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# A taxonomy-inspired hierarchical classification of plastic litter

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## ABSTRACT

Plastic pollution represents one of the most pervasive and persistent material signatures of the Anthropocene, yet its scientific characterization remains fragmented across material-, size-, and compartment-based classification schemes. Although operationally effective, these approaches fail to capture plastics as structured anthropogenic entities embedded within coupled human–Earth systems. Here, we introduce the Taxonomy-inspired Hierarchical Classification of Plastic Litter (THCPL), a hierarchical and integrative classificatory framework that organizes plastic litter from broad material context to specific marketed products, explicitly linking material composition, functional form, industrial origin, market identity, and environmental persistence. THCPL is structured across six taxonomic levels (Phylum, Class, Order, Family, Genus, and Species) using biological taxonomy strictly as a structural analogy, while maintaining clear ontological and epistemological boundaries between living systems and industrial artifacts. Grounded in Earth system science and Anthropocene research, the framework is designed to preserve scalability, traceability, and analytical coherence under real-world field conditions, including fragmentation and weathering. The operational feasibility and transferability of THCPL are demonstrated through its application to standardized coastal litter datasets from six countries (Brazil, Colombia, Italy, Morocco, Panama, and Spain), encompassing 912 plastic items across diverse coastal typologies and socio-environmental contexts. Across all regions, THCPL enabled consistent hierarchical resolution, revealed high producer- and brand-level richness, and supported robust cross-regional comparison, even when fine-scale identification was constrained. Beyond classification, THCPL provides a foundational structure for quantitative analysis, enabling diversity, dominance, and functional assessments, forensic source attribution, and policy-relevant evaluation without normative assumptions. By aligning environmental observations with governance instruments such as Extended Producer Responsibility and by offering a structured framework for interpreting plastics as future technofossils, THCPL advances the integration of plastic pollution research into Earth-system monitoring, environmental governance, and Anthropocene stratigraphy.

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## 1. Introduction

Plastic pollution has emerged as one of the most pervasive and rapidly intensifying environmental problems affecting coastal and marine systems worldwide (Jambeck et al., 2015; Thompson et al., 2024). Plastics account for approximately 80–85% of all marine litter, reflecting both their extensive production and their persistence in natural environments (LI et al., 2016). Each year, between 9 and 12.4 million tonnes of plastic are estimated to enter the oceans, largely due to mismanaged land-based waste, inadequate disposal practices, and direct inputs along coastlines and waterways (Critchell et al., 2019; Rangel-Buitrago, 2025). Land-based sources contribute roughly 80% of marine plastics, including urban stormwater runoff, riverine transport from densely populated coastal regions, industrial discharges, and poorly managed landfills (Andrady et al., 2011; Sonke et al., 2025), while sea-based activities such as fishing, aquaculture, and maritime transport provide additional inputs (Rangel-Buitrago et al., 2025). Global assessments further suggest the presence of between 5 and 75 trillion plastic and microplastic particles in the oceans, with marked accumulation in subtropical gyres and deep-sea depositional environments (Eriksen et al., 2014; Zhao et al., 2025).

Because of their unprecedented production, persistence, and global distribution, plastics have emerged as one of the most distinctive and diagnostically powerful material signals of the Anthropocene, due to their global distribution, persistence, and unequivocal anthropogenic origin (Zalasiewicz et al., 2016 and 2025). Since the rapid expansion of industrial plastic production in the mid-twentieth century, plastics have been incorporated into all Earth system compartments (Rangel-Buitrago et al., 2022). Their absence from the pre-industrial geological record, combined with their exponential post-World War II proliferation, provides a clear temporal association with the proposed onset of the Anthropocene In sedimentary contexts, plastics occur as discrete particles, fibers, films, and fused materials, forming novel anthropogenic deposits with distinct textures, compositions, and structures (Russell et al., 2025). The description of plastic-derived geological materials (i.e., plastiglomerates, pyroplastics, plasticrusts, and related hybrid formations) further demonstrates the integration of plastics into sedimentary processes and the emergence of a plastic geological cycle (Rangel-Buitrago et al., 2024). Although plastics may not constitute a perfectly isochronous stratigraphic marker due to spatial variability in production, disposal, and accumulation, their widespread occurrence, resistance to degradation, and lack of a natural geogenic background support their value as robust indicators of Anthropocene strata (Corcoran et al., 2018a; Godin et al., 2024). In this sense, plastics complement other anthropogenic markers such as radionuclides and persistent pollutants, while uniquely reflecting cultural, industrial, and consumption-driven processes (Rangel-Buitrago et al., 2022). Collectively, these characteristics position plastics as defining material expressions of the Anthropocene, capturing both the scale and societal nature of human transformation of the Earth system (Corcoran et al., 2014).

Despite the growing recognition of plastic pollution as a systemic/chronic environmental problem, most existing plastic classification frameworks remain fundamentally descriptive and operational rather than integrative. Predominant approaches categorize plastics according to material composition (e.g., polymer type), size classes (macro-, meso-, micro-, and nanoplastics), or environmental compartments (shorelines, water column, seafloor, biota). While these schemes are essential for monitoring, risk assessment, and laboratory analysis, they fragment the plastic problem into isolated dimensions, limiting their capacity to capture the broader socio-environmental dynamics governing plastic production, circulation, accumulation, and persistence . Material-based classifications emphasize chemical properties and degradation behavior (Niaounakis, 2017) but provide little insight into sources, functional use, or responsibility. Size-based frameworks, although valuable for understanding biological interactions and transport processes (Rangel-Buitrago, 2025), are intrinsically reductionist and progressively lose information on the original form, function, and origin of plastic items as fragmentation advances. Similarly, compartment-based approaches focus on where plastics are found (Ocean Conservancy, 2009) rather than why they accumulate or how they are interconnected across the Earth system. From an Anthropocene perspective, this fragmentation is not simply a technical limitation, but a conceptual one, as it prevents plastics from being interpreted as coherent material entities embedded within coupled human–Earth systems.

The scale, persistence, and systemic behavior of plastic pollution therefore call for a classificatory framework capable of working explicitly at the Earth system level. Plastics move through interconnected environmental compartments (e.g., air, land, and the open ocean) exhibiting stocks and fluxes that increasingly rival those of natural geochemical cycles (Stubbins et al., 2021). As such, they function as emergent anthropogenic geomaterials whose distribution, transformation, and accumulation cannot be adequately represented through isolated material-, size-, or compartment-based schemes (Hartmann et al., 2019). The absence of a unified hierarchical structure has also contributed to persistent inconsistencies in terminology and classification criteria, impeding data comparability across regions, monitoring programs, and regulatory contexts (Bank et al., 2021). Like biological, sedimentological, or geochemical systems, plastics require a structured taxonomy that allows observations made at different levels of resolution to be systematically linked, from broad material classes to specific functional and source-related entities. Such a hierarchical framework enables integration across spatial scales, supports long-term and cross-compartment analyses, and provides the conceptual foundation necessary for the development of standardized indicators and control variables. Moreover, as plastics are increasingly framed as a "novel entity" within planetary boundary discussions (Villarubia-Gómez et al., 2024), their effective governance depends on classification systems capable of bridging scientific understanding with accountability, traceability, and policy relevance.

In response to these conceptual and methodological gaps, this paper introduces the Taxonomy-inspired Hierarchical Classification of Plastic Litter (THCPL) as a framework designed to classify plastic litter as structured anthropogenic entities within the Earth system. The use of taxonomy is adopted as a methodological and structural analogy, enabling the organization of complex, multi-dimensional information across scales, from material properties to socio-economic origin. This approach allows plastic items to be systematically linked across levels of resolution, facilitating analytical integration in a manner that is not achievable through single-dimension classification systems.

The primary objective of THCPL is to provide a coherent classificatory structure that supports cross-scale analysis, comparative assessment, and source attribution of plastic assemblages. In particular, THCPL is designed to enhance: (i) the identification of production and consumption patterns through producer- and brand-level resolution; (ii) the analysis of assemblage composition and dominance across regions; (iii) the integration of environmental observations with governance frameworks such as Extended Producer Responsibility; and (iv) the interpretation of plastics as material indicators within Anthropocene Earth system processes. Rather than replacing existing classification systems used in monitoring programs, THCPL complements them by embedding material, functional, and socio-economic dimensions within a unified hierarchical framework.

The operational applicability of THCPL is illustrated using multi-regional field datasets from Brazil, Colombia, Italy, Morocco, Panama, and Spain (Canary Islands), before discussing its advantages over existing classification approaches and its role as a foundation for quantitative indices, monitoring strategies, governance frameworks, and interpretations of the Anthropocene geological record.

