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Abundance, provenance, and characteristics of plastic beverage bottles in human settlements and on beaches of the Latin American Pacific region: a citizen science study

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A R T I C L E I N F O

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A B S T R A C T

Plastic pollution is a global issue affecting both urban and natural environments. On coastlines, bottles and loose caps, either locally sourced or carried by ocean currents, represent a major share of this pollution. Identifying their sources is essential for developing measures to reduce and prevent this environmental threat. In this study, citizen scientists sampled plastic beverage bottles and loose caps, using product information to determine their abundance, provenance, and characteristics across 38 human settlements, 92 continental beaches, and 15 island beaches spanning ∼12,000 km of coastline in 10 Latin American Pacific countries. Human settlements and beaches in Central American countries had higher bottle pollution, driven mainly by high beverage consumption and deficiencies in waste management. Of the items with identifiable origin, 59 % came from within the Latin American Pacific countries. Most items found in human settlements and on continental beaches were from national sources, but Central American beaches had a higher contribution from other countries. The latter are likely transported by ocean currents, as also indicated by a high frequency of bottles with high-to-medium wear, epibionts, and older age. Island beaches had more plastic bottles from Asia, likely dumped from ships. Among all analyzed items, 26 % were manufactured by The Coca-Cola Company, followed by PepsiCo and the Aje Group. Since locally operated production plants of multinational companies and single-use individual-sized bottles are the main contributors to this type of littering, shifting to reusable bottles with a standardized format across the region could substantially reduce plastic pollution along Pacific shorelines.

Abbreviations:

- AJE Group: Peruvian multinational beverage company
- C Contingency coefficient
- CRA *Comisión de Regulación de Agua Potable y Saneamiento Básico (Colombia)*
- CPPS *Comisión Permanente del Pacífico Sur*
- EAN European Article Number
- EU European Union
- GLM Generalized linear model
- GS1 Global Standards One
- IBM SPSS International Business Machines – Statistical Package for the Social Sciences
- KW Kruskal–Wallis test
- MARPOL: International Convention for the Prevention of Pollution from Ships
- Minvivienda *Ministerio de Vivienda, Ciudad y Territorio (Colombia)*
- N/A Not applicable
- NOAA National Oceanic and Atmospheric Administration
- PERMANOVA Permutational Multivariate Analysis of Variance
- PET Polyethylene terephthalate
- PepsiCo Multinational food and beverage corporation
- PCoA Principal Coordinates Analysis
- PNUMA *Programa de las Naciones Unidas para el Medio Ambiente*
- UN United Nations
- UPC Universal Product Code
- USA: United States of America

1. Introduction

Plastic litter pollution is widespread across our planet and affects both human settlements and natural ecosystems, with repercussions for biodiversity, environmental health, and human livelihoods (Maharja et al., 2024). Both inland and coastal human settlements (key sources of plastic litter) are interconnected through rivers, coastal dynamics, and ocean currents with rural or remote continental and island shorelines. These pathways facilitate the transport and redistribution of plastic litter from source areas (e.g., urban centers) to nearby or distant ecosystems, including beaches (Ryan et al., 2019, 2021, 2024; Ryan and Perold, 2021; Shankar et al., 2023, 2024).

Plastics constitute the largest share of marine litter on beaches worldwide. Bottles and loose caps are among the most abundant items contributing to plastic pollution (Brooks et al., 2020; Chen et al., 2020; Shankar et al., 2023, 2024; Ryan, 2020; Benito-Kaesbach et al., 2024; Howlader et al., 2024; Shaibur et al., 2024; Ryan et al., 2024a; Garcés-Ordóñez et al., 2025). However, few studies have investigated plastic bottles across both human settlements and beaches simultaneously (for an exception, see Ryan, 2020), and none have examined their abundance, origin, and characteristics at a large regional scale, such as the Latin American Pacific region. Such an approach is necessary to support the development of solutions to mitigate marine plastic pollution.

Plastic bottles are used for a wide range of beverages, including soft drinks, water, and juices (Benyathiar et al., 2022; Shaibur et al., 2024). They have high consumption rates and short shelf lives, usually ranging from six to twelve months (Phimolsiripol and Suppakul, 2016; Omokpariola, 2022). An estimate suggests that over 580 billion polyethylene terephthalate (PET) bottles were manufactured globally in 2022 alone (Gordon, 2023). A major proportion of these PET containers ultimately ends up polluting coasts and cities due to low recycling rates and poor waste management practices (Monteverde, 2020; Ryan, 2020; Garcés-Ordóñez et al., 2020a, 2020b, 2025; Benyathiar et al., 2022; Arteaga et al., 2023; Grangxabe et al., 2024).

Plastic bottles deteriorate over time in the environment, exhibiting discoloration, wear, and fragmentation due to physical processes (Ioakeimidis et al., 2016; Bonifazi et al., 2023). Like other marine litter, bottles and caps are often colonized by organisms such as bryozoans, barnacles, and mollusks (Mghili et al., 2023), and display degradation patterns typical of marine exposure (Duhec et al., 2015; Smith et al., 2018; Bui et al., 2024; Ryan et al., 2024a).

Despite these changes, plastic beverage bottles often retain key identifying features such as product codes (e.g., European Article Number – EAN), brand names, manufacturing locations, and dates (Šenk et al., 2013; Ryan, 2020). This information helps trace their provenance, even when the bottles are damaged or extensively colonized, providing valuable insight into their origin and transport pathways (Ryan et al., 2019; Schuitemaker and Xu, 2020; Benito-Kaesbach et al., 2024; Cowger et al., 2024).

While regional-scale research can be challenging, citizen science offers a unique opportunity for collaboration and empowerment, as demonstrated by the participation of local communities in Latin America (De Veer et al., 2023), Oceania (Sciutteri et al., 2024; Gacutan et al., 2024), Europe (Nelms et al., 2020), Africa and Asia (Catarino et al., 2023; Chen et al., 2020), and globally (Cowger et al., 2024; Krawczyk et al., 2025). Such collaboration involves the training of local community leaders, strengthening a research network on coastal litter issues, generating data, and raising environmental awareness (Kawabe et al., 2022; Gacutan et al., 2024). It also promotes recognition of plastic litter pollution and encourages actions for its prevention and mitigation (Gacutan et al., 2023; Mishra et al., 2023).

The main aim of this study is to analyze the abundance, provenance, and characteristics of plastic beverage bottles in human settlements and on continental and island beaches in the Latin American Pacific region, collaborating with the citizen science network "*Científicos de la Basura*" (Litter Scientists). Ocean circulation connects the entire region, which has shared strategic environmental management plans aimed at identifying the sources and characteristics of marine litter (CPPS, 2022; PNUMA and MarViva, 2022; Honorato-Zimmer et al., 2024). The current research focuses on plastic beverage bottles due to their abundance, ease of traceability and sampling by citizen scientists, as well as usefulness for understanding macrolitter source dynamics over large spatial scales across human settlements and beaches.

The research questions addressed are as follows: (i) What is the abundance of plastic beverage bottles in human settlements, continental beaches, and island beaches of the Latin American Pacific region? (ii) Do the plastic beverage bottles found on beaches originate locally, or do they come from more distant places? (iii) What post-consumption characteristics (wear state, age, and epibiont presence) indicate the pathways of plastic bottles found in the studied environments? (iv) Who are the main producers (companies, brands), and (v) what are the product traits (beverage types, sizes) of the plastic bottles found?

This study is based on a citizen science methodology that enables the assessment of plastic bottle pollution while ensuring the collection of quality-checked data, which could be adapted and applied elsewhere. It also establishes a regional baseline for this type of pollution in human settlements and beaches along the ~12,000 km East Pacific coast from México to Chile, helping to design local and regional solutions to prevent this environmental problem at its sources.

2. Materials and methods

2.1. Study area

The study area included 38 human settlements, 92 continental beaches, and 15 island beaches along the Latin American Pacific region, encompassing 10 countries between 32°N and 57°S (Fig. 1). These countries were grouped into three subregions: North America (México); Central America (Guatemala, El Salvador, Nicaragua, Costa Rica, and Panamá); and South America (Colombia, Ecuador, Perú, and Chile). The human settlements (cities, towns, villages, and hamlets) and beaches (sandy, rocky, and mixed) were selected by local volunteer collaborators (hereafter referred to as "citizen scientists") based on proximity to their places of residence, availability of logistical resources, safety for sampling, and opportunities provided by other projects to participate in scientific expeditions in natural areas, including remote islands. In terms of coastal population density across the study area, Central American countries showed the highest values, particularly El Salvador, Nicaragua, and Guatemala, while the lowest densities were recorded along the coasts of Colombia and Chile (Fig. 1; Table S2).

2.2. Citizen science participation

2.2.1. Teamwork coordination and activities

The *Científicos de la Basura* program (Universidad Católica del Norte, Chile) coordinated the study using its established citizen science strategies (Thiel et al., 2023): (1) developing clear sampling protocol, (2) recruiting citizen scientists and training local leaders, (3) conducting sampling activities and data submission, and (4) validating data quality and analyzing them. As a cross-cutting activity, guidance was provided throughout the entire process (Fig. 2).

A didactic protocol was developed to guide citizen scientists in collecting data on plastic beverage bottles and loose caps, which was adapted for sampling in human settlements or beaches (Científicos de la Basura, 2024). From May to November 2023, ~1000 citizen scientists and 200 local leaders were recruited from 74 organizations across 10 countries in the region. These organizations included schools, universities, research institutes, municipalities, environmental ministries, and community associations (Científicos de la Basura, 2025).

Between July and November 2023, 13 online training sessions on these protocols were imparted to the 200 local leaders, who subsequently coordinated sampling efforts in their localities through citizen scientists, including students, teachers, researchers, and community members. Three members of the central coordination team visited 31 sampling sites (beaches and human settlements) across eight countries (El Salvador, Nicaragua, Costa Rica, Panamá, Colombia, Ecuador, Perú, and Chile) from July to October 2023, conducting in-person training while strengthening ties with local organizations. Each local leader conducted one or more sampling events (specific sampling activities at a site at a specific time), with teams comprising at least two members, including the local leader.

