CRITICAL REVIEW ARTICLE

Contributions of scientific expeditions to marine litter knowledge in the Seaflower Biosphere Reserve, Colombian Caribbean: analysis of contamination, impacts, and public policies

Contribuciones de las expediciones científicas al conocimiento de la basura marina en la Reserva de la Biósfera Seaflower, Caribe colombiano: análisis del estado de contaminación, impactos y políticas públicas

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ABSTRACT

This study examines marine litter and plastic pollution based on scientific expeditions conducted in the Seaflower Biosphere Reserve, Colombia. It identifies potential sources of pollution, assesses its impacts on marine health, and evaluates the role of public policies in addressing this critical issue. The analysis highlights the vulnerability of remote islands to plastic pollution and the challenges associated with limited and inefficient waste management systems, which have serious consequences for marine and coastal ecosystems. The distribution and impacts of marine litter are analyzed to propose effective environmental protection measures and sustainable management strategies. This study emphasizes the urgent need to reduce plastic usage to mitigate the environmental and economic challenges posed by restricted waste management capacity on remote islands with limited operational space.

KEYWORDS: marine pollution; plastics; marine debris; remote islands; waste management; marine conservation

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RESUMEN

Este estudio analiza la basura marina y la contaminación por plásticos a partir de las expediciones científicas realizadas en la Reserva de la Biósfera Seaflower, Colombia. Identifica las posibles fuentes de contaminación, evalúa sus impactos en la salud marina y examina el papel de las políticas públicas en la gestión de este problema crítico. El análisis destaca la vulnerabilidad de las islas remotas a la contaminación por plásticos y los desafíos asociados con sistemas de gestión de residuos limitados e ineficientes, que generan serias consecuencias para los ecosistemas marino-costeros. Se analizan la distribución y los impactos de la basura marina para proponer medidas efectivas de protección ambiental y estrategias sostenibles de gestión. Este estudio enfatiza la urgente necesidad de reducir el uso de plásticos para mitigar los desafíos ambientales y económicos derivados de la limitada capacidad de gestión de residuos en islas remotas con espacio operativo restringido.

PALABRAS CLAVE: *contaminación; plásticos; desechos marinos; islas remotas; gestión de residuos; conservación*

INTRODUCTION

Marine litter pollution, defined as solid waste originating from human activities that reaches marine and coastal areas, is a critical environmental issue with severe impacts on ecosystems and human communities worldwide (Stoett *et al.*, 2024). Island regions are especially vulnerable to this problem due to their remote location, isolation, and the influence of ocean currents that transport marine litter from other nearby or distant places to the islands, where it accumulates in their ecosystems (Lavers and Bond, 2017; Jones *et al*., 2021; Pérez-Venegas, *et al.,* 2017; Portz *et al.,* 2022).

The accumulation of litter, primarily plastics, poses an environmental and economic challenge in island regions, due to the effects on biodiversity, the health of marine ecosystems, and tourism and fishing activities, among others (Portz *et al.,* 2020; Rambojun *et al.,* 2024; Thiel, *et al.,* 2021). This situation highlights the need to investigate this problem in island areas to better understand its dynamics, identify its sources and assess its long-term environmental impacts. This knowledge is essential to raise awareness and work on the implementation of sustainable and effective practices at the local, regional and global levels, in order to contribute to the prevention and reduction of this type of pollution (Portz *et al.,* 2020).

The islands of the Caribbean region have been affected by marine litter pollution (Blanke, Steinberg, & Donlevy, 2021; Diez *et al.,* 2019). Some of this marine litter comes from local sources, such as tourism, inadequate waste management practices, low recycling rates, limited environmental awareness, and poor management by local authorities (Garcés-Ordóñez *et al.,* 2020a; Portz *et al*., 2024). Another part of the litter on the islands comes from external sources, such as that transported by ocean currents from other regions or surrounding countries (Courtene-Jones *et al.,* 2021; Ivar do Sul and Costa, 2007; Portz *et al.,* 2022, 2020; Rangel-Buitrago *et al.,* 2019) and illegal dumping of various wastes into the sea from boats (De Scisciolo *et al.,* 2016).

Coastal communities in the Caribbean region also face challenges due to inadequate infrastructure for solid and liquid waste management (Diez *et al.,* 2019). Added to this are the complexities associated with the limitations of the surface area available on the islands to manage their own household waste (Courtene-Jones *et al.,* 2021). As a result, much of the waste generated is disposed of in landfills or burned, but it almost always ends up in the sea, contributing to the pollution of the ecosystems on which the local communities themselves depend economically (Portz *et al.,* 2022).

The Seaflower Biosphere Reserve (BSR), located in the Colombian Caribbean region (Fig. 1), consists of three main islands (San Andres, Old Providence and Ketlina), seven cays (Serrana, Serranilla, Alburquerque or Southwest, Roncador, Queena Reef, Bajo Nuevo and Cayos de Bolívar Islands – also known as Courtown Cays), and multiple shoals and marine banks.

Together, they form an archipelago composed of carbonate platforms and reef barriers of varied geomorphological features (CIOH, 2009; Geister & Díaz, 2007). This protected area is notable for its high biodiversity of ecosystems and marine species. However, its fragility in the face of marine litter pollution raises significant concerns for its long-term preservation.