## 2. Conceptual foundations

### 2.1. Plastics as anthropogenic entities within the earth system

Plastics are synthetic, human-produced materials that did not exist in the Earth system prior to the Anthropocene, and their introduction represents a direct outcome of technological development, industrial production, and mass consumption (Corcoran et al., 2018b). Unlike naturally occurring substances, plastics have no geogenic or biogenic analogue in the Holocene record, making them unequivocally anthropogenic in origin. For this reason, plastics are increasingly classified as novel entities, a category encompassing synthetic materials deliberately created and mobilized by human societies that now interact with Earth system processes at global scales . Among novel entities, plastics are often considered archetypal, as they are industrially manufactured, globally distributed, chemically diverse, and persistent across environmental compartments (Villarubia-Gómez et al., 2024).

From a conceptual perspective, plastics can be defined as non-biological anthropogenic entities that actively interact with physical, chemical, biological, and geological processes (Davies et al., 2020). Physically, plastics are transported by wind, water, gravity, and biotic vectors, moving across atmospheric, terrestrial, freshwater, coastal, and marine systems (Rangel-Buitrago, 2025). Chemically, they undergo weathering, oxidation, and additive leaching, while also acting as vectors for persistent organic pollutants and metals (Okoye et al., 2022). Biologically, plastics interact with organisms through ingestion, entanglement, colonization by microbial communities, and incorporation into food webs (Shumway and Ward, 2025). Geologically, plastics accumulate in soils, sediments, landfills, and engineered structures, where they may be buried, compacted, and preserved over extended timescales (DellaSala and Goldstein, 2020).

The ubiquity and persistence of plastics further reinforce their status as anthropogenic Earth-system entities. Plastic particles have been documented in virtually all environments, including remote and minimally disturbed regions (Stubbins et al., 2021). Their resistance to complete degradation allows them to persist long after their original use, forming long-lived anthropogenic deposits that are increasingly recognized in sedimentary archives (Cyvin et al., 2021). In this context, plastics function not only as pollutants but also as material indicators of human disturbance, acting as stratigraphic and chronological markers of Anthropocene deposits (Hazen et al., 2017).

Plastics have also been framed as emergent carbon-based geomaterials, contributing anthropogenic non-living organic carbon to the Earth system (Bachmann et al., 2023). The concept of a "plastic cycle" has been proposed to describe the continuous production, use, disposal, fragmentation, transport, accumulation, and burial of plastics across interconnected ecosystems, analogous in structure (though not in function) to natural biogeochemical cycles (Zhu, 2021). Within the planetary boundary framework, plastics are now recognized as a critical class of novel entities whose uncontrolled release is already disrupting Earth-system processes (Rangel-Buitrago and Neal, 2023).

### 2.2. Analogy with biological taxonomy: usefulness and limits

Biological taxonomy provides a valuable structural analogy for organizing plastics within the THCPL, not because plastics resemble living organisms, but because taxonomy offers a well-established hierarchical logic for managing complexity, heterogeneity, and scale. In biology, taxonomic systems enable the systematic ordering of diverse entities, facilitate comparison across spatial and temporal scales, and support the application of analytical tools such as diversity, dominance, and functional metrics ( Simpson, 1961; Berman, 2019). These same structural advantages are directly transferable to the study of plastic pollution, which is characterized by extreme material diversity, global distribution, and multiscale interactions within the Earth system (Rangel-Buitrago, 2025; Shumway and Ward, 2025). By adopting a hierarchical framework analogous to biological taxonomy, THCPL enables plastic observations made at different levels of resolution (from broad material categories to specific marketed products) to be coherently linked within a single conceptual system.

However, the analogy with biological taxonomy is strictly structural and must not be interpreted as implying ontological equivalence. Plastics are non-living, industrially produced entities that do not evolve through natural selection, lack reproductive capacity, and do not possess intrinsic ecological functions. Unlike biological taxa, plastic "lineages" are shaped by technological innovation (Medupin et al., 2025), market dynamics (Stanley et al., 2025), regulatory environments (Corsini et al., 2024), and consumer behavior (Ertz et al., 2023), rather than by genetic inheritance or evolutionary processes. Consequently, taxonomic ranks within THCPL do not represent phylogenetic relationships, but instead reflect nested layers of material composition, functional design, and socio-economic origin.

Recognizing these limits is essential to avoid conceptual overreach. THCPL does not seek to biologize plastics, nor to impose ecological meanings where none exist. Rather, it adopts the hierarchical logic of biological taxonomy as an organizational tool capable of structuring complex anthropogenic materials within Earth system science. In this sense, taxonomy is employed as a methodological framework rather than a biological model, enabling plastics to be treated as coherent anthropogenic entities while preserving a clear and necessary distinction between living systems and industrial artifacts.

The use of the term "taxonomy" in THCPL is methodological rather than biological, referring to a hierarchical system designed to organize complex anthropogenic materials across scales. Its application within an Anthropocene context reflects the need to interpret plastics as integrative material signals of human–Earth system interactions. Also, the retention of taxonomic terminology (e.g., Phylum, Class, Order, Family, Genus, Species) is a deliberate methodological decision intended to preserve the hierarchical logic and analytical familiarity of the system. These terms are not used in a biological sense, but are redefined to represent nested levels of material, functional, and socio-economic organization. Their use facilitates comparability with established hierarchical frameworks in ecology and Earth system science, while avoiding the conceptual fragmentation that would arise from introducing entirely new and potentially ambiguous terminology.

### 2.3. Ontological and epistemological boundaries of THCPL

The Taxonomy-inspired Hierarchical Classification of Plastic Litter deliberately extends beyond traditional material classifications to include corporations, brands, and specific marketed products as taxonomic units. This choice reflects an epistemological position based in Earth system science rather than an attempt to anthropomorphize or moralize industrial actors. Plastics enter the environment not as abstract polymers, but as designed, manufactured, and marketed products whose material properties, functional forms, and environmental fates are inseparable from decisions made within industrial and commercial systems (Smet et al., 2019). Classifying these socio-economic entities therefore responds to the empirical reality of how plastics are produced, distributed, used, and ultimately released into the environment.

From an ontological perspective, corporations, brands, and products are treated in THCPL not as biological or ecological entities, but as stable, traceable organizational units that structure the material flow of plastics through the Earth system. These units provide reproducible identifiers that enable source attribution, comparative analysis, and accountability, particularly in the context of Extended Producer Responsibility (Tumu et al., 2023) and environmental governance (Wu et al., 2025). Their inclusion allows plastics to be analyzed as components of coupled human–environment systems, rather than as chemically isolated particles divorced from their origins.

At the same time, THCPL defines clear boundaries regarding what it does and does not classify. The taxonomy-inspired hierarchical classification does not seek to categorize human behavior, consumer pattern, or corporate ethics, nor does it evaluate environmental performance or assign responsibility in normative terms. Instead, THCPL focuses strictly on the materialized outcomes of industrial and commercial processes as they manifest in environmental settings. Likewise, THCPL does not replace polymer-specific chemical analyses, toxicity assessments, or biological impact studies, but rather provides a structural framework within which such information can be coherently integrated.

### *2.4. Plastics as cultural, industrial, chronological and stratigraphic markers*

Plastics function simultaneously as cultural artifacts, industrial products, chronological markers and stratigraphic signals, reflecting the material imprint of human societies on the Earth system ( Weber and Lechthaler, 2021). Like consumer goods and packaging materials, plastics encode patterns of production, consumption, and disposal that vary across regions, economic systems, and historical periods (Wang et al., 2022). The diversity of plastic forms, brands, and product types found in environmental settings provides indirect but robust evidence of societal behaviors, market structures, and technological choices, making plastics effective proxies for contemporary consumption dynamics (Brabo et al., 2024).

From an industrial perspective, plastics symbolize the organization and scale of modern manufacturing systems (Salwin and Kraslawski, 2024). Polymer types, product designs, additive formulations, and branding practices reflect industrial standards, regulatory regimes, and supply-chain configurations. Once released into the environment, these industrial signatures persist, allowing plastics to be traced back to specific production sectors and timeframes (Brabo et al., 2024). In this sense, plastics operate as material records of industrial activity, linking environmental contamination to upstream processes of extraction, production, and distribution (Rangel-Buitrago et al., 2022).

Beyond their cultural and industrial significance, plastics are increasingly recognized as stratigraphic markers of the Anthropocene (Zalasiewicz et al., 2016). Their durability, global distribution, and absence from pre-industrial strata enable plastics to delineate a distinct horizon in recent geological records (Russell et al., 2025). Plastic particles, fibers, and fused materials are now incorporated into soils, sediments, and anthropogenic deposits, where they may be preserved over long timescales (Rangel-Buitrago and Neal, 2023).