Samplings for this study took place from July 14th, 2023, to February 3rd, 2024. Initial samplings were conducted by members of the central coordination team, with new citizen scientists trained and progressively incorporated into this activity. Product information from bottles and caps collected on April 22nd, 2023, during a cleanup at a remote beach by the Galápagos National Park management team (Ecuador) was also included after validation. The central coordination team continuously responded to inquiries from local leaders regarding sampling evidence (photos and data forms) and data reporting through cellphone messages or e-mail. All submitted data underwent an initial review by the coordination team, a critical step to ensure that data contributed by the volunteers were complete before proceeding to validation and quality assessment for inclusion in the study.

2.2.2. Sampling protocol

The sampling protocol consisted of two parts: (i) collection and quantification of plastic beverage bottles and loose caps in human settlements or beaches, and (ii) identification and recording of product information from collected items (Científicos de la Basura, 2024). This division allowed independent validation of abundance data and product details, ensuring high-quality data from citizen scientists (see subsection 2.2.3).

2.2.2.1. Collecting and quantifying item abundance data. At the start of each sampling event, citizen science teams took panoramic photos of the sampling site and filled out a field survey form with the number of participants, sampling date, local leader name, site name, sampling time, and nearby relevant features (e.g., litter accumulations, shops, vendors). Teams collected all plastic bottles and loose caps found within 30 min, although duration could vary depending on site size, number of participants, and item abundance. Bottles and loose caps were sampled exactly as found, without removing labels or caps. Participants used

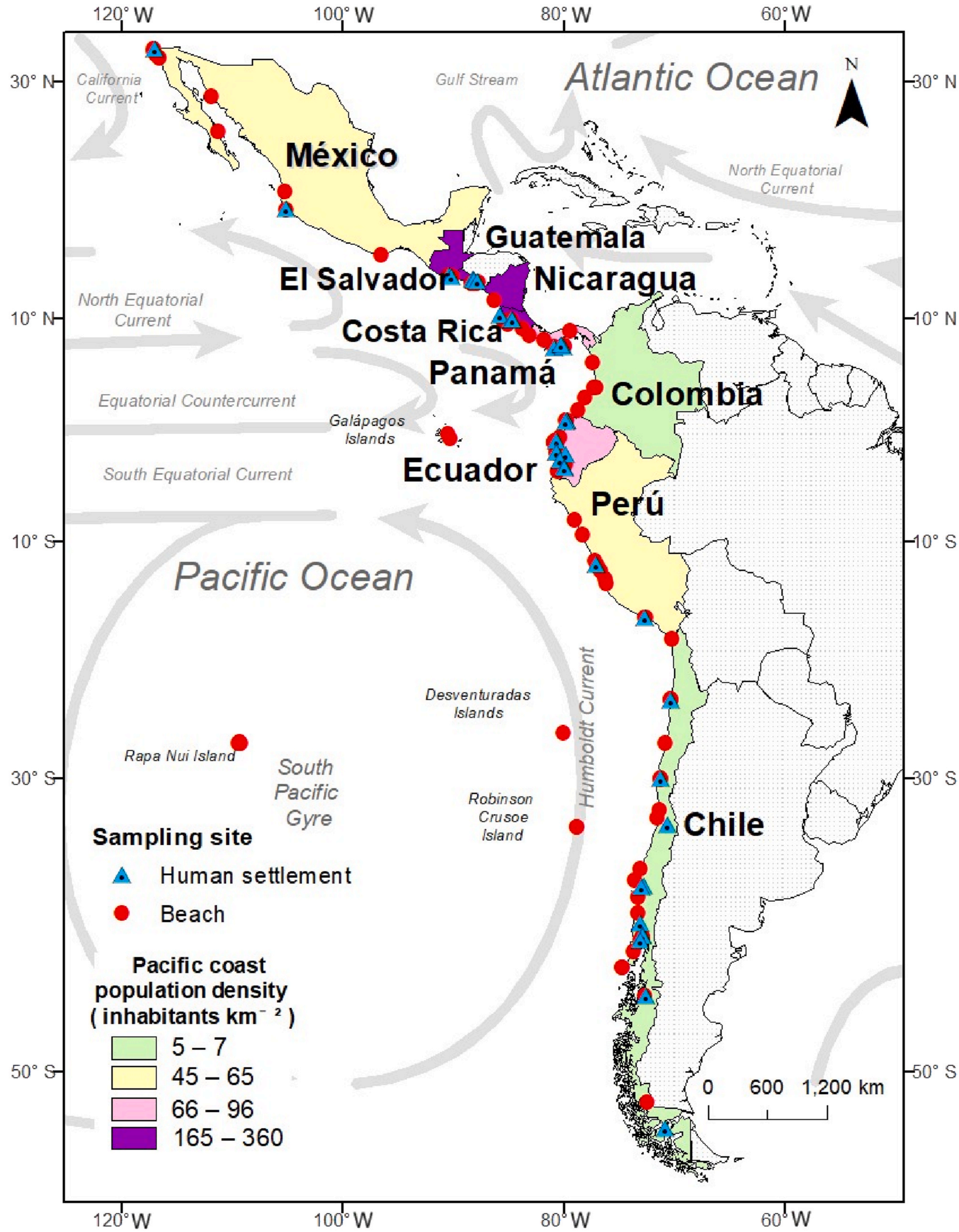

Fig. 1. Study area showing sampling sites for plastic beverage bottles and loose caps in human settlements (blue triangles) and beaches (red dots) across ten Latin American countries, from northern México to southern Chile (highlighted in yellow), including several oceanic islands. Grey arrows represent the large-scale surface ocean currents, with information obtained from NOAA (n.d.). See Tables S1 and S2 in the Supplementary materials for details on sampling sites and sources of information on population density, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

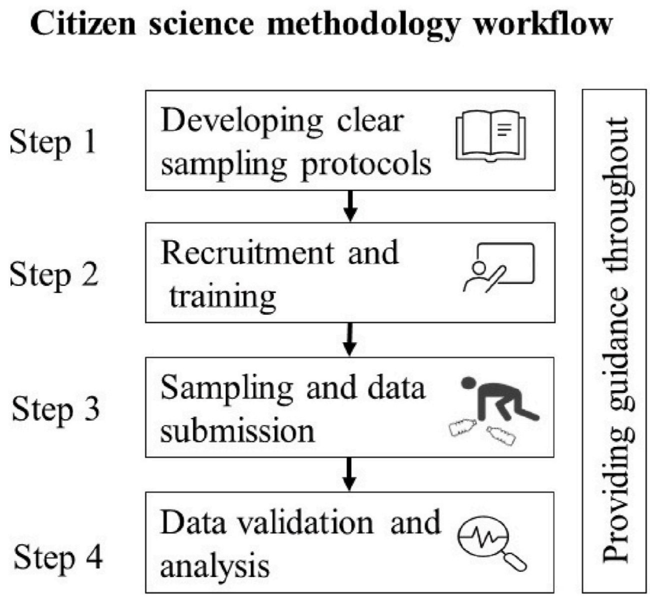

Fig. 2. Workflow of the citizen science methodology used for this study.

gloves and stored collected items in large trash bags or sacks.

Sampling took place between the last high tide line and the upper beach boundary or across the entire street width in human settlements, avoiding trash accumulations and the areas around containers, as they may not represent litter that was freely discarded or transported by natural processes. After sampling, items were organized and sorted into three categories: loose caps, bottles without caps, and bottles with caps. Items in each category were counted, placed on labeled mats, and photographed along with labels indicating sampling date, site name, location, country, and local leader's name. Completed field survey forms were photographed or scanned and saved (Fig. S1).

2.2.2.2. Recording product information data. To identify producers and product characteristics, up to 30 items per category (loose caps, bottles without caps, and bottles with caps) were randomly selected at each sampling site. Items were numbered and labeled for individual tracking. A designated team member recorded detailed product information, while other participants examined the bottles and caps. Each item was carefully inspected to document brand, dates, codes (on caps, bottle necks, and bodies), barcodes, volume, bottling plant name and location, epibiont presence (without species identification), and wear state (low, medium, or high; Fig. S2), following guidelines provided in the sampling protocols.

2.2.2.3. Sending sampling evidence and data to the central coordination team. All forms containing data on loose caps, bottles without caps, and bottles with caps were scanned or photographed. Citizen scientists selected the first three bottles with caps for detailed photographic documentation of dates, codes, and complete labels. All sampling evidence, including panoramic photos of sampling sites, photos of bottle items on labeled mat, scanned or photographed field survey and product information forms, and detailed label and code photographs of up to three bottles with caps (Fig. S1), was submitted to the central coordination team for validation. Data from the forms were also digitally submitted as Excel files.

2.2.3. Data validation and standardization

Sampling evidence and data quality were systematically assessed (section S3 in supplementary materials) by two scientists from the coordination team, who verified data completeness and accuracy against photographic evidence. Errors were identified and corrected, and data were standardized for consistency. Close communication with citizen scientists ensured timely correction of mistakes, guaranteeing high-quality data. The data validation process is described in Fig. 3. The number of sampling events is higher than the number of sampling sites because large citizen scientist groups were divided into subgroups, each conducting separate events at different subsites within the same location site.

2.2.3.1. Abundance of plastic beverage bottle items. Validated sampling data (number of participants, sampling duration, and item counts) were verified to ensure all items were plastic beverage bottles. Item counts were checked using photographs and recounted automatically with OTARIIDAE® 1.0 software, which allows zooming and marking items by category. Non-beverage containers (e.g., oils, shampoos, disinfectants) were identified, counted separately, and subtracted from totals. Standardized counts were expressed as items person^{-1} min^{-1} (Eq. (1)), enabling consistent comparisons across sampling teams and locations.

$$Abundance = nItems / \; Time \; / \; nP \qquad \text{(Eq. 1)}$$

where:

- *nItems*: the number of items registered.
- *Time*: the duration of sample collection in minutes.
- *nP*: the number of participants who collected samples at the sampling site.

