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# Galápagos and the plastic problem

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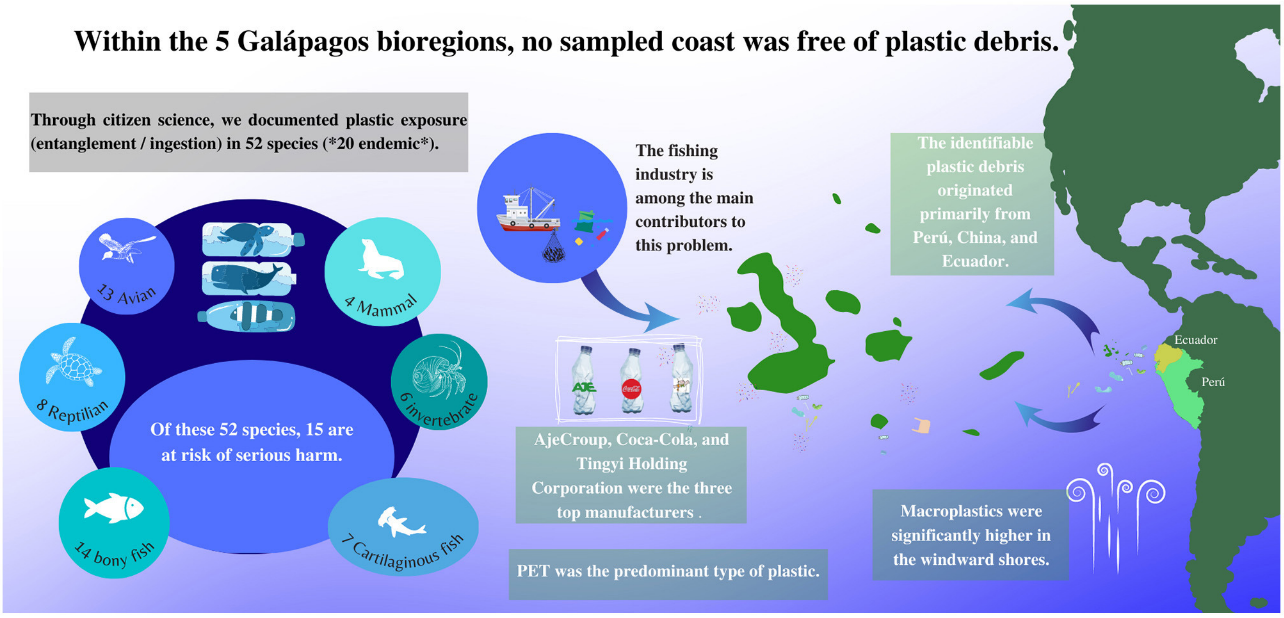
Plastic pollution (PP) is an ongoing, pervasive global problem that represents a risk to the Galápagos archipelago, despite it being one of the world's most pristine and well-protected regions. By working closely with citizen scientists, we aimed to quantify and map the magnitude and biological effects of PP. With macroplastic abundance ranging from 0.003 to 2.87 items/m$^2$, our research indicates that all five sampled Galápagos bioregions are contaminated with PP along their coastlines. The distribution of this debris is not uniform, with macroplastics significantly higher on the windward shores. Based on the identification information found on the examined items, Polyethylene terephthalate (PET) was the most predominant type of plastic originating from both consumer and fisheries-based products deriving primarily from Perú, China, and Ecuador. The top three manufacturers were AjeCroup, Coca-Cola, and Tingy Holding Corporation. Through citizen science, we documented PP exposure in 52 species (20 endemic) in Galápagos terrestrial and marine environments, with exposure occurring in two ways: entanglement and ingestion. These included reptiles (8 species), birds (13 species), mammals (4 species), cartilaginous fish (7 species), bony fish (14 species), and invertebrates (6 species). The top five species with the greatest risk of serious harm due to entanglement (in decreasing order) were identified as green sea turtles, marine iguanas, whale sharks, spine-tail mobulas, and medium-ground finches. In contrast, Santa Cruz tortoises, green sea turtles, marine iguanas, black-striped salemas, and Galápagos sea lions were at the highest risk of harm due to the ingestion of plastics. Our research indicates that PP is a growing problem in the Galápagos archipelago and that additional work is necessary to mitigate its impact now and in the future.

KEYWORDS

**Galápagos, macroplastics, ingestion, entanglement, threat, assessment, citizen science**

## 1. Introduction

Plastic pollution (PP) is discarded, lost, or abandoned plastic debris that builds up, persists, and is not degraded in the environment to the point that it could pose difficulties for animals, their habitats, and human populations (Joyner and Frew, 1991). The first synthetic plastic, Bakelite, was invented in 1907 as an environmental alternative to natural plastics such as amber, ivory, and tortoiseshell (Mossman, 2017). Discarded, lost, or abandoned plastic has



Within the 5 Galápagos bioregions, no sampled coast was free of plastic debris.

Through citizen science, we documented plastic exposure (entanglement / ingestion) in 52 species (*20 endemic*).

Of these 52 species, 15 are at risk of serious harm.

The fishing industry is among the main contributors to this problem.

The identifiable plastic debris originated primarily from Perú, China, and Ecuador.

AjeCroup, Coca-Cola, and Tingyi Holding Corporation were the three top manufacturers .

PET was the predominant type of plastic.

Macroplastics were significantly higher in the windward shores.

GRAPHICAL ABSTRACT
The main findings of this study are presented visually, showing how many and which species of animals are most at risk, the main countries of manufacturing and manufacturers that were predominant, and the direction of pollution.

since become permanent and pervasive pollution. It is a widespread and escalating problem, with 51 trillion microplastic particles floating in the oceans of the world (Eriksen et al., 2014; Van Sebille et al., 2015). Plastic pollution (PP) is also found in polar regions to the tropics and from surface waters to the depths of the ocean (Pruter, 1987; Laist, 1997; Thompson, 2004; Andrady, 2011; Gall and Thompson, 2015; Taylor et al., 2016; Brahney et al., 2020; Kane et al., 2020; Rillig and Lehmann, 2020; Lucas-Solis et al., 2021; Pakhomova et al., 2022). Plastic pollution has been identified in the human blood, liver, lung, stool, placenta, and breast milk (Ragusa et al., 2021, 2022; Jenner et al., 2022; Leslie et al., 2022). Given the ubiquity of PP, it is imperative for scientists, managers, decision-makers, and the public to comprehend its sources and potential harm to the environment and human health (Jambeck et al., 2015; Smith et al., 2018; Shi et al., 2022).

Plastics have several advantages over conventional materials when used with care. However, when not disposed of properly or leaked into the environment, they pose an existential social, environmental, and economic threat (Beaumont et al., 2019; Williams and Rangel-Buitrago, 2022). Global data indicate that plastics were uncommon along coastlines before 1950. Today, there may not be a single coastline on the planet that is entirely free of plastics (Bergmann et al., 2015). Approximately three-quarters of the world's coastlines have been affected by marine litter in the form of plastic waste (Thompson, 2004; Browne et al., 2010; Andrady, 2011; Jambeck et al., 2015; Law, 2017). This problem has spread to all ocean basins (Pakhomova et al., 2022). There has been rapid growth in the production and use of plastics in both wealthy and developing countries. This rapid production and indiscriminate plastic use, combined with linear economic strategies, have contributed to the widespread presence of plastic pollution (Jambeck et al., 2015; Lau et al., 2020; Lavers et al., 2022; Williams and Rangel-Buitrago, 2022). In addition, plastic pollution production and disposal are linked to climate change owing to the extraction of fossil fuels and their impacts on ecosystems (Ford et al., 2022; Lavers et al., 2022).

The improper disposal of plastics is a serious issue, as recycling infrastructure is not efficient, and a circular economy has yet to be successfully implemented because plastics leak into the environment and the amount of plastic in circulation increases in size (King and Locock, 2022; Williams and Rangel-Buitrago, 2022). Most importantly, there are currently insufficient regulations to encourage proper disposal (Willis et al., 2022). Accordingly, modeling plastic production and management scenarios indicate that 710 million metric tons of plastic waste will enter aquatic and terrestrial ecosystems by 2040; even with immediate and agreed-upon global administration, it could have catastrophic effects on humanity and the environment (Lau et al., 2020).

Plastic pollution (PP) continues to exponentially impact the oceans worldwide (Jambeck et al., 2015; Serra-Gonçalves et al., 2019). Globally, over 1400 marine species interact with plastic debris (Claro et al., 2019), posing a significant threat to wildlife. These threats include ingestion, entanglement, and habitat degradation, which have sublethal and lethal effects on marine animals. Chronic exposure to PP can affect feeding, energy, growth, health, and reproductive output (Gall and Thompson, 2015; Li et al., 2016; Galloway et al., 2017; Law, 2017; Lavers et al., 2019; Senko et al., 2020; Yamashita et al., 2021). Accumulation of PP in marine food webs can affect the entire ecosystem (Galloway et al., 2017; Smith et al., 2018). Moreover, the plastic pollution crisis is more pronounced in protected oceanic and isolated islands (Lavers and Bond, 2017). In addition, there is a notable trend

FIGURE 1
Macroplastic categorization process. CSIRO categorization system (Schuyler et al., 2020) with adaptations. Categories are: HPF (Hard plastic fragments); FISH (Engine oil bottles, fishing buoys, fishing nets, monofilament fishing line, eel traps, plastic rope, string, twine); BB (Plastic beverage bottles); BC (Beverage bottle caps); BAG (Plastic bags); HI (Household items, razors, toothbrushes, deodorants, toys, straws, popsicle sticks, utensils, cutlery, food containers, tetra pack, plastic cups, plastic packing straps, shoes, sandals, balloon, cigarette, cloth item); FP (Film plastic food wrap, chip bags, "other" soft plastic); OB (Other bottles, i.e., shampoo, kitchen oil); LPI (Large plastic items, i.e., buckets, boxes, tubes); FOAM (Any foam); RUB (Rubber gloves or other rubber items, i.e., tires.); OC (Other caps/lids); OTHER (Other items, i.e., glass, metal, paper). The measuring tape was 10 m in length. This figure shows a macroplastic density of 2.10 items/m$^2$ from the windward remote San Cristóbal Island in El Pescador (LAT-0.917083°; LONG−89.404444°).

between windward and leeward plastic debris deposition rates on islands, with windward coastlines being more polluted with plastic debris than leeward coastlines (McDermid and McMullen, 2004; Morishige et al., 2007; Debrot et al., 2013; Hidalgo-Ruz and Thiel, 2013; Brignac et al., 2019; Rangel-Buitrago et al., 2019; Nichols et al., 2021). This places species on remote islands and those that forage and nest on windward coastlines at a potentially greater risk of their health being affected by plastic pollution.

