# Accumulation and exposure classifications of plastics in the different coastal habitats in the western Philippine archipelago

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## ABSTRACT

Studies consistently ranked the Philippines as one of the top contributors of plastic wastes leaking into the ocean. However, most of these were based on probabilities and estimates due to lack of comprehensive ground-truth data, resulting also in the limited understanding of the contributing factors and drivers of local pollution. This makes it challenging to develop science-driven and locally-contextualized policies and interventions to mitigate the problem. Here, 56 sites from different coastal habitats in the western Philippine archipelago were surveyed for macroplastics standing stock, representing geographic regions with varying demography and economic activities. Clustering of sites revealed three potential influencing factors to plastic accumulation: population density, wind and oceanic transport, and habitat type. Notably, the amount and types of dominant plastics per geographic region varied significantly. Single-use plastics (food packaging and sachets) were the most abundant in sites adjacent to densely populated and highly urbanized areas (Manila Bay and eastern Palawan), while fishing-related materials dominated in less populated and fishing-dominated communities (western Palawan and Bolinao), suggesting the local industries significantly contributing to the mismanaged plastics in the surveyed sites. Meanwhile, isolated areas such as islands were characterized by the abundance of buoyant materials (drinking bottles and hygiene product containers), emphasizing the role of oceanic transport and strong connectivity in the oceans. Exposure assessment also identified single-use and fishing-related plastics to be of "high exposure (Type 4)" due to their high abundance and high occurrence. These increase their chances of encountering and interacting with organisms and habitats, thus, resulting into more potential harm. This study is the first comprehensive work done in western Philippines, and results will help contextualize local pollution, facilitating more effective management and policymaking.

**Keywords:** plastic accumulation, exposure assessment, West Philippine Sea, single-use plastics, archipelago

## INTRODUCTION

Plastic pollution has become a global concern, with a projected increase in emissions in the coming years with no signs of slowing down (Taylor, 2017), it is expected to continue to negatively affect many ecosystems including the marine environment where they tend to accumulate (Thushari and Senevirathna, 2020). The Philippines was consistently ranked in the top ten contributors of mismanaged plastic wastes potentially entering the oceans (Jambeck et al., 2015; Law et al., 2020). Specifically, Pasig River that drains into Manila Bay had been suggested to account for around 6% of global riverine emissions (Meijer et al., 2021). However, most of these estimations were based on models and inferences due to lack of or limitation for comprehensive ground truth data. To date, only a few studies have surveyed and quantified plastic accumulation and plastic types in different coastal habitats in the country (Alindayu et al., 2023), resulting also in limited capability to come up with science- and evidence-based approaches to mitigate the problem.

Some of the plastics released into the oceans accumulate in coastal environments due to debris circulation dynamics leaving beaches, mangroves, and seagrass beds vulnerable to plastic pollution (Lebreton et al., 2019). The vulnerabilities of these coastal environments should be investigated as they provide valuable ecosystem services such as coastal protection, erosion control, sediment stabilization, wildlife habitats, nutrient supply and regeneration, among others (Primavera, 2004). Seagrass beds help sequester carbon dioxide (Deyanova et al., 2017), improve water quality (Gacia et al., 2003), and serve as nursery and refuge for invertebrates and fishes (Whitfield, 2017). Beaches meanwhile provide nesting sites for marine animals such as sea turtles, nutrient cycling, and recreation for humans (Defeo et al., 2021). In the Philippines, such important habitats and ecosystems are mostly found in the western part of the Archipelago lying in the West Philippine Sea in the South China Sea (WPS). The WPS biogeographic region is an economically and ecologically significant area of the country as it hosts the highest diversity and biomass of reef fishes (Nañola et al., 2006, 2011; Quimpo et al., 2019) and corals (Lalas et al., 2022) in the Philippines. It also hosts the largest extent of mangrove forests (Long and Giri, 2011) and seagrass beds (Fortes et al., 2018). This region also contributes 7% of the total fisheries production in the country (Ocampo, 2021), providing livelihood and food security to Filipinos. It also serves as spawning grounds for important schools of fishes, replenishing and supplying coastal fish stocks (Aliño and Batongbacal, 2011).

Due to the direct and indirect harm that plastics may bring to both organisms and the habitats where they get deposited, their mere presence in the marine environment can be considered as contamination. Thus, when these contaminants further accumulate, exposure to organisms of different plastic categories should be assessed. These assessments can guide the prioritization of policies as part of the “whole-of-society” response to the plastics problem (Karasik et al., 2022, 2020). Here, we hypothesized that the abundance of plastics debris accumulating in coastal areas could be related to the density of the population living in or around the surveyed coastal areas with the dominant plastic types influenced by the prevailing economic activities. To test this, 56 sites from different coastal habitats in the WPS biogeographic region representing geographic areas with varying demography (Philippine Statistics Authority, 2021) and economic activities were surveyed for their standing stocks of plastic debris. Particularly, the levels of plastic accumulation per site were determined, the most abundant plastic categories and their distributions were identified and evaluated for each site and per region, and the vulnerability of different coastal habitats were assessed. We then integrated information on their abundance and occurrence to create categories and assess the level of ‘exposure’, which may then be related to possible risks of the different plastic types may pose to both the environment and the organisms therein. New insights from this work will be helpful in drawing long-term, appropriate, and locally contextualized sustainable policies for the proper management, reduction, and mitigation of the effects of plastics pollution.

## MATERIALS AND METHODS

### Sampling Sites

A total of 56 sites were selected and divided into geographical areas, seven sites in Manila Bay, 40 sites in Palawan (30 in eastern and 10 in western sides), four sites in Pag-asa Island, and five sites in Bolinao (Table S1, Supplementary Material). There were more sites surveyed in Palawan island compared to other regions because of its vast coastline (1,959 km, Palawan Provincial Government, 2019) along with the coastal exposure to different oceanic currents and bodies of water (Sulu Sea in the east and West Philippine Sea in the South China Sea in the west). These sites comprised of seagrass beds (n=8), mangroves (n=8), and beaches (n=40) (Figure 1, shapes: triangle – seagrass, square – mangrove, and circle – beach), with most seagrass and mangrove sites being adjacent to beaches. Different coastal habitats were then compared to investigate the effects of habitat profiles on the accumulation of plastics debris.

Here, the main geographic regions/areas represented gradients of population density (Figure 1, inset) based on the data from the(Lippiatt et al., 2013) Philippine Statistics Authority (2021) including sites within Metro Manila (High: 13,484,462), Eastern Palawan (Mid: 944,647), Western Palawan (Low: 301,883), Bolinao (Low: 83,979), and isolated islands in the Kalayaan Island Group in the West Philippine Sea (Low: 193). Other criteria for site selection include having no coastal communities directly in front or adjacent to chosen survey sites to avoid effects of direct leakage/littering, accessibility with at least 100 m of shoreline (Lippiatt et al., 2013), and no visible evidence of periodic beach cleanups or direct dumping. Sampling was done in the second half of 2021, early June to July for sites in Manila Bay and Palawan, October for sites in Pag-asa Island, and early December for sites in Bolinao. Sampling spanned from southwest monsoon to the early onset of northeast monsoon.