2.2.3.2. Product information for provenance tracking and characterization of bottle items. Product information was used to determine bottle and loose cap origins and characteristics. A subsample of 280 bottles (40 %) from a total of 698 bottles with detailed photos was assessed for data quality. Ten key characteristics were evaluated (Table 1). Data visibility (clarity in photos) and accuracy (agreement between citizen reports and reviewers) were rated qualitatively (high to very low; Tables S3–S4). For inclusion of a given item, ≥70 % of data needed high accuracy. Results showed 93 % high visibility (Table S5), indicating 70 %–100 % of characters were clearly visible in bottle and label photos. Furthermore, 92 % of the data showed high accuracy (Table 1), with no errors in the reported data and a 100 % match with the data observed during the verification process. Details are provided in subsection S3.2 in Supplementary materials.

Data were standardized by verifying brands and bottling plants via online searches (https://www.google.com/), producer websites, social media, and supermarkets. Complete barcodes were checked using GS1 (https://www.gs1.org/services/verified-by-gs1) and Go-UPC (https://go-upc.com/) platforms, confirming product details such as brand, description, country of sale, and company information. Brands were classified into beverage categories (e.g., soft drinks, waters, alcoholic drinks, juices). Bottle and cap codes were verified online using keywords ("plastic bottles," "plastic caps," "company") in Spanish and English to identify manufacturers and complete missing brand or company data. Some codes corresponded to container or cap producers rather than beverage brands. Bottle volumes were standardized to liters, and bottle ages were calculated from the oldest date stamp and categorized into four groups: <1 year, 1–3.9 years, 4–10 years, and >10 years.

Bottle and loose cap provenance was determined using label information and barcode country codes. When both sources matched or only one was available, the country was directly assigned, with occasional discrepancies being reviewed and corrected. Priority was given to label data when barcodes were incomplete or unreadable. Items without clear provenance were reviewed using company or bottling plant locations identified online. Single-location companies were assigned to specific cities and countries, while multinational producers were categorized by region (e.g., Latin America, Asia). Locations associated with alphanumeric codes were reviewed to identify patterns for assigning specific

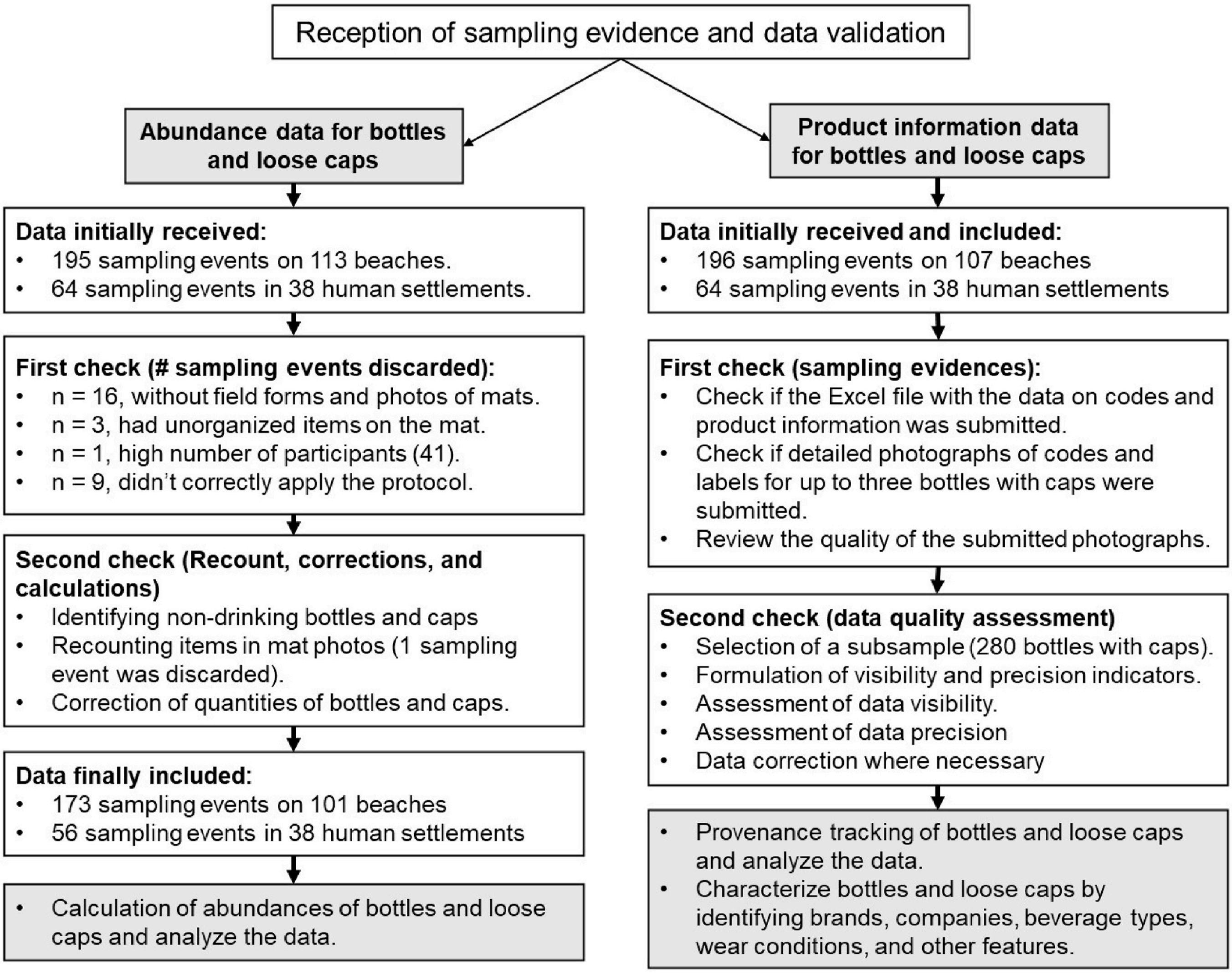

Fig. 3. Process flow for validating data on the abundance and the codes and product information used to trace the origin and characteristics of bottles and loose caps in this study. See section S3 in Supplementary materials for further details.

Table 1
Results of the data accuracy assessment reported by citizen scientists based on the match with the data verified by the reviewing scientists on the photographic evidence from the sampling. High accuracy = No errors, 100 % match between reported and verified data. Medium accuracy = Minor errors, 60–99 % match between reported and verified data. Low accuracy = Noticeable errors; 40–59 % match between reported and verified data; Very low accuracy = <40 % match between reported and verified data. N/A: not applicable.

Characteristics	High (%)	Medium (%)	Low (%)	Very low (%)	Total (%)
Bottle wear (n = 280)	92.9	6.8	0.3	N/A	100
Label wear (n = 233)	91.4	8.2	0.4	N/A	100
Brand (n = 256)	98.8	0.8	0.4	0.0	100
Bottler name (n = 194)	91.2	3.1	5.7	0.0	100
Bottler location (n = 177)	79.7	9.0	9.6	1.7	100
Bottle volume (n = 225)	91.2	5.3	0.4	3.1	100
Neck code (n = 250)	91.2	7.2	0.8	0.8	100
Body code (n = 203)	93.6	1.5	2.5	2.4	100
Barcode (n = 220)	93.2	3.6	0.5	2.7	100
Dates (n = 217)	89.9	6.9	2.3	0.9	100
General (n = 2255)	**92.0**	**5.0**	**2.0**	**1.0**	100

countries or regions. Items with no identifiable provenance were classified as "Unidentified".

2.3. Statistical analysis

Data from multiple sampling events were standardized and combined to report a single mean abundance value per human settlement, continental beach, and island beach. Descriptive analyses were used to explore trends across sampling sites. A Kruskal–Wallis (KW) test with post-hoc comparisons was used to determine whether plastic bottle abundance differed significantly by type of environment (human settlement, continental beach, island beach), subregion (North, Central, and South America), and country. This non-parametric test was appropriate due to non-normal data and unequal variances, as confirmed by the Shapiro–Wilk and Levene's tests, respectively. The null hypothesis assumed no significant differences in median abundance among the groups.

A Spearman's rank correlation test was used to assess the relationship between coastal population density and bottle abundance, including data from all countries and types of environments. The analysis was based on the hypothesis that the two variables are positively correlated. Population density data were calculated by dividing the population by the area of Pacific coastal provinces in each country, based on official reports (Table S2).

Associations between categorical variables, specifically the country of origin of bottles and the producer companies, were assessed using Pearson's χ^2 test, Cramér's V, and the contingency coefficient (C), under the null hypothesis of independence between variables. These coefficients range from 0 (no association) to 1 (perfect association), allowing us to evaluate the strength of categorical relationships (Dytham, 2011).

A Permutational Multivariate Analysis of Variance (PERMANOVA) was used to test differences in the composition of bottle origin among sites, grouped by type of environment, country, and subregion. The null hypothesis stated that composition did not differ significantly among groups. This non-parametric test was appropriate given the multivariate nature of the data (percentages) and the lack of normality and homogeneity of variances (Anderson, 2017). To visualize patterns of group separation, a Principal Coordinates Analysis (PCoA) based on Bray–Curtis dissimilarity was performed. PCoA is an ordination technique that transforms a distance matrix into a set of orthogonal axes, allowing the representation of multivariate differences among samples in a reduced-dimensional space. This method is useful for exploring similarities or dissimilarities in compositional data and helps to visually assess clustering patterns among groups (Zuur et al., 2007).

A generalized linear model (GLM) with binomial distribution and logit link function was used to assess whether the probability of finding epibionts on plastic beverage bottles (binary response variable) was associated with item wear level and age classification (categorical predictor variables). The null hypotheses were that there are no significant differences in the probability of epibiont presence among wear levels (low, medium, high) or among bottle age classes (<1 year, 1–3.9 years, 4–10 years, >10 years). Due to missing data, each predictor was analyzed separately using all available observations with complete information. All statistical tests were performed following Dytham (2011), using IBM SPSS® and R® software, with a significance level set at 0.05.