The Galápagos archipelago, also known as the Enchanted Islands, is located 972 km west of mainland Ecuador and is home to unique biodiversity. It consists of 13 large and six small islands, 107 islets and rocks, a total area of ∼8,000 km$^2$, a coastline of 1,753 km, and a marine reserve covering 198,000 km$^2$ (Edgar et al., 2008; Denkinger et al., 2014; DW News, 2022; Hearn et al., 2022). The evolutionary paradigm was developed based on adaptations to the Galápagos volcanic environment (Darwin, 1876). Since 1959, the Ecuadorian government has maintained strict regulations for more than 97% of the archipelago. It has been largely successful in protecting this unique ecosystem from anthropogenic pressures such as overfishing, overpopulation, invasive species, and hunting species (Denkinger et al., 2014). Consequently, most non-urban areas of Galápagos maintain conditions before human presence. In other words, 97% has remained well-managed and restored (Izurieta et al., 2014; Negru et al., 2020). Despite its isolation, the islands are safeguarded; therefore, we may observe almost the same environment as Darwin observed nearly 200 years ago. Nonetheless, it is paradoxically vulnerable to stresses from human-caused global factors such as climate change and plastic pollution (Alava et al., 2022).

Consequently, PP continues to be present on the most remote Galápagos coastlines. During the preceding 5 years, fishermen, volunteers, residents, scientists, and park rangers removed 71 metric tons of plastic waste from the remote beaches of Santa Cruz, Baltra, Floreana, Santiago, Isabela, Pinta, Marchena, and San Cristóbal. This waste was unloaded and sorted on the islands of Santa Cruz and San Cristóbal before being transported to municipal waste facilities for final disposal (Galápagos National Park Directorate, 2020; Galapagos National Park Directorate, 2021a,b,c; Alarcon and Alvarado, 2022). This demonstrates that the Galápagos Marine Reserve (GMR) is no exception to the global plastic pollution crisis. Consequently, it is necessary to document the possible adverse effects of exposure to PP, establish a baseline for endemic species, feeding areas, and populations, and monitor the patterns of the presence and absence of PP. Thus, addressing crucial knowledge gaps and providing the data required for decision makers to advocate timely intervention and mitigation measures.

At a global scale, the endemic wildlife of the Galápagos archipelago is of critical importance (Ballesteros-Mejia et al., 2021). Anecdotal reports indicate that several of these species are directly affected by plastic debris. However, standard information is not currently available. Therefore, it is necessary to assess their scope to develop specific conservation plans to reduce the potential impacts of plastic pollution on wildlife in Galápagos. Our research aims to provide the first comprehensive analysis of an innovative *in situ* effort to investigate the distribution, composition, source, and environmental impact of plastic pollution at an archipelago scale. We also generated a threat assessment based on the dangers and potential risks posed by plastic debris exposure to Galápagos wildlife, allowing us to identify and rank the most at-risk species.

TABLE 1 Macroplastic categories adapted for the Galápagos study using the CSIRO protocol (Schuyler et al., 2020).

| Categories | Meaning |
|---|---|
| HPF | Hard plastic fragments. |
| FISH | Engine oil bottles, fishing buoys, fishing nets, monofilament fishing line, eel traps, plastic rope, string, twine. |
| BB | Plastic beverage bottles. |
| BC | Beverage bottle caps. |
| BAG | Plastic bags. |
| HI | Household items (razors, toothbrushes, deodorants, toys, straws, popsicle sticks, utensils, cutlery, food containers, tetra pack, plastic cups, plastic packing straps, shoes, sandals, balloon, cigarette, cloth item). |
| FP | Film plastic (food wrap, chip bags, “other” soft plastic). |
| OB | Other bottles, i.e., shampoo, kitchen oil. |
| LPI | Large plastic items, i.e., buckets, boxes, tubes. |
| FOAM | Any foam. |
| RUB | Rubber gloves or other rubber items, i.e., tires. |
| OC | Other caps/lids. |
| OTHER | Other items, i.e., glass, metal, paper. |

## 2. Materials and methods

### 2.1. Macroplastic density (items/m$^2$)

There are five major bioregions in Galápagos, each with distinct oceanographic conditions, species diversity, distribution, composition, and endemism (Edgar et al., 2004; Castrejón and Charles, 2020). To determine the macroplastic density (items/m$^2$) for the typically inaccessible and vast irregular 1,753 km Galápagos coastline (Edgar et al., 2008). Field sampling was conducted on 20 remote (no public access) shorelines covering the five Galápagos bioregions. On each selected island, a 50 m transect was laid parallel to the water on the leeward side, and another 50 m transect was laid parallel to the water on the windward side of the same island ($n = 2$ for each island) for a total of 20 transects. All visible plastic elements and fragments larger than 5 mm between the water and vegetation lines of this transect were removed and stored for subsequent laboratory examination. Following the method used by Jones et al. (2021), the shoreline area was calculated using satellite images (obtained from Google Earth, May 2022) to allow us to convert the data into macroplastic density (items/m$^2$) for each of the transects.

Macroplastics were counted and classified (Figure 1) using an adapted Galápagos CSIRO classification protocol

TABLE 2 Scoring criteria for the threat scale on reported species with PP interactions in Galápagos.

| Score | 1 | 2 | 3 |
|---|---|---|---|
| ($S^T$) Species distribution or taxon origin | (U) Unknown or not evaluated | (M) Migratory | (E) Endemic |
| | | (N) Native | |
| ($S^C$) Conservation status | (DD) Data deficient | (NT) Near threatened | (EN) Endangered |
| | (NE) Not evaluated | (VU) Vulnerable | (CR) Critically endangered |
| | (LC) Least concern | | |
| ($S^F$) Feeding type | (C) Carnivorous | (O) Omnivorous | (Pl) Planktivorous |
| | | | (H) Herbivorous |
| ($S^H$) Species habitat and ecology | (TN) Terrestrial natural | (TW) Terrestrial wetlands | (MI) Marine intertidal |
| | | | (MO) Marine oceanic |
| | | | (MN) Marine neritic |
| | | | (TU) Terrestrial urban |
| ($S^E$) Entanglement | No evidence | Moderate ≥1 up to 3 evidence | Major ≥3 evidence |
| ($S^I$) Ingestion | No evidence | Moderate ≥1 up to 3 evidence | Major ≥3 evidence |

$S^T$, species distribution or taxon origin; $S^C$, conservation or IUCN red list status; $S^F$, feeding type; $S^H$, species habitat and ecology; $S^E$, entanglement; $S^I$, ingestion.

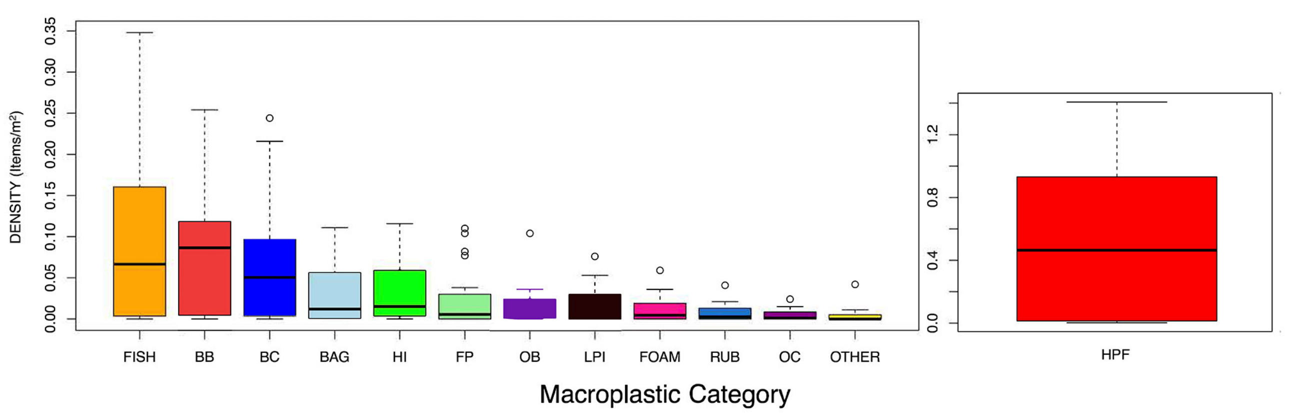


FIGURE 2
Macroplastic category density (items/m$^2$) for all surveyed sites in the five bioregions. CSIRO categorization system (Schuyler et al., 2020) with adaptations. Categories are: HPF (Hard plastic fragments); FISH (Engine oil bottles, fishing buoys, fishing nets, monofilament fishing line, eel traps, plastic rope, string, twine); BB (Plastic beverage bottles); BC (Beverage bottle caps); BAG (Plastic bags); HI (Household items, razors, toothbrushes, deodorants, toys, straws, popsicle sticks, utensils, cutlery, food containers, tetra pack, plastic cups, plastic packing straps, shoes, sandals, balloon, cigarette, cloth item); FP (Film plastic food wrap, chip bags, "other" soft plastic); OB (Other bottles, i.e., shampoo, kitchen oil); LPI (Large plastic items, i.e., buckets, boxes, tubes ); FOAM (Any foam); RUB (Rubber gloves or other rubber items, i.e., tires.); OC (Other caps/lids); OTHER (Other items, i.e., glass, metal, paper).