Stranded macroplastics were surveyed using a method developed by the MicroSEAP Consortium (Microbial transformation of plastics in SE Asian seas, UKRI). Briefly, three 30-m transects were laid on the strandline or the highest high tide line (Figure S1, Supplementary Material) as it represents the recently deposited plastic debris (Baak et al., 2022). Surveys in all sites were done during low tide. The three transects were parallel to the shoreline, and the minimum distance between the two consecutive transects were at least two meters. Macroplastic pieces greater than 2.5 cm were recorded and tallied along the 30-m transect, 2 m to the left and 2 m to the right. The macroplastics were classified into 24 categories, with the list being modified from the NOAA protocol (Table S2, Supplementary Material; Lippiatt et al., 2013) based on the context of the common plastic product types in the Philippines and Southeast Asia. To emphasize plastic accumulation, only plastic pieces were counted.

The macroplastics item concentration (plastic pieces/square meter) per transect was calculated as follows (modified from Lippiatt et al., 2013):

$$C = \frac{n}{wl}$$

where,

$C$ = concentration of plastic pieces (# of plastic pieces/square meter, pp/sq-m),
$n$ = total number of macroplastic pieces counted,
$w$ = width (m) of shoreline section recorded during sampling = 4 m, and
$l$ = length (m) of the shoreline sampled = 30 m.

All data were deposited and can be accessed in the Philippine's online repository for plastics pollution accessible at www.plasticount.ph (Alindayu et al., 2023; PlastiCount Pilipinas, 2022).

## Exposure Assessment Matrix for different plastic categories

The U.S. Environmental Protection Agency (Norton et al., 1992) and (Werner et al., 2016) proposed a risk assessment scheme that can be applied to marine litter, particularly macroplastics. For this, the first step is hazard identification, followed by exposure assessment, exposure-response assessment, and finally risk characterization. However, information usually collected during baselining surveys only includes presence, abundance of each category/type, and their distribution. Using this commonly collected information, only hazard identification and exposure assessment can be done following the framework of Norton et al. (1992) and Werner et al. (2016). Data remains limited for dose-dependent response on different plastic categories due to the difficulty in defining an "ecologically relevant metric" (ERM) (Koelmans et al., 2017). The exposure assessment of pollutants however remains an important tool to evaluate and identify possible threats, with the assumption that the higher the exposure, the higher the possible risks that these plastics pose to living organisms and the ecosystem services in a particular environment.

For this study, commonly collected information during surveys such as plastic abundance (pp/sq-m) per plastic category and their occurrence (presence in 56 sites), were used to construct an exposure assessment matrix. Exposure refers to the likelihood that the harm will occur (EFSAchannel, 2013), which may then be related to probable risks. Abundance on the other hand corresponds to the number of pieces of a plastic category in an area, which could represent the level of exposure that organisms and habitats may experience relative to plastic pollution. It is then presumed that the higher the abundance of plastics, the higher the exposure and chance encounter between plastic and organisms or habitats. These possible interactions could then potentially lead to harmful effects. Here, harmful effects were not directly tested but rather inferred from those reported in literature. Meanwhile, occurrence refers to the physical presence of the plastic category in defined geographical points or its distribution relative to the total number of sites/habitats surveyed. Although the presence and absence of plastics in an area may be associated with potential degradation or deterioration (Webb et al., 2012), this characteristic has not yet been studied. Thus, here, presence of the material has been assumed to be mostly associated with transport or littering.

Using both indices, a scatter plot was generated, and from this plot we distinguished four classes of exposure: 1) "direct dumping" corresponded to plastic with high abundance (> 50% of the maximum log total average abundance) but present in less than 67% (2/3) of the sites, 2) "low usage" corresponded to low abundance and presence in less than 67% of the sites, 3) "high dispersal" corresponded to low abundance but presence in more than 67% of the sites and 4) "high exposure" corresponded to high abundance and presence in more than 67% of the sites. Fifty percent was set as an arbitrary threshold for the high and low abundance, while 67% was determined to represent the majority in terms of presence of the plastic category.

## Statistical analyses and data visualization

Results of the plastic survey were expressed as means ± standard deviation of three replicates, as average plastics abundance. The results were visualized in Ocean Data Viewer (v 5.6.2, Schlitzer, 2021) using surface plots. The average abundances were grouped by environmental gradients/areas and visualized using boxplots. Then the percentage composition for all plastics surveyed per region were visualized using a bar graph. The sampling sites were clustered using Unweighted Pair Group Method with Arithmetic Mean (UPGMA) based on Bray-Curtis similarity derived from the values of the average plastics abundance which were computed in PAST v4.0 (Hammer et al., 2001). The plastic accumulation per cluster expressed as means ± standard deviation was tested for significant differences using a t-test with a significance value of $p \leq 0.05$. Sites classified with the same habitat were grouped together and their common characteristics were mapped back into the metadata sheets with the descriptions, and the average abundance per habitat type was calculated and visualized using a bar graph. The log of the total average abundance per plastic category was graphed with the number of sites present using a scatter plot.

## RESULTS AND DISCUSSION

### Contributing factors to marine plastic accumulation in the western Philippine archipelago

UPGMA clustering of sites based on plastics composition (Figure 2) revealed three potential influencing factors to plastic accumulation in the western Philippine archipelago. Clustering showed that population density had the strongest influence since sites with low population also had low plastic accumulation (Cluster 1), and sites with high population had the highest plastic accumulation (Clusters 3 and 5). It also revealed the role of wind and oceanic transport (Cluster 2), especially in sites that were generally isolated (i.e., islands), where levels of plastics accumulation were similar to those in mainland sites despite having low number of residents. Last is the influence of habitat type (Cluster 4), suggesting that habitat characteristics (i.e., vegetation, structure) may affect the level of accumulation of plastics, resulting in varying vulnerabilities of different coastal habitats.

We observed that patterns of plastic density closely followed that of the population density with average plastic abundance ranging from 0.017 ± 0.01 pp/sq-m (Balingasay in Bolinao, Pangasinan) and 0.017 ± 0.02 pp/sq-m (Candawaga S, Western Palawan) to 23.77 ± 0.40 pp/sq-m (LPPCHEA, Manila Bay) (Figure 1). Here, the main criterion for choosing the sites was based on local population as this is directly related to the generation of plastic wastes attributed to increase in consumption or use of plastic products (Alabi et al., 2019). Other factors such as consumption patterns and waste management practices were not considered due to limited availability of data. A total of 40,306 macroplastic pieces greater than or equal to 2.5 cm were tallied in 56 select sites in the western Philippine archipelago belonging to 24 categories. The presence of plastics in all surveyed sites demonstrates the extent and gravity of this pollution.

