UNA UNIVERSIDAD NACIONAL COSTA RICA · euna · REVMAR REVISTA CIENCIAS MARINAS Y COSTERAS

# Characterizing plastic pollution on beaches of Cozumel Island, Mexico: abundance, distribution, and influencing factors

# Caracterización de la contaminación por plástico en las playas de la Isla de Cozumel, México: abundancia, distribución y factores influyentes

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**ABSTRACT**

Plastic pollution in marine environments represents a significant threat to ecosystems worldwide. This study focuses on Cozumel Island, located in the Caribbean Sea, where plastic debris, primarily from inadequate management, adversely affects its beaches. Nine beaches were selected to conduct debris sampling and determine the abundance, density, and type of objects found at the sites. Three sampling repetitions were conducted on the surface of each beach, while three samplings were conducted on eight beaches to analyze buried debris. One of the beaches was discarded for buried debris sampling because of its rocky composition. Data was collected between March 22 and June 15, 2019. A total of 25,102 surface debris items were found, 94% of which were plastic. Similarly, 4,365 buried items were recorded, with the vast majority (97.8%) being plastic debris. Surface and buried debris densities vary, influenced by factors such as beach location, substrate composition, and human visitation. Beaches with lower human presence exhibit the highest debris densities, particularly in windward areas. Statistical models indicate that low-to-medium visitor influx and beach location significantly impact debris characteristics. Insights from this research contribute to understanding the dynamics of marine debris on Cozumel beaches, which plays a crucial role in informed policymaking and conservation efforts.

**Keywords:** plastic pollution, marine debris, Cozumel Island, conservation, Caribbean Sea.

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**RESUMEN**
La contaminación plástica en los ambientes marinos representa una amenaza importante para los ecosistemas de todo el mundo. Este estudio se centra en la Isla de Cozumel, situada en el mar Caribe, donde los residuos plásticos, originados principalmente por un manejo inadecuado, afectan, de forma negativa, a sus playas. Se seleccionaron nueve playas para realizar muestreos de residuos y determinar la abundancia, densidad e identidad de los objetos encontrados en los sitios. En cada playa se realizaron tres repeticiones de muestreo en superficie y en ocho de esas playas también se realizaron tres muestreos para el análisis de residuos enterrados. Una playa fue descartada para el muestreo de residuos enterrados debido a su composición rocosa. La recolección de datos fue realizada entre el 22 de marzo y el 15 de junio de 2019. Se encontraron un total de 25 102 residuos superficiales, de los cuales el 94% eran plásticos. Del mismo modo, se registraron 4 365 elementos enterrados, siendo la gran mayoría (97.8%), desechos plásticos. Las densidades de desechos superficiales y enterrados varían, influenciadas por factores como la ubicación de la playa, la composición del sustrato y las visitas humanas. Las playas con menor presencia humana presentan las mayores densidades de residuos, sobre todo en las zonas de barlovento. Los modelos estadísticos indican que la afluencia de visitantes baja a media y la ubicación de la playa impactan significativamente las características de los desechos. Los conocimientos de esta investigación contribuyen a comprender la dinámica de los desechos marinos en las playas de Cozumel, crucial para la formulación de políticas informadas y los esfuerzos de conservación.

**Palabras clave:** conservación. contaminación por plásticos, desechos marinos, Isla de Cozumel, mar Caribe.

## INTRODUCTION

In 2019, the global production of plastic, a raw material for manufacturing all kinds of materials (e.g., resins, fibers), was estimated to be close to 460 million tons (Mt) per year (OECD, 2022). An estimated 4.8 to 12.7 million metric tons of plastics are introduced into the ocean yearly because of inappropriate waste management practices. These plastics are found in many marine habitats, including the seabed, ocean surface, and beaches (Geyer *et al.* 2017; Tigreros-Benavides *et al.* 2024). Plastic debris pollution has been reported in most Atlantic and Caribbean islands, and several factors could explain plastic distribution on those islands (Cruz-Salas *et al.* 2022; Xu *et al.* 2024). Some studies have shown that human activity does not determine the level of contamination on the beaches of these islands, as they are in remote or difficult-to-access areas. However, the current debris density is still significant (Monteiro *et al.* 2018; Schmuck *et al.* 2017). Other



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studies have found that the primary explanation for the distribution of plastic debris on these beaches is linked to wind impacts, ocean currents, and wave action; these beaches tend to be on the windward side of the Caribbean Sea (Debrot *et al.* 2013). On the other hand, waste is more related to local human activities on leeward beaches, given that single-use plastic is more abundant (de Scisciolo *et al.* 2016).