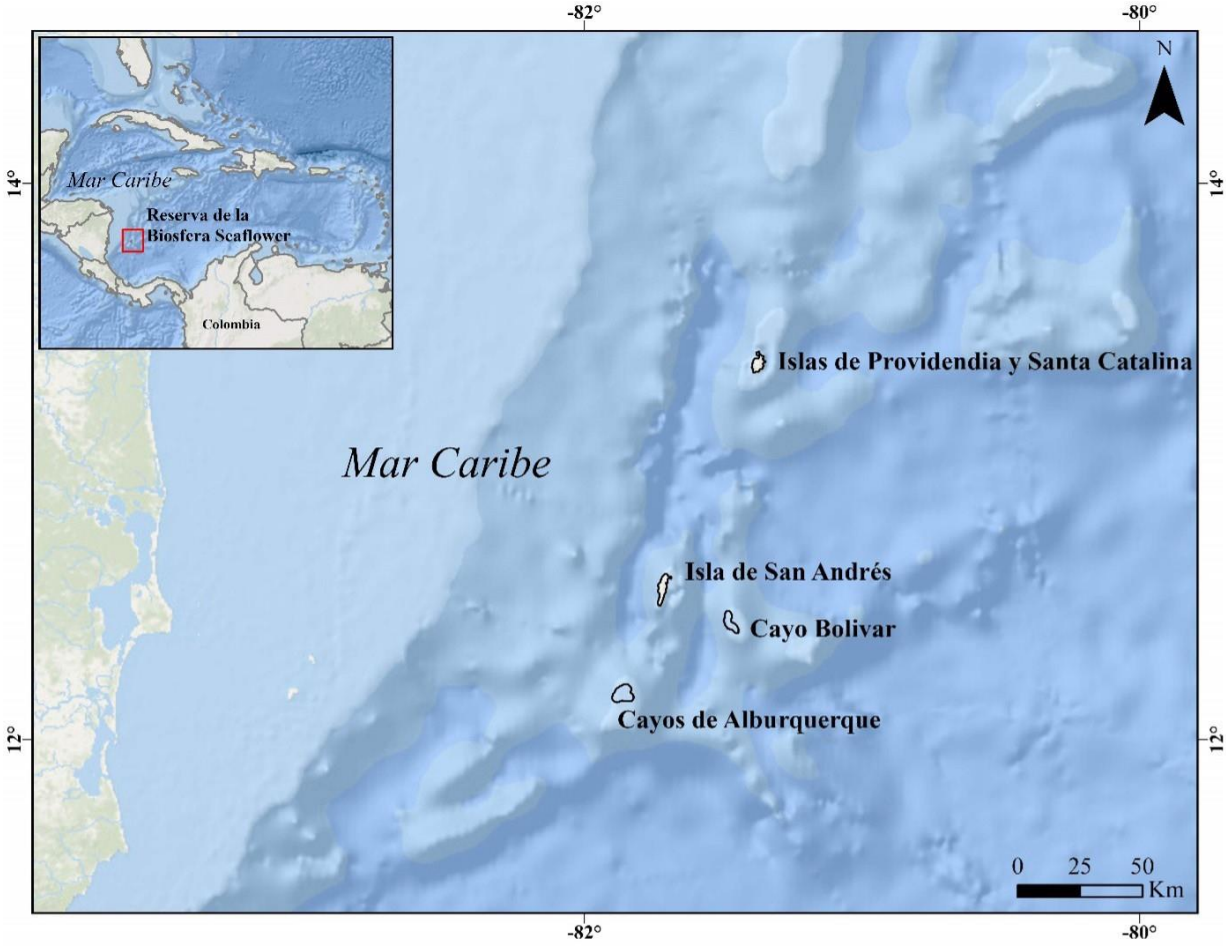

Figure 1. Location of the area of the Seaflower Biosphere Reserve in the department of the Archipelago of San Andrés, Providencia y Santa Catalina, Colombia, highlighting the islands in which scientific expeditions described in this study were carried out.

Multiple scientific expeditions have been carried out in the SBR with the aim of generating knowledge about biodiversity and its state of conservation, including studies to quantify and analyze the marine litter problem. These expeditions are the result of an inter-institutional collaboration coordinated by the Colombian Ocean Commission (CCO) with the participation of the Colombian Navy (ARC), the General Maritime Directorate (Dimar) and the Corporation for the Sustainable Development of the Archipelago of San Andres, Providencia y Santa Catalina (Coralina), among other public and private entities interested in the country's marine sciences. Furthermore, these expeditions aim to establish short-term monitoring plans and, in the medium term, standardize sampling protocols while highlighting the environmental importance of the SBR (Dimar, 2024).

In this context, the main objective of this review is to summarize and analyze the contributions of the Seaflower Expeditions to the knowledge of the problem of marine litter

pollution in this insular nature reserve, and to examine its environmental impacts from a comprehensive perspective for the Colombian Caribbean. To this end, this review seeks to answer the following key questions: What are the main sources and magnitude of marine litter pollution in the SBR? What environmental impacts does the accumulation of marine litter generate in the different ecosystems of the reserve (beaches, mangroves and coral reefs)? How do Seaflower expeditions contribute to the understanding and management of marine litter pollution, and what public policies can be most effective to address this problem more efficiently?

These questions guide a critical analysis of the sources of pollution, their magnitude, and the formulation of public policies necessary to tackle this environmental challenge more effectively. The significance of this review lies in its capacity to synthesize existing knowledge and inform future research and public policies in the region. This, in turn, can help mitigate the effects of marine litter pollution in both the Seaflower Biosphere Reserve (SBR) and the Colombian Caribbean.

Description of Seaflower Scientific Expeditions

Alburquerque Cays. They are located 37 km southwest of the island of San Andres and 190 km east of the coast of Nicaragua. This atoll has a circular shape, with a diameter of approximately 8 km in an east-west direction. It is characterized by a semi-enclosed lagoon protected by a coral reef, with depths ranging from 0.3 m to 164 m (CCO, 2015; Martínez-Clavijo *et al.* 2021). The ecosystems present include coral reefs and sandy beaches. The emerging cays are composed of two sandbanks: the North Cay (412 m²), which houses a military base of the Colombian Navy, and the South Cay, which is occasionally occupied by fishermen.

The scientific expedition to Alburquerque Cays took place from October 4 to 14, 2018. In this survey, 71 marine litter sampling sites (>2.5 mm) were carried out on the beaches, as well as 3 microplastic sampling sites on the beach sand and 9 marine transects for the evaluation of macro and microplastics. The study covered both terrestrial areas (beaches) and surface waters in the marine environment. The precise coordinates of the sampling points are available in Portz *et al.* (2020).

The results, along with the specific sampling site coordinates, were published by Portz *et al.* (2020) and can be consulted on the portal: https://pnec.cco.gov.co/ seaflower/.

Old Providence and Ketlina Islands. These islands are remnants of an ancient extinct volcano, characterized by mountainous terrain and Quaternary deposits. The islands are separated by a shallow channel 150 m wide and cover a total area of approximately 18 km². The ecosystems present include mangroves, coral reefs, and beaches. Part of the region's coral reef is protected within the Old Providence McBean Lagoon National Natural Park, which covers an area of 9.95 km² and is part of the Special Area of the Archipelago of San Andres, Providencia y Santa Catalina, as well as the Seaflower Marine Protected Area (Invemar and Coralina, 2012).

Two scientific expeditions were carried out on these islands. The first was the IV Seaflower Expedition, held from September 9 to 19, 2019, while the second took place from July 20 to 26, 2021. The 2019 expedition analyzed 30 marine litter sampling sites on beaches (26 sites) and mangroves (4 sites), along with 13 dive sites for coral assessment. In the 2021 expedition, 27 marine litter sampling sites were evaluated on beaches (23 sites) and mangroves (4 sites), in addition to 11 diving sites in the same sites previously investigated.

Samples collected during both expeditions were used to assess the health of marine and coastal ecosystems. The results and exact location of the sampling points are available in Portz *et al.* (2022), Portz *et al.* (2024) and can be consulted on the website: https://pnec.cco. gov. co/seaflower/.

Courtown Cays. Located 25 km southeast of the San Andres Island, the atoll has a length of 6.4 km and a width of 3.5 km, with a total emerged area of 0.12 km². Pescadores Cay (East Cay) has an area of 8 hectares and is partially covered by vegetation, while Bolívar Cay (West Cay) has 3.7 hectares of emerged area and houses a permanent military base of the Colombian Navy. Ecosystems include coral reefs and beaches (Invemar and Coralina, 2012).

The Seaflower Expedition to the Courtown Cays took place from September 9 to 20, 2022. During this expedition, 44 marine litter sampling sites of 10 m in length were carried out on the beach of Bolívar Cay, as well as 891 marine litter sampling sites on Pescadores Cay. Additional monitoring stations were carried out on the Banco de la Virgen (1 site) and on the Bajo Sunny Boar (1 site). For the analysis of microplastics, 2 monitoring stations were carried out in Bolívar Cay and 5 in Pescadores Cay, collecting a total of 18 samples of sediments and water. Likewise, 9 marine transects were executed for the evaluation of floating marine litter, along with the collection of 9 seawater samples.