## 3. Methodological development OF THCPL

The taxonomy-inspired hierarchical classification of plastic litter was developed through a multi-stage process combining conceptual synthesis, comparative evaluation of existing classification systems, and iterative empirical testing under real-world conditions. This approach was designed to ensure that the taxonomy is not only theoretically grounded, but also operationally robust, reproducible, and adaptable across environmental contexts.

The first stage consisted of a critical review of existing plastic classification frameworks, including material-based (polymer type), size-based (macro-, meso-, microplastics), and monitoring-oriented systems such as OSPAR, the MSFD Joint List (Fleet et al., 2021), and Ocean Conservancy protocols (Ocean Concervancy 2009). These frameworks were evaluated in terms of their analytical scope, scalability, and capacity to support cross-regional comparison and source attribution. While these systems are highly effective for standardized monitoring and environmental assessment, they were found to operate largely along single dimensions and to lack a hierarchical structure capable of integrating material, functional, and socio-economic information (Rangel-Buitrago, 2025).

The second stage involved the conceptual design of a hierarchical framework, informed by Earth system science principles and the need to treat plastics as coupled socio-material entities. Biological taxonomy was adopted strictly as a structural analogy to organize complexity across scales, allowing the integration of multiple dimensions (material composition, functional form, industrial origin, and product identity) within a unified classificatory system.

The third stage consisted of iterative empirical testing and refinement of the taxonomy through its application to standardized coastal litter datasets collected across six countries (Colombia, Panama, Brazil, Morocco, Italy, and Spain), comprising a total of 912 items. During this process, taxonomy was applied independently to items exhibiting varying degrees of preservation, fragmentation, and labeling. Classification challenges, such as partial label loss, ambiguous product identity, and mixed-material items, were systematically evaluated and used to refine taxonomic definitions, hierarchical boundaries, and decision rules.

To ensure consistency, a standardized classification protocol was implemented across all datasets, including explicit criteria for taxonomic assignment at each level and a conservative truncation rule whereby items were classified only to the highest level supported by observable evidence. This approach minimized subjectivity and prevented overclassification, particularly at the Genus and Species levels.

The taxonomy-inspired hierarchical classification of plastic litter was evaluated in terms of internal coherence, scalability, and cross-regional applicability, ensuring that it could accommodate both high-resolution datasets and fragmented or legacy data. This iterative and integrative development process ensures that THCPL is based in both conceptual rigor and empirical reality, bridging the gap between theoretical classification and operational monitoring.

## 4. Structure

### *4.1. The hierarchical logic of THCPL (from phylum to species)*

The THCPL is structured as a hierarchical system designed to organize plastic litter according to increasing levels of informational resolution, from broad material categories to specific marketed products (Fig. 1). This structure follows the principle that higher taxonomic levels capture generalized material and functional properties, while lower levels progressively encode source specificity, socio-economic origin, and traceability.

At the highest levels, Phylum and Class establish the material and contextual framework, distinguishing plastics from other anthropogenic and natural materials within mixed debris assemblages. The Order level introduces a functional–material dimension, grouping plastics according to physical form and use (e.g., rigid, flexible, foamed, composite), which strongly influence environmental behavior, transport pathways, and fragmentation processes (van Sebille et al., 2020).

At finer resolutions, the hierarchy incorporates socio-economic information. The Family level captures corporate producers, enabling source attribution and governance relevance. The Genus level identifies brands or product lines, reflecting market structure and consumption patterns. Finally, the Species level corresponds to specific marketed products, representing the highest achievable resolution for item-level identification in environmental settings.

Across this hierarchy, informational content increases downward: higher levels support broad-scale environmental analyses, while lower levels enable detailed traceability, comparative assessments, and integration with governance frameworks.

### *4.2. Criteria for taxonomic assignment*

Taxonomic assignment within the THCPL follow a set of explicit, observable, and hierarchically ordered decision rules designed to ensure consistency, reproducibility, and analytical robustness across datasets and environmental contexts (Fig. 2). Rather than redefining taxonomic levels, this framework establishes how items are assigned to each level

| Phylum | Litter | Wrack | Driftwood |
|---|---|---|---|
| **Class** | **Glass, Metal, Plastics, Rubber, Paper/Cardboard, Textile** | Macroalgae, Seagrasses, Saltmarsh plants, Mangrove leaves. | Hardwood, Softwood, Processed wood (treated timber, pallets) |
| **Order** | **Glass**: bottles, shards.<br>**Metals**: cans, foils.<br>**Plastics**: rigid, non-rigid, foams, composites.<br>**Rubber**: tires, fragments<br>**Textiles**: ropes, fabrics | **Macroalgae**: kelp, Sargassum, Ulva.<br>**Seagrasses**: Thalassia, Zostera .<br>**Mangrove leaves**: Rhizophora, Avicennia. | **Hardwood logs**: large trunks<br>**Softwood**: branches, drift stems<br>**Processed wood**: planks, pallets |
| **Family** | For plastics: Corporate producers (i.e., Coca-Cola, PepsiCo, Nestlé, Unilever, local industry).<br>For metals: breweries, beverage companies.<br>For glass: distilleries, food industry. | Families of species groups (e.g., Sargassaceae, Zosteraceae, Avicenniaceae). | Wood source (natural forest species, mangrove wood, anthropogenic timber industry). |
| **Genus** | Brands/product lines: Coca-Cola, Sprite, Fanta, Pepsi, KitKat, Dove. | Genus of macroalgae/seagrass (Sargassum, Zostera, Ulva) or mangrove (Rhizophora, Avicennia). | Botanical genus (e.g., Pinus, Quercus) or industrial product type (pallet, plank). |
| **Species** | Specific marketed products: Coca-Cola PET 500 mL bottle, Sprite 1.5 L, KitKat 2-finger wrapper. | Species: *Sargassum fluitans*, *Zostera marina*, *Avicennia germinans*. | Specific log/piece type: pine log, oak plank, treated timber beam. |

**Fig. 1.** Conceptual structure of the Taxonomy-inspired Hierarchical Classification of Plastic Litter (THCPLL). Schematic representation of the hierarchical organization of THCPL, showing six taxonomic levels (Phylum to Species) and their application across three major material assemblages: litter, wrack, and driftwood. THCPL integrates anthropogenic and natural materials within a unified classificatory framework, preserving ecological and geomorphological context while enabling increasing informational resolution toward product-level identification. Wrack and driftwood are included to illustrate the broader material context of coastal assemblages but are not the focus of the present study, which is restricted to plastic litter.

| Rank | Categories / Examples | |
|---|---|---|
| **Phylum** | Litter | |
| **Class** | Plastics | |
| **Order** | Rigid Plastics (hard containers, PET, HDPE, PP). | Bottles, Caps/Lids, Containers (jars, boxes), Cutlery, Cups, Fragments. |
| | Non-Rigid Plastics (films, bags, wrappers, LDPE). | Bags (shopping, trash), Wrappers (snack, candy), Films (industrial, agricultural). |
| | Foams (EPS, polyurethane). | EPS Food containers, EPS Packaging, Foam cups, Foam fishing buoys. |
| | Composites (multi-layer packs, laminates, tetrapaks). | Multi-layer snack packaging, Tetrapak beverage cartons, Metallic laminates, Plastic-paper laminates. |
| **Family (Producers)** | Corporate/industrial producers responsible for the marketed product. | Coca-Cola Company, PepsiCo, Nestlé, Unilever, Procter & Gamble, Mondelez, Local manufacturers. |
| **Genus (Brand/Product line)** | Brand or trademark under a producer. | Coca-Cola, Sprite, Fanta, Pepsi, Gatorade, KitKat, Maggi, Dove, Ariel. |
| **Species (Specific Product)** | Individual marketed item identifiable in the environment. | Coca-Cola (zero, original), Sprite (zero,Original), Fanta, Pepsi, Gatorade. |

**Fig. 2.** Taxonomic-inspired hierarchy and categories for plastics within THCPL. Detailed breakdown of the THCPL hierarchy applied to plastic litter, presenting the definitions and representative examples associated with each taxonomic level from Phylum (litter) to Species (specific marketed products).

based on available empirical evidence.

Classification proceeds sequentially from higher to lower levels, beginning with material identification and progressing toward increasing socio-economic specificity. At higher levels (Phylum, Class, and Order), assignment relies primarily on directly observable physical attributes, including material composition, structural form, and functional characteristics. These features are generally preserved even in fragmented or weathered items, allowing robust classification despite environmental degradation (Andrady, 2011; Hartmann et al., 2019; Song et al., 2023).