Cozumel Island, the largest insular territory in Mexico within the Caribbean Sea, is home to many endemic and critically endangered species (Cuarón, 2009). One of the local threats that constitutes a significant problem to be solved is the inadequate disposal of solid waste in urban and natural areas. However, it must be noted that natural sites are exposed to debris generated both on the island and by external sources (Rivera-Garibay *et al.* 2020). Efforts have been made by municipal public services, a private collection network, and an informal volunteer sector to collect debris generated by urban residents and to take it to final disposal areas; the collection percentage reaches almost 100% in urban areas (Zettl & Téllez Martínez, 2015). As mentioned before, a significant proportion of waste found on the beaches comes from outside the island and has been carried by the currents and the wind towards the various beaches. Waste is collected by volunteers cleaning the beaches or staff from restaurants, hotels, and souvenir shops. Volunteers cleaning Cozumel beaches have identified that 97% of the waste in these marine environments is plastic (Mansilla-García, *personal communication*).

Currently, there are no satisfactory or practical solutions to the numerous problems caused by plastic waste in various marine environments (Galloway, 2015). However, public interest has contributed to expanding research coverage through local beach cleanups and international events (Law *et al.* 2014; Zettler *et al.* 2017). This study aimed to assess the physical and anthropogenic factors influencing the content and distribution of marine debris on Cozumel beaches. Understanding the impact of marine debris on Cozumel beaches is crucial for policymaking and interventions. In addition, the results obtained can contribute to efforts made to address marine debris globally.

## MATERIALS AND METHODS

Cozumel Island (20°16’ 18.2’’ to 20°35’ 32.8’’ N; 86°43’ 23.3’’ to 87°01’ 31.1’’ W) is located 17.5 km from the Yucatan peninsula in the Mexican Caribbean Sea (Fig. 1). Its current population is *ca*. 86,000 inhabitants and receives approximately 500,000 tourists monthly (INEGI, 2021). In addition, it has terrestrial and marine Protected Natural Areas and has received distinctions such as the designation as

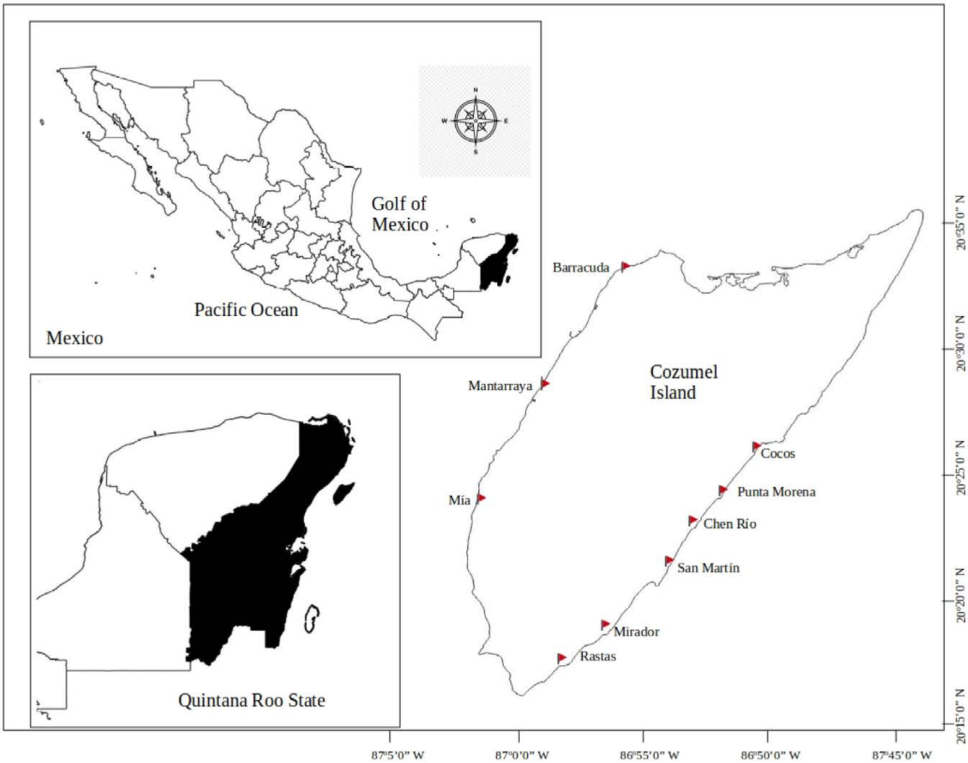


**Fig. 1.** Location of studied beaches on Cozumel Island, Quintana Roo, Mexico
**Fig. 1.** Ubicación de las playas de estudio en Isla Cozumel, Quintana Roo, México

a RAMSAR Site and a Biosphere Reserve of UNESCO's Man & Biosphere Program (RAMSAR, 2005; 2009).