The results included the collection and analysis of marine litter in the terrestrial and marine areas of the atoll (López *et al.*, 2024). The exact location of the sampling points, along with the results obtained is available on the https://pnec.cco. gov.co/seaflower/ and https:// seaflower-dimar.hub. arcgis.com/ portals.

METHODOLOGIES

Marine litter is any persistent, manufactured, or processed solid material that is discarded, thrown away, or abandoned in the environment (UNEP, 2005). The collection and characterization protocols used in the expeditions are described in detail in Portz *et al.* (2020) and Portz *et al.* (2022). Overall, the sampling environments encompassed a variety of important ecosystems in the Reserve, including mangroves, beaches (both tourist and non-tourist), vegetation areas behind the beachline, and coral reefs. Each of these environments requires specific sampling approaches, due to their unique physical characteristics and environmental dynamics.

On the beaches, both tourist and non-tourist, marine litter (>2.5 cm) was systematically sampled. To this end, 10 m wide sections were established, covering the area from the limit of the water line to the beginning of the vegetation or dunes, depending on the type of beach. This methodology allows capturing the variability in the distribution of marine litter along the beach profile, from the intertidal zone to the areas furthest from the water. In addition, in the vegetated areas behind the upper limit of the beach, the first 5 m of vegetation were included in the survey. This extension ensures that marine litter transported inland by wind, tides, and extreme waves is also accounted for.

In the mangroves, due to the dense vegetation and the presence of aerial roots (pneumatophores), linear transects 5 m wide were established, oriented from the local access points into the mangrove. This method facilitates the identification of marine litter, as mangroves tend to act as natural traps for litter.

In the coral reefs, the sampling of marine litter was carried out on the island shelf (between 10 m and 30 m deep), using diving techniques (3 divers). This allowed researchers to access the most critical underwater areas to assess the amount and types of litter accumulating in and around corals. Marine litter (>2.5 cm) was collected and categorized, providing insight into the level of contamination.

In each of these environments, the collected marine litter was classified according to its type and material. Marine litter types included plastics, metals, glass, rubber, and other anthropogenic materials. Each item was recorded and quantified to provide a detailed overview of the composition of marine litter in each environment (Portz *et al.,* 2020, 2022).

In addition to the field research, a comprehensive bibliographic search was conducted on the associated topic, using Web of Science, Google Scholar, ScienceDirect, and Scopus, prioritizing studies published within the last 20 years. Boolean operators were used with specific keywords such as "Microplastics," "Plastic litter," "Plastic pollution," "Marine litter," and "Marine debris"; in addition to "Coastal," "Coastal zones," "Caribbean," "Islands," and "Colombia," thus ensuring the relevance of the results for the geographical and thematic context.

Marine Litter Results in the SBR

The increase in marine litter pollution poses a threat to the island ecosystems of the SBR. While all islands face marine litter pollution issues, it is clear that some areas are more affected than others. Data collected during the 2018-2022 Seaflower expeditions, along with additional studies, revealed significant differences in pollution levels between the more tourist-focused islands and the more remote cays islands with restricted tourism. Mangroves in Old Providence and Ketlina were identified as the most affected, with levels of up to 9.07 items/m², while tourist beaches showed much lower levels, with an average of 0.22 items/ m². San Andres presented a greater variability, highlighting the non-tourist beaches with an average of 1.45 items/m². Although isolated and remote, Alburquerque Cays and Courtown Cays also recorded significant pollution, particularly on beaches, with a predominance of plastic (Table 1).

Results of Seaflower expeditions

The results of the expedition to Alburquerque Cays, published by Portz *et al*. (2020), revealed an average pollution level of 0.5 items/m² on beaches (Table 1). Plastics dominated the composition of marine litter, accounting for 90% of the total, followed by materials classified as other (6%), glass (2%), and fisheries-related items (0.8%). The other category encompassed building materials (2%), tetra pack packaging (1%), and a combined 1% comprising rubber, fabrics, and non-plastic footwear.

The significant presence of plastic fragments and microplastics in this region suggests persistent and fragmented pollution, with multiple potential sources, such as transport by ocean currents, given that local sources are limited by the island's restrictions on use. Additionally, the high prevalence of plastic fragments, which account for 96% of plastic items collected on beaches, makes it difficult to identify specific sources. Once plastics reach the beaches, they continue to fragment and eventually integrate into natural sediment cycles, making the beaches a secondary source of microplastics for the atoll (Alburquerque).

Furthermore, the importance of hydrodynamics in the distribution of marine litter was analyzed. The results showed a greater accumulation of plastic in the southeastern sector of the atoll, which is directly exposed to prevailing winds and surface currents. Ocean currents and waves appear to concentrate marine litter in this sector, while more protected areas of the atoll had lower litter densities. This finding is crucial for the SBR, as it demonstrates that local hydrodynamic characteristics can influence the accumulation of marine litter, even in remote areas with limited human activity (Portz *et al.,* 2020).

Table 1. Types of marine litter found on the different islands and cays emerged from the Seaflower Biosphere Reserve during the different Seaflower expeditions (tagged with*), as well as other research and field campaigns in which the co-authors have participated.

Year	Place	Ecosystem	Items/m²			Most frequent items	Reference
			Min.	Max.	Average		
Feb. 2017	San Andres	Tourist beaches (n=5)	0.17	0.63	1.22	Plastic, tobacco, paper, metal	Portz *et al.,* (2018)
		Non-tourist beaches (n=3)	0.61	1.45	2.92	Plastic, glass, metal, paper	
		Rocky, tourist beaches (n=3)	0.53	0.54	0.55	Plastic, metal	
		Rocky, non-touristy beaches (n=5)	0.4	0.77	0.65	Plastic, metal, glass	
Feb. – Apr. 2013	San Andres	Beach (n=3)	2.95	3.71	3.3	Plastic, glass	Gavio *et al.,* (2022)
Oct. 2018	Alburquerque	Beaches (n=71)	0.03	1.94	0.5	Plastic, glass, fishing material	Portz *et al.,* (2020) *
		Shallow continental shelf			12 items	Plastic, glass, fishing material	
Aug. 2022	Courtown Cays Bolívar Cay	Beach (n=2)	0.01	1.68	0.85	Plastic, rubber, glass, wood	López *et al.,* (2024) *
	Courtown Cays Pescadores Cay	Beaches (n=3 very long)	0.01	1.56	0.79	Plastic, rubber, glass, wood	López *et al.,* (2024) *
Sept. 2019	Old Providence	Tourist beach (n=8)	0.01	0.72	0.22	Plastic, paper, metal, glass	Portz *et al.,* (2022) *
		Non-tourist beach (n=10)	0.31	5.41	1.87	Plastic, fabrics, metal, glass	
		Mangrove (n=1)	-	-	8.38	Plastic, metal, glass, MO	
		Gravel beach	0.48	16.17	4.69	Plastic, metal, glass, fabrics	
Sept. 2019	Ketlina	Tourist beach (n=1)	-	-	0.72	Plastic, metal, paper	Portz *et al.,* (2022) *
		Non-tourist beach (n=1)	-	-	0.71	Plastic, glass, rubber, fabrics	
		Mangrove (n=3)	8.38	10.4	9.07	Plastic, Metal, Glass, MO	
Sept. 2019		Corals (N=13)	0	0.02	0.01	Glass, line	Portz *et al.,* (2022) *
Dec. 2020-Jan. 2021	Old Providence and Ketlina	Mangrove	0.4	1.4	-	Plastic, metal, glass, processed wood	Garcés-Ordóñez *et al.,* (2021)
Microplastics							
Oct. 2018	Alburquerque	Beach (N=3)	99 - 141 particles/m²				Portz *et al.,* (2020) *
		Sea surface (N=9)	0.009 - 0.244 particles/m³				