At these levels, functional–material properties are particularly relevant, as they directly influence environmental behavior. Attributes such as rigidity, flexibility, and buoyancy control transport pathways, fragmentation dynamics, and persistence across environmental compartments (van Sebille et al., 2020; Kaandorp et al., 2023; Kachef et al., 2025). Consequently, classification at the Order level provides a process-relevant basis for linking plastic form to environmental fate.

At lower levels (Family, Genus, and Species), assignment depends on the presence of diagnostic identifiers, such as logos, labels, standardized packaging features, shape, color schemes, or product-specific markings. These attributes enable the identification of corporate producers, brands, and specific marketed products, supporting source attribution and alignment with governance frameworks such as Extended Producer Responsibility (Dalhammar et al., 2021; Tumu et al., 2023). However, because such features are more susceptible to abrasion, fragmentation, and biofouling, classification at these levels is contingent upon sufficient preservation of identifying evidence.

A key operational principle of the THCPL is the conservative truncation rule, whereby items are classified only to the highest taxonomic level supported by reliable observations. When ambiguity arises due to fragmentation or loss of diagnostic features, classification is intentionally restricted to higher levels, avoiding speculative attribution and ensuring analytical integrity. This approach is consistent with established practices in marine litter monitoring, where degradation progressively limits item-level identification ( Smith and Turrell, 2021).

This rule-based framework allows all items to contribute to the analysis at an appropriate level of resolution, preserving comparability across sites and datasets while accommodating variability in preservation state. As a result, the THCPL maintains internal coherence across heterogeneous assemblages, ensuring that classification reflects empirical evidence rather than interpretative inference.

The taxonomy-inspired hierarchical classification of plastic litter is designed to be inherently scalable and adaptable, allowing its application across a wide range of spatial scales, datasets, and research objectives. The hierarchical structure enables analyses to be conducted at coarse resolutions (i.e., such as material class or functional order) for large-scale surveys and global assessments, while also supporting fine-resolution studies focused on specific producers, brands, or products at local or regional scales. This approach also can be applied to diverse data sources, including beach surveys, seabed monitoring, riverine sampling, and legacy datasets, without requiring complete item identification at all levels. Users may operate at the highest level of resolution supported by available data, while maintaining compatibility with more detailed classifications.

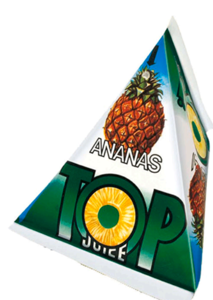
## 5. Taxonomic levels

Into the THCPL each level is formally defined and justified in relation to the specific type of information it encodes, ranging from broad material context to fine-scale product identification (Fig. 2). To illustrate how the hierarchy operates in practice, a single, globally recognizable plastic item, a Coca-Cola PET bottle, is used consistently as an illustrative example across all levels (Fig. 3). This approach allows the progressive increase in informational resolution to be demonstrated clearly, while maintaining conceptual continuity.

### 5.1. Phylum and class

The highest taxonomic levels of this approach are designed to establish the broad material and contextual boundaries within which plastic litter is analyzed. At this level, the objective is not detailed source attribution, but the correct positioning of plastics within the wider assemblage of materials interacting with coastal and marine systems. The Phylum level groups entities according to their overarching origin


| | |
|---|---|
| Phylum | Litter |
| Class | Plastics |
| Order | Rigid Plastics |
| Family (Producer) | The Coca Cola Company |
| Genus (Brand/Product line) | Coca-Cola |
| Species (Specific Product) | Coca-Cola 500 mL PET bottle |




| | |
|---|---|
| Phylum | Litter |
| Class | Plastics |
| Order | Composites |
| Family | Liban-Jus S.A.L. |
| Genus | Top Juice |
| Species | Top Juice Ananas (Pineapple) 190 mL Tetra Pak |


| | |
|---|---|
| Phylum | Litter |
| Class | Plastics |
| Order | Rigid Plastics |
| Family | Tingyi (Cayman Islands) Holding Corp. |
| Genus | Master Kong (康师傅) |
| Species | Master Kong Lemon Iced Black Tea (500 mL PET Bottle) |


| | |
|---|---|
| Phylum | Litter |
| Class | Glass |
| Order | Bottles |
| Family | Fábrica de Licores de Antioquia |
| Genus | Aguardiente Antioqueño |
| Species | Aguardiente Antioqueño 24° Sin Azúcar 375 mL |

**Fig. 3.** Worked examples of THCPL application to individual plastic items. Application of THCPL to select collected items, demonstrating classification from Phylum to Species for different packaging types and materials (e.g., rigid plastics, composites, glass). The examples show how diverse items can be consistently classified within the same hierarchical framework, independent of origin or product category.

and role within anthropogenic debris, while the Class level differentiates materials based on fundamental compositional properties that control environmental behavior.

Within THCPL, Phylum identifies plastics as a subset of litter, a category encompassing persistent, human-derived solid materials introduced into natural environments (Williams and Rangel-Buitrago, 2022). This level deliberately includes non-plastic comparators such as metal, glass, rubber, paper, textiles, and natural wrack or driftwood. The inclusion of these comparators is essential to preserve ecological and geomorphological context, as plastics rarely occur in isolation. Coastal and marine environments are shaped by mixed-material assemblages in which plastics interact physically and spatially with organic debris, sediments, and other anthropogenic solids (Costa and Barletta, 2015). By situating plastics within a broader litter phylum, THCPL avoids analytical isolation and enables comparative assessments of material behavior, accumulation patterns, and environmental interactions.

The Class level refines this distinction by separating plastics from other material categories based on intrinsic composition. Plastics are defined as synthetic polymer-based solids (UNEP 2021), distinct from glass (amorphous silicates), metals (elemental or alloyed solids), rubber (natural or synthetic elastomers), or organic materials such as driftwood and macroalgae. This differentiation is analytically critical, as material class governs key environmental properties including density, durability, fragmentation pathways, chemical reactivity, and long-term persistence (Davenport et al., 2022).

Using a Coca-Cola bottle as an example, its classification as plastic litter is determined at this level by material composition rather than function or branding. Although bottles may also be manufactured from glass or metal, the Coca-Cola item under consideration is composed of polyethylene terephthalate (PET), a synthetic polymer absent from natural geological systems. This polymeric composition confers characteristics, such as resistance to biodegradation, susceptibility to photo-oxidative fragmentation, and buoyancy, dependent transport, that fundamentally distinguish it from glass bottles, aluminum cans, or organic debris (Berry et al., 2023, Liro et al., 2022, 2023; Hoellein et al., 2024). These properties determine how the item moves through the environment, interacts with organisms, and accumulates in sediments or shorelines (Rangel-Buitrago, 2025).

### 5.2. Order: functional–material level

The Order level of the THCPL captures the functional–material form of plastic items, representing a critical interface between intrinsic material properties and environmental behavior. At this level, plastics are organized according to their physical configuration and intended functional use (such as rigid items, flexible films, foams, and composite materials) attributes that strongly influence transport pathways, fragmentation dynamics, residence times, and ecological interactions (van Sebille et al., 2020). Unlike higher taxonomic levels, which emphasize composition and context, the Order level is explicitly process-oriented, linking plastic form to environmental fate.

Rigid plastics are characterized by structural stiffness and dimensional stability, typically manufactured to retain shape under normal use conditions (Flett et al., 2021). This category includes bottles, containers, caps, and other hard packaging items, commonly produced from polymers such as PET, HDPE, or PP. Using a Coca-Cola bottle as example, the item is classified as a rigid plastic because its PET structure is designed to maintain shape, resist compression, and protect liquid contents during transport and storage. This rigidity has direct environmental implications once the item becomes litter.

From a transport perspective, rigid plastics exhibit size- and shape-dependent mobility (Lofty et al., 2024). Intact PET bottles often retain buoyancy due to trapped air, enabling long-distance transport across surface waters and along coastlines (Maclean et al., 2021). Their three-dimensional form promotes accumulation in wrack lines, vegetation traps, and geomorphological convergence zones, rather than uniform dispersal (Rangel-Buitrago et al., 2025). Over time, physical abrasion, UV exposure, and mechanical stress lead to fragmentation, but this process is typically slower for rigid items than for thin films or foams (Andrady 2021).

Fragmentation pathways at the Order level are particularly important. Rigid plastics tend to break into angular fragments rather than fibers or films, producing secondary microplastics with distinct shapes and surface properties (Andrady 2021). These fragments may persist for extended periods in sediments or shorelines, contributing to long-term environmental reservoirs. In contrast, flexible plastics fragment rapidly into films or fibers, while foams disintegrate into lightweight particles with high dispersal potential (Fox et al., 2024). Thus, functional form directly conditions the size distribution and morphology of plastic debris over time (Liro and Zielonka, 2025).