Specifically, Manila Bay sites had the highest plastic accumulation either individually or cumulatively, and the widest range from 0.36 to 23.77 pp/sq-m (Figure S2, Supplementary Material). This region was selected as a representation of a highly populated area, as it is the catchment basin of Metro Manila and neighboring provinces. Metro Manila is the biggest and most densely populated city in the Philippines and considered as one of the megacities in Southeast Asia. It has higher per capita waste generation of 0.78 kg/day than the national average, with plastics making up 13% of this waste, which translates to 0.10 kg plastic wastes/day produced by each person (Tanchuling and Osorio, 2020). Cumulatively, taking into consideration the 2020 population of Metro Manila (Philippine Statistics Authority, 2021), this is equivalent to around 1,348 tons of daily plastic waste generated. Using the estimates by the Ocean Conservancy and McKinsey Center for Business and Environment (2015) of the percentage of the total plastic waste that leaks into the oceans, which is around 20% of 1,348 tons, we found an approximate amount of around 270 tons of plastic wastes per day. This is equivalent to 18 garbage trucks, where one fully loaded garbage truck is estimated to hold around 15 tons of load of plastic wastes leaking into the Bay per day. These wastes pass through 17 riverine systems that drain into Manila Bay, four of which have been suggested to contribute to 10% of the total global riverine plastics pollution (Meijer et al., 2021; Ritchie, 2021). This is consistent with global observations reporting that river-dominated coasts receive 52% of plastic pollution (Harris et al., 2021), and thus, are expected to transport the plastics to the marine environment. A modeling simulation for floating plastics in Manila Bay during the southwest monsoon showed that plastic particles move around locally before getting deposited (Cruz and Shimozono, 2021). Two of the Manila Bay survey sites in this study were identified as hotspots for depositions, namely Baseco and LPPCHEA. This corroborates our previous work done in a different year and month in the same sites in Manila Bay (Gomez and Onda, 2023), indicating the consistency of plastic occurrence and accumulation.

Palawan was in the middle of the gradient with a population of more than 1 million people. It is the largest province by land area (PhilAtlas, 2020) and considered as the “last ecological frontier” of the country for its rich biodiversity and coastal ecosystems supporting diverse marine life (Förderer and Langer, 2019; Gonzales, 2013). Eastern Palawan had higher plastic accumulation (0.022 to 5.48 pp/sq-m) than western Palawan (0.017 to 0.49 pp/sq-m). Plastic accumulation in the eastern and western parts were investigated separately, as the eastern part is a more densely populated area than the west. A similar study by Sajorne et al. (2021) that only surveyed beaches on the eastern and western sides of Puerto Princesa City, Palawan also reported that the amount of plastic litter was related to human population. These two areas also have different drainage basins, which may have different circulation patterns influencing the transport and distribution of plastic debris. During the surveys, it was observed that most of the communities on both sides of Palawan were located either near the coast or along bodies of water (i.e., rivers), increasing the probability of plastics- and wastes leakage. Meanwhile, Bolinao is a coastal town situated in northwestern Philippines and treated as the low population of the gradient with only 80,000 inhabitants, and with a booming tourism industry that may have inputs on plastic waste generation. Sites in Bolinao, Pangasinan had the least, with values from 0.017 to 0.48 pp/sq-m.

The situations observed in Manila Bay and mainland Palawan can be mainly associated with the high usage of the material coupled with inefficient waste management. A report by Ocean Conservancy and McKinsey Center for Business and Environment (2015) for example showed that despite the high rate of trash collection (ca. 85% for the national average), a considerable amount still ended up in the open environment. This is staggering since in 2015 alone, the Philippines has been estimated to have produced 2.7 million tons of plastic waste, with 20% leaking into the ocean because of poorly located (e.g., adjacent to waterways) or lacking dumpsites/sanitary landfills (e.g., Palawan, EMB-MIMAROPA, 2021) resulting in the illegal dumping of uncollected wastes. Interestingly, ca. 74% of the plastics leaking into the ocean in the Philippines can be considered as ‘managed’ as they were collected by garbage trucks or brought to the materials recovery facilities (MRF; Ocean Conservancy and McKinsey Center for Business and Environment 2015). However, because of insufficient and sub-standard infrastructure for waste disposal (i.e., sanitary landfills), these collected plastics still ended up in waterways and ultimately in our oceans (Tanchuling and Osorio, 2020). Such scenarios are evident in Palawan as well as in many areas around Metro Manila, with these waste leakages being seen washed up on different coastal environments and floating in bodies of water.

Among the regions surveyed, Pag-asa Island was an exceptional case because despite only having at most 200 inhabitants, plastics accumulation in its coasts ranged from 0.42 to 1.71 pp/sq-m. This was almost the same as the density of plastic debris found in eastern mainland Palawan, indicating that population in the adjacent coastal community was not the most significant contributor. Pag-asa Island is one of the biggest islands in the Spratlys Island Group located in WPS in the middle of the South China Sea and the farthest from major population centers (Villanoy and Mancebo, 1998). Interestingly, other islands off the coast of mainland Palawan also had high density of accumulating plastics (0.42-5.48 pp/sq-m) despite most having very low number of residents (Figure 3, Cluster 2). These possibly indicate the significant contributions of wind and oceanic transport on the dispersal of buoyant plastic materials (van Sebille et al., 2020), causing much of the debris to be transported far from where they originated. This is evident for example in the macroplastics found in Pag-asa Island, where most of the labeled trash (~60% of PET bottles) had product labels coming from Vietnam, Malaysia, Indonesia, and mainland China (Onda et al., 2020; this study). This was also the case for remote islands in the Andaman Sea in India (Krishnakumar et al., 2020), in Maldives in the Indian Ocean (Imhof et al., 2017), and in Sable Island in Canada (Baxter et al., 2022). These debris items could have been mostly brought in by currents given the hydrography and strong connectivity in the South China Sea basin (Ko et al., 2018; Pata and Yñiguez, 2021), emphasizing that plastic pollution is a transboundary issue.

Habitat type was identified as another potential influencing factor to plastic accumulation (Supplementary Figure S3). For this part of the study, only beaches (n=13) that were adjacent to seagrass (n=8) and mangrove (n=8) sites were used for direct comparisons (Figure 3). Mangroves had the highest plastic accumulation in terms of average total plastic pieces per site (530.13 ± 955.94), followed by beaches (288.41 ± 380.99), and lastly by seagrasses (12.58 ± 18.55).