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The results obtained in the two largest emerging areas of Courtown Cays, Bolívar Cay and Pescadores Cay, revealed a high prevalence of plastic waste in areas where all tourist activity is prohibited (Table 1). These findings were published in the Final Report of the Expedition by López *et al.* (2024). Eight categories of marine litter were identified, with plastic (89%) predominating, followed by glass (5%), wood (2%), textiles (2%), metal (1%), paper (1%), rubber (0.1%), and others (1%). PET bottles, polystyrene (styrofoam) and rigid plastic fragments (such as methacrylate, polycarbonate and PVC) were the most abundant types within the plastics category.

In the metal category, aluminum cans were predominant, while in the glass category, glass containers stood out, in terms of rubber, flip-flops or Crocs-type shoes were the most frequent. The density of marine litter showed significant levels of pollution, especially in Pescadores Cay (Table 1).

In terms of distribution, a notable presence of marine litter was observed throughout the atoll. However, Pescadores Cay showed higher levels of pollution compared to Bolívar Cay, when considering the internal vegetated areas of each island. On the other hand, by focusing only on the exposed areas of the beaches, Bolívar Cay presented greater pollution per square meter than Pescadores Cay, though not at the levels observed in the small neighboring sandbanks (Banco de la Virgen and Bajo Sunny Boar).

Old Providence and Ketlina, with their important coastal and marine ecosystems, face significant challenges of marine litter pollution. In 2019, tourist beaches registered an average of 0.22 items/m², while non-tourist beaches showed an average of 1.87 items/m². In 2021, an increase in tourist beaches was observed, with an average density of 1.70 items/m², reflecting the impact of tourism and reconstruction waste after Hurricane Iota (a category 4 event that occurred from November 13 to 18, 2020). However, in non-tourist beaches, the average increased slightly to 2.31 items/m² (Portz *et al.,* 2024).

On the other hand, mangroves, which are critical habitats for many marine species, had a high average of 8.38 items/m² in 2019. In 2021, after the hurricane, it was reduced to 3.22 items/m² due to the destruction of the ecosystem by the hurricane and cleanup campaigns (Portz *et al.,* 2024).

Regarding the characterization of marine litter on the Old Providence and Ketlina Islands, the most common categories of marine litter were plastic (76%), followed by metal (6%), glass (6%), fabrics (3%), and other materials (3%) (average of the 2019 and 2021 expeditions).

The spatial distribution of marine litter on the islands showed that mangroves and beach vegetation areas act as key accumulation zones, especially of plastics. Tourist beaches had a low density of marine litter due to regular cleanups, while non-tourist beaches presented greater accumulation and variety of sources. Coral reefs around the island showed low litter density, indicating a lower connection to this ecosystem.

Complementary studies

The study by Garcés-Ordóñez *et al.* (2021) focused on marine litter pollution in the mangroves of Old Providence and Ketlina after Hurricane Iota. The results showed that mangroves near urban areas registered a greater accumulation of litter compared to those located in areas with less human influence. Plastics of various sizes were the predominant type of marine litter (more than 60%).

This study highlights how extreme weather events, such as hurricanes, can exacerbate the problem of marine litter, especially in critical ecosystems such as mangroves, and how local response actions are critical to the recovery of these ecosystems after disasters. Furthermore, the participation of the local community in the cleaning and recovery of the mangrove was emphasized.

Research conducted on San Andres Island by Portz *et al.* (2018) and Gavio *et al.* (2022) provides valuable complementary insights,

offering an additional perspective on the marine pollution problem in the SBR.

San Andres, one of the most visited islands in the region, exhibits moderate levels of pollution on its beaches. According to Portz *et al.* (2018), tourist areas register an average of 0.63 items/m², while non-tourist areas have a higher concentration, with an average of 1.45 items/m². The most common litter includes plastic (74%), cigarette butts (8%), metals (7%), and glass (5%). On the other hand, Gavio *et al.* (2022) found an average of marine litter on beaches of approximately 3.30 items/m². Marine litter is mainly composed of plastic (between 84% and 89%), followed by glass, cigarette butts, and other materials such as paper and metals, in smaller proportions.

Studies conducted at different times provide interesting insights into the extent and distribution of marine litter along the island's coastline. Gavio *et al.* (2022) found a high concentration of marine litter, mainly plastics and glass on tourist beaches, highlighting the need for stricter control over waste disposal in general. On the other hand, Portz *et al.* (2018) revealed a disparity in the amount and origin of marine litter between tourist and non-tourist beaches, highlighting the urgent need for actions to ensure the conservation of interconnected coastal ecosystems, especially in those areas furthest from the tourist center.

Integrated Evaluation of Marine Litter in the SBR

Comparing pollution levels across islands reveals a variety of troubling environmental situations and challenges. In the case of San Andres, an island characterized by an influx of tourists, moderate pollution was observed on the beaches, with a slight tendency to increase in non-tourist areas. This phenomenon suggests a possible correlation between beach cleanup actions and the amount of marine litter present.

However, non-tourist areas do not necessarily have regular cleaning or waste collection services. This is the case of Alburquerque Cays and Courtown Cays. It is worth noting that Bolívar Cay houses a permanent base of the Colombian Navy, while Pescadores Cay is used as temporary accommodation by artisanal fishermen from San Andres during their fishing days.

In contrast, Old Providence and Ketlina Islands face particular challenges in terms of marine litter pollution. On these islands, high levels of litter are recorded in the beach vegetation area and in the mangroves, essential habitats of many marine species.

The analysis of marine litter in the beach vegetation suggests a greater impact from local activities and inefficient disposal practices following beach cleanups. The studies by Portz *et al.* (2022) and Garcés-Ordóñez *et al.* (2021) provide an exhaustive overview of this problem, highlighting the importance of community participation and the application of management strategies adapted to the particularities of each context.

On the other hand, Alburquerque Cays and Courtown Cays have registered relatively low levels of pollution with respect to coastal areas of the islands with the highest population (San Andres, Old Providence and Ketlina Islands). However, these values are still considered high levels of marine litter (Table 1), given that they are remote, uninhabited islands with strict tourism restrictions.