(Schuyler et al., 2020). These categories are listed in Table 1. To conduct a more comprehensive and detailed search for information regarding the polymer type, the manufacturer of the item, and the country of origin, a random subsample of 30 items from each transect/location with a potential identifier (such as legible inscriptions, stamps, or labels) was selected. Information from the Society of the Plastics Industry (SPI) code was recorded to identify the polymer types. In 1988, SPI established a classification system to enable consumers and recyclers to differentiate between various plastic types. By regulation, manufacturers imprint an SPI code or number on the bottom of every plastic product (Mertes, 2019). Finally, we identify the manufacturer and country of origin by examining the information contained in legible inscriptions, stamps, and labels. Google Lens was used to collect information on items with inscriptions in languages unknown to us.

## 2.2. Galápagos wildlife interactions with plastic pollution (ingestion or entanglement)

ArcGIS Survey123 was used to conduct citizen science surveys (accessible *via* the link https://arcg.is/0bTLKv and Supplementary Figure 2). The survey collected photographic or video evidence of interactions between the wildlife of Galápagos and plastic pollution (ingestion or entanglement). Similarly,

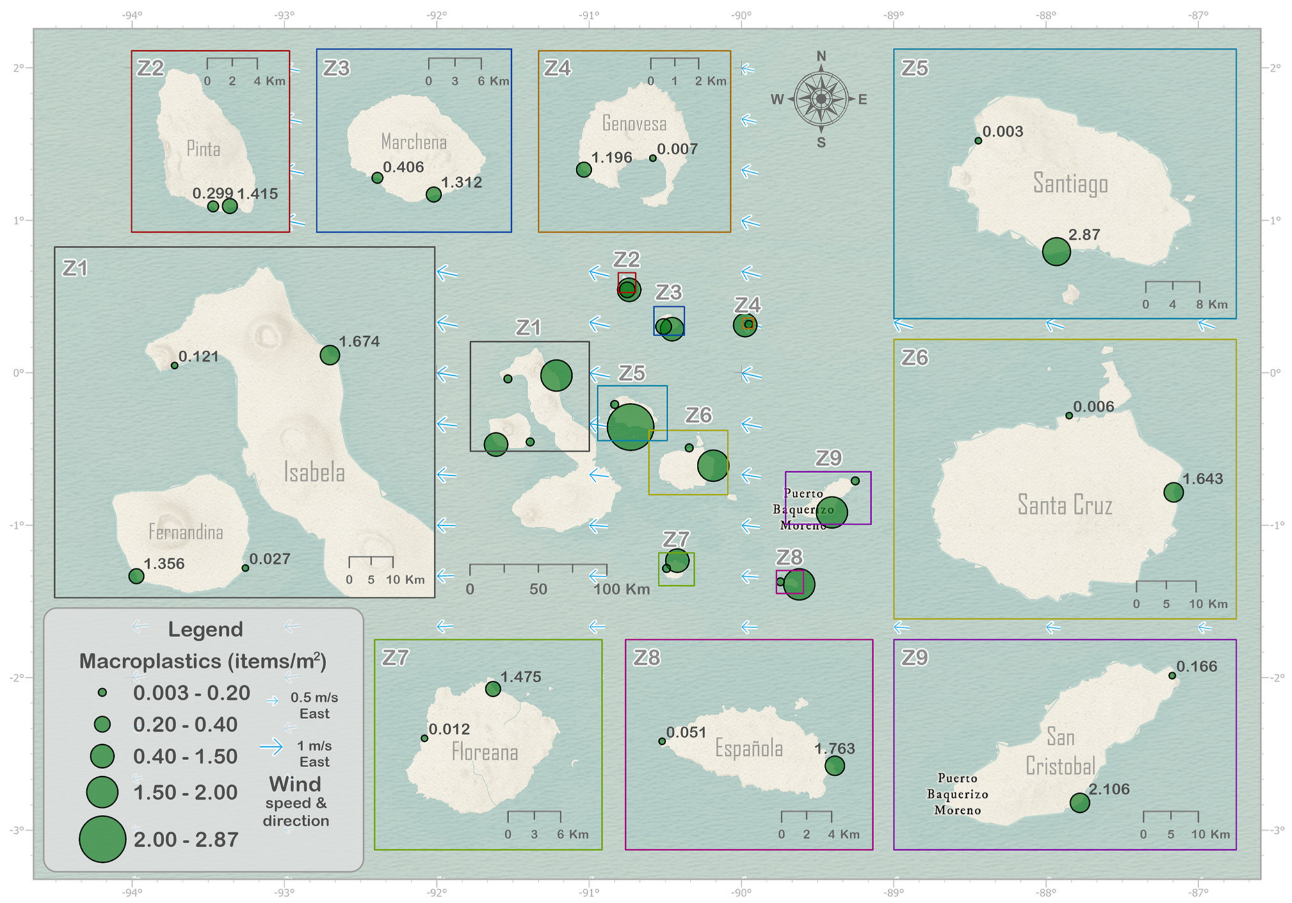


FIGURE 3
Macroplastic total density (items/m$^2$) for all sample sites in the Galápagos Archipelago. In the map, we divided our sample sites into 9 Zones/Islands (Z) to improve data visualization. Z1: Fernandina and Isabela Island; Z2: Pinta island; Z3: Marchena island; Z4: Genovesa island; Z5: Santiago Island; Z6: Santa Cruz Island; Z7: Floreana island; Z8: Española Island; Z9: San Cristóbal Island. Wind data were derived from the Global Ocean Data Assimilation (SODA) dataset, which is a part of the Global Ocean Data Assimilation System (GODAS), from the National Oceanic and Atmospheric Administration (NOAA) of the US. The u and v components of the wind currents over the oceans were plotted on a grid of 0.5°arc-degree over the Galápagos area, and the yearly average was presented as the wind speed and direction. The range of wind speeds was between 0.1 and 1 m/s. The predominant wind direction throughout the year is NWW at most locations in Galápagos, south of the equator (NCAR, 2022).

records were collected through social media. Only those species that possessed clear photo or video evidence were considered for the threat assessment.

## 2.3. Galápagos wildlife plastic pollution threat assessment (PPT)

Once species with PP interactions in Galápagos were confirmed, the priority scoring method developed by Wilcox et al. (2016), Jones et al. (2021), and Roman et al. (2022) were adapted and used. We constructed a threat assessment for the reported species using scores for distribution or taxon origin ($S^T$), IUCN conservation status ($S^C$), feeding type ($S^F$), habitat and ecology ($S^H$), entanglement harm ($S^E$), and ingestion harm ($S^I$). Table 2 presents the scoring criteria and threat categories used to rank the Galápagos species most affected by PP based on the distribution, diet, conservation status, habitat, and PP evidence available for each species. The International Union for Conservation of Nature (IUCN) Red List of Threatened Species (https://www.iucnredlist.org/) and The Charles Darwin Research Station Natural History Collections database (https://www.darwinfoundation.org/en/datazone) were consulted for information on distribution or taxon origin, conservation status, feeding type, habitat, and ecology. Finally, to calculate the priority species at a high threat of entanglement and ingestion in Galápagos, we used the following equations:

Entanglement threat (E)

$$(E) = S^T \times S^C \times S^F \times S^H \times S^E$$

Ingestion threat (I)

$$(I) = S^T \times S^C \times S^F \times S^H \times S^E$$

# 3. Results

## 3.1. Macroplastic density (items/m$^2$)

All Galápagos-sampled shorelines contained macroplastics. The density of the surface plastic debris varied from 0.003 to