3. Results

3.1. Abundance of plastic beverage bottle items

A contrasting distribution pattern was found among beverage bottle item types across the study area: loose caps and bottles without caps predominated in human settlements (41.1 %) and on continental beaches (54.9 %), whereas bottles with caps were more frequent (73.4 %) on island beaches (Table 2). The mean abundance (± standard deviation) of beverage bottles was highest on continental beaches (1.4 ± 1.8 items person^{-1} min^{-1}), followed by human settlements (0.9 ± 0.8 items person^{-1} min^{-1}), and island beaches (0.4 ± 0.8 items person^{-1} min^{-1}), with significant differences between island beaches and the other two locations (KW test = 12.39, df = 2, p = 0.002). Plastic bottle abundances were higher across all types of environments in Central America, showing significant differences compared to those recorded in North and South America (KW test = 14.4, df = 2, p < 0.001) (Fig. 4).

Comparisons among countries showed significant differences in beverage bottle abundances in human settlements (KW test = 15.20, df = 7, p = 0.032) and continental beaches (KW test = 25.62, df = 9, p = 0.002). Post-hoc rank tests indicated significant differences between human settlements in Chile, México, and Ecuador compared to Panamá (Fig. 4A), and between continental beaches in México and Chile compared to those in El Salvador, Costa Rica, Panamá, and Perú (Fig. 4B). No significant differences were found between countries for island beaches, but the highest mean abundance was recorded in Panamá (Iguana Island) and the lowest in Chile (San Félix and Robinson Crusoe Islands) (Fig. 3C). A significant positive correlation was found between coastal population density and beverage bottle abundance (Spearman's ρ = 0.594, df = 20, p = 0.002), which support the hypothesis that higher population density is associated with increased plastic bottle abundance.

3.2. Provenance of plastic beverage bottle items

Most analyzed plastic beverage bottle items with identifiable origins (59.2 %) came from within the Latin American Pacific countries (Fig. 5). Smaller proportions originated from Asia (1.8 %), North America (0.3 %), and Europe (0.04 %), while 38.7 % remained unidentified (Fig. 5). In human settlements, many bottles and caps originated locally (Fig. 5A). Small percentages of items from Asia (0.5 %) appeared in El Salvador, Panamá, and Chile, while North American items (0.4 %) were found in Guatemala, El Salvador, Panamá, and Chile.

On continental beaches in México, Guatemala, and southern countries (Colombia, Ecuador, Perú, and Chile), most beverage items originated from within the same country (Fig. 5B). In contrast, in Central American countries (El Salvador, Nicaragua, Costa Rica, and Panamá), the percentages of locally originated items were substantially lower, showing a higher proportion from external sources (Fig. 5B). Items originating from Asia were more abundant on continental beaches in Costa Rica, El Salvador, Panamá, and Perú. North American items occurred in México and Central American countries (El Salvador, Guatemala, Costa Rica, and Panamá) (Fig. 5B).

On island beaches, 42.4 % of beverage items originated within Latin American countries, but these locations also had the highest percentage of items from Asia (12.0 %), along with smaller proportions from Europe (0.5 %) and North America (0.2 %) (Fig. 5C). Panamá showed the greatest source diversity, with items from at least six countries across

Table 2
Total number of items (n) and percentages of each category of plastic beverage bottles (loose caps, bottles with caps, and bottles without caps) collected on streets of human settlements, continental beaches, and island beaches in the study area. Highest values per column are shown in bold. Countries where no samplings were conducted in human settlements or on island beaches are marked with "-". North America: México. Central America: Guatemala, El Salvador, Nicaragua, Costa Rica and Panamá. South America: Colombia, Ecuador, Perú and Chile.

Countries in the study area	38 human settlements				92 continental beaches				15 island beaches			
	n	Loose caps (%)	Bottles with caps (%)	Bottles without caps (%)	n	Loose caps (%)	Bottles with caps (%)	Bottles without caps (%)	n	Loose caps (%)	Bottles with caps (%)	Bottles without caps (%)
México	372	38.4	26.9	34.7	254	**87.0**	6.3	6.7	–	–	–	–
Guatemala	197	51.3	15.7	33.0	140	62.1	17.1	20.7	–	–	–	–
El Salvador	573	34.0	40.0	26.0	**4655**	40.2	48.8	10.9	–	–	–	–
Nicaragua	–	–	–	–	1366	42.0	24.9	**33.1**	–	–	–	–
Costa Rica	502	24.3	**49.6**	26.1	4426	59.0	37.3	3.7	–	–	–	–
Panamá	638	16.9	46.2	**36.8**	1491	34.8	**55.2**	10.0	**292**	30.8	60.6	**8.6**
Colombia	–	–	–	–	1452	50.8	27.0	22.2	58	8.6	84.5	6.9
Ecuador	**1179**	**58.8**	23.7	17.5	2993	72.1	19.4	8.5	289	2.4	**95.5**	2.1
Perú	372	38.7	36.6	24.7	2887	62.4	22.5	15.1	–	–	–	–
Chile	612	52.1	30.4	17.5	2023	65.2	20.0	14.9	147	**44.2**	51.0	4.8
Total/%	4445	**41.1**	33.9	25.1	21,687	**54.9**	33.0	12.1	786	21.2	**73.4**	5.3

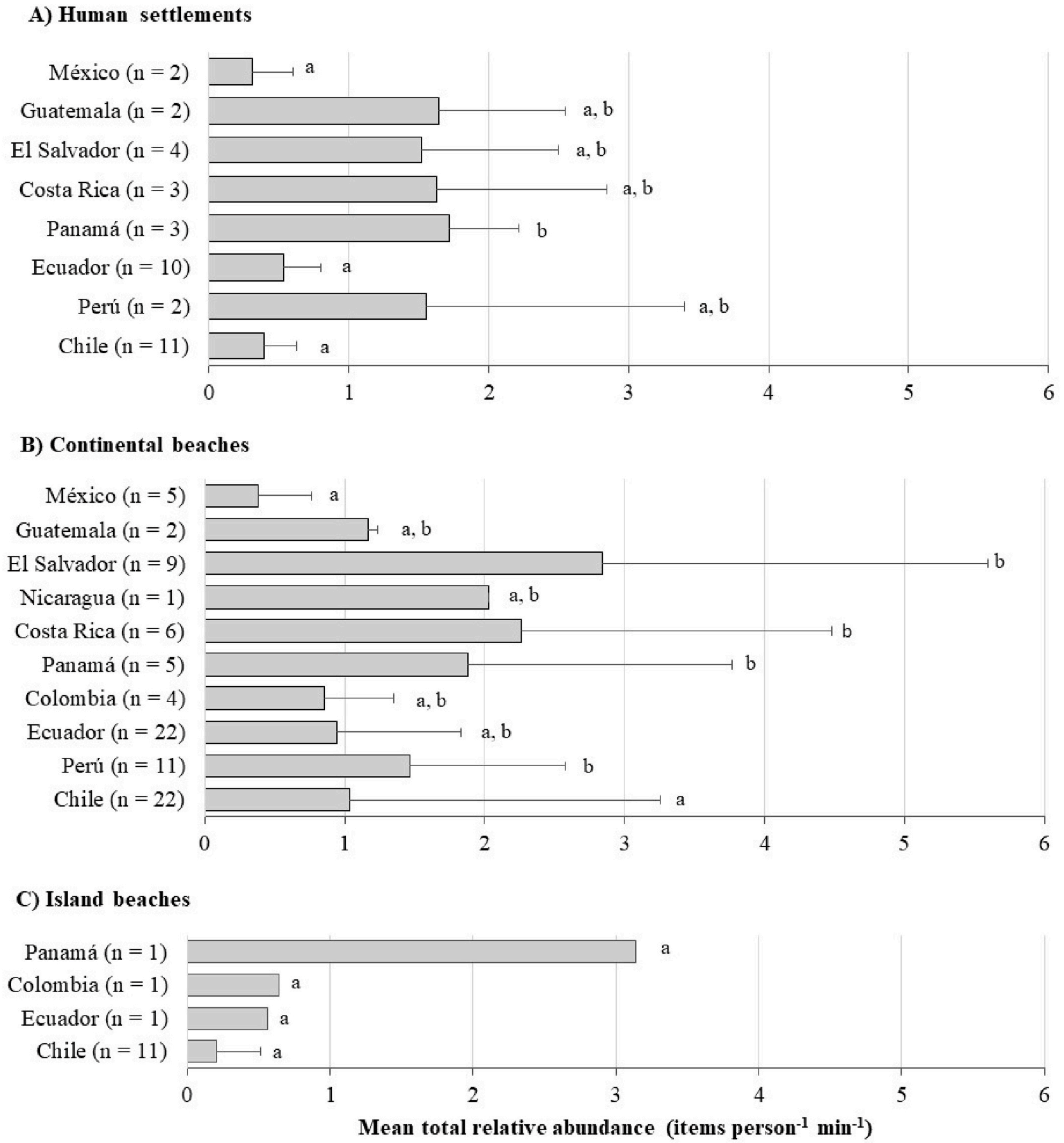

Fig. 4. Mean (grey bars) ± standard deviation (lines) of total relative abundances of beverage bottle items in human settlements (A), continental beaches (B), and island beaches (C) in the study area. North America: México; Central America: Guatemala, El Salvador, Nicaragua, Costa Rica, and Panamá; South America: Colombia, Ecuador, Perú, and Chile. The (n) values for each country correspond to the number of sampling sites. Bars sharing a common letter are not significantly different (p > 0.05). No human settlement was sampled in Colombia and Nicaragua.

Latin America, Asia, and North America (Fig. 5C). Island beaches in Chile (Rapa Nui) and Ecuador (Galápagos Islands) had very low percentages of locally originated items and substantial proportions from Asia (Fig. 5C), highlighting their exposure to bottles originating from outside the region.