The most significant finding is that the most prevalent type of marine litter (>2.5 cm) in the SBR islands corresponds to plastic, predominantly food storage items such as PET bottles. It is important to emphasize that food packaging is the most common type of marine litter in the Reserve. This pattern is consistently observed across continents, revealing a global trend that reflects the wide distribution of plastic in marine environments (BFFP, 2023).

Comparing SBR to other regions shows that although inhabited islands such as San Andres, Old Providence and Ketlina face significant marine litter problems, pollution levels are lower than on other Caribbean islands and the world.

San Andres, influenced by tourism, has moderate pollution, especially in tourist areas. In Old Providence and Ketlina, litter is high in the vegetation line and the mangrove, similar to what is observed in Santa Marta, Colombia, where tourist beaches register up to 12 items/m², with plastics representing between 35% and 72% of marine litter (Garcés-Ordóñez *et al.,* 2021). On islands such as Hunting Caye, Belize, densities reach up to 4.09 items/m² on beaches without staff responsible for regular maintenance (Blanke *et al.,* 2020b). Variations in the density of litter on beaches, even within the same island, are observed in Bonaire, where densities range from 0.1 items/m² to 5 items/m² (Debrot *et al.,* 2013).

The worrisome presence of microplastics (<2.5 cm) on uninhabited islands reflects a broader and more complex pollution issue (Portz *et al.,* 2020). This finding indicates the significant presence of diverse sources of pollution, such as the fragmentation of materials by local marine-atmospheric processes, the dragging of waste by meta-oceanographic interactions (waves and winds), as well as transport by ocean currents, whose behavior in this region is closely linked to the general pattern of the Panama-Colombia gyre (Andrade *et al.,* 2003; Mooers & Maul, 1998; Richardson, 2005).

Previous research, such as that of Wüst (1963), supports the idea of the existence of this gyre. It is postulated that its dominant influence on oceanographic conditions of the region facilitates the transport of light materials suspended in water. This phenomenon, aggravated by the waves, creates a dynamic context that could explain the presence of pollutants in this remote region of the Caribbean (Portz *et al.,* 2020).

The inhabited islands of the Reserve, especially those with significant tourism, generate marine litter that pollutes both their beaches and the adjacent sea. In addition, these islands can contribute to marine pollution of other nearby islands. For example, Wilson and Verlis (2017) demonstrated the influence of tourism in the southern Great Barrier Reef and its impact on nearby islands.

Several studies have shown that ocean currents can carry marine litter over long distances (Moore *et al.,* 2001; Schneider *et al.,* 2018). This means that pollution generated on an island or even in a neighboring country can substantially affect remote and isolated islands. This phenomenon has been evidenced in Alburquerque Cays and on Courtown Cays, where marine litter and microplastics have been found both in submerged areas and on exposed beaches, including uninhabited areas such as isolated banks and microplastics both in submerged areas and on exposed beaches, including uninhabited areas such as isolated banks.

Effects of Pollution on BioDiversity and Sea Health

Mangroves

Mangroves act as natural traps for marine litter, preventing it from dispersing into the marine environment (Ivar do Sul & Costa, 2014; Martin, Almahashee & Duarte, 2019; Portz *et al.,* 2022; Rambojun *et al.,* 2024). The presence of marine litter in mangroves threatens not only the landscape, but also biodiversity and ecosystem functions. Plastic litter can entangle mangrove roots and pneumatophores, preventing plants from properly absorbing nutrients and oxygen, which can lead to plant death and ecosystem decline (Van Bijsterveldt *et al.,* 2021).

In addition, the presence of plastic waste represents a direct threat to the wildlife that inhabits mangroves, which generates physical barriers and accidental ingestion (Garcés-Ordóñez *et al.,* 2020b; Van Bijsterveldt *et al.,* 2021).

Marine litter can also jeopardize mangrove restoration efforts, harming both adult trees and seedlings. The collision of floating litter with roots and aerial trunks can increase tree mortality, while the accumulation of marine litter prevents natural regeneration by suffocating seedlings and blocking areas suitable for new root growth (Gorman & Turra, 2016; Pranchai *et al.,* 2019).

In the mangrove areas analyzed in the SBR, pollution by litter, especially plastics, represents a serious threat to the recovery and maintenance of these ecosystems. These effects hinder mangrove rehabilitation efforts, especially in areas where restoration programs rely on planting seedlings, which may not prove efficient due to interference from marine litter.

Beaches and dunes

Similar to mangroves, beach and dune environments are also critical accumulation zones for marine litter (Manzolli & Portz, 2024; Poeta *et al.,* 2017; Portz *et al.,* 2011). In addition to compromising the natural beauty of the dune landscape and reducing the tourist appeal of the coastline, marine litter can cause direct damage to local flora and fauna. The vegetation present in the beach system is one of the most important landscape components, as it provides a precious habitat for bird nesting, feeding, and wildlife protection (Martínez and Psuty, 2004).

The vegetation area of the beach serves as a natural barrier that traps and accumulates marine litter, fragments it, and increase its quantity over time with the help of wind (Portz *et al.,* 2011). This pollution can interfere with the structure and development of the dune ecosystem, disrupting natural processes such as germination and seedling-plant interactions that are critical for ecosystem stabilization (Menicagli *et al.,* 2019).

Coral reefs

Coral reefs are affected by pollution caused by marine litter, particularly plastics (macro and micro) and abandoned or discarded fishing materials. The presence of plastics in the oceans can promote microbial colonization by pathogens involved in disease outbreaks. Lamb *et al.* (2018) found that when corals come into contact with plastics, the likelihood of disease increases dramatically from 4% to 89%. Specifically, plastics such as polypropylene, commonly found in bottle caps and toothbrushes, are heavily colonized by bacteria associated with coral diseases, such as white band disease.

Corals, which are filter-feeding organisms, are also exposed to ingesting microplastics, which disrupt their intake of natural food, thereby impairing their development and growth (Hall *et al.,* 2015). Additionally, microplastics interfere with the symbiotic relationship between corals and zooxanthellae, increasing oxidative stress and vulnerability to disease and bleaching (Okubo *et al.,* 2018; Syakti *et al.,* 2019).

Since zooxanthellae provide 90% of corals' food, through photosynthesis, allowing them to live in oligotrophic conditions, any alteration to this relationship would have serious consequences for coral health (Campos *et al.*, 2020). Furthermore, abandoned fishing gear such as nets, hooks, and pots can become entangled in corals, causing physical damage. Marine litter not only affects corals, but also the associated aquatic wildlife species that depend on them for habitat, protection, and feeding, thereby threatening both the reef ecosystem and commercial fish populations.

Impact of Marine Litter on Economic Sectors Linked to the Sea

Marine litter pollution negatively affects economic sectors linked to the sea, such as tourism, fishing, and maritime transport (Abalansa *et al.,* 2020; Aretoulaki *et al.,* 2021; Rodríguez *et al*., 2020). The tourism industry, particularly beach tourism, faces significant challenges due to the presence of trash (Grelaud & Ziveri, 2020).