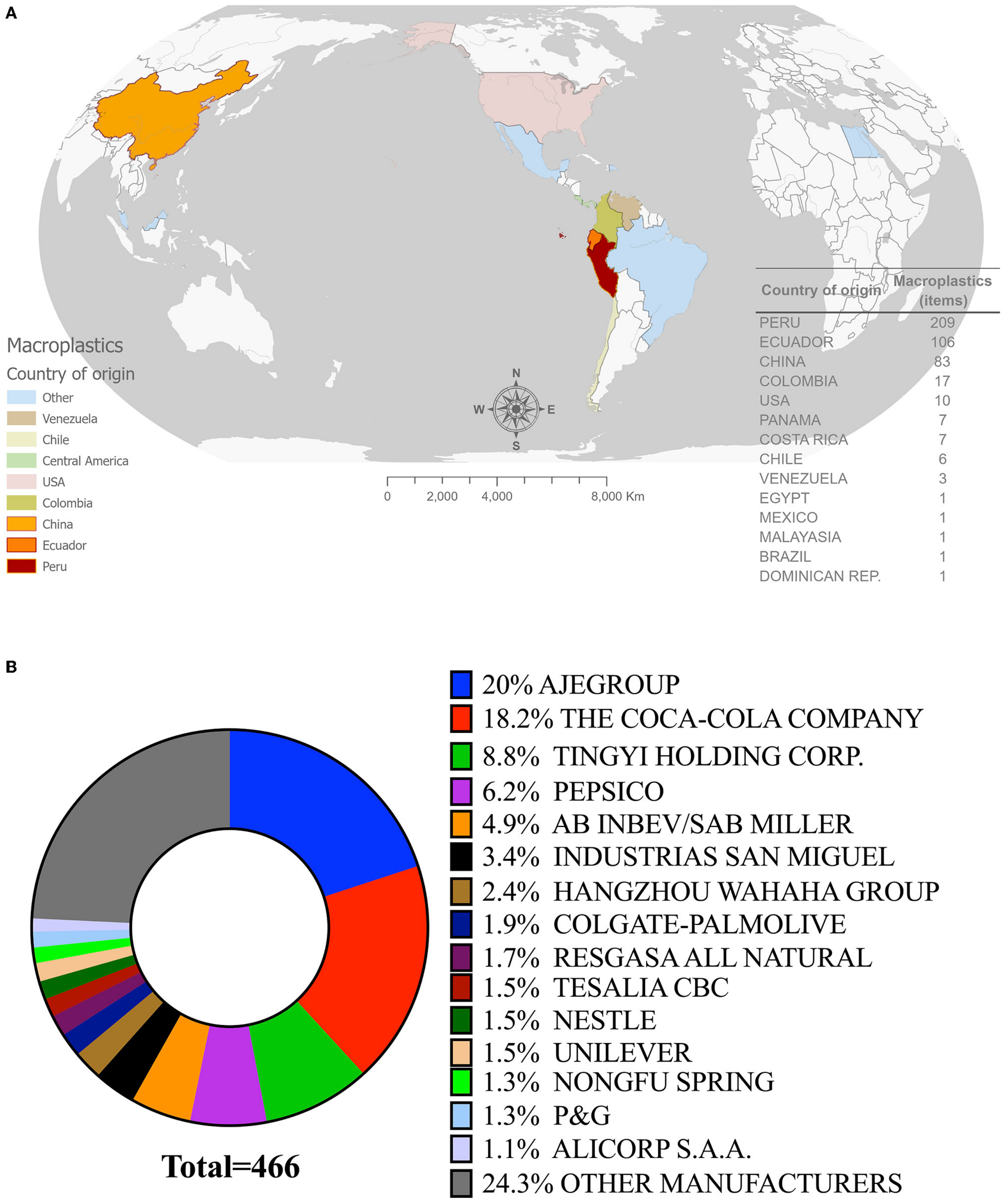


FIGURE 4

**(A)** Countries of origin of the examined macroplastics. Country of origin was identified from a random subsample of 466 items with a potential identifier (legible inscriptions, stamps, or labels) from all transects/locations in this study. A potential identifier was used to perform the search using Google Lens. Google Lens was a way to collect data on items with inscriptions in languages unknown to us, such as Mandarin. Countries with stronger colors: more items from that country were found. **(B)** The 15 top manufacturers of examined macroplastics.

2.87 to items/m$^2$. At 0.51 (SEM = 0.11) items/m$^2$, hard plastic fragments (HPF) were the most prevalent plastic classification category at all sampled sites, followed by fishing-related items (FISH), which numbered 0.09 (SEM = 0.02) items/m$^2$. Plastic beverage bottles (BB) with 0.08 (SEM = 0.02) items/m$^2$ were the third most prevalent category of macroplastics at all the sample sites (Figure 2).

The windward coast of Santiago Island had the highest density (2.87 items/m$^2$), while the leeward site on the same island had the lowest density (0.003 items/m$^2$) (Figure 3, Zone 5). The highest concentrations of macroplastics were observed on the windward coastlines of the archipelago. All windward study sites had a macroplastic density of 1.68 (SEM = 0.15) items/m$^2$, while all leeward study sites had a macroplastic density of 0.11 (SEM = 0.04) items/m$^2$. Macroplastic density (items/m$^2$) was significantly different between all windward and leeward sites (paired $t$-test, $t = 9.06$, $df = 9$, $P < 0.0001$).

After analyzing 466 macroplastic objects collected from the shores of Galápagos, the country of origin, manufacturer, and polymer type were determined for each study site. The most frequently identified source countries were Perú with 13.9 objects (SD = 6.9), China with 5.9 objects (SD = 3.5), and mainland Ecuador with 5.8 objects (SD = 3.7) (Figure 4A). In total, 98 manufacturers were established (Table 3). AjeGroup (20%), Coca-Cola Company (18.2%), and Tingy Holding Corporation (8.8%) had the highest proportion of plastics in the archipelago-sampled coasts (Figure 4B). Finally, the predominant type of plastic was polyethylene terephthalate (PET) at 12.3 objects (SD = 7.8) and high-density polyethylene (HDPE) at 3.1 objects (SD = 2.2).

## 3.2. Galápagos wildlife interactions with plastic pollution (ingestion or entanglement)

We received 197 reports on Galápagos wildlife PP interactions (entanglement or ingestion) *via* email, social media, and ArcGIS Survey123. Seventy-eight scientists, 34 citizens, 24 naturalistic guides, 20 anonymous individuals, 16 park rangers, 12 students, 10 tourists, and four fishermen submitted the reports. We documented PP exposure in 52 species (20 endemic, 24 native, 5 migratory) in terrestrial and marine environments of the Galápagos Islands, with exposure occurring *via* entanglement and ingestion (see Supplementary Figure 1 for more evidence). These included reptiles (8 species), birds (13 species), mammals (4 species), cartilaginous fish (7 species), bony fish (14 species), and invertebrates (6 species) (Table 4).

## 3.3. Galápagos wildlife plastic pollution threat assessment (PPT)

Plastic pollution (PP) posed the greatest threat to 15 of the 52 species examined in this study. Santa Cruz tortoises (*Chelonoidis porteri*) had the highest ingestion threat score among reptiles. The green sea turtle (*Chelonia mydas*) was most susceptible to entanglement. Among the evaluated avian species, the medium-ground finch (*Geospiza fortis*) and Galápagos flightless cormorant (*Phalacrocorax harrisi*) experienced the greatest risk of entanglement. Lava gull (*Larus fuliginosus*) had the highest ingestion score. Among mammals, the Galápagos sea lion (*Zalophus wollebaeki*) has the highest risk of entanglement and ingestion. The elasmobranchs most susceptible to entanglement and ingestion are the whale sharks (*Rhincodon typus*) and spinetail mobula (*Mobula japonica*). The teleost fish species that were most susceptible to entanglement and ingestion were black-striped salemas (*Xenocys jessiae*) and white-spotted sand bass (*Paralabrax albimaculatus*). Finally, the invertebrates most susceptible to PP were green sea urchins (*Lytechinus semituberculatus*), Ecuadorian hermit crabs (*Coenobita compressus*), and sally lightfoot crabs (*Grapsus grapsus*) (Figures 5, 6 and Table 4).

# 4. Discussion

Our threat assessment score provides a rapid, accurate, and efficient method for measuring the interaction between plastic pollution and species in any region. This method can be used to target species for more in-depth assessments of health and environmental impacts. This method considers the abundance of various species and their sensitivity to plastic debris, thereby allowing conservationists to rapidly identify the species most likely to be affected by plastic pollution. The universality of the impact assessment method is already being utilized in our regional project: Pacific Plastics Science to Solutions (PPSS) (https://www.pacificplasticssciencetosolutions.com/), on eastern Pacific species. We compared the species to those found in Galápagos and determined whether there were any differences or similarities with the species from other regions. Using a similar scoring method, *C. mydas* ranked first in entanglements off the coast of Perú (Eliana Alfaro 2022 personal communication).

Microplastic and nanoplastic surveys have yet to be conducted throughout the rest of the Galápagos archipelago. For example, microplastics have been found in beach sediments, benthic sediments, and in the digestive systems of marine invertebrates at all study sites on San Cristóbal Island. The most recent publication, which used citizen science, found more than 2,500 microplastic particles per m$^2$ on Santa Cruz Island (Jones et al., 2022). These studies have begun to demonstrate the abundance of plastics on islands and the risks that PP poses to wildlife. However, research has been limited to tourist shorelines and shorelines in urban areas. Jones et al. (2021) explored remote areas, but only one Galápagos Island (San Cristóbal). Standardized research must continue to comprehend the macro-, micro-, and nanoplastic densities of the five bioregions. Only then will we be able to understand the sources, sinks, and patterns of PP deposition to effectively address this global problem.

Our findings indicate that the Galápagos archipelago conforms to the well-established pattern observed on other isolated oceanic islands, where the highest concentrations of plastic debris were found on the most remote, off-limit, and windward coasts (Morishige et al., 2007; Debrot et al., 2013; Hidalgo-Ruz and Thiel, 2013; Lavers and Bond, 2017; Perez-Venegas et al., 2017; Monteiro et al., 2018; Brignac et al., 2019; Rangel-Buitrago et al., 2019). Multiple factors can affect the deposition rates, in addition to windward and leeward effects. Morishige et al. (2007) found that

TABLE 3 Ranking of 98 manufacturers from 466 macroplastic items collected from the Galápagos Archipelago, in which information could be identified.