There was a significant association between the countries of origin of the bottles and the types of environments (χ^2 = 2168, df = 30, V = 0.265, C = 0.351; all $p < 0.001$), subregions (χ^2 = 15088, df = 30, V = 0.698, C = 0.703; $p < 0.001$), and sampling countries (χ^2 = 50517, df = 135, V = 0.602, C = 0.875; $p < 0.001$). The strength of these associations, as indicated by the V and C coefficients, was moderate for environments and strong for subregions and sampling countries. These results indicate that the distribution of bottle origins is not random but geographically structured, with certain countries of origin

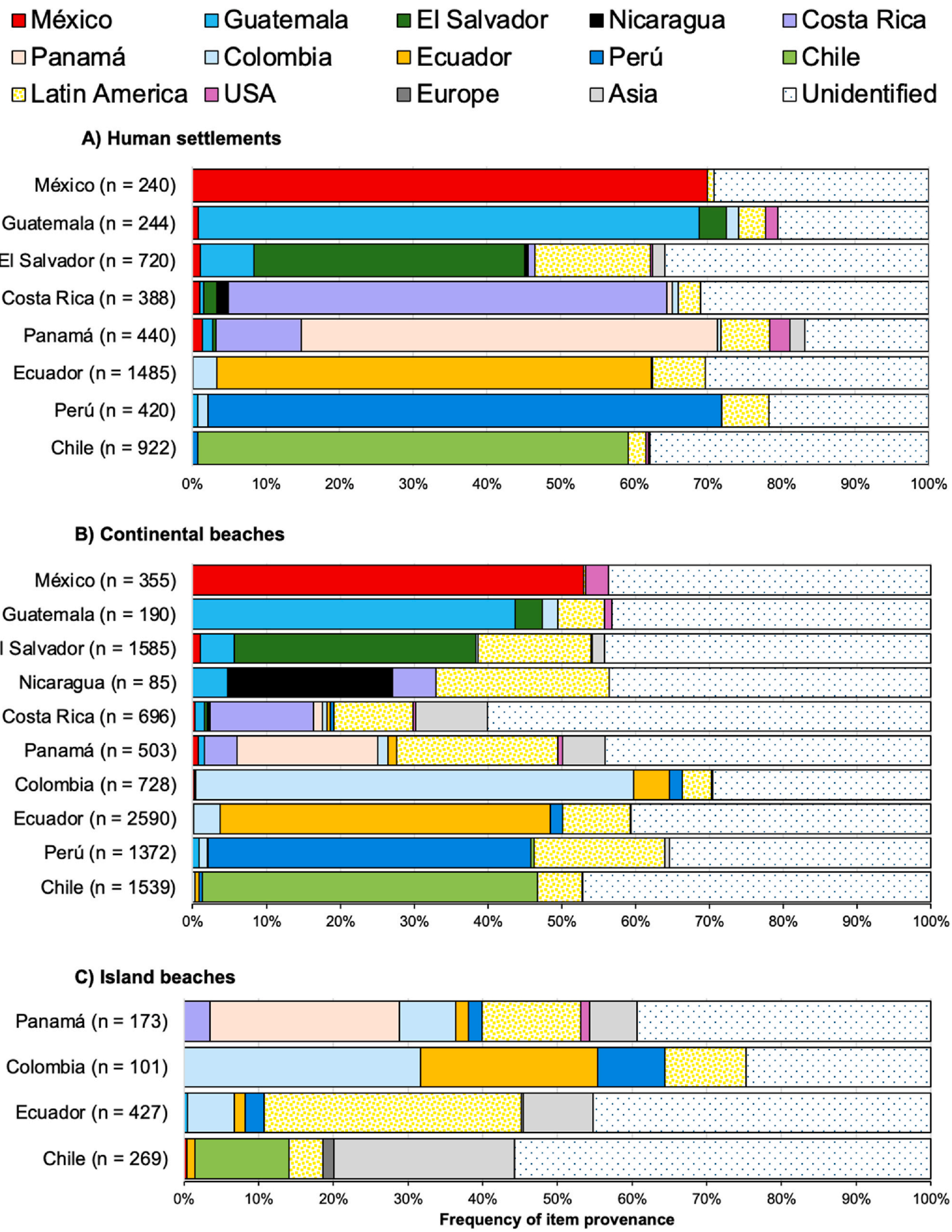

Fig. 5. Provenance of plastic beverage bottles and loose caps collected in human settlements (A), continental beaches (B), and island beaches (C) in the Latin American Pacific region. North America: México; Central America: Guatemala, El Salvador, Nicaragua, Costa Rica, and Panamá; South America: Colombia, Ecuador, Perú, and Chile. The (n) values indicate the total number of items collected at sampling sites in each country. Bar colors correspond to the identified country or region of origin, based on product information. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

predominating in specific environments, subregions, and sampling countries. This likely reflects consumption habits, waste management practices, and oceanographic transport processes influencing their distribution.

PERMANOVA results indicated significant differences in the composition of beverage bottle origins among subregions ($F = 4.02$, $R^2 = 0.30$, $p = 0.001$) and countries ($F = 3.86$, $R^2 = 0.91$, $p = 0.001$), highlighting strong geographic variation. The PCoA of item origins revealed distinct multivariate patterns, although the cumulative contribution of the first and second axes explained only a moderate portion of the total variation (Fig. 6). A clear separation was observed between Central American and South American subregions (Fig. 6A). The ellipses indicated greater internal consistency within Central America, while South American sites showed more variability in composition. In the PCoA by type of environment, sites in México appeared somewhat isolated, but overall, the ellipses for the different environments overlapped, suggesting compositional similarities across environments and national borders (Fig. 6B). In both PCoA plots, the distance between points reflects the degree of similarity in the composition of item origins among sites.

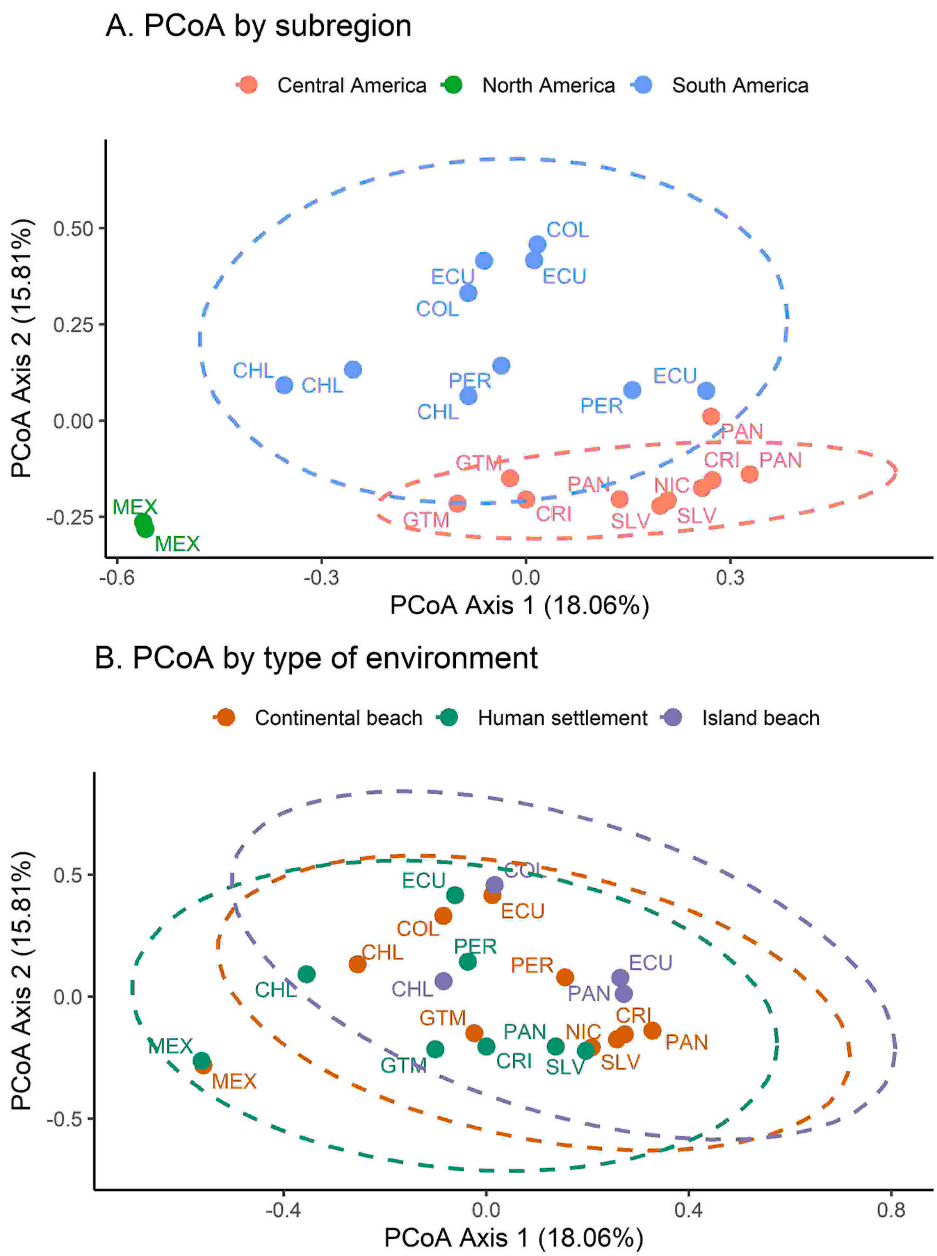

Fig. 6. **A.** Principal Coordinates Analysis (PCoA) based on Bray–Curtis dissimilarity, showing differences in the composition of countries of origin of plastic bottles across subregions. **B.** PCoA of the same dataset, grouped by type of environment (continental beach, human settlement, island beach). PCoA is an ordination method that reduces the dimensionality of multivariate data, allowing visualization of patterns of similarity or dissimilarity between samples (see subsection 2.3 for further details). In both figures, each point represents the average composition of bottle origins per site. The distance between points reflects the degree of similarity in composition: closer points indicate more similar source profiles. Ellipses represent the multivariate dispersion (95 % confidence intervals) for each group (subregion or type of environment). These ellipses illustrate the variability or spread of the samples in the multivariate space, showing the range within which most sites are expected to fall for each group. However, they do not imply formal statistical clustering. Labels show ISO country codes for each sampling site: México (MEX), Guatemala (GTM), El Salvador (SLV), Nicaragua (NIC), Costa Rica (CRI), Panamá (PAN), Colombia (COL), Ecuador (ECU), Perú (PER), and Chile (CHL). The percentages on the axes indicate the proportion of variance explained by each axis. The cumulative contribution of the first and second axes is 33.87 %, reflecting the proportion of variation in the dataset represented in the 2D plot.