Nine beaches were selected to conduct debris sampling and determine the abundance, density, and type of objects found at the sites. Three sampling repetitions were conducted on the surface of each beach, while three samplings were conducted on eight beaches to analyze buried debris. One of the beaches was discarded for buried debris sampling because of its rocky composition. The minimum separation between beaches was 1.2 km. Data was collected during three periods, with a one-month interval between samplings, from March 22 to June 15, 2019. Identical sample locations were used to account for substantial discrepancies in data collection.

Sampling sites were selected based on three main variables influencing waste composition on the island beaches: beach location (east or leeward; west or windward), the


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composition of the beach substrate, and human visitation influx (Debrot *et al.* 2013, Table 1). To differentiate between the dominant oceanographic currents affecting the island, the variable beach location is categorized as "east," where windward winds predominate, and "west," where leeward winds prevail. On the island's eastern side, the Yucatan current typically flows from southeast to northeast. In contrast, on the western side, beaches face the Cozumel Island Channel, which receives the current flowing from southwest to northwest. Therefore, international waste carry-over may differ on both sides of the island (Athié *et al.* 2020). The variable composition of the beach substrate was defined in three groups: sandy, rocky, and mixed since these were the different characteristics found in the sampled beaches. Finally, the variable human visitation was defined using direct observation and counting people *in situ* per day on each beach. Observations were conducted along a 100 m stretch of beach, the maximum area where visitors are observed coming in and out. Based on these observations, three categories were defined: low presence of visitors with a maximum of 10 visitors per day; medium presence of visitors including a maximum of 150 people per day; and high presence of visitors to busier beaches with more than 150 people per day (de Sciscíolo *et al.* 2016).

**Table 1.** General characteristics of studied beaches in Cozumel Island, considering their location (west, W; east, E), substrate (sand, A; rock, R; mixed, M), human visitation influx (low, B; medium, M; high, A) and type of sampling used (surface, S; buried, E)
**Cuadro 1.** Características generales de las playas estudiadas en Isla Cozumel, considerando la localización (Oeste, W, Este, E), el sustrato (arenoso, A; rocoso. R; mezcla, M), la influencia de visitas humanas (baja, B; mediana, M; alta, A) y el tipo de muestreo llevado a cabo (superficial, S; enterrado, E)

| Sampling sites | Location | Substrate | Human visitation influx | Sampling type |
|---|---|---|---|---|
| Barracuda | O | A | B | S, E |
| Chen Río | E | M | A | S, E |
| Cocos | E | A | B | S, E |
| Mantarraya | O | R | A | S |
| Mía | O | A | A | S, E |
| Mirador | E | M | M | S, E |
| Punta Morena | E | A | M | S, E |
| Rastas | E | M | B | S, E |
| San Martín | E | A | A | S, E |

The technique proposed by Kusui and Noda (2003) was adapted to fit the specific dimensions and shapes of the beaches on Cozumel Island. Both surface and buried debris were measured and assessed as follows: surface debris was collected from nine beaches. At each location, three 5 x 20-meter plots were marked parallel to the sea along the high tide mark to ensure they accurately represented similar beach areas at each site. Buried debris was sampled in beaches with sandy or mixed composition (one beach was discarded due to its rocky composition). At each plot, ten points were randomly selected, each covering an area of 0.25 $m^2$ and extending to a depth of 80 cm, equivalent to 0.20 $m^3$. Objects found from the surface to a depth of 2 cm were excluded from this sampling, as they were classified as surface debris (Kusui & Noda, 2003). Each object found during the sampling process was counted, weighed with an electronic scale, and classified according to the waste categorization defined by the Marine Debris Program of the United States National Oceanic and Atmospheric Administration, NOAA (Burgess *et al.* 2021). A total of 29 additional categories were adapted to this classification of beach waste because some types of waste could not be fitted within the base list. Waste was classified into 61 categories with objects of different materials (plastics, metals, wood, rubber, textiles, glass) and different uses. As far as the plastics group, styrofoam fragments were separated from the rest of the plastic due to their significant volume, and each fragment was separated according to its size (potential microplastic <5 mm, mesoplastic 5 mm - 2.5 cm, macroplastic > 2.5 cm).

The first level of analysis for sampled sites along the island was conducted to determine the total waste abundance, weight, density, and composition according to the variety of waste found. The Shannon and Wiener diversity index (*H'*) and the equity index (*E'*) were used to interpret waste diversity on beaches and relate their composition to the sites where they were collected. The abundance of total waste per beach, their density, i.e., the number of objects per $m^2$, and the variety of debris found independently on each beach were also calculated. The Bray-Curtis dissimilarity index (Ricotta & Podani, 2017) was used to evaluate similarities between surface and buried waste on the beaches. The Wilcoxon-Mann-Whitney and Kruskal-Wallis tests were used to determine whether the means of two or more groups differed. Finally, a Generalized Linear Model (GLM) analysis was conducted to determine possible causes of waste distribution in relation to location, substrate composition, and visitors' presence on the analyzed beaches. All statistical analyses


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were performed using R version 4.2.1 (R Core Team, 2022).