| Manufacturer | *n* | Proportion | Manufacturer | *n* | Proportion |
|---|---|---|---|---|---|
| AJEGROUP | 93 | 19.96 | RECKITT | 1 | 0.21 |
| THE COCA-COLA COMPANY | 85 | 18.24 | TEXACO | 1 | 0.21 |
| TINGYI HOLDING CORP. | 41 | 8.80 | CMD-ZEPOL | 1 | 0.21 |
| PEPSICO | 29 | 6.22 | ECUAORGANIC | 1 | 0.21 |
| AB INBEV/SAB MILLER | 23 | 4.94 | JET | 1 | 0.21 |
| INDUSTRIAS SAN MIGUEL | 16 | 3.43 | ACTIVE PRODUCT S.A. | 1 | 0.21 |
| HANGZHOU WAHAHA GROUP | 11 | 2.36 | AFRICA'S BEST | 1 | 0.21 |
| COLGATE-PALMOLIVE | 9 | 1.93 | COLORESCIENCE | 1 | 0.21 |
| RESGASA ALL NATURAL | 8 | 1.72 | CONFITECA C.A. | 1 | 0.21 |
| TESALIA CBC | 7 | 1.50 | JGB S.A | 1 | 0.21 |
| NESTLE | 7 | 1.50 | VIVANT | 1 | 0.21 |
| UNILEVER | 7 | 1.50 | AQUAVIVA BOTTLING CO. | 1 | 0.21 |
| NONGFU SPRING | 6 | 1.29 | GANTEN | 1 | 0.21 |
| P&G | 6 | 1.29 | PICCO ENTERPRISE | 1 | 0.21 |
| ALICORP S.A.A. | 5 | 1.07 | AQUAFIT S.A. | 1 | 0.21 |
| KSF-ASIA MARKET | 5 | 1.07 | BIC CORPORATE | 1 | 0.21 |
| GRUPO GLORIA | 4 | 0.86 | CERVEJAS DA MADEIRA | 1 | 0.21 |
| LA FABRIL S.A. | 3 | 0.64 | GRUPO BICOLOR | 1 | 0.21 |
| BJARNER C.A. | 3 | 0.64 | KIMBERLY-CLARK | 1 | 0.21 |
| EDUARDOÑO S.A. | 3 | 0.64 | ALKOFARMA | 1 | 0.21 |
| CCU-Chile | 3 | 0.64 | PICA | 1 | 0.21 |
| VISTONY | 3 | 0.64 | SUPERMAXI | 1 | 0.21 |
| DURAPLAST S.A. | 3 | 0.64 | YAMBAL | 1 | 0.21 |
| JABONERÍA WILSON S.A. | 3 | 0.64 | AGUA PELICAN BAY | 1 | 0.21 |
| JOHNSON & JOHNSON | 2 | 0.43 | MEDIFARMA S.A. | 1 | 0.21 |
| PURISSIMA S.A. | 2 | 0.43 | NIKE | 1 | 0.21 |
| CHEVRON | 2 | 0.43 | NUTRIVITAL S.A. | 1 | 0.21 |
| JONJEE HI-TECH IND.& COM. | 2 | 0.43 | ÁGUA MINERAL TIMBU | 1 | 0.21 |
| DIMABRU CIA LTDA | 2 | 0.43 | LACOFA | 1 | 0.21 |
| DON JORGE S.A.C | 2 | 0.43 | LÁCTEOS SAN ANTONIO | 1 | 0.21 |
| BRINSA S.A. | 2 | 0.43 | NATURA & CO | 1 | 0.21 |
| PDVSA | 2 | 0.43 | ABG-GALÁPAGOS | 1 | 0.21 |
| EP PETROECUADOR | 2 | 0.43 | CIG S.A. | 1 | 0.21 |
| CORPORACIÓN AZENDE S.A. | 1 | 0.21 | GILCA LTDA | 1 | 0.21 |
| MONSANTO COMPANY | 1 | 0.21 | POLINPLAST SAC | 1 | 0.21 |
| GENERAL MILLS INC. | 1 | 0.21 | LA POLACA GUSTLAC S.A. | 1 | 0.21 |
| GRUPO BIMBO S.A.B. | 1 | 0.21 | REAL S.A. | 1 | 0.21 |
| CALBAQ S.A. | 1 | 0.21 | PPC FLEXIBLE PACKAGING | 1 | 0.21 |
| ESTRELLAAZUL S.A. | 1 | 0.21 | DANEC S.A. | 1 | 0.21 |
| LA MEJOR SAS | 1 | 0.21 | ECUAQUIMICA | 1 | 0.21 |
| C.A ECUASAL | 1 | 0.21 | LABORATORIOS ZOO | 1 | 0.21 |

*(Continued)*

TABLE 3 (Continued)

| Manufacturer | *n* | Proportion | Manufacturer | *n* | Proportion |
|---|---|---|---|---|---|
| AQUALINDA PANAMA S.A. | 1 | 0.21 | MAGAP | 1 | 0.21 |
| NATURE'S PHARMA | 1 | 0.21 | SIKA S.A. | 1 | 0.21 |
| INDUFAR CIA. LTDA | 1 | 0.21 | ADM (COMPANY) | 1 | 0.21 |
| C'ESTBON BEVERAGE CO. | 1 | 0.21 | EMPAQPLAST S.A. | 1 | 0.21 |
| SHENYANG XIN YI YUEN CO | 1 | 0.21 | HESSTONE S.A.C. | 1 | 0.21 |
| AMALIE OIL CO. | 1 | 0.21 | GRUPO DIANA | 1 | 0.21 |
| APOTHECARY PRODUCTS | 1 | 0.21 | ILE C.A. | 1 | 0.21 |
| GULF | 1 | 0.21 | JOHNSON OUTDOORS INC | 1 | 0.21 |

plastic debris deposition was significantly higher in the Hawaiian Islands during El Niño Southern Oscillation (ENSO) than during La Niña events. Therefore, standard long-term monitoring of plastic debris in Galápagos is recommended. Mestanza et al. (2019) found that the province with the best litter quality was the Galápagos Islands, where 88% of the beaches received an "A" rating (from "A"-excellent to "D"-poor) based on the EA/NALG (2000) scale. This is because the author sampled tourist beaches close to population centers. As shown in our study, the windward side of each surveyed island contained the highest concentrations of macroplastics. Our study focused on remote coastlines with no public or tourist access ($n = 20$) that were systematically sampled. To the best of our knowledge, and based on a review of the relevant literature, this is the first attempt at measuring plastic pollution on shorelines and in species at the archipelago level.

The primary macroplastic sources observed in this study were Perú, China, and mainland Ecuador. For Perú and Ecuador, the findings are consistent with the oceanographic patterns that sustain the archipelago's unique biodiversity (Houvenaghel, 1978; Palacios, 2004). Therefore, it is anticipated that plastic pollution will continue to flow from mainland Ecuador and Perú to Galápagos. This was further supported by high-resolution computer models that showed that floating plastic particles that enter the ocean in Perú, Ecuador, Colombia, and Chile could reach the Galápagos Islands (Van Sebille et al., 2019). However, these models indicate that it is highly improbable that PP released in Asia would reach the Galápagos Islands (Van Sebille et al., 2019). Regardless, China was the second largest source of macroplastics identified in our study. This perhaps echoes the "open secret" of the enormous industrial fishing fleet that surrounds the Galápagos Marine Reserve (GMR) and illegally fishes outside and within its boundaries (Schiller et al., 2015; Alava et al., 2017; Alava and Paladines, 2017; Hearn and Bucaram, 2017; Van Sebille et al., 2019; Bonaccorso et al., 2021; Vega Granja, 2022). The labels on the analyzed China-origin products were legible, lacking biofouling, and containing recent expiration dates, thus suggesting that they experienced little environmental degradation and were likely to have been in the water and on the beaches for a relatively brief period. It is likely that the poor waste management systems of industrial fishing fleets are responsible for the abundance of plastics with China origins on the islands (Donnelly et al., 2020; Moreno, 2021; Schofield et al., 2021; Alava et al., 2022; Leonhardt, 2022). It is important to note that the items found cannot be readily purchased in Galápagos or mainland Ecuador, further supporting the theory that they originated from the Chinese fishing fleet.

Contemporaneously with our research, a group of Santa Cruz Island residents called "Frente Insular" initiated an intensive coastal clean-up program and ecological activism. Upon examining the collected objects, they noticed a consistent "China origin trend" that correlated roughly with when the Chinese fleet began fishing in the Galápagos region (Rust, 2020; Moreno, 2021; Alarcon and Alvarado, 2022). The industrial ships that encircle the GMR are, in essence, floating cities that remain at sea for 2 or 3 years while their crews rotate, and no one knows or keeps track of where their trash ends (Moreno, 2021; Leonhardt, 2022).

The Galápagos marine reserve species may be negatively affected by ingestion, entanglement, and transfer of invasive species caused by plastic pollution. The Galápagos Islands are located at the convergence point of several major marine currents, which allows species from the eastern Pacific Ocean to arrive (Ballesteros-Mejia et al., 2021). Keith et al. (2018) found in Galápagos that plastics associated with fishing, such as rope, fishing nets, and buoys, were the most likely to be colonized by marine hitchhikers and accounted for 88% of the total weight of plastics colonized by marine organisms. Except for sponges and mollusks, fishing-related plastics supported the greatest diversity of organisms, with relatively high numbers in all the other groups. The only non-native species detected was the stalked barnacle *Dosima fascicularis*. A pleustonic specialist, which has been considered introduced but does not display characteristics that can classify it as invasive as it is a fugitive species that is readily outcompeted by local barnacle species (Cheng and Lewin, 1976; Blankley and Branch, 1985; Zambrano and Ramos, 2021). Nevertheless, plastic debris provides an effective "raft" for plants and animals to enter the Galápagos Marine Reserve, thereby emphasizing the need for vigilance (Keith et al., 2018).

Globally, fishing resources are overexploited. Each year, the world catches and harvests ∼200 million tons of fish and shellfish (FAO, 2020). The scale of these activities to obtain resources is sufficient to endanger marine life and generate an enormous amount of marine debris that is inappropriately managed (Richardson et al., 2021, 2022). When this stress is added to the impacts caused by climate change, ocean acidification, unsustainable aquaculture, oil drilling, and habitat destruction,

TABLE 4 The 52 species recorded interactions with plastic pollution (PP) in the Galápagos Islands (entanglement or ingestion) and the threat scale in Galápagos for the reported species.