Ecological interactions are also mediated by Order-level characteristics. Rigid plastics such as PET bottles present large, durable surfaces that facilitate biofilm development and rafting of organisms, while also posing ingestion and entrapment risks to fauna (Gracia et al., 2018). Their persistence and visibility increase the likelihood of repeated biological interactions across ecosystems. Moreover, rigid containers can act as microhabitats or traps for organisms and sediments, further differentiating their ecological role from other plastic forms (Waldschläger et al., 2022)

By classifying plastics at the Order level according to functional–material form, THCPL explicitly connects item design to environmental processes. In the case of a PET bottle, its designation as a rigid plastic explains not only how it moves and degrades in the environment, but also why it accumulates, persists, and interacts with ecosystems in ways distinct from other plastic orders. This level therefore represents a key bridge between material classification and environmental impact assessment.

### 5.3. Family: corporate producers

The Family level introduces corporate producers as formal taxonomic units, reflecting the empirical reality that plastics enter the environment as outcomes of organized industrial systems rather than as anonymous materials (Houssini et al., 2025). This level is not intended to attribute blame or evaluate corporate behavior, but to provide a stable, traceable, and analytically meaningful category that links plastic items to their point of production within global material flows. Including producers at this level allows THCPL to integrate environmental observation with source attribution, governance relevance, and policy-oriented analysis while remaining grounded in material evidence.

From a taxonomic perspective, a corporate producer qualifies as a Family when it represents a coherent organizational entity responsible for the design, manufacturing, or placement of plastic products on the market. Corporate producers exert decisive control over polymer selection, product design, packaging formats, additive use, and distribution scale, all of which influence the environmental behavior and fate of plastic items (Williams and Rangel-Buitrago, 2019). As such, the producer constitutes a higher order organizing unit that groups multiple brands, product lines, and individual items sharing a common industrial origin (Kadiyali et al., 1998).

In our example, The Coca-Cola Company functions as the Family-level taxon because it represents the corporate entity responsible for the standardized production and global distribution of that packaging format. Although the same polymer (PET) may be used by numerous manufacturers, the producer-level classification captures differences in product portfolios, packaging strategies, regional deployment, and temporal production trends that cannot be resolved at the material or functional level alone (Williams and Rangel-Buitrago, 2019). This distinction is essential for comparative analyses across regions and datasets, as it allows plastic assemblages to be examined in relation to specific industrial systems rather than aggregated polymer categories.

The inclusion of corporate producers also has clear governance relevance. Family-level classification aligns directly with Extended Producer Responsibility frameworks, which assign responsibility for post-consumer waste management to producers rather than consumers or municipalities (Mallick et al., 2024). By enabling consistent identification of producer-specific plastic items in environmental surveys, THCPL provides a scientifically neutral mechanism for linking observed pollution patterns to regulatory instruments, reporting obligations, and policy evaluation. Importantly, this linkage is descriptive rather than normative, preserving the analytical integrity of the approach.

Incorporating corporate producers as Family-level entities therefore enhances traceability, supports cross-scale comparisons, and connects environmental science with governance frameworks. Within THCPL, the Family level represents the transition point where material properties and functional design intersect with industrial organization. This enables plastics to be analyzed as components of coupled human–environment systems rather than as decontextualized debris.

### 5.4. Genus: brands and product lines

The Genus level refines producer-level classification by identifying brands and product lines as distinct analytical units. While the Family level captures the corporate entity responsible for production, the Genus level reflects how plastic items are differentiated, marketed, and distributed within consumer-facing systems. Brands represent stable socio-economic constructions that mediate the relationship between industrial production and consumer behavior (Chotisarn and Phuthong, 2025), making them essential for understanding how plastics are introduced into, and circulate within, the Earth system.

From an analytical perspective, brands function as signals of market structure, consumption patterns, and cultural penetration (Fournier and Alvarez, 2019). They encode information related to product positioning, target demographics, pricing strategies, and regional or global range (Torelli et al., 2012). These attributes influence the volume, spatial distribution, and temporal persistence of plastic items in the environment. As a result, brand-level identification allows plastic assemblages to be examined not only in terms of material properties, but also in relation to consumption dynamics and market organization.

In the proposed example, Coca-Cola constitutes a distinct Genus within THCPL because it represents a globally standardized brand with high market visibility and consistent packaging formats across regions. Although multiple brands may be produced by the same corporate Family, each brand maintains unique design elements, labeling, color schemes, and product lines that facilitate reliable identification in environmental surveys (i.e., The Coca-Cola Company produces Coca – Cola, Fanta, Sprite, among other brands). These features enable field-based classification even when labels are partially degraded, thereby enhancing reproducibility and analytical consistency.

Brand-level classification also improves resolution in comparative studies. Two plastic bottles produced by the same corporation but marketed under different brands may differ substantially in distribution patterns, regional prevalence, and temporal occurrence. By distinguishing brands at the Genus level, THCPL allows to detect spatial contrasts, consumption-driven accumulation patterns, and shifts in market dominance that would remain hidden under producer-only classification. This level therefore supports analyses of plastic diversity, dominance, and turnover within and across regions.

The inclusion of brands does not imply normative judgment or attribution of responsibility. Within THCPL, brands are treated as descriptive socio-economic identifiers that structure material flow between producers and consumers. The Genus level thus represents an intermediary between industrial organization and individual plastic items, linking material evidence observed in the environment to the consumer-facing dimensions of plastic production and use.

### 5.5. Species: specific marketed products

The Species level represents the finest taxonomic resolution, corresponding to individual marketed products that can be consistently distinguished in environmental contexts. At this level, classification shifts from general categories of material, function, producer, or brand to the specific item as it is manufactured and placed on the market. Species-level identification is critical because it preserves maximum informational content, enabling product-level traceability, high-resolution comparative analysis, and quantitative metrics analogous to species-based approaches in community ecology.

In THCPL, a plastic “Species” is defined as a specific marketed product with recognizable and sufficiently stable attributes that allow reproducible identification in field surveys. These attributes may include packaging format, size/volume, label design, cap type, distinctive shape, material configuration, and standardized markings. The Species level is operationally constrained by detectability: it represents the highest level at which an item can be reliably distinguished given typical environmental degradation, fragmentation, and loss of labeling. Consequently, Species-level classification is most feasible for intact or partially intact items, whereas fragments may remain classifiable only at higher ranks.

Using the example, a “Coca-Cola PET bottle (X mL)” is treated as the highest-resolution unit because it specifies a discrete product identity beyond brand recognition alone. The inclusion of volume (e.g., 500 mL, 1.5 L) and packaging format materially refines classification because these attributes are linked to production batches, distribution channels, consumption contexts, and waste pathways. In many markets, bottle volume is closely associated with use environments (e.g., on-the-go consumption versus household purchase), retail packaging (single units versus multipacks), and disposal behavior. Consequently, the same Genus-level brand may generate multiple Species-level products whose environmental occurrence differs spatially and temporally.

Species-level resolution enhances analytical capacity in three principal ways. First, it improves forensic traceability, allowing them to connect recovered items to product designs, manufacturing standards, and regionally specific variants when such identifiers remain visible. Second, it supports diversity and dominance metrics at the highest informational resolution, enabling the quantification of “plastic species richness” and assemblage structure within and among sites. Third, it strengthens comparative monitoring, as shifts in the relative abundance of specific products can reveal changes in consumption patterns, packaging transitions, or regulatory interventions that would be obscured at higher taxonomic ranks.

In this way, the Species level completes the THCPL hierarchy translating plastic litter into discrete, identifiable units suitable for high-resolution environmental analysis. While not always attainable for degraded items, it provides the upper limit of taxonomic specificity and is essential for linking environmental observations to the most granular expressions of industrial production and consumer use.

### 5.6. Internal coherence and logical necessity of THCPL levels

The hierarchical structure of the THCPL is not arbitrary but reflects the minimum set of taxonomic levels required to capture the full material, functional, and socio-economic complexity of plastic pollution. Each level encrypts distinct and non-redundant information, and the removal or collapse of any rank results in a measurable loss of analytical resolution. Higher levels (Phylum and Class) establish material context and enable comparisons among different debris types, while intermediate levels (Order) link plastic form to environmental behavior and process-based dynamics (Figs. 1 and 2). Lower levels (Family, Genus, and Species) progressively introduce traceability, market structure, and product-level specificity, which are essential for source attribution, governance relevance, and high-resolution comparative analysis (Figs. 1 and 2).

Simplified or partial taxonomies (such as those based solely on polymer type, size class, or environmental compartment) presents only isolated dimensions of the plastic problem. While operationally useful, these approaches fragment the real signal of plastics by separating material properties from functional design, industrial origin, and consumer-facing identity. As a result, they limit cross-scale integration, hinder the application of diversity-based metrics, and do not present/explain the existing links between environmental observations and production systems.

