Conclusions

In Colombia, despite beaches having an important economic relevance for tourism purposes, and mangrove forests constituting a strategic ecosystem for climate change adaptation, such environments are under pressure mainly due to anthropogenic activities and urbanization processes. The results of this paper show how litter, mainly linked to land based activities, reaches beaches and mangrove forests along the Caribbean Sea coast through the Magdalena River. Once litter is stranded, it accumulates and becomes trapped in mangrove forests. Beach users constitute a secondary relevant source of pollution. In the

Pacific Ocean coast of Tumaco, the mismanagement of solid waste in coastal settlements is considered the main source of litter that arrives by rivers and tidal creeks at the coast and, then, because of wind, waves, and ocean currents, enters into the mangrove forests—where it accumulates and is eventually buried. The cleaning programs that are used for beaches are not applicable to a complex ecosystem such as the mangrove forest and, therefore, strategies aimed at avoiding the entering of litter into such an environments are fundamental tools to protect them. In order to decrease the arrival of litter and especially of plastic items to beaches and mangrove forests, it is therefore mandatory to enhance the appropriate solid-waste disposal systems in many areas of Colombia and to enforce specific laws to prohibit single-use plastic items. In addition, future studies on the abundance of microplastics and their effects on mangrove forests and associated ecosystems are needed due to the large amount of plastic litter items observed. Lastly, it is necessary to work hard on environmental education at all levels, especially for the inhabitants and tourists of the coastal cities and those who live along riverbanks or in stilt houses on coastal lagoons and tidal creeks, such as in the case of Tumaco on the Pacific Ocean coast.

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