| Species | Taxon origin | IUCN | Feeding type | Habitat and ecology | Entanglement threat | Ingestion threat | Pooled threat |
|---|---|---|---|---|---|---|---|
| Reptilian | | | | | | | |
| **∗Santa Cruz tortoise (*C. porteri*)∗** | E | CR | H | TN, TU | 81 | 243 | 162 |
| **∗Green sea turtle (*C. mydas*)∗** | N | EN | H, O | MN, MO, MI | 162 | 162 | 162 |
| **∗Marine iguana (*Amblyrhynchus cristatus*)∗** | E | VU | H | MN, MI | 108 | 108 | 108 |
| Hawksbill turtle (*Eretmochelys imbricata*) | M | CR | O | MN, MO, MI | 72 | 72 | 72 |
| San Cristóbal lava lizard (*Microlophus bivittatus*) | E | NT | O | MI, TN, TU | 72 | 36 | 54 |
| Olive Ridley (*Lepidochelys olivacea*) | M | VU | O | MN, MO, MI | 72 | 24 | 48 |
| San Cristóbal tortoise (*Chelonoidis chathamensis*) | E | EN | H | TN, TU | 27 | 54 | 41 |
| Santa Cruz lava lizard (*Microlophus indefatigabilis*) | E | LC | O | MI, TN, TU | 36 | 18 | 27 |
| Avian | | | | | | | |
| **∗Medium ground Finch (*G. fortis*)∗** | E | LC | H | TN, TU, MI | 81 | 27 | 54 |
| **∗Lava gull (*L. fuliginosus*)∗** | E | VU | O | MN, MI | 36 | 72 | 54 |
| **∗Flightless cormorant (*P. harrisi*)∗** | E | VU | C | MN, MI | 54 | 36 | 45 |
| Small ground Finch (*Geospiza fuliginosa*) | E | LC | O | TN, TU, MI | 54 | 36 | 45 |
| Waved Albatross (*Phoebastria irrorata*) | E | CR | C | MN, MO, MI | 27 | 54 | 41 |
| Galápagos penguin (*Spheniscus mendiculus*) | E | EN | C | MN, MI | 27 | 54 | 41 |
| Oyster catcher (*Haematopus palliatus* galapagoensis) | E | VU | C | MI | 18 | 36 | 27 |
| Galapagos mockingbird (*Mimus parvulus*) | E | LC | O | TN, TU, MI | 18 | 36 | 27 |
| Brown pelican (*Pelecanus occidentalis* urinator) | E | LC | C | MN, MO, MI | 9 | 27 | 18 |
| Yellow warbler (*Setophaga petechia* aureola) | E | LC | C | TN, TU, MI | 18 | 9 | 14 |
| Nazca Booby (*Sula granti*) | N | LC | C | MN, MI | 18 | 6 | 12 |
| Red-Footed Booby (*Sula Sula*) | N | LC | C | MN, MI | 6 | 12 | 9 |
| Great frigatebird (*Fregata minor*) | N | LC | C | MN, MO, MI | 12 | 6 | 9 |
| Mammal | | | | | | | |
| **∗Galápagos sea lion (*Z. wollebaeki*)∗** | E | EN | C | MN, MO, MI, TU | 81 | 81 | 81 |
| Galápagos fur seal (*Arctocephalus galapagoensis*) | E | EN | C | MN, MO, MI | 54 | 54 | 54 |
| Humpback whale (*Megaptera novaeangliae*) | M | LC | Pl | MN, MO | 36 | 18 | 27 |
| Short-finned Pilot Whale (*Globicephala macrorhynchus*) | M | LC | C | MN, MO | 12 | 6 | 9 |

*(Continued)*

TABLE 4 (Continued)

| Species | Taxon origin | IUCN | Feeding type | Habitat and ecology | Entanglement threat | Ingestion threat | Pooled threat |
|---|---|---|---|---|---|---|---|
| Cartilaginous fish | | | | | | | |
| **∗Whale shark (*R. typus*)∗** | M | EN | Pl | MN, MO | 108 | 54 | 81 |
| **∗Spinetail mobula (*Mobula japanica*)∗** | N | EN | Pl | MN, MO | 108 | 54 | 81 |
| **∗Scalloped hammerhead (*Sphyrna lewini*)∗** | N | CR | C | MN, MO | 36 | 18 | 27 |
| Galápagos shark (*Carcharhinus galapagensis*) | N | NT | C | MN, MO | 24 | 12 | 18 |
| Black tip shark (*Carcharhinus limbatus*) | N | VU | C | MN, MO | 24 | 12 | 18 |
| Spotted eagle ray (*Aetobatus narinari*) | N | NT | C | MN | 12 | 24 | 18 |
| Galápagos bullhead shark (*Heterodontus quoyi*) | N | LC | C | MN | 12 | 6 | 9 |
| Bony fish | | | | | | | |
| **∗Black-striped salema (*X. jessiae*)∗** | E | VU | Pl | MN | 54 | 108 | 81 |
| **∗Whitespotted sandbass (*Paralabrax albomaculatus*)∗** | E | EN | C | MN | 27 | 54 | 41 |
| Flathead Mullet (*Mugil cephalus*) | N | LC | H | MN, MI | 18 | 36 | 27 |
| Bacalao grouper (*Mycteroperca olfax*) | E | VU | C | MI, MN | 18 | 36 | 27 |
| Razor surgeon fishes (*Prionurus laticlavius*) | N | LC | H | MN | 18 | 36 | 27 |
| Swordfish (*Xiphias gladius*) | N | LC | C | MN, MO | 6 | 12 | 9 |
| Wahoo (*Acanthocybium solandri*) | N | LC | C | MN, MO | 6 | 12 | 9 |
| Yellow fin tuna (*Thunnus albacares*) | N | LC | C | MN, MO | 6 | 12 | 9 |
| Striped Bonito (*Sarda orientalis*) | N | LC | C | MN, MO | 6 | 12 | 9 |
| Ocean whitefish (*Caulolatilus princeps*) | N | LC | C | MN | 6 | 12 | 9 |
| Mexican hogfish (*Bodianus diplotaenia*) | N | LC | C | MN | 6 | 12 | 9 |
| Pacific Sierra (*Scomberomorus sierra*) | N | LC | C | MN, MO | 6 | 12 | 9 |
| Almaco Jack (*Seriola rivoliana*) | N | LC | C | MN | 6 | 12 | 9 |
| Mottled Scorpionfish (*Pontinus clemensi*) | N | LC | C | MN | 6 | 12 | 9 |
| Invertebrate | | | | | | | |
| **∗Green sea urchin (*L. semituberculatus*)∗** | N | NE | H | MN, MI | 36 | 18 | 27 |
| **∗Ecuadorian hermit crab (*C. compressus*)∗** | N | NE | O | MI | 36 | 12 | 24 |
| **∗Sally lightfoot crab (*G. grapsus*)∗** | N | NE | O | MI | 24 | 12 | 18 |
| Giant barnacle (*Megabalanus peninsulari*) | U | NE | Pl | MI | 9 | 18 | 14 |

*(Continued)*

TABLE 4 (Continued)

| Species | Taxon origin | IUCN | Feeding type | Habitat and ecology | Entanglement threat | Ingestion threat | Pooled threat |
|---|---|---|---|---|---|---|---|
| Xanthid crab (*Eurypanopeus planus*) | U | NE | O | MI | 12 | 6 | 9 |
| Anemona (*Anthopleura nigrescens*) | U | NE | C | MI | 6 | 3 | 5 |

Only species with confirmed video or photographic reports were considered for the threat scale. Table organization, as proposed by Thiel et al. (2018), with adaptations. The threat scale is calculated, including species distribution or taxon origin that can be U, unknown or not evaluated; E, endemic; N, native; and M, migratory. Conservation status or IUCN Red List classification can be DD, data-deficient; NE, not-evaluated; LC, least concern; NT, near threatened; VU, vulnerable; EN, endangered; and CR, critically endangered. Then, the feeding type can be C, Carnivorous; H, Herbivorous; O, omnivorous, and Pl, Planktivorous. Finally, species habitat and ecology can be MI, marine intertidal; MO, marine oceanic; MN, marine neritic; TU, terrestrial urban; TW, terrestrial wetlands; or TN, terrestrial natural. The weighting for each of these categories is presented in Table 2.

many ecosystems and the services they provide are pushed to the edge of collapse. Artisanal and industrial fishing is among the largest global sources of plastic pollution (Rochman, 2018; Stafford and Jones, 2019; Richardson et al., 2021, 2022); Galápagos is no exception. Our macroplastic classification category FISH, which includes all fishing-related items (industrial and artisanal), was the second most prevalent category across all sampled study sites.

Prevention is the most effective method of combating plastic pollution (Hardesty and Wilcox, 2011). Once plastics enter the ocean, it is challenging to remove or manage them, particularly when they degrade into microplastics and nanoplastics. Therefore, to reduce the prevalence of plastic pollution, the entry of plastics into oceans must be prevented. Plastic waste management is challenging for island communities, such as the Galápagos Islands, as they are sent to landfills. The Isabela, San Cristóbal, and Santa Cruz Islands waste management facilities receive all the trash generated by the islands' 25,244 residents (INEC, 2016) and 271,238 tourists as of 2019 (Caisaguano et al., 2019). On each island, non-recyclable and recyclable materials are buried in landfills. The same applies to all macroplastics collected during the annual Galápagos coastal clean-up campaigns funded by the Coca-Cola Company in partnership with Conservation International (DeSmit, 2019). Extreme weather conditions can cause plastic movement and sometimes interfere with human systems, resulting in their release. Therefore, the key recognized sources of plastic debris in the Eastern Pacific area and globally should adhere to the recommendations of Kirchherr et al. (2017), Jenkins et al. (2019), Wang et al. (2020), and King and Locock (2022). Perhaps then, the Galápagos plastic problem will be resolved. (1) Advocate a circular economy by introducing 6Rs of waste management (refuse, reduce, reuse, repurpose, real-recycle, and remediate), in which manufacturers have direct responsibility for items generated after their useful life; (2) Trash traceability: to track the success of the 6Rs and ensure that legislators, consumers, and producers are aware of the life cycle of manufactured plastic items; and (3) innovate to create plastic-enhanced construction materials from plastic waste that has been collected but cannot be recycled using standard procedures; and (4) Continue urban and remote cleanups to raise awareness and monitor the success of waste management programs.

Multiple local and international institutions, such as governments, academic institutions, municipalities, and non-governmental organizations, are aware of global and local plastic pollution problems. Plastic bottles are one of the highest-recorded macroplastic items found in this study. In 2015, the government of Galápagos enacted a ban on single-use plastics, based on the preliminary findings of our study, which became effective in 2018 (Klingman, 2015; Consejo de Gobierno de Régimen Especial de Galápagos, 2018). This mandates that companies such as Coca-Cola be required by this law to sell their products on the Galápagos Islands as part of a 100% return program. The next step is to apply the same strategy globally. Global legislation and management of single-use plastics should be the next step in mitigating this growing problem on oceanic and protected islands. However, it is essential to note that despite the current legislation, many banned single-use plastic items remain in the Galápagos Archipelago. Consequently, the enforcement of current local laws is vital. To protect our remaining pristine ecosystems from plastic pollution, local, regional, and global legislation as well as the enforcement of legislation regarding single-use plastics are required.