THCPL overcomes these limitations maintaining internal coherence across hierarchical levels, allowing plastic entities to be analyzed as components of coupled human–environment systems. This integrated structure is essential for interpreting plastics not merely as pollutants, but as material expressions of industrialization, consumption, and long-term Earth system transformation.

## 6. Operational application of THCPL in field surveys

### 6.1. Study areas and field sampling approach

To demonstrate the empirical applicability and transferability of THCPL, the framework was applied to coastal litter datasets collected across six countries spanning distinct oceanographic, geomorphological, and socio-environmental contexts: Colombia, Panama, Brazil, Morocco, Italy, and Spain - Canary Islands (Fig. 4). The selected sites include a wide gradient of coastal typologies, comprising remote sandy beaches, semi-remote rocky shores, protected natural areas, semi-urban embayments, and metropolitan-influenced coastlines. This diversity was intentionally wanted to test the robustness of THCPL under contrasting environmental conditions and anthropogenic pressures.

At each site, field surveys were conducted following the same protocol (OSPAR 2010). All visible litter items were collected along a continuous 200 m shoreline transect, extending across the full width of the beach or coastal platform, from the waterline to the backshore or natural boundary (Rangel-Buitrago et al., 2018; ).This approach ensured comprehensive sampling of the active accumulation zone, collecting both recent inputs and retained debris across different coastal morphologies. The protocol was applied consistently across all sites to facilitate cross-country comparability.

In Colombia, surveys were conducted at Punta Astilleros, a remote, medium-energy sandy beach characterized by intact geomorphological dynamics but extreme accumulation of driftwood and plastic litter, resulting in critically degraded environmental quality despite the absence of infrastructure (Rangel-Buitrago et al., 2026). In Panama, Santo Domingo Beach is located within the Bay of Panama, adjacent to the historic district of Panama City. This urban-influenced sandy beach has experienced chronic pollution, restricted access, and is currently subject to long-term restoration efforts aimed at rehabilitating metropolitan coastal environments (Seemann et al., 2023).

In Brazil, the site of Tamandaré lies on the southern coast of Pernambuco within the Costa dos Corais Environmental Protection Area. This high-energy sandy beach is influenced by a tropical climate, semidiurnal mesotides, and nearby fluvial inputs, with environmental quality affected by inadequate waste management and land-based pollution sources. In Morocco, Anchor Point represents a semi-remote, high-energy rocky coastline subject to intense surf-based tourism. Litter accumulates primarily within rock crevices and along the backshore, reflecting both hydrodynamic concentration and growing anthropogenic pressure (Ben-Haddad et al., 2024).

In Italy, surveys were conducted at Albinia, a microtidal sandy beach in southern Tuscany, located near the Albegna River mouth and adjacent to the WWF Orbetello Lagoon Nature Reserve. Despite preserved coastal dynamics and high natural value, the site is influenced by agricultural runoff and upstream land-use pressures. In Spain, Bahía de Formas (Canary Islands) is a high-energy mixed beach system with volcanic rocky shelves and narrow sandy sectors, situated within a biologically sensitive area hosting multiple protected marine and avian species. Although geomorphologically intact, the site experiences localized environmental degradation due to industrial proximity, recreational activities, and chronic litter accumulation (SDI Canarias, 2025).

### 6.2. Multi-country application and workflow

The Taxonomy-inspired Hierarchical Classification of Plastic Litter was applied consistently across the six national datasets using a harmonized classification workflow designed to maximize

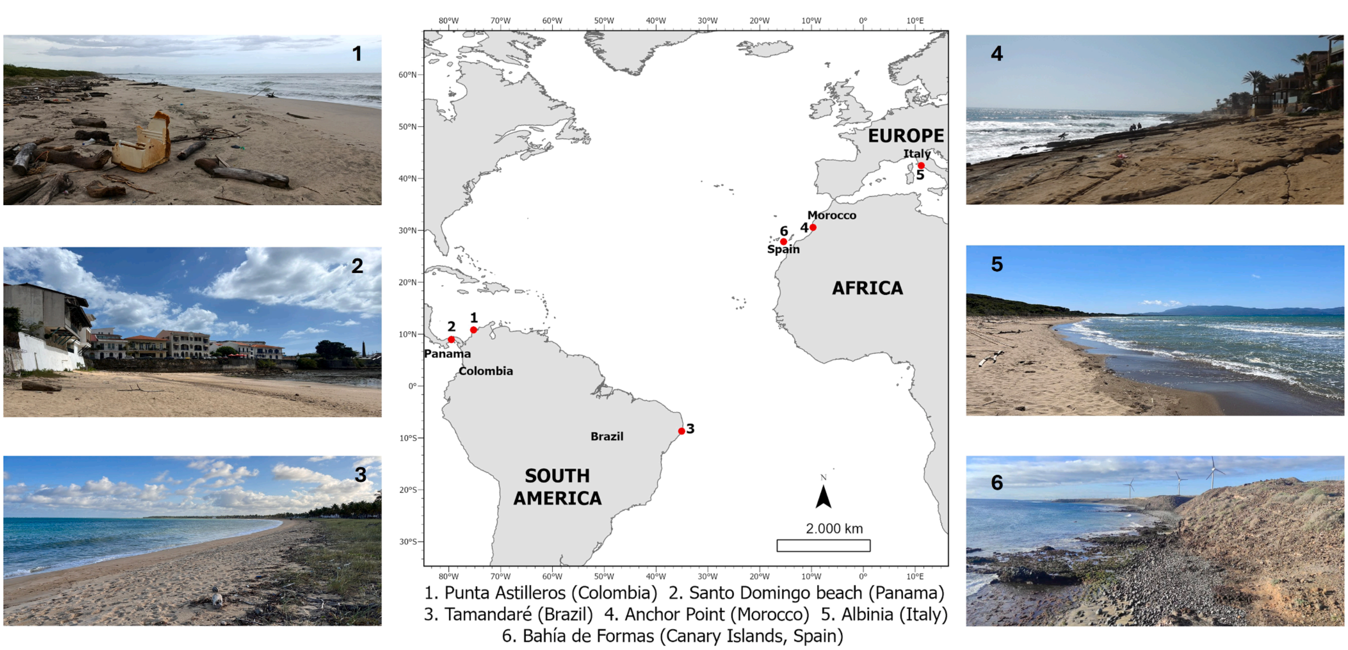



**Fig. 4.** Study area location and coastal typologies. Geographical distribution of the six coastal study sites used to demonstrate the operational applicability of THCPL: Punta Astilleros (Colombia), Santo Domingo Beach (Panama), Tamandaré (Brazil), Anchor Point (Morocco), Albinia (Italy), and Bahía de Formas (Canary Islands, Spain). Photographs illustrate the diversity of coastal typologies and environmental contexts represented in the dataset.

comparability, transparency, and reproducibility (Fig. 5). Although the surveys were conducted in contrasting coastal settings, all litter items were processed following the same taxonomic decision sequence, progressing from higher to lower hierarchical levels according to the quality and completeness of information preserved on each item.

For each collected item, classification began at the Phylum and Class levels based on material composition, which could be determined for all items regardless of fragmentation state. Assignment to Order followed, using observable functional–material characteristics such as rigidity, flexibility, or composite structure. These three upper levels provided a common baseline that ensured full inclusion of all items across datasets, even when advanced identification was not possible.

Assignment to Family, Genus, and Species levels was conducted only when sufficient diagnostic features were present. Corporate producers were identified through readable labels, logos, or standardized packaging features, while brand and product-level identification required progressively finer attributes such as brand-specific color schemes, typography, bottle shape, cap design, or volume markings. When ambiguity existed (due to abrasion, partial fragmentation, or biofouling) classification was conservatively truncated at the highest reliable level, avoiding forced or speculative attribution. This rule-based truncation ensured internal consistency and prevented inflation of lower-level resolution.