Notably, most of the mangrove sites were also located near densely populated areas such as sites in Manila Bay and Eastern Palawan, which could have also contributed to their high plastic accumulation. The proportion of plastics density in beaches over mangroves ranged from 0.1 to 13, with only 3 out of 8 sites having values of >1. These sites include the extremely polluted environments of LPPCHEA, Zigzag (Eastern Palawan), and Kamuning (Eastern Palawan) (Figure S4a, Supplementary Material). Although the differences were not significant between mangroves and beaches ($p > 0.05$), mangroves likely seem to be more vulnerable to plastic pollution due to the longer retention (Paler et al., 2022), which may be attributed to their specialized roots that can effectively trap debris (Govender et al., 2020; Martin et al., 2019) and accumulation resulting in longer exposure and potential risks. Plastics may cover the pneumatophores, causing decreased leaf area index leading to their eventual deterioration (van Bijsterveldt et al., 2021), and cause mortality to mangrove seedlings by blocking sunlight, preventing photosynthesis (Suyadi and Manullang, 2020; Williams and Simmons, 1996). Plastics, particularly bags, produce sounds during strong winds which may dispel resident and migratory birds, forcing them to permanently leave, which in turn may have effects on the nutrient cycling and supply in mangroves (Sandilyan and Kathiresan, 2012). Plastics may also affect burrowing crabs and snails by reducing their foraging area through the blockage of their holes (Luo et al., 2021).

The mangrove site with the highest plastic accumulation was LPPCHEA in Manila Bay. Its proximity to densely populated areas of Manila Bay and being within the city's drainage basin caused it to receive most of what gets transported out of the delta. It is also sheltered from wave action as part of the Cavite spit, consistent with the backward-in-time particle tracking model done for the area, indicating that the sources of litter around LPPCHEA were limited to its immediate vicinity (Cruz and Shimozono, 2021). This means that plastics may have come from nearby sources. Mangroves act as a transitional interface between marine and terrestrial systems, intercepting debris from nearby settlements before going to the sea (Cordeiro and Costa, 2010). The vulnerability of mangrove forests in the western Philippine archipelago is alarming, as this biogeographic region is home to almost 25% of the overall mangrove cover in the country (Long and Giri, 2011).

Interestingly, seagrass sites had significantly lower plastics density compared to adjacent beaches ($p < 0.05$), with proportions (beach/seagrass) that ranged from 0.2 to 119. (Figure S4b, Supplementary Material). The lower plastic accumulation in seagrass meadows surveyed may be due to plastics getting washed ashore from the shallow seafloor (Sanchez-Vidal et al., 2021) or simply because the sites were isolated since the adjacent beaches in the surveyed sites also had relatively lower plastics accumulation. Seagrasses also have flexible leaves compared to the rigid root systems of mangroves, thus, making them less effective in trapping plastic debris. Although the count of plastics surveyed in seagrass environments was the lowest, their mere presence still increases the risk of invasive algal species and sedimentation, which in turn, may reduce light penetration leading to a decline in seagrass growth (Menicagli et al., 2021; Ralph et al., 2007; Saunders et al., 2017).

The open structure of beaches on the other hand allows the easy dispersal of plastics by strong winds and waves (Martin et al., 2019), which may explain the lower accumulation in beaches relative to mangroves. It should also be noted that we only surveyed the strandline and adjacent areas and did not include backshore where long-term accumulations may occur. The presence and the accumulation of plastic debris on beaches have been reported to cause extreme changes in beach temperature, which could affect the physiology of many organisms and their ecological functions (Lavers et al., 2021). One example observed is the changes in the foraging behavior of the intertidal snail *Nassarius pullus* indicated by the decrease in the gastropod's ability to locate and move towards food with increasing plastic cover (Aloy et al., 2011). Increasing plastic cover may also lead to the obstruction of the nesting grounds of sea turtles (Hoare et al., 2022).

The vulnerability of different habitats to plastic pollution has direct implications on their ecosystem services, and in turn, to the organisms that depend on them. Thus, understanding their vulnerabilities is important to assess exposure and later identify the possible associated risks when exposed to increasing plastic accumulation.

**Plastic composition and contributing industry sectors**

The accumulating wastes in the environment represent the types and bulk of materials that are probably mismanaged from the source, thus, resulting in their leakage and eventual deposition in the marine environment (Schmaltz et al., 2020). Notably, by identifying the plastics by usage categories, it is also possible to associate and determine the potential industry sectors (e.g., food, medical, fishing) that produced them. Here, we looked at the clustering of the different sites based on the composition of the plastics debris (categories; Figure 2) and identified the patterns that might be related to the factors influencing their release and accumulation.

Areas with higher population densities, such as those sites in Manila Bay (Figure 2, Cluster 5) and eastern Palawan (Cluster 3B) were mainly dominated by disposable, single-use plastics such as thin plastic wraps/labels/packagings, straws, and plastic bags, which are generally considered non-recyclable (Geyer et al., 2017). Specifically, sites from eastern Palawan, an area with a higher population than the west, were part of Clusters 3 (mostly beaches) and 4 (seagrasses and mangroves). Cluster 3 notably also had relatively higher plastic accumulation than Cluster 4 ($p$=0.001; 0.05 – 3.30 pp/sq-m). Plastics under the category wraps/labels/food packaging were found the most abundant in both clusters followed by fishing lines/nets/rods, ropes/strings. Cluster 3a, however, was differentiated by the added abundance of fishing lines/nets/rods, and cigarette butts. Sites in Cluster 5 were all found in Manila Bay, which were the surveyed areas with both the highest population and accumulation levels (6.99-23.77 pp/sq-m). Most of the packaging found in these clusters was in the form of sachets or packets, which are sealed small plastic packaging intended for single use. They are usually sold containing food (i.e., snacks, instant noodles, condiments, cooking supplies) and personal care products (i.e., hair, soap, toothpaste). These sachets provide low-cost and convenient consumer goods for poor to middle-income families in the Philippines, fueling an entire single-use market also referred to as the ‘sachet economy’

(Liamson et al., 2020; Sarmiento, 2018; World Bank Group, 2021). Previous studies also reported that 52% of the residual wastes in the Philippines are mostly composed of sachets (Liamson et al., 2020). The demand for the use of sachets and other single-use materials as packaging (e.g., plastic bags, plastic containers) could have also been exacerbated by the COVID-19 pandemic when deliveries became the norm due to restrictions (Filho et al., 2021).