## RESULTS

The waste recorded on the surface of the beaches included 25,102 items (23.43 kg). Their density varied from 0.57 items/m$^2$ (Mía Beach) to 23.48 items/m$^2$ (Rastas Beach), with an average density for all the island's beaches of 9.3 objects/m$^2$. Weight varied from 0.001 kg/m$^2$ (Mía Beach) to 0.02 kg/m$^2$ (Cocos Beach), with an average weight of 0.009 kg/m$^2$. A general pattern was found in the waste distribution, in which abundance and weight were lower on western beaches but higher on eastern beaches, with fewer visitors. The type of waste with the heaviest weight is fragments of hard plastic and caps of plastic bottles (Figs. 2 and 3), corresponding to 25% and 10% of the total weight, respectively.

Buried waste included 4,365 items (0.65 kg). Their density varied from 43 items/m$^3$ (Mía Beach) to 650 items/m$^3$ (Cocos Beach), with an average density for the entire island of 273 items/m$^3$ (Table 2). Their weight varied from 0.18 kg/m$^3$ (Barracuda Beach) to 0.75 kg/m$^3$ (Rastas Beach), with an average weight of 0.41 kg/m$^3$. Density and weight also coincide with the characteristics of the beaches; that is, a general distribution pattern was found: density and weight are low on western beaches but higher on eastern beaches, which have small crowds. In these samples, plastic was the

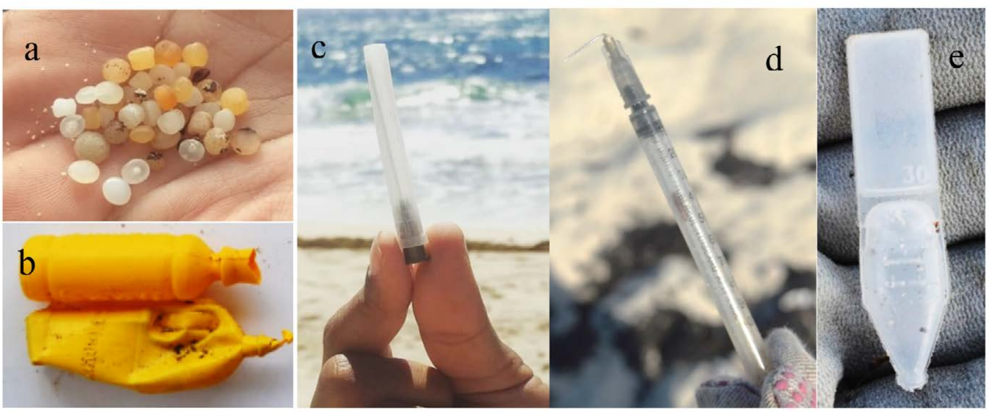


**Fig. 2.** Examples of plastic debris found in Cozumel Island beaches. Buried items: a) pellets, b) chlorine and vinegar container, c) needle, d) Syringe, Surface: e) pipette
**Fig. 2.** Ejemplos de residuos plásticos encontrados en playas de Isla Cozumel. Objetos enterrados: a) pelets, b) contenedores de vinagre y cloro, c) agujas, d) jeringa. Superficial: pipeta

predominant material, with 71% corresponding to fragments of potential microplastics, that is, plastics smaller than 2.5 cm. A composition of 61 types of surface debris was recorded on the beaches of Cozumel Island (Table 3). A residue diversity index was calculated, yielding a value of *H'*= 1.98 and an equity index of *E'*= 0.48. In the case of buried waste, its composition included 27 types of debris, yielding the values of *H'*= 1.23 and *E'*= 0.37. These samplings confirm that plastics are the most predominant elements, representing 94% and 98% of total surface and buried waste, respectively, which was reflected in the low equity indices.

**Table 2.** Density and variety of the surface and buried waste recorded on Cozumel Island
**Cuadro 2.** Densidad y variedad de desechos superficiales y enterrados registrados en playas de Isla Cozumel

| Site | Surface | | Buried | |
|---|---|---|---|---|
| | Density (object/ $m^2$) | Variety | Density (object/ $m^3$) | Variety |
| Barracuda | 6.85 | 38 | 68.5 | 10 |
| Chen Río | 3.85 | 22 | 264.5 | 10 |
| Cocos | 11.89 | 34 | 650.5 | 14 |
| Mantarraya | 6.14 | 25 | - | - |
| Mía | 0.57 | 23 | 43.5 | 9 |
| Mirador | 14.90 | 37 | 254 | 13 |
| Punta Morena | 10.07 | 28 | 205.5 | 17 |
| Rastas | 23.48 | 32 | 473.5 | 17 |
| San Martín | 5.92 | 26 | 222.5 | 13 |