## 5. Conclusions

This is the first comprehensive assessment of plastic pollution distribution, composition, source, and impact on animals within the Galápagos archipelago. Macroplastics were observed on every shoreline surveyed throughout the archipelago, including every major island. The prevailing wind direction affected the distribution and macroplastic density (items/m$^2$), with the windward coast of Santiago Island having the highest density of plastics, while the leeward coast had the lowest density. Hard plastic fragments (HPF) are the most common type of debris, while fishing-related waste is the second most common and distinguishable category of macroplastics. The main countries of origin of the examined macroplastics were Perú, China, and Ecuador, and they were primarily produced by AjeCroup, Coca-Cola, and Tingyi Holding Corporations. While oceanographic models indicate that waste from Perú and mainland Ecuador could certainly reach Galápagos, it is highly improbable that plastic debris released from China could. Therefore, it is hypothesized that debris with Chinese markings may have been sourced from large fishing fleets surrounding the Galápagos marine reserve. However, further research is required.

Our study uncovered evidence of 52 species (including 20 endemic species) interacting with plastic pollution through ingestion and entanglement. Moreover, 15 of

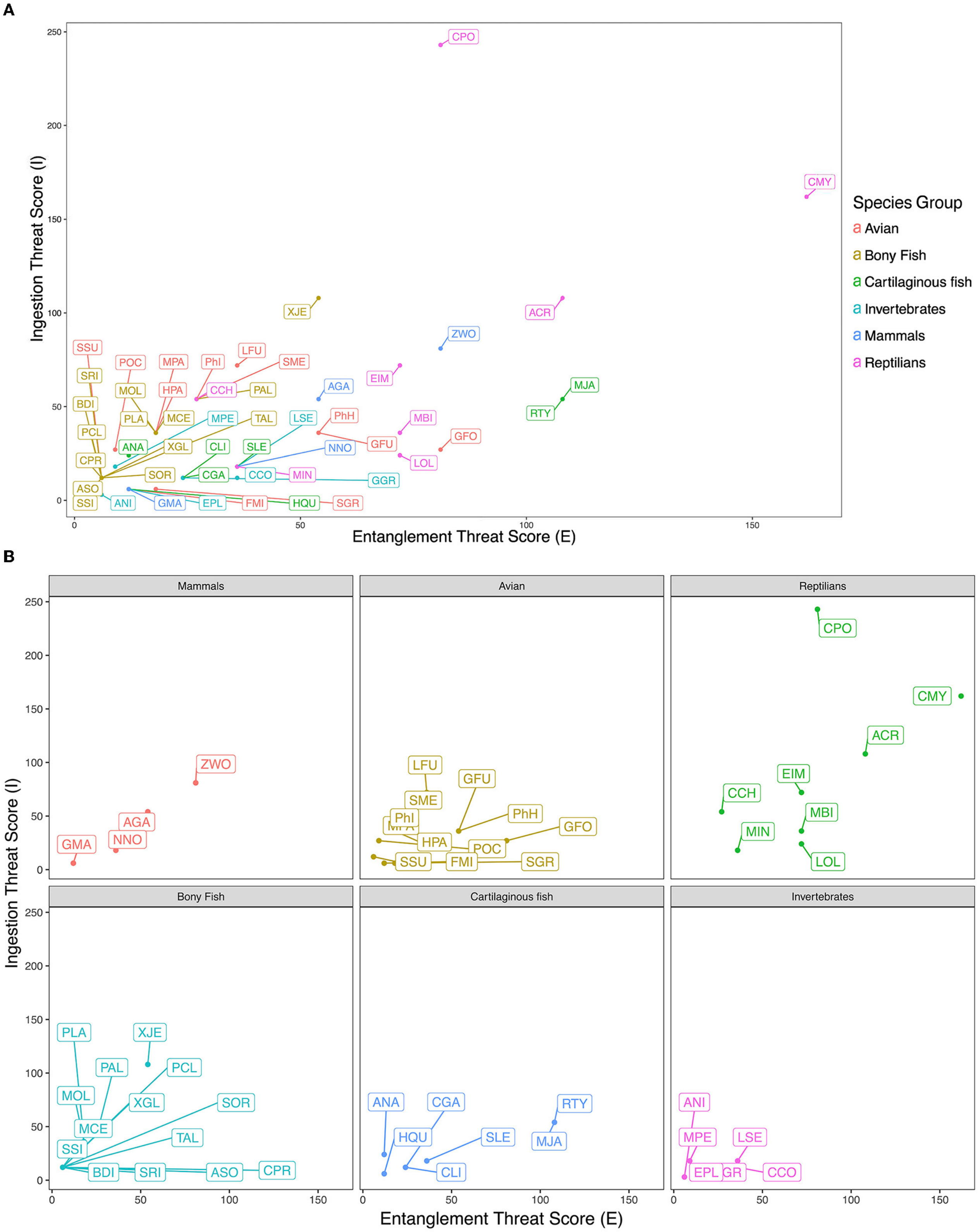


FIGURE 5

**(A)** Calculated plastic pollution threat scores for the 52 species evaluated in this study. Entanglement Threat Score (E); Ingestion Threat Score (I). AVIAN: *Medium ground Finch *(G. fortis)* GFO*; *Lava gull (*L. fuliginosus*) LFU*; *Flightless cormorant (*P. harrisi*) PhH*; Small ground Finch (*Geospiza fuliginosa*) GFU; Waved Albatross (*Phoebastria irrorata*) PhI; Galápagos penguin (*Spheniscus mendiculus*) SME; Oyster catcher (*Haematopus palliatus galapagoensis*) HPA; Galápagos mockingbird *(Mimus parvulus)* MPA; Brown pelican (*Pelecanus occidentalis urinator*) POC; Nazca Booby (*Sula granti*) SGR; Red-Footed Booby (*Sula Sula*) SSU; Great frigatebird (*Fregata minor*) FMI. BONY FISH: *Black-striped salema (*X. jessiae*) XJE *; *Whitespotted sandbass (*Paralabrax albomaculatus*) PAL*; Flathead Mullet (*Mugil cephalus*) MCE; Bacalao grouper (*Mycteroperca olfax*) MOL; Razor surgeon fishes

*(Continued)*

FIGURE 5 (Continued)
(*Prionurus laticlavius*) PLA; Swordfish (*Xiphias gladius*) XGL; Wahoo (*Acanthocybium solandri*) ASO; Yellow fin tuna (*Thunnus albacares*) TAL; Striped Bonito (*Sarda orientalis*) SOR; Ocean whitefish (*Caulolatilus princeps*) CPR; Mexican hogfish (*Bodianus diplotaenia*) BDI; Pacific Sierra (*Scomberomorus sierra*) SSI; Almaco Jack (*Seriola rivoliana*) SRI; Mottled Scorpionfish (*Pontinus clemensi*) PCL. CARTILAGINOUS FISH: *Whale shark *(R. typus)* RTY*; *Spinetail mobula (*Mobula japanica*) MJA *; *Scalloped hammerhead *(Sphyrna lewini)* SLE*; Galápagos shark *(Carcharhinus galapagensis*) CGA; Black tip shark (*Carcharhinus limbatus*) CLI; Spotted eagle ray (*Aetobatus narinari*) ANA; Galápagos bullhead shark (*Heterodontus quoyi*) HQU. INVERTEBRATES: *Green Sea urchin (*L. semituberculatus*) LSE*; *Ecuadorian hermit crab *(C. compressus)* CCO *; *Sally lightfoot crab *(G. grapsus)* GGR* Giant barnacle *(Megabalanus peninsulari)* MPE; Xanthid crab (*Eurypanopeus planus*) EPL; Anemona *(Anthopleura nigrescens)* ANI. MAMMALS: *Galápagos sea lion *(Z. wollebaeki*) ZWO*; Galápagos fur seal (*Arctocephalus galapagoensis*) AGA; Humpback whale *(Megaptera novaeangliae)* NNO; Short-finned Pilot Whale (*Globicephala macrorhynchus*) GMA. REPTILIANS: *Santa Cruz tortoise *(C. porteri)* CPO*; *Green Sea turtle *(C. mydas)* CMY*; *Marine iguana *(Amblyrhynchus cristatus)* ACR*; Hawksbill turtle *(Eretmochelys imbricata)* EIM; San Cristóbal lava lizard (*Microlophus bivittatus*) MBI; Olive Ridley *(Lepidochelys olivacea)* LOL; San Cristóbal tortoise *(Chelonoidis chathamensis)* CCH; Santa Cruz lava lizard *(Microlophus indefatigabilis*) MIN. **, High scores. **(B)** The calculated plastic pollution threat score for each group of species (mammals, avian, reptilian, bony fish, cartilaginous fish, and invertebrates).