In contrast to Manila Bay and eastern Palawan, sites with low population and low plastic accumulation have clustered together in Cluster 1. Although all stations in this cluster had similar plastics density (0.07 to 0.49 pp/sqm), interestingly, they were further divided into three sub-clusters that differed in the dominant plastic categories. Specifically, the dominant plastic categories for Cluster 1a were hard plastic fragments and caps/lids/cover while for Cluster 1b were the thin plastic wraps/labels/food packaging and ropes and strings, and for Cluster 1c were the fishing lines/nets and foamed fragments. These plastic categories were fishing-related (hard plastic fragments, ropes/strings, fishing lines/nets, and foamed fragments) as well as food-related (thin plastic wraps/labels/packaging and caps/lids/covers). Notably, most sites in Cluster 1 were either far from urban areas or mostly near fishing coastal communities. Specifically, both western Palawan and Bolinao are characterized by fishing being one of the main livelihoods of the local communities as they are also rich fishing grounds (Reyes and Blanco, 2011; Sajorne et al., 2021). Items found include strings made from nylon, used for tying, building, and repairing boats, and hook-and-line or nets for fishing activities. Notably in Palawan, an emerging industry – spiny lobster fishing – has become a significant contributor to plastic wastes. This practice uses nylon ropes to hang the traps near the shore (Mecha et al., 2022), but because they are largely unregulated, many of the fisherfolks tend to abandon the traps including the ropes after the fishing season, resulting in their deposition and accumulation in the different coastal habitats (this study).

Notably, the islands or those sites that are far from mainland with very low number of residents (Pag-asa Island, Patongong Island, Mitra Island, and Sombrero Island) all had high accumulation of both fishing-related and buoyant materials. These include foamed fragments, hard plastics or high-density polyethylene (HDPE; e.g., personal care products), and beverage bottles. The beverage bottles (mostly PET) and shampoo or personal hygiene product containers are large compared to other plastic categories, and in combination with wind/oceanic transport, they will be able to travel longer distances (Hatzonikolakis et al., 2022) than the smaller particles that sink faster due to biofouling (Ryan, 2015).

The clustering of sites according to region and composition of plastic categories implies that different regions have different dominant plastic categories because of the type of industries or economic activities present – single-use plastics mainly used for food packaging for urbanized areas and fishing-related plastics near fishing communities. Islands, which usually have little to no residents, however, are an exception, with their coasts mainly being littered with larger and more buoyant plastic categories brought about by wind and currents as the most dominant. As plastics drift in the ocean, they travel over long distances with ocean currents and some are pushed to coastal environments (Ko et al., 2018) like in Pag-asa Island.

**Exposure classifications of different plastic categories**

Using the categories identified earlier based on the combined abundance and occurrence of each plastic category and following the proposed framework of Norton et al. (1992) and Werner et al. (2016), no plastic category was classified under Type 1. This was expected since sites with direct dumping were intentionally filtered from the datasets and/or avoided during the surveys. Most plastics were categorized under Types 2 to 4.

Plastic categories belonging to Type 2 include pipe/hoses, buckets/jerry cans, six-pack rings, buoys/floats, foamed cups/bowls/food containers, knives/forks/spoons, masks, lighters, thick plastic wraps, and cigarette tips. These plastics can be characterized as having ‘low usage’, as they tend to appear in lower abundance and few sites in the environment, suggesting that they might have longer usage duration, highly recycled, or generally have low demand due to their specific use. Interestingly, disposable face masks belonged to Type 2, which were a significant component in some sites despite the survey being conducted at the onset of the COVID-19 pandemic. They were mostly found in sites near populated areas such as Manila Bay and Eastern Palawan. The implementation of face mask policies worldwide due to the COVID-19 pandemic has not only led to the surge in its use but to its waste production as well, with an 80-fold increase in terms of litter proportion from less than 0.01% (Roberts et al., 2021). It was estimated that 449.5 billion masks were consumed globally during the start of the pandemic, comprising 6.5% to 11.9% of the total plastic leaking into the oceans (Li et al., 2022). Notably, field surveys in this study were done in the middle of the pandemic, thus, masks most likely have not yet accumulated and been dispersed to other locations. Their continued production and use however are of great concern since they are not usually recycled or reused due to hygiene concerns, classifying them as wastes upon disposal (Song et al., 2022). Due to their plastic nature (generally made of polypropylene, PP) and persistence in the environment, masks can cause fatalities to wildlife by ingestion, smother habitats leading to hypoxic conditions, and may disrupt breathing and gill structures when at sea, thus hindering swimming (Hassan et al., 2022; Li et al., 2022). Masks have also been shown to contain toxic chemicals from dyeing leachates, organic additives, and heavy metals (Li et al., 2022).

Plastic types present in most of the sites but have relatively lower total average plastic abundance were classified as “high dispersal” under Type 3. These plastic types include caps/lids/covers, beverage bottles, clear cups, shampoo bottles, and cigarette tips. The most notable are the larger beverage bottles and shampoo containers (see Fig. 4), generally made of PET and HDPE, respectively. Due to their high value and recyclability/reusability, they also tend to have high recovery rates (Merrington, 2017). Thus, even though they are produced in very significant quantities, they also tend to have low accumulation. Specifically, in the Philippines, the collected-for-recycling rates for PET and HDPE were 48% and 30%, respectively, resulting in a large portion of these plastic types ending up being recycled instead of disposed (World Bank Group, 2021). For example, beverage/PET bottles and HDPE containers are being repurposed domestically as buoys or floaters for seaweed culturing in local fishing communities, as containers for condiments and even water, as storage for food and supplies, and as plant pots. When not recycled and accumulated in coastal areas, they may entrap and obstruct macrofauna going into the sea. However, because these plastics are large and buoyant, they also have the most potential to drift farther offshore (Ryan, 2020) and travel longer distances causing them to be present in many sites surveyed. An example of this is the high percentage (45%) of bottles found in the southwestern portion of Australia that had labels originating from China and Southeast Asia (Smith et al., 2018). This ability to cross oceanic fronts as seen in the bottles accumulating in islands like Pag-asa (this study) and Sable Island in Canada (Baxter et al., 2022), may contribute to the dispersal of pathogenic, harmful, and invasive species since their surfaces may be conducive for colonization and survival of different organisms (Onda et al., 2020).

Interestingly, most of the single-use plastics were categorized under Type 4, or those found in more than 67% or all of the sites in relatively high abundance, more than one-half of the maximum log of total average abundance (Figure 4). These include thin plastic wraps/labels/packaging, foamed fragments, soft plastic fragments, fishing lines/nets, ropes/strings/strapping bands, straws, bags, and hard plastic fragments. These pieces may be considered as “high exposure” as these are often used and have the potential to be dispersed to other locations, increasing the chances of organisms encountering said plastic types, thus, the higher the probability of directly affecting them. Here, focus was given on the possible harm these product types may bring as they accumulate in coastal habitats. These include the plastic bags, usually made from polyethylene (PE) (Andrady, 2011), which when deposited in the coast or benthos, can reduce primary productivity and lower abundances of infaunal invertebrates in the benthos (Green et al., 2015), and possibly affect the coastal community dynamics and structure of coastal dunes by its leachates (Menicagli et al., 2019). Straws are mainly composed of polypropylene (Wagner and Toews, 2018) and are not recyclable due to its size and flexibility (Mosquera, 2019), which are then often mistaken as foods by some marine animals, ingesting them by accident and affecting the animals' digestive system (Iacurci, 2015; Mosquera, 2019). Foamed fragments on the other hand, made up of polystyrene, can be mistaken as food by fish and birds (Turner, 2020), and can act as both source and sink for contaminants found in the marine environment (Turner, 2021). The accumulation of plastics can choke drainages and cause flooding, block sunlight for organisms living in coastal areas, and affect foraging behavior of macroinvertebrates, influencing their normal functions. When exposed to natural weathering, they also tend to abiotically degrade, resulting in fragmentation and production of microplastics (Andrady, 2011; Nithin and Goel, 2017). Fishing lines/nets/rods, also referred to as abandoned, lost, or discarded fishing gear (ALDFG) marine debris, could continue to “ghost fish” shellfish and other fishes with or without commercial value, which may impact fish catch (Macfadyen et al., 2009). Primary harm associated with ALDFG in coastal areas include morbidity and mortality of the flora and fauna in the intertidal zone (Gajanur and Jaafar, 2022), i.e., ingestion of and entanglement in these net lines/fishes.