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**Table 3.** Waste categories and items collected on the surface of beaches on Cozumel Island (Area sampled: 2,700 m$^2$, total items collected: 25,102. Sampled beaches: Bar = Barracuda, Che = Chen Río, Coc = Cocos, Man = Mantarraya, Mia = Mía, Mir = Mirador, Pun = Punta Morena, Ras = Rastas, San = San Martín)
**Cuadro 3.** Categorías y elementos de desechos registrados en la superficie de playas de Isla Cozumel (área muestreada: 2 700 m$^2$, total de elementos colectados 25 102. Playas muestreadas: Bar = Barracuda, Che = Chen Río, Coc = Cocos, Man =Mantarraya, Mia = Mía, Mir = Mirador, Pun = Punta Morena, Ras = Rastas, San = San Martín)

| Debris categories and items | Sampling sites | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Bar | Che | Coc | Man | Mia | Mir | Pun | Ras | San |
| Rubber: | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| Glove | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Tire | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| Processed lumber: | 4 | 3 | 1 | 8 | 2 | 1 | 1 | 0 | 0 |
| Bottle cork | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Paper and cardboard | 4 | 2 | 0 | 7 | 2 | 1 | 0 | 0 | 0 |
| Piece of lumber | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 |
| Metal: | 13 | 0 | 4 | 202 | 17 | 11 | 3 | 0 | 4 |
| Aerosol can | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Aluminum | 4 | 0 | 0 | 7 | 1 | 0 | 1 | 0 | 0 |
| Fragment | 1 | 0 | 1 | 82 | 1 | 0 | 0 | 0 | 1 |
| Aluminum can | 0 | 0 | 2 | 0 | 1 | 1 | 0 | 0 | 0 |
| Fishing bait | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bottle cap | 6 | 0 | 0 | 60 | 10 | 9 | 2 | 0 | 3 |
| Aluminum can rings | 1 | 0 | 0 | 53 | 4 | 0 | 0 | 0 | 0 |
| Coin | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Other: | 5 | 2 | 14 | 1 | 0 | 3 | 1 | 3 | 1 |
| Needle | 2 | 2 | 1 | 0 | 0 | 0 | 1 | 2 | 1 |
| Medicine bottle | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 |
| Gauze pads | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Syringe | 0 | 0 | 8 | 0 | 0 | 2 | 0 | 1 | 0 |
| Sandpaper | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pill blister | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Battery | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Plastic: | 2 023 | 1 143 | 3 531 | 613 | 142 | 4 429 | 3 012 | 7 024 | 1 770 |


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| **Debris categories and items** | **Sampling sites** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Bar** | **Che** | **Coc** | **Man** | **Mia** | **Mir** | **Pun** | **Ras** | **San** |
| Pipette | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 3 | 0 |
| Bag | 16 | 0 | 6 | 2 | 0 | 22 | 19 | 11 | 2 |
| Bracelet | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 |
| Toothbrush | 2 | 0 | 4 | 0 | 0 | 0 | 1 | 8 | 1 |
| Chlorine/vinegar container | 0 | 0 | 9 | 0 | 0 | 3 | 0 | 3 | 1 |
| Cigarette tips | 10 | 1 | 0 | 39 | 24 | 7 | 4 | 6 | 11 |
| Bucket | 1 | 0 | 1 | 0 | 0 | 2 | 0 | 0 | 0 |
| Cutlery | 18 | 3 | 17 | 3 | 0 | 21 | 13 | 12 | 8 |
| Food wrappers | 6 | 0 | 0 | 1 | 0 | 5 | 0 | 3 | 2 |
| Disposable cigarette lighter | 0 | 0 | 2 | 0 | 0 | 0 | 2 | 1 | 0 |
| Clothes hanger | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 |
| Ballon | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Toy | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Hair tie | 0 | 0 | 0 | 3 | 2 | 0 | 1 | 1 | 0 |
| Macroplastic | 666 | 80 | 588 | 0 | 31 | 373 | 398 | 661 | 183 |
| Styrofoam macroplastic | 133 | 201 | 200 | 0 | 0 | 401 | 275 | 395 | 135 |
| Mesoplastic | 648 | 214 | 1 306 | 329 | 33 | 679 | 942 | 1 852 | 507 |
| Styrofoam mesoplastic | 75 | 492 | 977 | 45 | 8 | 2 476 | 984 | 3 237 | 620 |
| Mixer | 33 | 10 | 52 | 14 | 4 | 66 | 37 | 100 | 17 |
| Other potential microplastic | 63 | 47 | 0 | 40 | 11 | 45 | 131 | 133 | 192 |
| Styrofoam potential microplastic | 0 | 0 | 0 | 0 | 0 | 34 | 28 | 315 | 0 |
| Large object | 0 | 0 | 6 | 0 | 2 | 2 | 2 | 1 | 0 |
| Other beverage containers | 2 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 2 |
| Pellets | 0 | 2 | 1 | 0 | 0 | 1 | 7 | 3 | 1 |
| PET | 9 | 0 | 52 | 0 | 1 | 18 | 2 | 1 | 0 |
| Pencil | 10 | 1 | 13 | 4 | 2 | 17 | 5 | 5 | 2 |
| Straw | 14 | 5 | 11 | 1 | 1 | 19 | 8 | 19 | 7 |
| Small net pieces | 43 | 59 | 173 | 96 | 16 | 32 | 54 | 70 | 38 |
| Flip-flops | 8 | 2 | 6 | 0 | 0 | 11 | 2 | 0 | 2 |
| Bottle caps | 248 | 23 | 91 | 32 | 5 | 183 | 96 | 176 | 35 |