This pollution impacts both the coasts and the surrounding seawater, which directly affects the economy of tourist islands such as San Andres, Old Providence, and Ketlina, whose economies depend heavily on tourism. Marine litter reduces the scenic beauty of these destinations and diminishes the quality of the tourist experience, leading to a decrease in visitor numbers and, consequently, a negative impact on the local economy.

Beyond its visual impact, tourists' negative perception of unclean beaches is a critical factor for the health of the tourism sector. A study conducted in Brazil demonstrated that the presence of trash can reduce recreational activities by up to 39% (Krelling *et al*., 2017). Marine litter on beaches discourages recreational activities due to the perception of an unhealthy environment, influencing people's perceptions of environmental quality (Pendleton *et al.*, 2001).

This issue is a key determinant for the growth of tourism-dependent economic sectors, as confirmed by numerous studies conducted in tourist resorts and beaches (Krelling *et al.,* 2017; Rehman *et al.,* 2022; Santos *et al.,* 2005).

Marine pollution also affects submerged areas, such as diving and snorkeling sites, with aesthetic and ecological impacts. In Taiwan, a study in Kenting National Park and the Yilan Coast recorded 2,841 items of marine litter, the distribution of which varied according to season, location, and tide, highlighting the complexity of the problem (Lin *et al.,* 2022).

In response to this problem, initiatives such as "*Dive Against Debris*" and clean-up dives play a crucial role in mitigating marine litter. These activities not only conduct underwater cleanups, but also convert efforts into data-driven studies, contributing to the prevention of damage to marine life and the environment. In addition, they encourage policy changes towards better waste management practices (https://www.diveagainstdebris.org).

The fishing sector also experiences negative effects from marine litter, as it can damage fishing equipment, reduce catches, and require additional time for repairing or cleaning nets (Galimany *et al.,* 2019). These impacts reduce the overall productivity of the industry and are more pronounced in areas with high concentrations of marine litter, such as shallow areas, where 38% of the total catch consists of marine litter (Galimany *et al.,* 2019).

In addition to damaging fishing equipment, marine litter also impacts captured marine species, many of which show evidence of ingesting marine litter, particularly plastics (Fossi *et al.,* 2018; Garcés-Ordóñez *et al.,* 2020b). For the local community, whose cultural traditions and economy are based on fishing, these consequences represent a significant challenge and put at risk their ancestral way of life, including that of the Raizal people.

The risks to navigation are also considerable. Floating plastics pose hazards to navigation and can damage ships, ports, and coastal infrastructure, resulting in additional costs for port authorities and maritime operators (IMO, 2024).

Policies, Future Guidelines and Ways to Follow

One of the primary factors limiting efforts against marine litter in the Caribbean Sea is the lack of effective regulations and public policies. Many of the countries in this region are island territories with economies that face challenges such as poverty, technological lag, and infrastructure deficiencies (Vélez, 2019). Additionally, these economies depend heavily on imported goods, which generate large quantities of plastic packaging (Clayton *et al.,* 2021).

However, there are positive developments. According to Fernández *et al.* (2021), in recent years, at least 27 of the 33 countries in Latin America and the Caribbean have implemented laws banning or eliminating single- use plastics. Antigua and Barbuda became a pioneer in 2016, by banning the import, distribution and use of plastic bags. In the Bahamas, the ban on single-use plastics was enacted in 2019 and came into force in 2020 with the Environmental Protection Act (2019). Barbados also banned the import of plastics as part of its transition to a green economy, and Grenada passed the Non-Biodegradable Waste Control Act in 2018.

In addition, regional initiatives such as the Regional Action Plan for Marine Litter Management (RAPMaLi) are being implemented in the Wider Caribbean Region. This plan promotes waste management with the support of community groups and the business sector. Countries such

as Guyana, Barbados, and Saint Lucia are pilots of this program.

Other countries such as Belize have launched programs like 'Belize: Blue, Clean, Resilient and Strong' to prevent marine litter and improve waste management. Panama has been implementing a national plan to reduce marine litter since 2021, involving the Government, communities and the private sector throughout the country.

National Policies

Colombia has developed a comprehensive policy framework to combat marine pollution caused by single-use plastics, aiming for elimination by 2030. Its Sustainable Plastic Management strategy engages all sectors to prevent, reduce, reuse, recycle, and replace plastics (Fernández *et al.,* 2021).

In 2018, the country launched the National Circular Economy Strategy and in 2019, the National Plan for the Sustainable Management of Single-Use Plastics, focused on reducing plastic consumption and promoting a circular design (Fig. 2).

In 2016, a regulation was imposed that banned and taxed plastic bags, achieving a 35% reduction in their consumption between 2016 and 2019 and a 59.4% decrease in their distribution. The combination of the ban and the tax on single-use plastic bags has had a positive impact on reducing the consumption of plastic bags and has strengthened awareness of the importance of reducing plastic waste in the country (Fernández *et al.,* 2021).

Figure 2 presents a synthesis of Colombia's regulatory and policy framework in relation to solid waste management and its connection with pollution in marine-coastal territories. A chromatic code is used to classify the regulations, not in chronological order, but by categories.

First, the concepts of marine pollution are addressed, followed by regulations on solid waste, sanitation services and circular economy as a tool to reduce and take advantage of waste. Also included are two related standards that establish local committees to organize beaches and create coordination bodies, as well as a technical standard to improve tourism quality under sustainability principles.

Seven standards focused on the reduction of single-use plastics stand out. The scheme covers two large groups of policies and standards of the international framework hosted by Colombia, such as United Nations treaties for the control of pollutants and microplastics.

Finally, policies and documents of the National Council for Economic and Social Policy (Conpes) are presented, which promote sustainable development and the circular economy, allowing the identification of key standards for the reduction of waste at sea, articulated with environmental planning and management instruments.