3.3. Characteristics of plastic beverage bottle items

In human settlements, most countries had high percentages (51.7 %–77.8 %) of items with low wear, except El Salvador (38.5 %) (Fig. 7A). Continental beaches in Central America (El Salvador, Nicaragua, Costa Rica, and Panamá) had more medium and high-wear items compared to their human settlements, with El Salvador having the highest proportions (Fig. 7B). In Guatemala, continental beaches showed fewer low-wear items (50.0 %) compared to its human settlements. Continental beaches in México, Ecuador, Perú, and Chile had similar wear patterns as their respective human settlements (Fig. 7B). Island beaches in Panamá, Ecuador, and Chile had predominantly medium- and high-wear items (63.6 %–70.7 %), while in Colombia's island beaches, low-wear items dominated (63.1 %) (Fig. 7C). Overall, wear levels tended to be lower in human settlements and higher on island and continental beaches, especially in Central American countries.

Fifty-three percent of collected beverage bottles and loose caps had visible dates. The oldest items were a Powerade® bottle from 2001 (23 years old, continental beach, Perú) and a Coca-Cola® bottle from 2002 (22 years old, island beach, Chile). The newest items were produced in December 2023 and were collected that same month from human settlements and continental beaches across seven countries. Bottles <1 year old were predominant (63.8 %–98.2 %) in all human settlements, consistent with low wear levels (Fig. 7A and D). In El Salvador's human settlements, bottles aged 1–3.9 years corresponded closely to the observed medium and high wear levels in the same country (Fig. 7A and D).

Items <1 year old predominated on continental beaches in most countries, except Panamá and Costa Rica, where over 50 % were older (Fig. 7E). Notably, all dated items on Guatemala's continental beaches

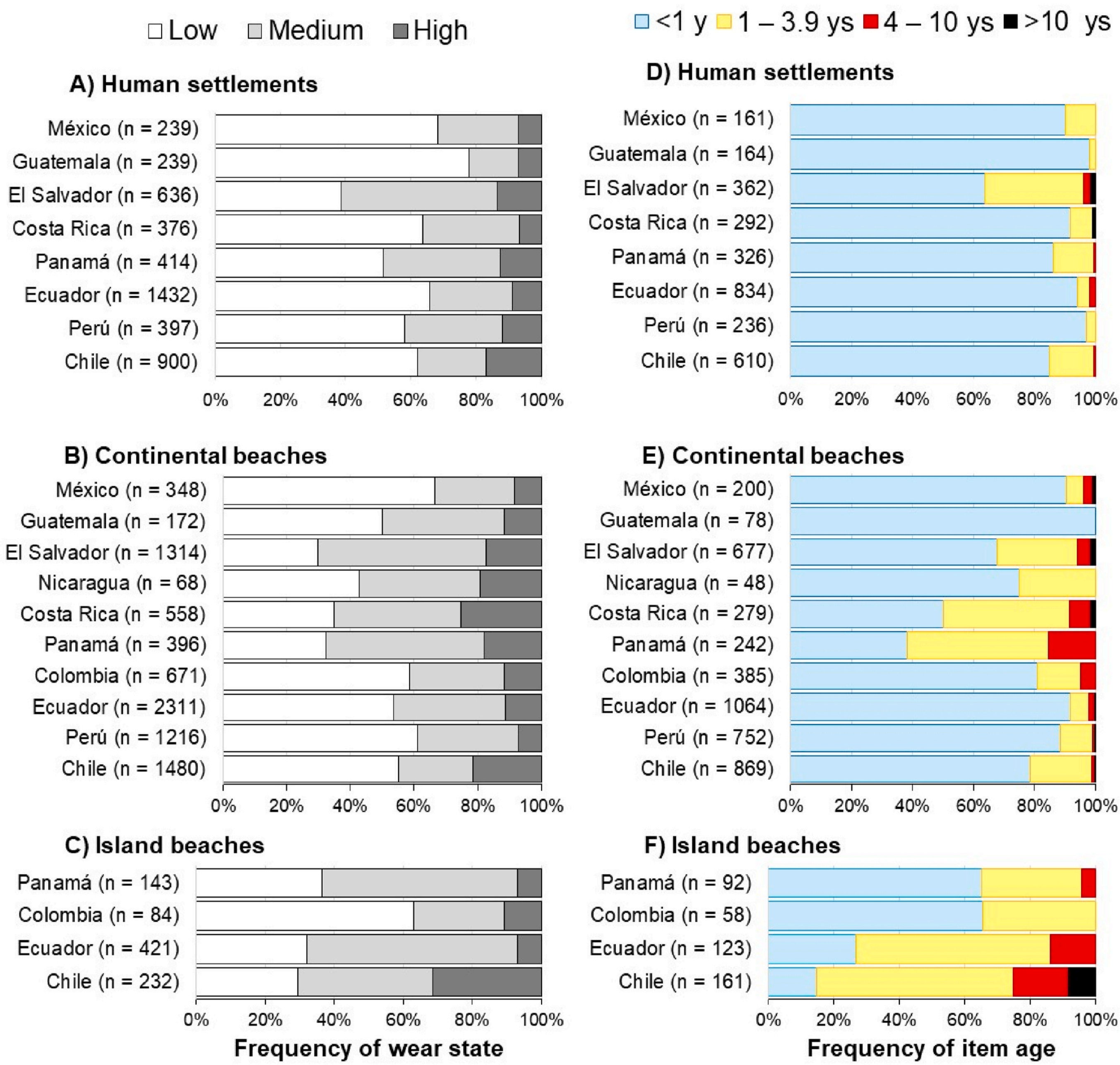

Fig. 7. Wear state (A, B, C) and age in years (D, E, F) of plastic beverage bottles and loose caps collected in human settlements, on continental and island beaches in each country of the study area. North America: México. Central America: Guatemala, El Salvador, Nicaragua, Costa Rica and Panamá. South America: Colombia, Ecuador, Perú and Chile. The n values correspond to the number of items collected in each country that could be assigned to wear and age categories.

were <1 year old. The highest proportions of very old bottles (>10 years) appeared on continental beaches in México, El Salvador, and Costa Rica (Fig. 7E). Island beaches in Chile and Ecuador had the highest percentages of older bottles (4–10 and > 10 years; Fig. 7F). Panamá's island beaches also had bottles aged 4–10 years, whereas Colombia's island beaches contained only bottles in the <1 year and 1–3.9 years categories (Fig. 7F). These findings point to a spatial pattern in item age, with newer bottles prevailing in human settlements and older items more frequent on beaches, particularly island beaches.

Epibionts were recorded on 8.8 % of the bottles found on the beaches (Fig. 8). The highest percentages of items with epibionts were found on the continental beaches of Central American countries (El Salvador: 11.8 %; Costa Rica: 19.5 %; Panamá: 19.7 %), while Chile and Perú had the lowest percentages (0.6 %–2.9 %) (Fig. 8A). The highest percentages of items with epibionts on island beaches were recorded in Chile and Panamá, with 25.0 % and 24.5 %, respectively, whereas in Ecuador and Colombia only 16.4 % and 1.2 % of the items had epibionts (Fig. 8B). This pattern suggests greater epibiont presence in areas more exposed to ocean current influence.

The GLM revealed that both wear state and age of bottles found on beaches significantly predicted the presence of epibionts. Compared to bottles with low wear (baseline probability of 2.6 %, Estimate = −3.65, SE = 0.09), medium-wear bottles showed a probability of 9.4 % (Estimate = 1.57, SE = 0.11), and high-wear bottles reached 16.8 % (Estimate = 2.17, SE = 0.12), all highly significant ($p < 0.001$). Similarly, relative to items <1 year old (3.8 %), bottles aged 1–3.9 years and 4–10 years had increased probabilities of hosting epibionts, 11.5 % and 16.4 %, respectively ($p < 0.001$), while those over 10 years reached 13.3 %. These findings support the hypothesis that both greater wear and older age, as indicators of prolonged exposure to the marine environment, are associated with a higher likelihood of epibiont colonization.

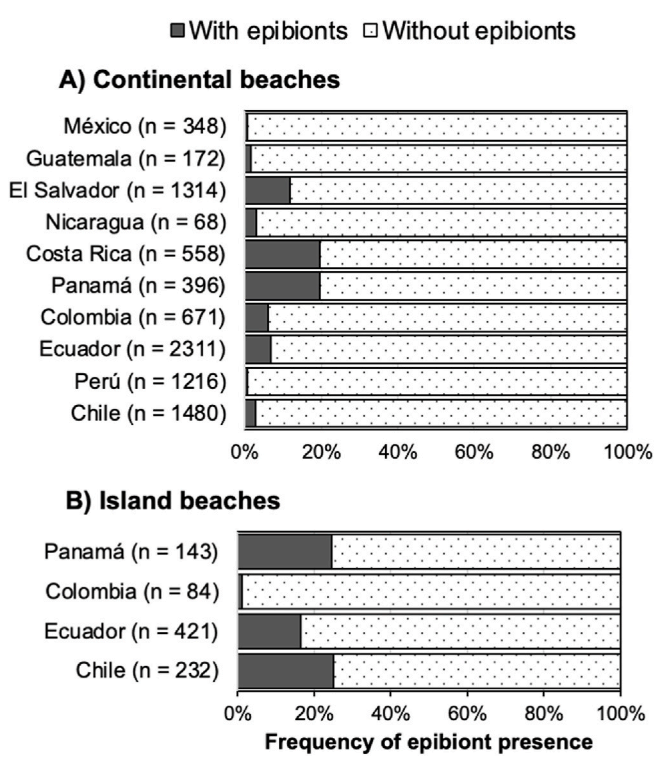

Fig. 8. Presence of epibionts on plastic bottles and loose caps collected on continental (A) and island (B) beaches in each country of the study area. North America: México. Central America: Guatemala, El Salvador, Nicaragua, Costa Rica and Panamá. South America: Colombia, Ecuador, Perú and Chile. The n values correspond to the number of items collected in each country.