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| Debris categories and items | Sampling sites | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Bar** | **Che** | **Coc** | **Man** | **Mia** | **Mir** | **Pun** | **Ras** | **San** |
| Styrofoam cups, plates | 3 | 0 | 6 | 0 | 1 | 1 | 0 | 0 | 1 |
| Tetra pack | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| School use | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Personal use | 12 | 3 | 5 | 0 | 1 | 8 | 1 | 6 | 2 |
| Cloth: | 3 | 2 | 10 | 9 | 7 | 2 | 3 | 1 | 0 |
| Synthetic fabric pieces | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Rope/net pieces (non-nylon) | 0 | 0 | 0 | 3 | 0 | 0 | 3 | 0 | 0 |
| Natural fabric pieces | 3 | 1 | 10 | 6 | 7 | 2 | 0 | 1 | 0 |
| Shoes | 0 | 0 | 3 | 0 | 0 | 5 | 0 | 7 | 1 |
| Glass: | 5 | 5 | 1 | 1 010 | 2 | 17 | 0 | 9 | 0 |
| Fragment | 5 | 5 | 1 | 1 010 | 2 | 16 | 0 | 9 | 0 |
| Other | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Bottle | 0 | 0 | 3 | 0 | 0 | 1 | 1 | 0 | 0 |

In addition, the Bray-Curtis dissimilarity index was used. Four groups of beaches were identified for surface waste; the first group includes Mía and Mantarraya Beaches, with high dissimilarity values of 90%. These two beaches have a high influx of visitors and are in the west part of the island. The second group is comprised only of Barracuda Beach because it is also in the western area; however, the low influx of visitors and its physical characteristics indicate that other types of waste are present. The third group of beaches includes Chen Río and San Martín, with a dissimilarity value of 25%. They are similar because they are in the east and are very crowded. The fourth and last group comprises Cocos, Punta Morena, Mirador, and Rastas, with a dissimilarity value of 20%. They are also located in the east; however, the influx of visitors is medium or low, which explains the affinity of the waste composition between them (Fig. 3).

The dissimilarity between surface waste weights was analyzed, and two groups were established. The first group, comprised of Mía, Mantarraya, and Chen Río Beaches, had a dissimilarity value of 90%, while the second group identified, consisting of Rastas, Cocos, Barracuda, Mirador, Punta Morena, and San Martín Beaches, had a 50% dissimilarity between sites (Fig. 3). Regarding buried waste, three groups of beaches were established

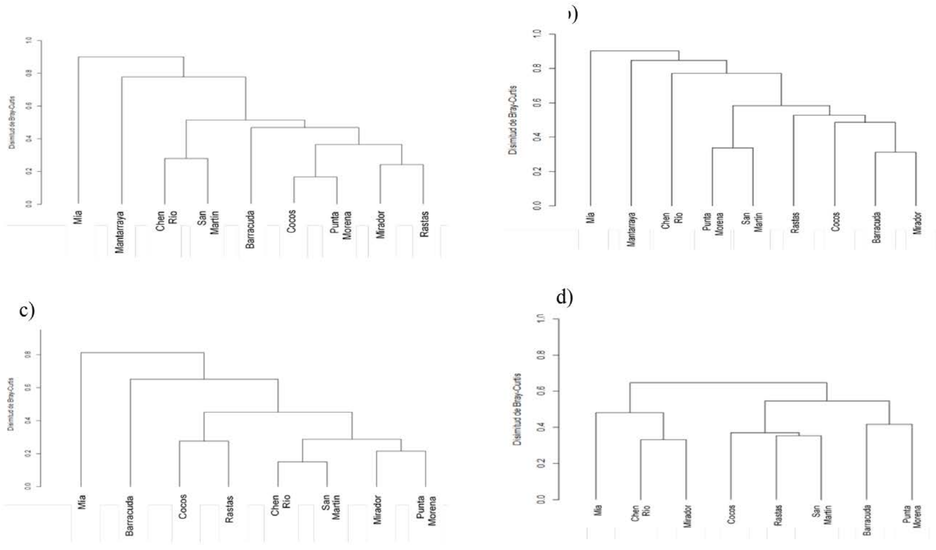


**Fig. 3.** Dendrograms obtained using Bray-Curtis' Dissimilarity Index to make groups according to a) surface waste composition, b) surface waste weight, c) buried waste composition, d) buried waste weight