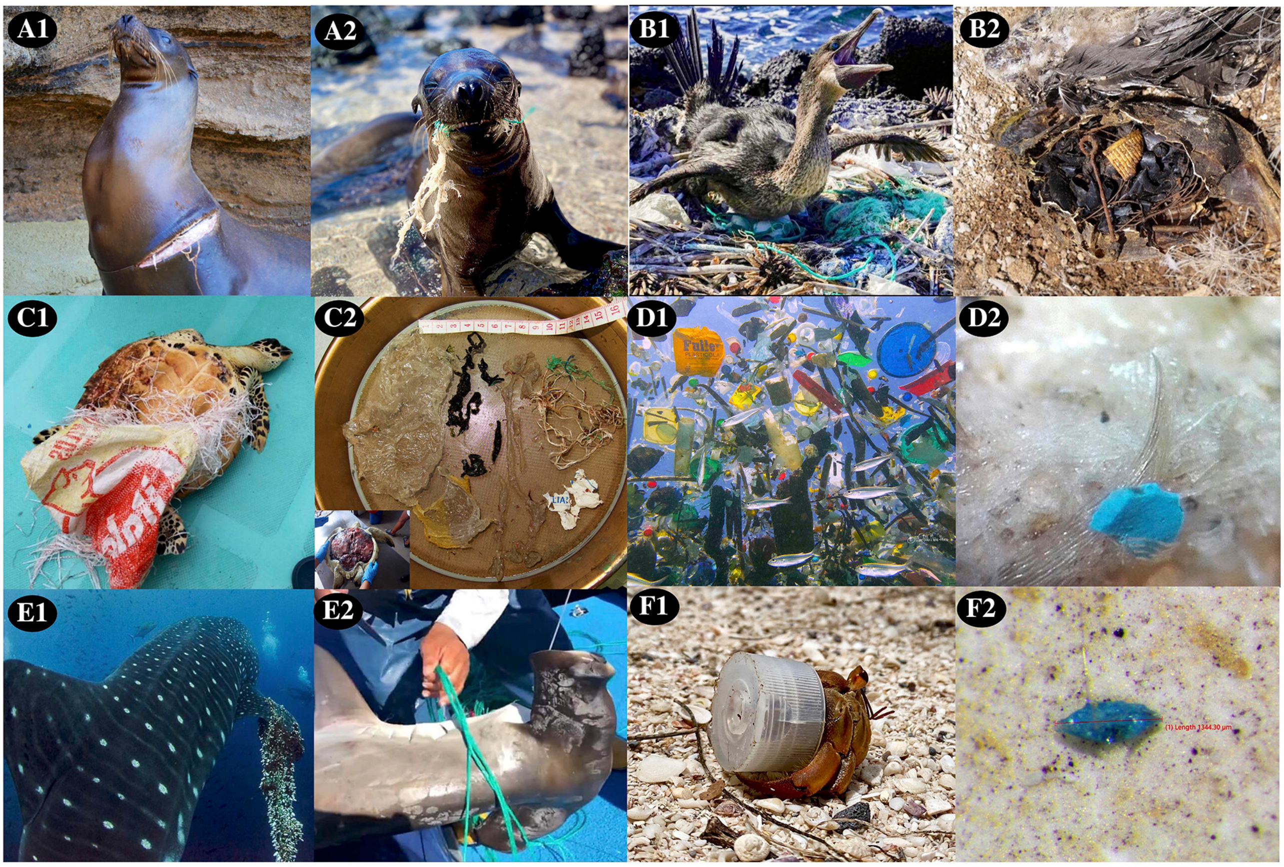


FIGURE 6
Examples of records of the evident interaction between plastic pollution (PP) and native and endemic species of Galápagos (entanglement or ingestion) used for the PP Galápagos wildlife threat assessment (PPT). Information for each figure is provided with the author's name. All the participants agreed that this information was included in the study. MAMMALS **(A1):** Galápagos Sea Lion (*Z. wollebaeki*) entanglement San Cristóbal island © Carolina Pesantez; **(A2):** *Z. wollebaeki* possible ingestion San Cristóbal island © Juan Pablo Muñoz-Pérez. AVIAN **(B1):** Flightless Cormorant (*P. harrisi*) entanglement Isabela Island © Rodrigo Buendia; **(B2):** Waved albatross (*Phoebastria irrorata*) ingestion and dead Española Island © Sebastian Cruz. REPTILIANS **(C1):** Hawksbill turtle (*Eretmochelys imbricata)* entanglement San Cristóbal island © Shinobi Chauca; **(C2):** Green Sea Turtle (*C. mydas*) ingestion and dead San Cristóbal island © Juan Pablo Muñoz-Pérez. BONY FISH **(D1):** Black-striped Salema (*X. jessiae*) possible ingestion of Rábida island © Juan Pablo Muñoz-Pérez; **(D2):** Wahoo (*Acanthocybium solandri)* microplastic ingestion Fernandina Island © Alice Skehel. CARTILAGINOUS FISH **(E1):** Whale Shark (*R. typus)* entanglement Darwin Island © Jenny Waack; **(E2):** Scalloped Hammerhead (*Sphyrna lewini*) entanglement and dead San Cristóbal Island © Galápagos Sky. INVERTEBRATES **(F1):** Ecuadorian hermit crab (*C. compressus*) entanglement San Cristóbal island © Juan Pablo Muñoz-Pérez; **(F2):** Giant barnacle (*Megabalanus peninsulari*) microplastic ingestion San Cristóbal island © François Oberhansli.

these species were ranked as being at the greatest risk of severe harm on the Galápagos Islands because of the possibility of ingesting or becoming entangled with PP. The top four species at overall risk of PP interactions in Galápagos include (1) Santa Cruz tortoises (*C. porteri*); (2) Green sea turtles (*C. mydas*); (3) Marine iguanas (*Amblyrhynchus cristatus*); and (4) Galápagos sea lion (*Z. wollebaeki*).

Our research indicates that plastic pollution is a problem in the Galápagos Islands; however, it is not restricted to this region. Therefore, global solutions must be implemented to alleviate global plastic pollution crises. Those who have learned to collaborate and improvise more effectively in the natural world have succeeded (Darwin, 1876). The Galápagos Islands have a relatively small human population, strict immigration laws, and a unique system of nature protection. As a result, the archipelago provides the opportunity and duty to serve as a "social and natural laboratory" to generate data for solving the complex global socio-ecological issue of plastic pollution.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

JM-P, GL, DA-R, CV, BW, and KT contributed to the study conception and design. JM-P, EC, RR, AJ, and HV organized the databases. LZ-A organized the database and produced the maps. JM-P performed the statistical analyses and wrote the first draft of the manuscript. GL, AS, CV, DA-R, BW, and KT wrote sections of the manuscript. JM-P, GL, DA-R, AS, EC, RR, AJ, HV, and KT worked in the field and laboratory to collect and analyze samples. JM-P and KT secured funding and managed the approval of the necessary research permits, ethics, and field logistics. All authors contributed to the development, synthesis of the information, contributed to manuscript preparation, manuscript revision and read, and approved the submitted version.

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## Conflict of interest

BW was employed by Ecolibrium, Inc.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2023.1091516/full#supplementary-material

SUPPLEMENTARY FIGURE 1

Additional examples of the evident interaction between plastic pollution (PP) and native and endemic species of Galápagos (entanglement or ingestion) used for PP Galápagos wildlife threat assessment (PPT). Information for each figure is provided with the author's name. All the participants agreed that this information was included in the study. MAMMALS **(A1)**: Short finned Pilot Whale (*Globicephala macrorhynchus*) entanglement Española Island © Manuel Yépez; **(A2)**: Galápagos Sea Lion (*Z. wollebaeki*) entanglement Caamaño island © Cian Luck; **(A3)**: Galápagos fur seal (*Arctocephalus galapagoensis*) possible ingestion Fernandina Island © Tui de Roy; **(A4)**: Humpback whale (*Megaptera novaeangliae*) entanglement and dead Isabela Island © Erika Carrera. AVIAN **(B1)**: Brown Pelican (*Pelecanus occidentalis urinator*) ingestion and dead Santa Cruz Island © Andrea Loyola; **(B2)**: Galápagos Penguin (*Spheniscus mendiculus*) apparent ingestion Isabela Island © BirdTrips Ecuador; **(B3)**: Oyster catcher *(Haematopus palliatus galapagoensis)* Santa Cruz Island © Kiyoko Gotanda; **(B4)**: Red-Footed Booby (*Sula sula*) possible ingestion San Cristóbal Island © Santiago Izuaste. REPTILIAN **(C1):** Santa Cruz Giant Tortoise (*C. porteri*) ingestion Santa Cruz Island © Andrea Loyola; **(C2)**: Marine Iguana (*Amblyrhynchus cristatus*) probable ingestion Santa Cruz Island © Getty Images; **(C3)**: Santa Cruz lava lizard *(Microlophus indefatigabilis)* entanglement Santa Cruz Island © Diego Intriago; **(C4)**: Olive ridley turtle (*Lepidochelys olivacea*) entanglement *San* Cristóbal Island © Shinobi Chauca. BONY FISH **(D1)**: Almaco Jack (*Seriola rivoliana*) ingestion Española Island © Santiago Inzuaste; **(D2):** Yellow Fin Tuna (*Thunnus albacares*) ingestion Isabela Island ©Alice Skehel; **(D3)**: Ocean whitefish (*Caulolatilus princeps*) ingestion Santiago Island ©Alice Skehel; **(D4):** Mottled Scorpionfish *(Pontinus clemensi)* ingestion San Cristóbal island © Cisne Zambrano y Maria del Mar Quiroga. CARTILAGINOUS FISH **(E1)**: Galápagos shark (*Carcharhinus galapagensis*) entanglement and dead Española Island © Manuel Yépez; **(E2)**: Spinetail mobula (*Mobula Japanica*) entanglement and dead Isabela Island © Ericka Carrera; **(E3)**: Galápagos Bullhead Shark (*Heterodontus quoyi*) entanglement and dead Fernandina Island © Ericka Carrera; **(E4)**: Spotted Eagle Ray (*Aetobatus ocellatus*) possible ingestion Isabela Island © anonymous. INVERTEBRATES **(F1)**: Anemona (*Anthopleura sp.*) entanglement San Cristóbal Island © Olivia Burleigh; **(F2)**: Xanthid Crab (*Eurypanopeus planus*) entanglement Santa Cruz Island © DPNG; **(F3)**: Sally lightfoot crab (*G. grapsus*) entanglement Santa Cruz Island © Johan Gonzalez; **(F4)**: Green Sea Urchin (*L. semituberculatus)* entanglement San Cristóbal Island © Adam Porter.

**SUPPLEMENTARY FIGURE 2**

Survey of wildlife interactions with plastic pollution in Galápagos.

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