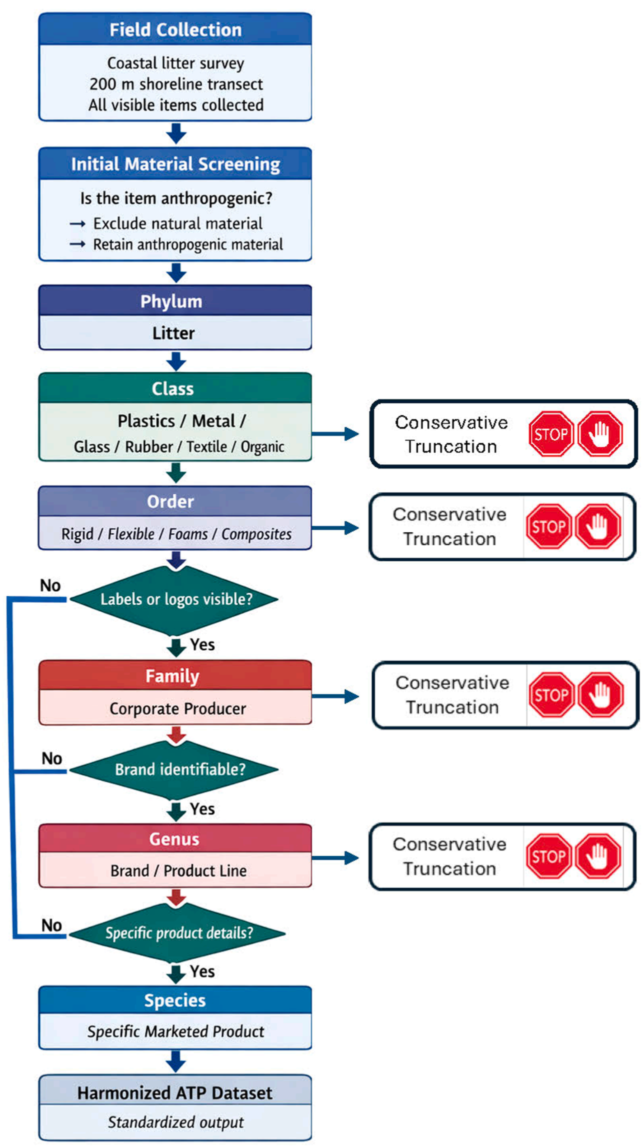



**Fig. 5.** Operational workflow for THCPL application in field surveys. Flowchart presents the stepwise, rule-based application of THCPL from field collection to dataset harmonization. The workflow shows hierarchical classification from Phylum to Species, including decision points where classification is conservatively truncated due to fragmentation or loss of diagnostic features, ensuring reproducibility and cross-regional comparability under real-world conditions.

To maintain harmonization across countries, a shared coding protocol was used, including standardized category definitions, decision rules for ambiguous items, and a common data structure for recording taxonomic levels. All datasets followed the same hierarchical logic and field definitions, allowing direct aggregation and comparison without post hoc reclassification. Importantly, THCPL does not require complete resolution to the Species level for analytical validity; rather, it preserves coherence by allowing items to contribute information at the highest level supported by their condition.

### 6.3. *Dataset overview*

In total, 912 individual litter items were classified across the six study. Sample sizes varied substantially among countries, reflecting differences in coastal typology, hydrodynamic exposure, and accumulation intensity, ranging from 22 items in Italy and 27 in Panama, to 110 items in Morocco, 128 in Spain, 142 in Brazil, and 483 in Colombia (Table 1). This variability provided a demanding and representative test of THCPL performance across both low- and high-abundance contexts.

Across the combined datasets, THCPL revealed substantial industrial and market diversity. At the Family (corporate producer) level, the number of distinct producers identified ranged from 14 in Panama and 20 in Italy, to 50 in Morocco, 53 in Spain, 79 in Brazil, and 118 in Colombia (Table 1). Resolution increased further at the Genus (brand or product line) level, with 20 genera in Panama, 21 in Italy, 65 in Spain, 72 in Morocco, 96 in Brazil, and 181 in Colombia (Table 1). At the Species (specific marketed product) level, the number of distinct items identified ranged from 22 to 214, depending on sample size and preservation state (Table 1). These values demonstrate that THCPL can accommodate high variability in both item abundance and taxonomic richness across regions.

Across all datasets, taxonomic resolution followed a consistent hierarchical pattern. All items were successfully classified at the Phylum, Class, and Order levels, while resolution decreased progressively at finer ranks as a function of fragmentation, abrasion, and label loss. Nevertheless, Family-level identification remained achievable for a substantial proportion of items in all countries, confirming the robustness of producer-level attribution under real-world field conditions. All datasets were compiled in standardized spreadsheet format using harmonized taxonomic fields and decision rules, ensuring internal consistency, reproducibility, and direct comparability across countries (Supplementary Material 1).

### 6.4. *Transferability and comparability across regions*

The application of THCPL at the Family (corporate producer) level enables robust cross-regional comparison by capturing industrial and market signatures that remain detectable even under conditions of fragmentation and weathering. Across the six study areas, Family-level assemblages exhibited clear and interpretable dominance structures, demonstrating that THCPL supports comparative analysis across contrasting coastal, cultural, and economic contexts (Table 2).

In Colombia, the Family spectrum was characterized by high richness and pronounced dominance gradients, with beverage and food producers strongly represented. The Coca-Cola Company ranked first (N = 51), followed by major national and multinational producers such as Postobón S.A. (N = 38), Bavaria - Anheuser-Busch InBev (N = 36), Grupo Diana (N = 36), and PepsiCo (N = 31). This distribution reflects a complex and diversified consumption system, where both global corporations and regional producers contribute substantially to coastal

**Table 1**
Taxonomic resolution and richness across six coastal study areas. Number of plastic items collected, and the corresponding taxonomic richness achieved at each hierarchical level of the THCPL) for the six study regions. The table presents the total number of items collected and the number of distinct entities identified at the Phylum, Class, Order, Family (corporate producer), Genus (brand or product line), and Species (specific marketed product) levels. Differences among countries reflect variation in sample size, coastal typology, and item preservation state, while illustrating the capacity of THCPL to maintain consistent hierarchical classification across contrasting datasets.

| | Country | | | | | |
|---|---|---|---|---|---|---|
| | Colombia | Panama | Brazil | Morocco | Italy | Canary Islands - Spain |
| Items Collected | 483 | 27 | 142 | 110 | 22 | 128 |
| Phylum | 1 | 1 | 1 | 1 | 1 | 1 |
| Class | 3 | 1 | 3 | 4 | 6 | 6 |
| Order | 10 | 2 | 4 | 9 | 13 | 10 |
| Family (Producer) | 118 | 14 | 79 | 50 | 20 | 53 |
| Genus (Brand/Product line) | 181 | 20 | 51 | 72 | 21 | 65 |
| Species (Specific Product) | 214 | 23 | 114 | 91 | 22 | 84 |

**Table 2**
Family-level dominance patterns by country. Top ten corporate producers (Family level of THCPL) identified in each study region, ranked by their relative contribution (%) to the local plastic assemblage. The table highlights cross-regional differences in producer dominance and market structure, showing both globally distributed producers and region-specific contributors. Percentages represent the proportional abundance of items attributed to each Family within each country, allowing direct comparison of industrial signatures across regions while remaining independent of absolute sample size.

| R | Colombia | | Panama | | Brazil | | Morocco | | Italy | | Canary Islands - Spain | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Family (Producer) | % | | | | | | | | | | |
| 1 | The Coca Cola Company | 10.6 | Coca-Cola Femsa de Panamá S.A. | 37.0 | Sistema Coca-Cola Brasil | 7.7 | The Coca-Cola company | 15.5 | San Benedetto | 9.1 | Coca-Cola System | 7.0 |
| 2 | Postobón S.A. | 7.9 | Ajepana S.A. | 18.5 | Vitarella | 4.2 | Centrale Danone | 6.4 | Société Bic | 9.1 | Danone | 5.5 |
| 3 | Bavaria - Anheuser-Busch InBev | 7.5 | Aguas Cristalina S.A. | 3.7 | Minalba | 4.2 | Société des Brasseries du Maroc | 8.2 | Mondelez International | 4.5 | Nestlé | 4.7 |
| 4 | Grupo Diana | 7.5 | Caribbean Bottle Holdings S.A. | 3.7 | Cia do Sorvete | 4.2 | Trident | 3.6 | Boschi Food and Beverage (Santal) | 4.5 | PepsiCo | 4.7 |
| 5 | PepsiCo | 6.4 | Golden Selection | 3.7 | Nestlé | 4.9 | Leaderfood | 3.6 | Granarolo S.p.A | 4.5 | Heineken Group | 3.9 |
| 6 | Drinks de Colombia S.A.S. | 3.7 | Good Foods Panama | 3.7 | PepsiCo do Brasil Ltda | 4.2 | Centrale Danone | 3.6 | Sun Pharmaceutical | 4.5 | Mahou-San Miguel | 3.9 |
| 7 | One Caribe S.A. S. | 3.1 | Juan Valdez | 3.7 | Santa Joana | 4.2 | Les eaux minérales d'Oulmès | 3.6 | Perfetti Van Melle | 4.5 | Estrella Galicia | 3.1 |
| 8 | Berlhan de Colombia S.A.S. | 2.7 | PepsiCo Inc. | 3.7 | Milet | 2.1 | Excelo | 3.6 | Coop Italia S.C | 4.5 | Grupo Damm | 3.1 |
| 9 | AJE Group | 2.3 | Refrescos Tropicales S.A. | 3.7 | Tingyi (Cayman Islands) Holding Corporation | 2.1 | R. J. Reynolds Tobacco | 2.7 | Pontevecchio S.r.l. | 4.5 | Unilever | 3.1 |
| 10 | Quala S.A. | 2.3 | Unicola Panamá S.A. | 3.7 | Engarrafamento Pitú | 2.8 | Bimo | 2.7 | S.I.V.A. S.R.L. | 4.5 | Procter & Gamble | 2.3 |

plastic assemblages. A similarly structured, though less abundant, dominance pattern was observed in Brazil, led by Sistema Coca-Cola Brasil (N = 11), followed by food, beverage, and confectionery producers such as Nestlé, Vitarella, and PepsiCo do Brasil Ltda.