3.4. *Producers of plastic beverage bottles*

A total of 356 brands from 253 companies were identified, with The Coca-Cola Company being the most common across all types of environments, followed by Aje Group and PepsiCo (Table 3). A significant moderate association was found between company frequencies and types of environments ($\chi^2 = 2201$, df = 328, V = 0.371, C = 0.465; all with $p = 0.001$). Soft drink containers (29.0 %), sports and energy drinks (15.4 %), and drinking water (14.5 %) were the most common (Table 4), reflecting regional beverage preferences and consumption trends. Most bottles (78.0 %) were of individual sizes (0.25–0.9 L), which are more portable and likely to be consumed on the go, increasing the likelihood of mismanagement and leakage into the environment.

4. Discussion

4.1. *Abundance and distribution of plastic beverage bottles*

Loose caps were the most abundant items in human settlements and on continental beaches, likely due to their small size and the common practice of removing and throwing away caps during or right after consumption, which facilitates their accumulation at specific places and subsequent dispersal (Ryan et al., 2020, 2024a). In contrast, bottles with caps dominated island beaches, likely eased by their greater buoyancy, which facilitates long-range transport by ocean currents (Ryan and Perold, 2021; Ryan, 2023). Bottles without caps were the least frequent overall, possibly because they sink or become buried more easily (Rech et al., 2014). These patterns suggest that loose caps often remain near their source (e.g., human settlements), while bottles with caps are more likely to reach remote locations such as oceanic islands, including uninhabited ones.

Our results show that Central American countries (Guatemala, El Salvador, Costa Rica, and Panamá) had the highest relative abundances of plastic beverage items across all studied environments. This pattern correlated positively with coastal population density, which was also

Table 3
List of the top 15 beverage-brand-owning companies with the highest relative frequencies among plastic bottles and loose caps collected in human settlements, continental beaches, and island beaches in the Latin American Pacific region. The (n) values represent the total number of items recorded in each environment.

Companies identified	Relative frequency (%)		
	Human settlement (n = 4859)	Continental beach (n = 9643)	Island beach (n = 970)
The Coca-Cola Company	29.3	25.8	16.9
PepsiCo	14.0	7.6	5.5
Aje Group	8.5	11.3	16.2
Compañía Cervecerías Unidas	3.6	2.0	1.8
Nongfu Spring	0.0	0.1	4.1
Industries San Miguel	1.9	1.1	0.1
Embotelladora La Cascada	1.9	2.2	0.0
Azende Corporation	1.8	0.2	2.1
Quala	1.6	0.9	0.6
Central America Bottling Corporation	1.5	1.4	0.0
Postobón	0.6	1.5	0.9
Bavaria & Cia	0.3	0.7	0.6
Anheuser-Busch InBev	1.0	1.2	0.6
Hangzhou Dingjin Food	0.0	0.1	0.9
Dongpeng Beverage	0.0	0.3	0.7
Other companies	19.8	18.4	18.8
Unidentified	14.2	25.0	30.2
Sum	100.0	100.0	100.0

Table 4
Total number of items (n) and percentages of each category of beverage type contained in the bottles and loose caps found in human settlements, on continental beaches, and island beaches in 10 countries in the Latin American Pacific region.

Drink type	Total (n)	Total (%)	% Human settlement (n = 4859)	% Continental beach (n = 9643)	% Island beach (n = 970)
Soft drink	4480	29.0	30.5	29.3	17.4
Sports & Energy Drinks	2376	15.4	19.8	12.7	19.8
Drinking water	2250	14.5	16.8	13.2	16.5
Nectar & juice	1070	6.9	7.2	7.1	3
Alcoholic drinks	215	1.4	2.2	1.1	0.2
Flavored water	101	0.7	1.1	0.5	0
Infusion drinks	96	0.6	0.9	0.5	0.2
Oral rehydration solution	76	0.5	0.7	0.4	0.3
Dairy drink	93	0.6	0.5	0.6	0.6
Non-alcoholic malt drink	95	0.6	0.3	0.8	0.6
Unclassified	4620	29.9	20	33.7	41.3
Total n/%	15472	100	**31**	**62**	**6**

highest in these countries, and is likely enhanced by high bottled beverage consumption driven by their tropical climate. For instance, Zapata (2021) found that a 1 °C temperature increase raised bottled water consumption in Ecuador, particularly in rural areas with unreliable tap water. Kovalskys et al. (2019) reported higher consumption of ready-to-drink sugary beverages in Central America (e.g., Costa Rica) compared to South America (e.g., Colombia, Ecuador, Perú, and Chile). Singh et al. (2015) also highlighted that Central American countries have among the highest consumption rates of bottled beverages compared to South American countries. Additionally, bottled water imports in Central America have substantially increased, especially in Guatemala, Panamá, and Costa Rica (CentralAmericaData, 2022).

Limited access to potable water and poor waste management further contribute to plastic pollution. For instance, Central American countries generate large amounts of plastic waste annually in Pacific coastal population, with 11 %–82 % of this waste being mismanaged (Brooks et al., 2020; Table S2). These findings align with litter abundances reported by De Veer et al. (2023) on beaches in these same countries, where plastics accounted for 60 %–90 % of beach litter, likely due to rivers and marine currents playing an important role in transporting plastic bottles to and along coastal areas. These patterns highlight unmet needs in drinkable water access and waste management that warrant urgent policy attention to reduce plastic leakage at its source.

Our data unveil that among South American countries, Perú has the highest pollution levels, despite having a coastal population density similar to México. This contrast likely reflects poorer waste management in Perú, where 58 % of plastic waste is mismanaged and 62 % ends up in open dumps (Brooks et al., 2020; Arteaga et al., 2023). In contrast, México and Chile (both with lower population densities) showed the lowest item abundances, supported by higher waste collection rates (93 %–95 %) and lower mismanagement levels (23 % in México, 16 % in Chile; Brooks et al., 2020). These two countries count with Extended Producer Responsibility programs, education efforts, and plastic recovery initiatives (Monteverde, 2020; Gómez and Martínez-Moscoso, 2023; Thiel et al., 2023), thus offering replicable models that, through regional collaboration, could strengthen waste management and reduce plastic leakage in neighboring countries.

The lowest item abundances were recorded on Chilean and Ecuadorian island beaches, while the highest occurred on a coastal island in Panamá, suggesting a link between abundance and distance from the continent (Hidalgo-Ruz et al., 2018). High accumulation in Panamá may be driven by coastal tourism, shipping, and wind exposure. Windward beaches on remote Chilean and Ecuadorian islands (e.g., Rapa Nui and Galápagos) showed more plastic bottles than leeward ones, including on uninhabited coasts (Muñoz-Pérez et al., 2023; Benito-Kaesbach et al., 2024). These remote natural areas face growing impacts from floating plastic bottles, calling for urgent regional action to protect their ecosystems.

4.2. Geographic provenance and distribution of plastic beverage bottle items

Over 50 % of plastic beverage items found in human settlements and on continental beaches originated locally or in other Latin American countries, indicating primarily local pollution. Similar trends have been observed on beaches worldwide (Topçu et al., 2013; Smith et al., 2018; Ryan, 2020; Bui et al., 2024). In human settlements, most bottles and caps originated from the same or neighboring Latin American countries, with some imported items from the U.S. (found in streets in Panamá and Guatemala) and Asia (e.g., one aloe vera drink identified in El Salvador, Panamá, and Chile). The availability of these products was confirmed through online searches of local supermarkets. Their presence reflects regional trade and suggests that litter is likely transported from urban areas to nearby beaches (Ryan, 2020).

Continental beaches in South American countries (Colombia, Ecuador, Perú, Chile) and in México showed similar patterns, with most bottles originating locally, likely reflecting inputs from nearby large coastal cities (Brooks et al., 2020) and seasonal beach tourism (Honorato-Zimmer et al., 2024). Increased tourist presence on beaches is often linked to higher litter abundance (Garcés-Ordóñez et al., 2020b; Salazar et al., 2022; Jachimowicz et al., 2024). In contrast, Central American beaches, where the highest accumulation of bottles and loose caps was observed, had lower proportions of locally sourced items and greater diversity, including bottles from neighboring countries and Asia. This suggests that some bottles are lost from Central American countries to the sea (e.g., via river discharges) and redistributed by coastal and ocean currents within the subregion, along with bottles carried by coastal and ocean currents from more distant locations (Honorato-Zimmer et al., 2024).

A higher proportion of bottles and caps from outside Latin America (especially from Asia, mainly China) was recorded on island beaches, particularly in Rapa Nui and Guafo (Chile) and the Galápagos (Ecuador), where many of these products are not sold locally. This pattern suggests illegal dumping from ships navigating the Pacific, with items later transported by ocean currents (van Sebille et al., 2019). Similar evidence has been reported on other remote islands in the South Pacific (Ryan, 2023; Muñoz-Pérez et al., 2023; Benito-Kaesbach et al., 2024) and in other regions (Smith et al., 2018; Ryan et al., 2019, 2024b; Savage et al., 2024), thus pointing to the vulnerability of these island ecosystems to pollution from offshore litter sources.

Most bottles found on coastal islands like Iguana (Panamá) and Gorgona (Colombia) came from local producers, likely due to their relative proximity (<100 km) to continental sources. However, these areas remain vulnerable to illegal dumping after maritime traffic to and from the Panama Canal or large Colombian (e.g., Buenaventura) ports. Notably, sources could not be identified for many of the bottles (25 %–56 %) found on these islands. Managing locally generated plastic waste will not only improve conditions within each country but also help reduce the export of plastics to the broader region and beyond via global trade or ocean currents, as illustrated by plastic items from Chile and Perú found on beaches in Vietnam (Bui et al., 2024), New South Wales, Australia (Smith et al., 2018), and South Africa (Ryan et al., 2021).