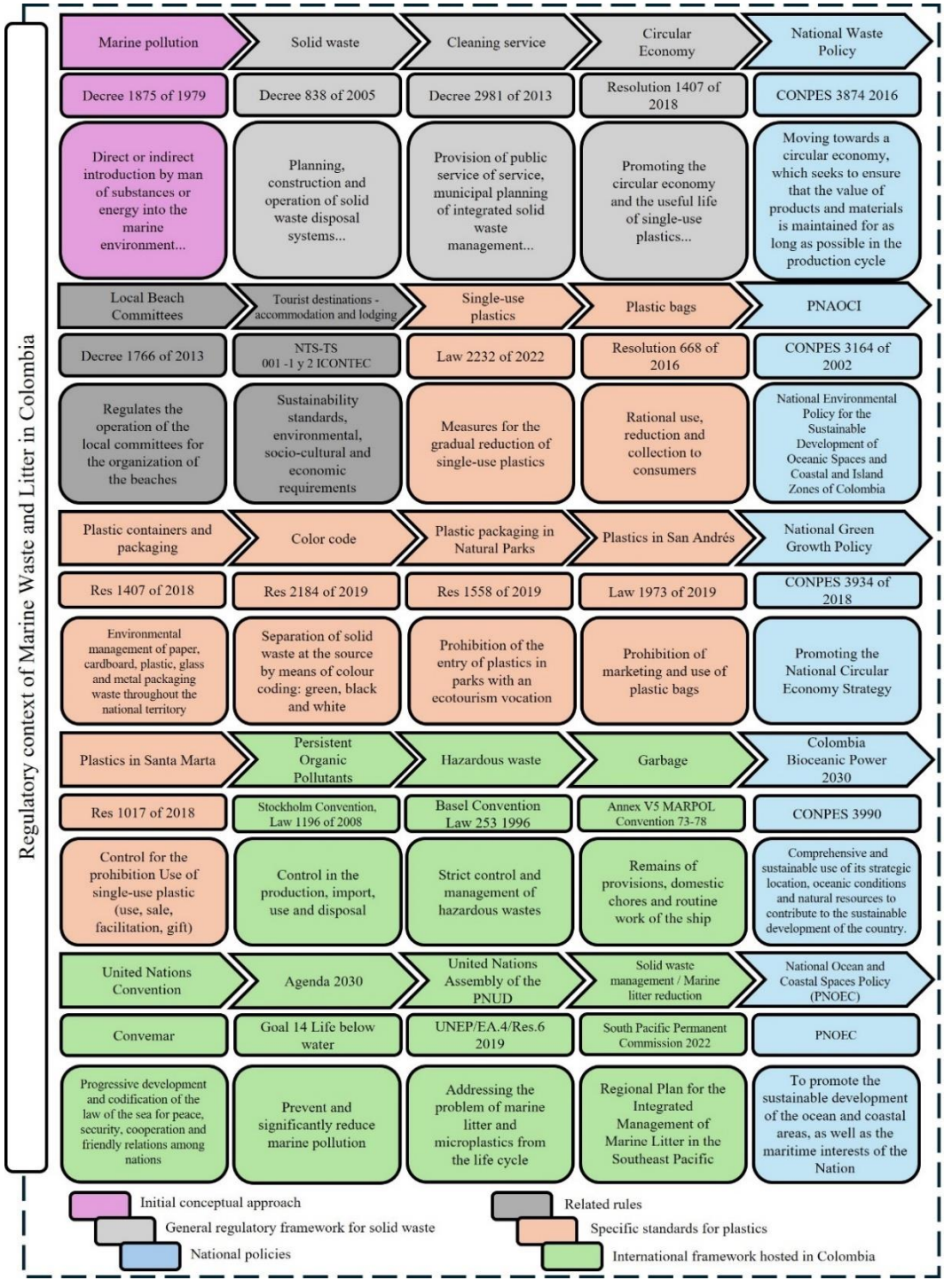

Figure 2. Regulatory context and policies on waste and marine litter in Colombia. [Modified from: Invemar, 2020 (based on the following rules, laws and regulations: Botero, 2018; CCO, 2007, 2018; Permanent Commission of the South Pacific, 2020; Congress of Colombia, 1996, 2019; National Council for Economic and Social Policy, 2002, 2020; International Convention for the Prevention of Pollution from Ships, 1973; CPPS, 2022; District Administrative Department of Environmental Sustainability, 2018, 2019; DNP, 2016, 2018; ICONTEC, 2007a, 2007b; Invemar, 2020; MAVDT, 2005; Ministry of Environment and Sustainable Development of Colombia, 2013, 2016, 2018, 2019a, 2019b, 2019c, 2021; Ministry of Environment, 2001; Ministry of Housing, City and Territory, 2013; United Nations, 1982, 2015, 2019; Republic of Colombia, 1979; Tourism, Cultural and Historical District of Santa Marta, 2018).

Policies for SBR

Specific laws have been established at the SBR to address marine pollution and reduce the use of plastics. Law 1973 of 2019 prohibits the entry, sale and use of bags and other plastic materials on the San Andres, Old Providence and Ketlina Islands. This legislation, supported by Resolution 283, came into force in July 2021 with the objective of reducing plastic pollution and promoting sustainable practices on the islands.

Measures implemented under this law include a ban on single-use plastics and awareness campaigns about plastic pollution. Additionally, incentives have been established to encourage the replacement of plastic materials with biodegradable and sustainable alternatives.

While these policies represent important advances in plastic waste management, it is important to assess their effectiveness and limitations. A major challenge is the effective implementation and enforcement of these laws. Although single-use plastics have been banned, studies show that high levels of plastics and microplastics are still found, suggesting that the ban has not been entirely effective.

The benefits of these policies include raising environmental awareness and promoting the transition from plastics to biodegradable alternatives. However, these regulations have not sufficiently addressed external sources of pollution, such as waste carried by ocean currents from other regions.

Suggested Measures to mitigate Pollution and Promote Health in the Caribbean Sea

This analysis highlights the persistent problem of marine litter, originating both locally and from ocean currents. The ongoing issue threatens a gradual degradation of the affected ecosystems. Although management initiatives exist, they remain insufficiently robust to mitigate environmental pressures.

The Colombian government should adopt integrated measures that incorporate prevention, recycling, and the promotion of a circular economy, alongside corporate social responsibility. Current recycling systems require significant adjustments to effectively limit the production of single-use plastics. As of May 2024, the responsibility for avoiding plastic use lies primarily with consumers, while recyclers are responsible for managing waste. This framework largely exempts companies that continue to produce plastics to minimize costs. It is essential to implement sustainable practices that reduce the use of hazardous substances, encourage innovative technologies, and promote specialized recycling systems.

Both tourists and local residents of the Archipelago of San Andrés, Providencia y Santa Catalina must recognize their role in exacerbating this issue. Raising awareness is critical to reducing its impact on the Reserve's oceans and ecosystems. The national and regional governments, in collaboration with local entities, can implement educational programs and awareness campaigns. These initiatives should include social media efforts to promote alternatives to single-use plastics, encourage the proper disposal of recyclable materials, and discourage the excessive consumption of plastic products.

Marketing initiatives in hotel chains, shopping centers, and other establishments could also play a key role. For instance, offering incentives to customers who contribute to recycling efforts can reduce the negative effects of plastic waste. Reward systems for recycling in hotels and shops can help mitigate the problem and foster sustainable habits.

A holistic approach is necessary to address marine litter from economic, social, and cultural perspectives. This includes strengthening regulations with penalties for non-compliance and ensuring constant monitoring of enforcement. Furthermore, international environmental agreements should be revisited to promote transboundary conservation efforts. Addressing marine litter in the SBR is essential not only to protect the local economy, but also to ensure the sustainability of fisheries and the preservation of marine ecosystems.

It is important to highlight the need for effective monitoring, rigorous controls and the proper implementation of policies to address the problem of marine litter in the Archipelago. From the perspective of local residents, it is evident that many regulations, resolutions, or laws remain largely unenforced, with inadequate supervision and limited enforcement mechanisms.

According to personal communications with the inhabitants of the Archipelago of San Andrés, Providencia y Santa Catalina, there is no rigorous program for the management and disposal of solid waste on the islands and cays. It is essential to develop education and awareness initiatives, both for the population and for government bodies, since waste management must be an integral part of public policies in the region.