Although exposure may be directly related to the abundance and presence of a plastic type, the size of the plastic that an organism encounters may also influence how the plastic will affect the organism (Rivers-Auty et al., 2023). Thus, classifying the plastics based on their sizes for exposure assessment, particularly for ingestion, would have also been advantageous. However, most of the existing survey methods (i.e., NOAA, GESAMP, this study), except that of COBSEA and CSIRO (2022) for marine debris do not include qualification of size beyond the category of >2.5 cm. Adding this category in baseline surveys will add another layer of information that might help towards the development of risk assessment index for marine debris. Such should be considered in current harmonization efforts of the current survey guidelines. Further, since the surveys were done on strandlines and areas where wave action may also resuspend the plastics, the harm of resuspension in the water column is also likely. Their potential harm then may be extended to the pelagic species.

## CONCLUSIONS

This study presented the most comprehensive archipelagic baselining work done in the western Philippines to date – a country that has been repeatedly included in the top ten plastics polluters of the oceans. Here, we observed plastic debris in all the sites surveyed, even in remote islands, which could be driven by both inputs from the coastal communities and/or transported by ocean currents. Clustering of sites based on composition of plastic categories also emphasized the varying contributions of different sectors based on the dominant economic activities in the regions or coastal communities. Specifically, among the plastic types, most single-use plastics, such as thin plastic wraps/labels/packaging, straws and plastic bags, including fishing-related materials were identified to be under Type 4 or 'high exposure' due to their high abundance and dispersibility. These wastes tend to also accumulate mostly in mangrove forests because of their plastic-trapping root systems, making them the most vulnerable coastal habitat to plastic pollution. The plastic exposure risk categories (Types 1-4) presented herein are the first attempt to integrate commonly collected information or data during baselining surveys to develop an exposure assessment matrix following the combined frameworks of Norton et al. (1992) and Werner et al. (2016). Such categorization will be helpful in determining priorities in terms of management and even mitigation, and also guide more targeted experiments. From here, dose-response experiments for plastic categories should be started for the risk assessment of plastics. Notably, observations in the Philippines may also be the case for the other archipelagos elsewhere in the world, thus, insights gained here may also be applicable in similar settings.

The information and insights provided by this study will also help in the prioritization of policies dealing with the regulation, mitigation, and reduction of plastics wastes in the marine environment. For example, used fishing gear should also be considered when crafting policies related to fisheries. Currently, the Philippines only requires commercial fishing vessels to register their fishing gears (The Philippine Fisheries Code, 1998), but not the registration and disposal of used fishing gear, resulting in our inability to track and monitor waste contributions from this sector.  In addition, the Philippines has just approved the Extended Producer Responsibility Act of 2022 (RA No. 11898) (Extended Producer Responsibility Act, 2022). Although this requires companies with assets greater than P1 billion pesos to recover a certain percentage of their plastic packaging waste (Extended Producer Responsibility Act, 2022; Ranada, 2022a) this might not effectively or directly help in mitigating the plastics problem in the country as pointed out also by environmental groups (Ranada, 2022b). This law only covers plastic packaging and not plastic products, and only requires large companies excluding medium, small, and micro-enterprise (MSMEs), which comprise 99.58% of all business in the Philippines (Philippine Statistics Authority, 2022; Ranada, 2022b). Recovery should not only be the focus in lessening plastic pollution in the country but should move towards "turning off" the tap when it comes to plastics production. Insights from this study will help in crafting science- and data-driven policies that could help minimize or phase out certain 'high exposure' materials.

## CREDIT AUTHOR STATEMENT

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## DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## FIGURES