4.3. Characteristics of plastic beverage items and transport dynamics in the East Pacific

The hypothesis that bottles from various sources around the Pacific Ocean are transported by ocean currents and deposited on Central American beaches is supported by the rather high percentage of items with attached epibionts (11.8 %–19.7 %). This indicates that the bottles had been in the marine environment for enough time to be colonized during their journey (Bui et al., 2024; Ryan et al., 2019, 2024b). The colonization of floating plastic items, such as bottles and loose caps, may be favored by nutrient availability and low densities of organisms feeding on epibionts in the carrying surface waters (Rech et al., 2021; Pinochet et al., 2024). Consequently, the presence of epibionts on items found on beaches is commonly associated with litter transport by ocean currents (Kiessling et al., 2015; Rech et al., 2014; Smith et al., 2018; Bui et al., 2024). Also, many bottles found in Central American countries showed medium to high wear and significantly older ages, factors that increase the likelihood of epibiont presence, further confirming their prolonged exposure to the marine environment (Duhec et al., 2015; Ryan et al., 2024a).

In the investigated human settlements, most bottles and loose caps were in good condition (i.e., very early state of degradation), suggesting recent consumption and disposal. In contrast, continental and especially island beaches showed higher proportions of items with medium and high wear. While marine transport may explain some of this (Duhec et al., 2015; Smith et al., 2018; Ryan et al., 2024a), it also indicates that many items remained on beaches for extended periods of time. During that time, environmental factors, such as intense solar radiation in tropical areas, abrasion by rocks or sand, interactions among litter items, and contact with fauna (e.g., bite marks), contribute to wear and the formation of smaller plastic fragments (Garcés-Ordóñez et al., 2020a; Dimassi et al., 2022; Bui et al., 2024).

The age distribution of bottles and caps (with most bottles in Panamá and Colombia under one year old) aligns with the high proportion of low-wear items, indicating recent littering. Likely sources include direct deposition (e.g., tourism), river discharges, or nearby cities (Ryan and Perold, 2021; Garcés-Ordóñez et al., 2020a, 2023). Items aged 1–3.9 years were the next most common across all environments. Their higher proportion on beaches may reflect longer accumulation due to less frequent cleaning compared to human settlements, where streets are cleaned more regularly (Brooks et al., 2020; Ryan, 2020; CRA and Minvivienda, 2022). Some bottles transported by rivers from inland human settlements may be temporarily retained and later mobilized during high flows caused by heavy rainfall (Newbould et al., 2021; Garcés-Ordóñez et al., 2023).

Older bottles (4–10 years and >10 years) were more common on island beaches, especially from Chile and Ecuador, but a minority in human settlements and on continental beaches. On uninhabited islands like Guafo (Chile) and Santiago Island in the Galápagos (Ecuador), these items likely arrived via ocean currents. Their lower presence in human settlements reflects more frequent cleaning, though results might differ in suburbs, alleys, or vacant lots. In contrast, beaches, particularly the remote ones, retain plastics longer and act as sinks (Ryan et al., 2019; Ryan, 2023). Notably, some bottles, like a 23-year-old Powerade® and a 22-year-old Coca-Cola® bottles, illustrate the long persistence of plastic in the marine environment. These bottles are older than those recorded on other island beaches worldwide (Ryan et al., 2019; Ryan, 2020; Savage et al., 2024; Garcés-Ordóñez et al., 2025).

4.4. Producers, study relevance, and management recommendations

Our findings not only describe the composition and sources of plastic bottle pollution but also offer actionable insights to inform waste management strategies and environmental policies across the region. The Coca-Cola Company, followed by AJE Group and PepsiCo, dominated the branded items found in our study (Statista, 2024), reflecting broader global patterns (Smith et al., 2018; Ryan et al., 2019; Cowger et al., 2024; Savage et al., 2024). The high proportion of small, single-use containers (0.25–0.9 L) for soft drinks, energy drinks, and drinking water suggests a strong link between high consumption, poor disposal practices, and increased plastic waste. Targeting this small packaging in waste management strategies could help reduce plastic pollution locally and globally (Clayton, 2021; Savage et al., 2024; Garcés-Ordóñez et al., 2025; Krawczyk et al., 2025).

Our study provides a citizen science-based methodological reference for assessing and collecting high-quality data on plastic beverage bottle pollution, which is replicable worldwide. Data reliability is ensured through photographic evidence, a predefined methodological guide (Científicos de la Basura, 2024), local leader training, and continuous communication, which guarantee traceability, trust, and data quality (Dittmann et al., 2023; Thiel et al., 2023). This is the first large-scale regional study to assess plastic beverage bottle pollution across urban areas, continental beaches, and island coasts in the Latin American Pacific, directly linking items to their sources. Consequently, it provides critical data on abundance, sizes, types, producer, and origins to support waste management strategies for urban and marine (e.g., fishing and shipping) pollution sources and reinforces international regulations, such as the MARPOL Convention, against waste disposal from ships (Ryan et al., 2024a, 2024b), which threaten ecosystems, especially on islands.

By identifying key beverage types, bottle sizes, and responsible companies with potential liability under extended producer responsibility laws (de Miguel et al., 2021), this study addresses coastal and marine plastic pollution. For instance, most bottles on continental beaches are produced by local manufacturers or multinational companies, while island beaches face significant external contributions from ships. Switching to standardized returnable packaging for individual-sized drinks, with cross-border return options, would greatly reduce environmental impacts while fostering sustainability and regional cooperation. Placing returnable bottle collection points on beaches and stricter enforcement of environmental laws would also help prevent further pollution. This approach could be supported through regional cash-back policies (Schuyler et al., 2018) and corporate social responsibility initiatives (Cezarino et al., 2022). The implementation of tethered caps (as in EU Directive, 2019/904), ongoing awareness jointly with cleanup efforts, and improved waste management, especially in coastal communities, would help reduce plastic pollution on beaches and in urban areas.

Finally, it is important to note that human behavior is crucial in reducing plastic pollution, but it requires the possibility to choose. When drinking water is only available in single-use plastic bottles, consumers have no alternative, limiting their ability to act sustainably (Clayton, 2021; Krawczyk et al., 2025). Offering reusable and environmentally friendly options is essential to enable responsible choices and drive meaningful change.

5. Conclusions

This is the first regional-scale study on plastic beverage bottles and loose caps across human settlements and beaches in 10 Latin American Pacific countries. Human settlements and continental beaches in Central America show the highest plastic bottle and cap abundance, likely due to poor waste management and ocean currents bringing items from other countries (both neighboring and distant). Most plastic bottles and loose caps polluting continental beaches have a local origin and are produced by large multinational companies operating in the region, such as The Coca-Cola Company, Aje Group, and PepsiCo, with island beaches containing a higher proportion of bottles and loose caps from Asia, likely due to dumping from ships and transport by ocean currents.

Given the widespread presence of mostly locally sourced single-use plastic bottles, the primary recommendation is to replace them with returnable bottles standardized across the region. This measure would facilitate bottle returns across countries and among transnational companies, promoting sustainability and collaboration. It should be supported by cash-back policies and corporate social responsibility by the involved companies. Promoting reusable containers and producer accountability, along with strong international actions like the UN Global Plastic Treaty, are essential strategies to reduce plastic pollution and protect coastal ecosystems. This study provides a methodological approach based on citizen science to collect valuable data on plastic beverage bottle pollution and evaluate the effectiveness of future policy measures, which can be replicated in other regions worldwide.

Future studies in the region could examine seasonal climatic variations, river discharges, and tourism activity to better understand the dynamics of plastic bottles and loose caps pollution. They could also integrate oceanographic modelling to track transport pathways and identify distant pollution sources. Additionally, this research could be expanded to the Caribbean Sea and Atlantic regions. Such efforts would provide a more comprehensive understanding of regional plastic pollution and support the development of mitigation strategies all across Latin American and Caribbean countries.

CRediT authorship contribution statement

Ostin Garcés-Ordóñez: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mauricio Ergas:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Data curation, Conceptualization. **Jostein Baeza-Álvarez:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Daniela Honorato-Zimmer:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Ninoshka López-Xalín:** Writing – review & editing, Validation, Methodology, Conceptualization. **Nelson Vásquez:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Miquel Canals:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Conceptualization. **Diamela De Veer:** Writing – review & editing, Validation, Conceptualization. **María Elisa Aguilera:** Writing – review & editing, Supervision, Resources, Investigation. **Illiana Arias:** Writing – review & editing, Supervision, Resources, Investigation. **Solange Bolaños:** Writing – review & editing, Supervision, Resources, Investigation. **Daphne Aguilar Fallas:** Writing – review & editing, Supervision, Resources, Investigation. **Mary Cuenca:** Writing – review & editing, Supervision, Resources, Investigation. **Andrea Carolina De La Torre León:** Writing – review & editing, Supervision, Resources, Investigation. **Edith Díaz Córdoba:** Writing – review & editing, Supervision, Resources, Investigation. **María de los Ángeles Gallardo:** Writing – review & editing, Supervision, Resources, Investigation. **Sebastián Hernández:** Writing – review & editing, Supervision, Resources, Investigation. **Lara Marcus:** Writing – review & editing, Supervision, Resources, Investigation. **Juan Manuel Muñoz-Araya:** Writing – review & editing, Supervision, Resources, Investigation. **Diego Joaquin Pérez-Venegas:** Writing – review & editing, Supervision, Resources, Investigation. **Osmel Alberto Sánchez:** Writing – review & editing, Supervision, Resources, Investigation. **Dominique Segura Estévez:** Writing – review & editing, Supervision, Resources, Investigation. **Deysi Valdivia-Chavez:** Writing – review & editing, Supervision, Resources, Investigation. **José Vélez Tacuri:** Writing – review & editing, Supervision, Resources, Investigation. **Marvin Xajil-Sabán:** Writing – review & editing, Supervision, Resources, Investigation. **Estelle Praet:** Writing – review & editing, Supervision, Resources, Investigation. **Ricardo Zambrano:** Writing – review & editing, Supervision, Resources, Investigation. **Rodrigo Zárate:** Writing – review & editing, Supervision, Resources, Investigation. **Martin Thiel:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.146234.

Data availability

I have shared the link to our data in the Acknowledgements section.

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