A priority action would involve conducting cleaning and awareness campaigns in Alburquerque and Pescadores Cay (Courtown Cays), which experience high levels of pollution, particularly in areas used by fishermen and in dense vegetation zones. These campaigns should engage the fishermen of San Andres, who use Pescadores Cay as a temporary refuge. Collaboration between state agencies and fishermen could facilitate the collection and transport of waste to San Andres, promoting more sustainable waste management and reducing pollution.

To achieve meaningful change, it is essential to impose stricter penalties for non-compliance with regulations. Substantial fines could serve as an effective incentive for people to understand the importance of reducing their environmental impact and comply with the established provisions. These sanctions must not only be dissuasive, but also educational, so that the community understands the seriousness of the problem and actively commits to its solution. This is especially relevant in the context of the SBR as a protected area, where tourists and tour operators are prohibited by law from entering. Awareness and education campaigns must also include these groups.

It is key to promote recycling as a mandatory practice, starting in educational institutions, where it is integrated into the curriculum. Companies, both public and private, must implement environmental management plans with recycling programs. This would not only reduce marine litter in the ocean, but also foster a culture of environmental responsibility. In addition, it is vital to promote recycling in homes, companies, and the tourism sector through awareness campaigns. Implementing separate collection systems and providing access to recycling points are critical steps to achieve this.

Addressing marine litter in the SBR is critical to protecting the islands' economic sectors and ensuring the sustainable development of the fishing industry. Figure 3 presents examples of short-, medium-, and long-term actions.

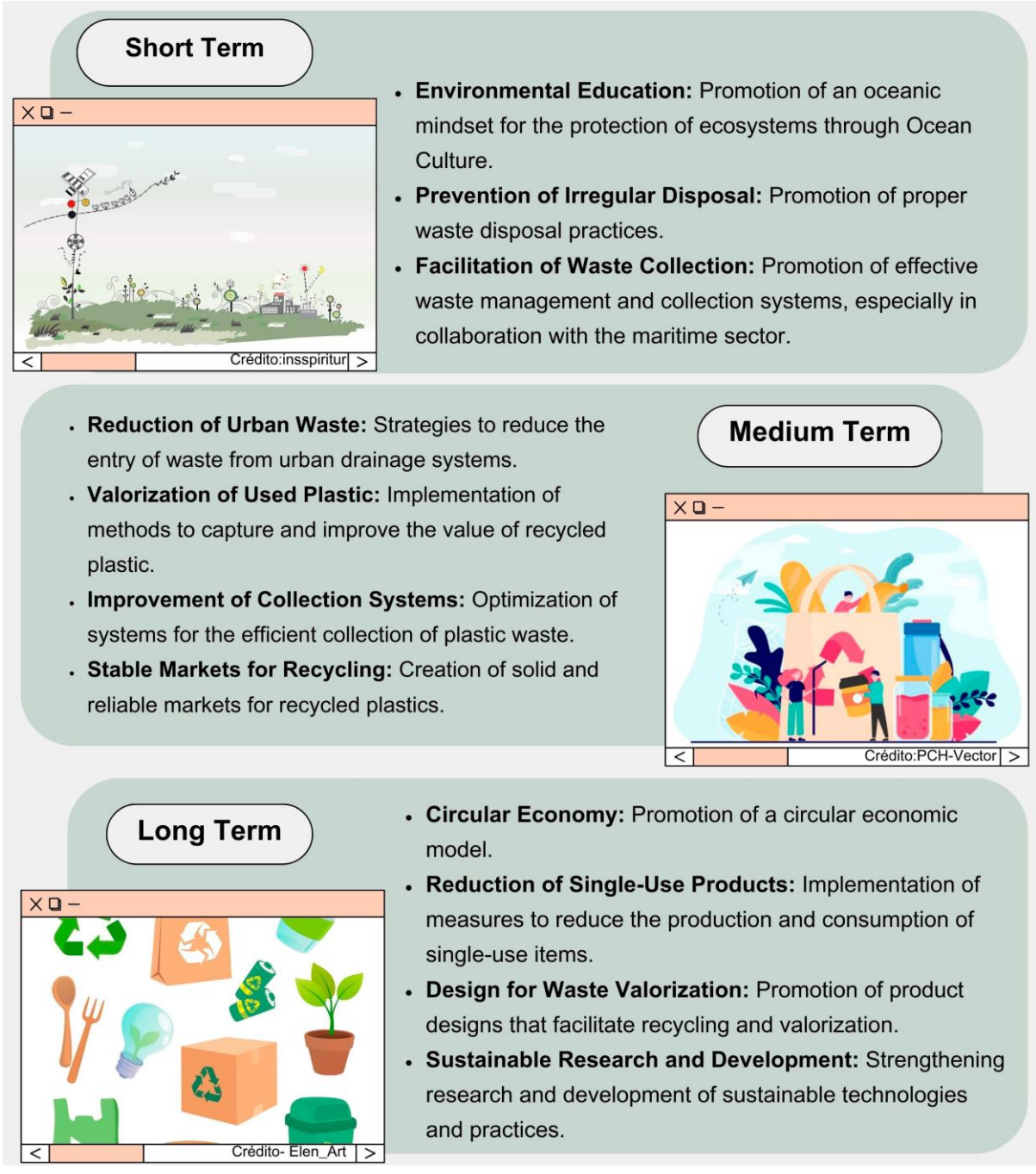

Figure 3. Examples of short-term (1-2 years), medium-term (3-5 years) and long-term (6-10 years) actions to address the problem of marine litter.

CONCLUSIONS

Marine litter pollution in the SBR poses a critical challenge to the health of marine and coastal ecosystems in the Caribbean region. The vulnerability of remote islands to this type of pollution underscores the urgent need to implement effective and sustainable environmental management practices.

The analysis of marine litter reveals the presence of multiple sources of pollution, both local and external. Inadequate land-based activities, such as ineffective waste management, combined with the arrival of plastics transported by natural processes like waves and ocean currents, are key factors in the accumulation of marine litter in these ecosystems.

The increasing accumulation of marine litter not only threatens the sustainability of marine and coastal resources, but also negatively impacts vital sectors such as tourism and fisheries, which are pillars of the regional economy. The presence of marine litter and microplastics in sensitive areas, such as mangroves and beach vegetation zones, highlights the need for coordinated actions that involve the community and adapt management strategies to local conditions.

Given the fragility of marine ecosystems in the SBR, it is imperative to adopt stricter management measures and educational programs that respond to the specific needs of each context. Collaboration between the Colombian government and local stakeholders is critical to promoting the conservation of these unique environments and ensuring their long-term sustainability.

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AUTHORS' CONTRIBUTION

Participation in the different Seaflower expeditions: L.P., P.T.C., G.I.L., N.G.B., G.C.U., R.P.M., R.C.B.; conceptualization and methodology: L.P., G.I.L., N.G.B., R.P.M.; analysis: L.P., P.T.C., G.I.L., N.G.B., R.P.M.; drafting-preparation of the original draft: L. P.; writing-contributions, revision and editing: L.P., P.T.C., G.I.L., N.G.B., G.C.U., R.P.M., D.A.V.D. All authors have read and accepted the published version of the manuscript.

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