**Fig. 3.** Dendrogramas obtenidos mediante el índice de disimilitud de Bray-Curtis. Se conformaron grupos en relación con: a) la composición de desechos superficiales, b) peso de desechos superficiales, c) composición de desechos enterrados, d) peso de desechos enterrados

according to their dissimilarity value. The first group identified is Mía and Barracuda Beaches, both located in the western area of the island with a dissimilarity value of 80%. The second group is comprised of Cocos and Rastas Beaches in the eastern part of the island. Given that their visitors' influx is low, their waste composition and abundance are similar and have a dissimilarity value of 45%. The last group identified was comprised of five beaches (Chen Río, San Martín, Mirador, and Punta Morena), all located to the east, with a dissimilarity value of 25% (Fig. 1). No dissimilarity was found between the weight of the waste sampled under the sand (Fig. 1).

The variables that define the characteristics of the beaches and that are used to select the most appropriate model are shown in Table 4. The best model to predict dependent variables (abundance, density, and variety) is the Akaike Information Criterion (AIC). The surface debris recorded is explained by the human presence or visitation variable (AIC= 152.31). Density



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**Table 4.** Parameter estimation for the best Generalized Linear Models, selected by the lowest AICs, to better predict the variety, density and abundance of waste recorded on the Cozumel Island beaches
**Cuadro 4.** Parámetro de estimación para los mejores modelos lineales generalizados, seleccionados por el más bajo valor de AIC, que mejor predice la variedad, densidad y abundancia de residuos registrados en playas de Isla Cozumel

| **Dependent variables** | | **Variety** | | | **Density** | | | **Abundance** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Independent variables** | | **Estimation** | **Std. Error** | ***p*** | **Estimation** | **Std. Error** | ***p*** | **Estimation** | **Std. Error** | ***p*** |
| Beach surface waste | Human visitation influx | -0.0016 | 0.0003 | 1.21e-05 *** | 0.0013 | 0.0003 | 0.00160 ** | 4.345e-06 | 1.211e-06 | 0.00155 ** |
| | Beach substrate | -0.0434 | 0.0894 | 0.627 | -0.1045 | 0.0677 | 0.1362 | -3.491e-04 | 2.246e-04 | 0.1338 |
| | Beach location | 0.1217 | 0.0960 | 0.205 | -0.3319 | 0.1342 | 0.02125 * | -1.101e-03 | 4.447e-04 | 0.02105 * |
| Beach buried waste | Human visitation influx | 0.0009 | 0.0008 | 0.247 | -8.684e-06 | 8.776e-06 | 0.368 | 0.0024 | 0.0001 | 0.368 |
| | Beach location | -0.0593 | 0.2241 | 0.791 | -2.921e-03 | 3.538e-03 | 0.447 | 0.6765 | 0.0427 | 0.447 |

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’

and abundance are better explained by the human presence or visitation and beach location variables (AIC= 105.93 and AIC= 413.75, respectively). A significant effect of the human presence or visitation and the beach location on the composition of the buried waste was also detected (AIC= 44.82). The beach substrate variable is not a predictor of surface or buried waste on the beaches of Cozumel Island.

## DISCUSSION

Recent studies indicate that the most significant contribution to the variety of debris found on beaches in various regions of the world is dominated by buried debris (Kusui & Noda, 2003; Lavers *et al.* 2019; Castro-Tavares *et al.* 2020; Cruz-Salas *et al.* 2022). This is also consistent with the findings on Cozumel Island, where 98% of the total buried waste is of plastic origin. It was determined that a large percentage of the buried waste is small fragments, which coincides with other studies that specify that the smallest articles are predisposed to remain buried longer, and its deposition depends on various factors such as wind, sediment, and the size of the object (William & Tudor, 2021; Cruz-Salas *et al.* 2022). Several factors can influence the abundance of waste on beaches. As defined by the GLM analysis, it was determined that one of the influencing factors is the low or medium influx of visitors to beaches. Those unpopular areas for visitors recorded higher densities of waste because some are in front of open waters; here, waste tends to accumulate and pollute at higher rates than visited beaches. Since these beaches are visited infrequently, cleanup activities are less usual because some are far from the urban center or have difficult access.