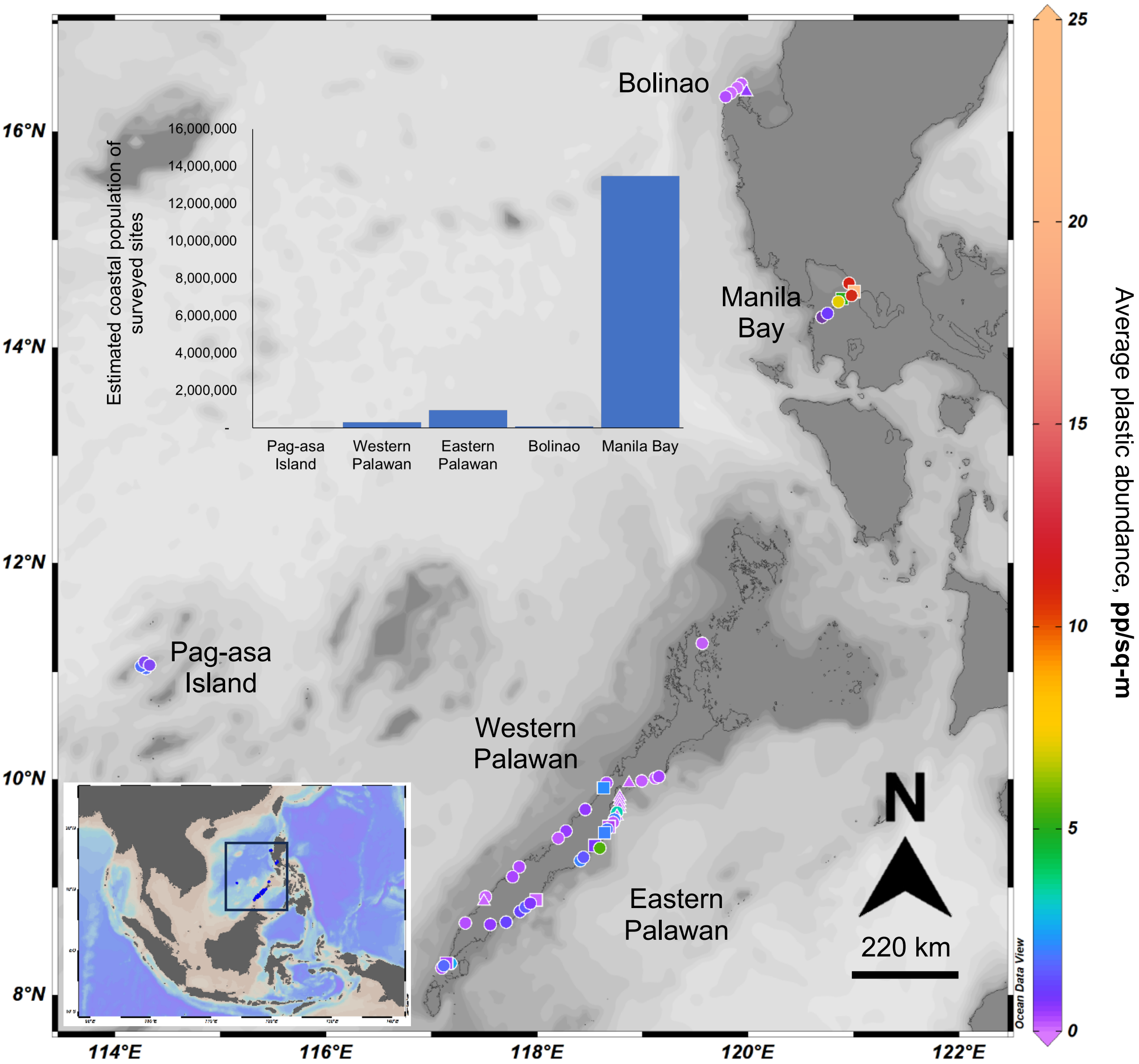


**Figure 1. Sampling sites and plastics abundance.** Map of sampling sites (seagrass – triangle, mangrove – square, beach – circle) with the corresponding plastics abundance (in average abundance of plastic items/square meter, pp/sq-m, where light violet circles being the lowest abundance and beige being the highest). Insets: bar plot of the estimated coastal population of surveyed sites in the different geographical areas and location of sampling sites relative to Southeast Asia

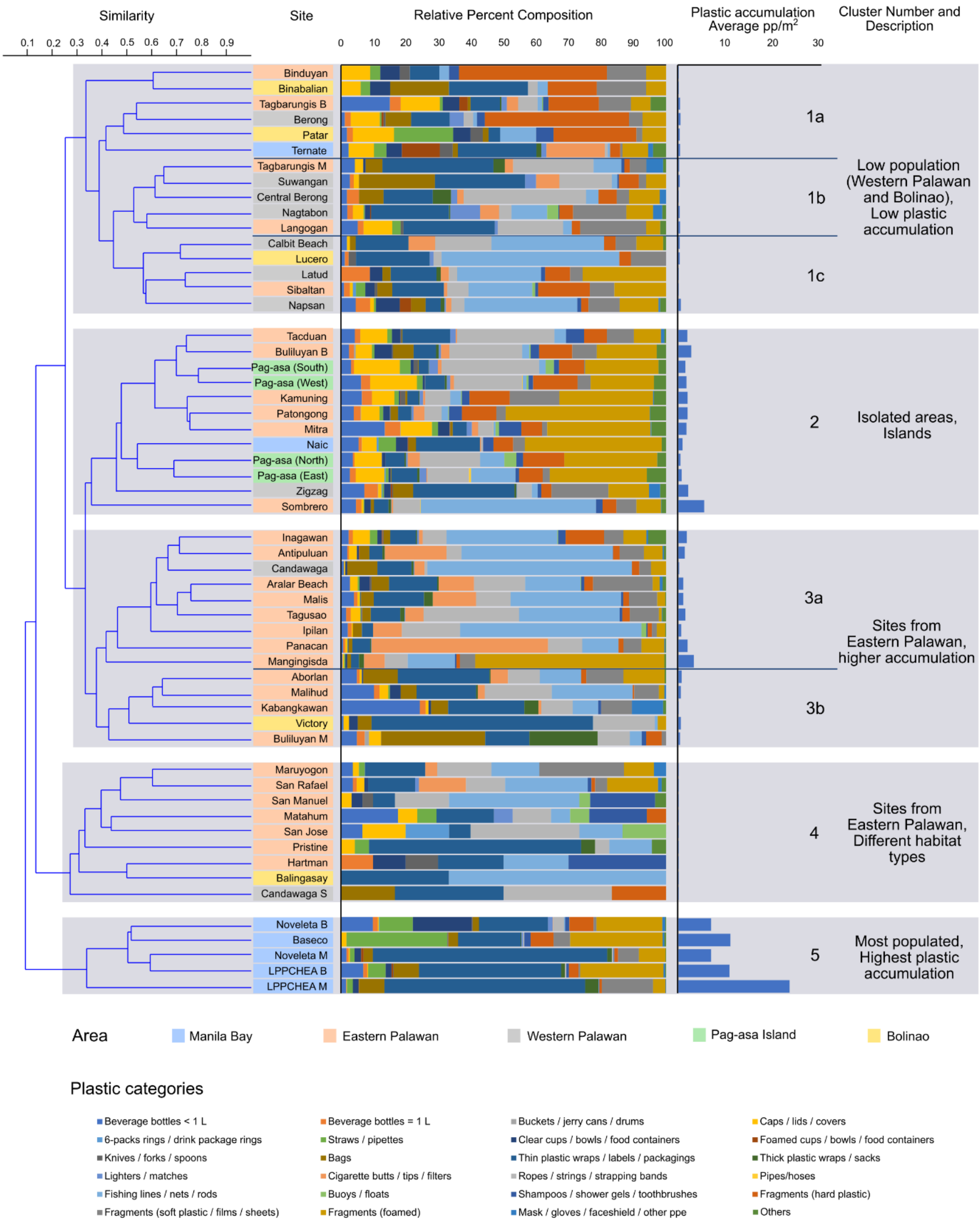


**Figure 2. Variation in the composition of plastic debris across sites.** Unweighted Pair Group Method with Arithmetic Mean (UPGMA) clustering using Bray-Curtis on the abundance of plastic categories per site. Hierarchical clustering based on the abundance and composition of the plastics per site resulted into five major clusters. Cluster 1 were sites with low population and low plastic accumulation, mostly from Western Palawan and Bolinao with sub-clusters 1a, 1b, and 1c classified by dominant plastic categories. Cluster 2 were isolated sites and islands. Cluster 3 were mostly sites from Eastern Palawan, high population and high plastic accumulation, with sub-clusters 3a and 3b classified by dominant plastic categories. Cluster 4 were also sites from Eastern Palawan but with low

plastic accumulation, which may be attributed to habitat type, and lastly, Cluster 5 were sites from Manila Bay which is the most populated and the highest plastic accumulation.

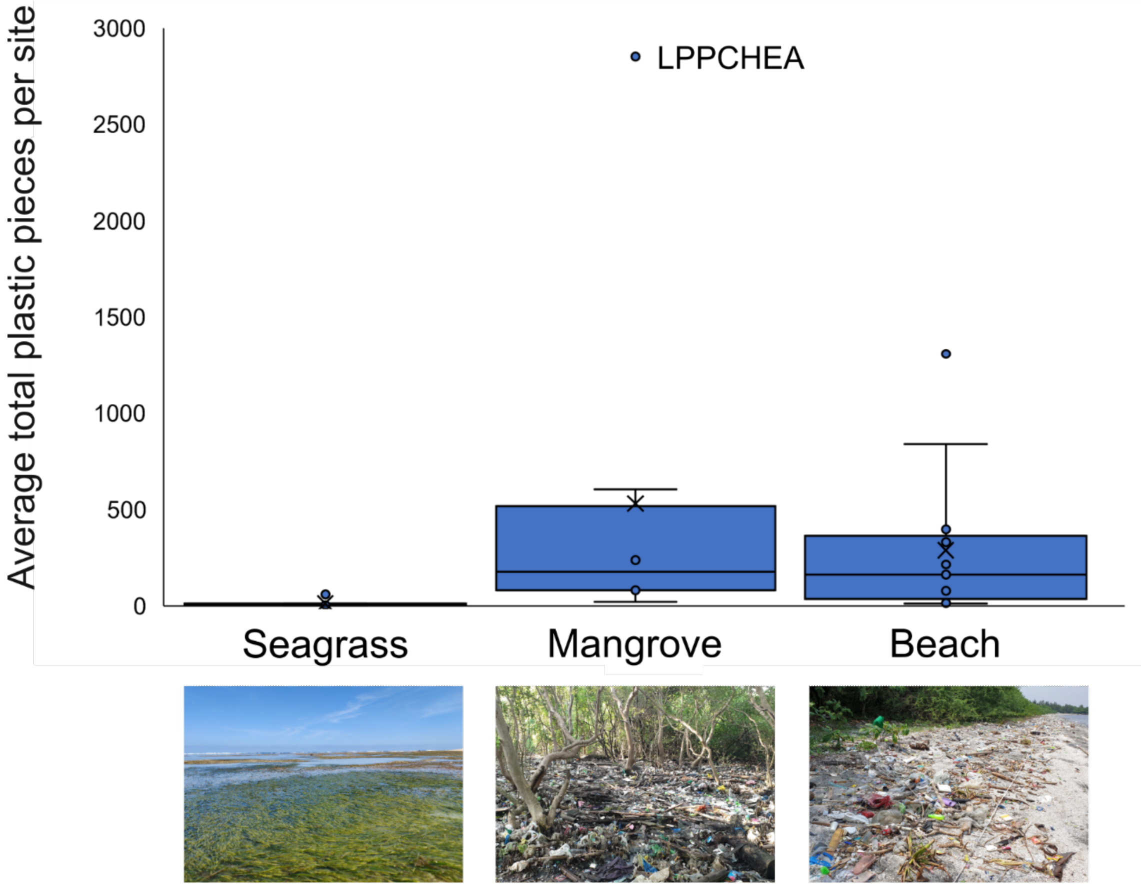


**Figure 3. Plastic accumulation variation by habitat type and photos of coastal environments.** Box plot of average total plastic pieces per site according to the habitat type: seagrass (n=8), mangroves (n=8), and beaches (n=13) with corresponding representative photos of the different coastal environments surveyed in this study, including seagrass (Photo credit: Daniel John Purganan), mangrove, and beach

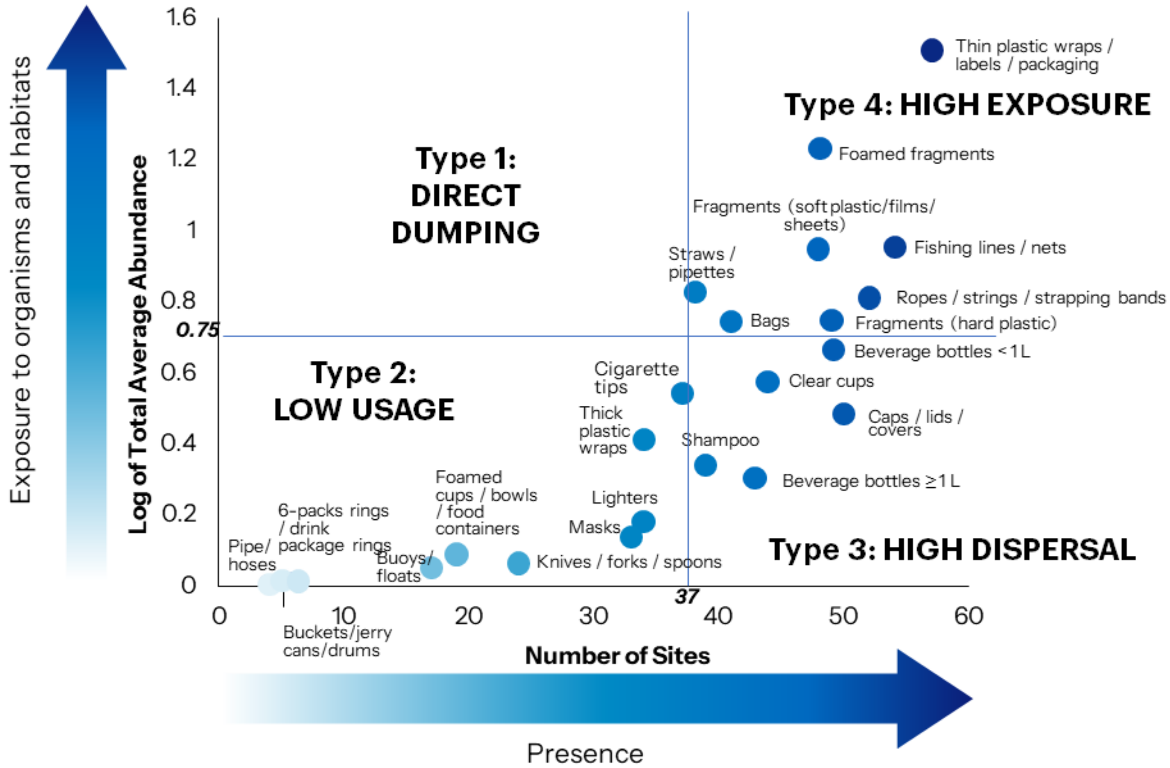


**Figure 4. Exposure assessment matrix of different plastic categories.** Plot of the exposure classifications of different plastic categories using abundance (pp/sq-m) and occurrence (presence in sites). Using both indices, plastic categories were classified into four types: Type 1 “direct dumping”, Type 2 “low usage”, Type 3 “high dispersal”, and Type 4 “high exposure”.

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