These findings support the research conducted by Schmuck *et al.* (2017), which shows that waste density may be greater in isolated regions far from urban areas and with lower tourism activity. The waste composition of this group of beaches with a low influx of visitors includes fragments of deteriorated brittle and opaque-looking objects. This denotes an advanced state of degradation, possibly because they have been on the island for a long time or recently arrived but have had a long journey from other areas (Mansilla-Garcia *comp pers*). It has been reported that waste present on remote beaches of other Caribbean islands is mostly unidentifiable plastic fragments, the result of environmental marine conditions (Shmuck *et al.* 2017).

The high visitation on the beaches can be related to a lower abundance of waste. It was observed that, in areas with commercial establishments, there are constant cleanup activities since permits granted to business owners require areas to be in perfect condition; therefore, concessionaires regularly


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collect from the beaches waste generated both on and outside of the island (Cruz-Salas *et al.* 2022). In addition, some groups of volunteers and the Municipality have a scheduled time to clean the most visited beaches; therefore, beaches tend to show a lower density of waste per area. Conversely, waste found on beaches with many tourists consists mainly of disposable debris produced on the island.

Some studies also indicate that the beach's location is a predictor of the probability of finding a higher density of waste and a different composition on the beach's surface (Corbin & Singh, 1993; Kukulka *et al.* 2012). Recent research in the area found that the densities on the windward beaches of twenty-four Caribbean islands are influenced by exposure to the significant current systems of the Atlantic Ocean and prevailing winds (Debrot *et al.* 2013; Schmuck *et al.* 2017; Cruz-Salas *et al.* 2022). The pattern on Cozumel Island is similar since there is a higher abundance of waste found on the eastern beaches, which are remote, exposed to outside waste, and dominated by windward winds. Regarding buried waste on Cozumel Island, this study suggests that the more diverse composition of objects found could be explained by the influx of visitors and the beach location. The intercept in the GLM model is statistically significant ($P < 0.001$) for the two independent variables (human visitation + beach location), which indicates that there could be other predictor variables that were not measured and could explain the characteristics of buried waste. In addition, samplings were repeated to represent significance in the research; however, including additional sampling areas may yield findings that differ from those obtained in the current statistical analysis. Although the role of coral reefs was not considered, they protect the western part of the island, are part of the Caribbean Barrier Reef, and probably limit the deposition of waste on Cozumel.

The analysis did not consider beach cleanup events because only some are publicly or officially socialized, making this information challenging to identify for each sampled beach. Some events are held by government entities, the Cozumel Parks and Museums Foundation, and personnel from private businesses in established areas; therefore, no sampling was conducted on those beaches. Also, at least six volunteer organizations on the island conduct beach cleanups without a public call and in different places, making it difficult to know the dates, places, and results of these activities.

The study revealed that the primary objective of beach cleanups is to remove objects visible on the surface. Typically, the focus is lifting large items, often resulting in smaller objects being overlooked and rarely collected. Although several beach cleanup groups exist, public data on densities and weights has yet to be collected. Neither was there knowledge about collecting buried waste on the island during the sampling period of this research. Knowing the dynamics of beach cleanups is also essential in this research to identify its economic impact. A clear example is shown in the research conducted in Aldabra Atoll, which estimated that removing 25 tons of waste has a cost of US $224,537, in addition to the challenges of organizing cleanups, as well as the distances from the beaches to disposal sites, transportation, and food and water for volunteers (Burt *et al.* 2020). Therefore, it is vital to explore the impact of beach cleanups, both in the analysis of their organization and in the study of buried waste, to learn more about the dynamics of distribution on the beaches (Takashi & Noda, 2003; Lavers *et al.* 2019; Castro-Tavares *et al.* 2020).

Plastic debris was found on all the beaches of Cozumel Island. Overcrowded beaches had more waste for immediate disposal or single-use. In contrast, less overcrowded areas coincided with eastern beaches, where waste was more abundant, mainly had originated outside the island, and had remained exposed to the environment for longer (Mansilla-Garcia *comp pers*). Over 90% of the debris found was estimated to have originated outside the island; however, further research is needed to obtain more accurate data. Therefore, the beach location and the influx of visitors impact the abundance, density, and variety of the debris found on the surface and under the sand on the beaches of Cozumel Island.

Establishing consistent, long-term monitoring systems and data collection worldwide will enhance the capacity to measure plastic emission routes and the efficiency of mitigation methods (Borrelle *et al.* 2020). The study of marine debris on beaches is important to Cozumel Island because of the schematically generated results that highlight a real problem that the island urgently needs to address. Data can create awareness among visitors, businesses that profit from recreational areas, companies that generate plastic waste, and the final consumer. It can also be helpful for local governments to identify areas for improvement in the conservation plans of the beaches and their surroundings. Research on beach waste is a precedent for further research on microplastics and materials other than plastic, such as glass and metal, and their potential uses.

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