In Morocco, Family-level dominance was more concentrated, with The Coca-Cola Company again ranking first (N = 17), followed by Société des Brasseries du Maroc (N = 9) and Centrale Danone (N = 7). This pattern suggests a narrower industrial footprint combined with strong market concentration. In contrast, Italy and Panama displayed low absolute abundances and flatter dominance profiles, with most Families represented by single items, reflecting both smaller sample sizes and lower accumulation intensity at the surveyed sites. In Spain (Canary Islands), Family-level patterns revealed a mixed structure dominated by multinational food and beverage corporations (Coca-Cola System, Danone, Nestlé, PepsiCo, Heineken Group), alongside private-label producers (Mercadona, Carrefour, Lidl), pointing the impact of large retail distribution systems.

These cross-country differences confirm that THCPL allows optimal comparative analysis by preserving producer-level resolution across regions, independent of differences in sample size or environmental context. Family-level dominance patterns emerge as a stable and transferable analytical lens, linking plastic assemblages to underlying industrial and consumption systems while maintaining comparability across diverse coastal settings.

### 6.5. *Resolution, uncertainty, and identification limits*

Field-based litter surveys are inherently constrained by item degradation, fragmentation, and loss of diagnostic features, particularly in high-energy coastal environments (i.e., Punta Astilleros, Colombia). Within the THCPL framework, these limitations are treated explicitly rather than as sources of bias. As plastic items fragment and weather, their taxonomic resolution typically decreases, with identification at the Genus and Species levels becoming progressively less feasible, while higher-level classification remains robust. THCPL accommodates this reality by allowing each item to contribute information at the highest taxonomic level that can be assigned with confidence.

Across the six study areas, all collected items could be consistently classified at the Phylum, Class, and Order levels, ensuring complete inclusion in baseline analyses. Resolution declined at finer levels, with Family identification remaining feasible for a substantial proportion of items, while Genus and Species assignments were primarily limited to intact or partially intact objects retaining labels, distinctive shapes, or standardized design features. Rather than forcing full-resolution classification, THCPL applies a conservative truncation rule, whereby ambiguous items are intentionally retained at higher taxonomic ranks.

A further and important limitation arises from the presence of unbranded or inherently non-diagnostic items, which constitute a significant fraction of environmental plastic assemblages. Common examples include fishing gear, ropes, buoys, buckets, footwear (e.g., flip flops), toothbrushes, and other generic consumer or industrial products that either lack brand identifiers at the point of manufacture or lose them rapidly under environmental exposure. These items are frequently among the most abundant components of coastal and marine litter, yet they cannot be reliably assigned to the Family, Genus, or Species levels.

Within THCPL, such items are systematically retained at higher taxonomic levels, primarily Order and Class, where classification remains both consistent and analytically meaningful. This constraint is not specific to THCPL but reflects a general limitation of field-based monitoring, where product traceability is inherently uneven across item types. Importantly, the inability to resolve these items to lower taxonomic levels does not reduce their analytical value. At the Order level, these objects contribute directly to the characterization of functional–material composition, which is closely linked to environmental behavior, transport pathways, persistence, and ecological interaction. For example, fishing gear and buoys can be consistently associated with durable, high-persistence categories, while footwear and household items may reflect distinct consumption and disposal patterns.

This approach preserves cross-site comparability by ensuring that all datasets share a common hierarchical structure, regardless of differences in fragmentation state or product identifiability. Rather than representing a weakness, hierarchical truncation constitutes an integral feature of THCPL, allowing the framework to remain applicable across heterogeneous datasets while maintaining analytical coherence.

## 7. Advantages of THCPL over existing classification systems

### 7.1. Review of existing plastic classification frameworks

Existing plastic classification systems have been developed primarily to support monitoring, environmental assessment, and policy reporting, and represent a substantial body of applied knowledge derived from decades of field-based research and operational practice (Table 3). Among the most widely used frameworks are material-based classifications (polymer types), size-based schemes (macro-, meso-, micro-, and nanoplastics), and standardized monitoring systems such as OSPAR, the MSFD Joint List, and Ocean Conservancy protocols.

These frameworks have demonstrated strong operational value. Material-based classifications are essential for understanding degradation processes, chemical behavior, and environmental persistence, while size-based schemes are critical for evaluating transport dynamics and biological interactions. Monitoring-oriented systems, such as the MSFD Joint List and OSPAR classification, provide standardized categories that enable large-scale data comparability and long-term environmental assessments. Similarly, global initiatives such as Ocean Conservancy's International Coastal Cleanup have generated extensive datasets that inform spatial and temporal trends in marine litter.

In addition, recent large-scale brand audit initiatives, particularly those coordinated by Break Free from Plastic, have significantly advanced the identification of corporate and brand-level contributions to plastic pollution. These initiatives, often based on citizen science approaches, have revealed consistent patterns of producer dominance across regions and have demonstrated the feasibility of attributing environmental plastic items to specific market actors under real-world

**Table 3**
Comparative overview of major plastic classification frameworks and the Taxonomy-inspired Hierarchical Classification of Plastic Litter (THCPL).

| Framework | Primary Purpose | Classification Basis | Structure Type | Strengths | Limitations | Traceability (Producer/ Brand) | Governance Relevance | Integration Capacity |
|---|---|---|---|---|---|---|---|---|
| **Material-based (Polymer)** | Chemical and environmental behavior | Polymer type (e.g., PET, HDPE, PP) | Non-hierarchical | Essential for degradation, toxicity, density analysis | No information on function, use, or origin | None | Indirect | Low (single dimension) |
| **Size-based (Macro–Nano)** | Transport and biological interaction | Particle size | Non-hierarchical | Critical for ecological risk and sampling design | Loss of original item identity and source | None | None | Low |
| **OSPAR / MSFD Joint List** | Monitoring and policy reporting | Item categories and usage | Semi-structured (flat categories) | Standardized, widely adopted, high comparability | Limited source attribution, low hierarchical depth | Limited | High (EU policy frameworks) | Moderate |
| **Ocean Conservancy (ICC)** | Global monitoring and public engagement | Item typology (common litter items) | Flat list | Large global dataset, long-term trends | Limited analytical depth, weak source linkage | None | Indirect | Moderate |
| **Brand Audits (e.g., Break Free From Plastic)** | Corporate accountability | Brand and producer identification | Non-hierarchical (brand-focused) | Strong source attribution, policy relevance | No integration with material or functional properties | High | High (EPR, accountability) | Moderate |
| **THCPL (This study)** | Integrated Earth system analysis | Material + Function + Producer + Brand + Product | Fully hierarchical (6 levels) | Multi-dimensional integration; supports diversity, dominance, and forensic analysis; scalable across datasets | Requires sufficient item preservation for lower levels | High (multi-level) | High (aligned with EPR and policy) | Very High (cross-scale integration) |

conditions.

Despite their strengths, these frameworks operate largely along single analytical dimensions. Material- and size-based systems prioritize physical and chemical properties but do not retain information on functional design, industrial origin, or market identity. Monitoring classifications, while highly standardized, typically aggregate items into predefined categories that limit traceability and reduce resolution at the level of producers and products. Brand audits, although highly effective for identifying corporate contributions, often lack integration within a broader hierarchical system that connects brand-level observations to material properties and environmental behavior.

THCPL builds directly upon these existing approaches by integrating their strengths within a unified hierarchical framework. Rather than replacing established systems, THCPL embeds material, functional, and socio-economic dimensions into a single structure, enabling cross-scale analysis, improved traceability, and enhanced compatibility between environmental monitoring and governance frameworks.

### 7.2. Comparison with material- and size-based classification systems

Material- and size-based classification systems constitute the foundation of most contemporary plastic pollution research and have proven highly effective for specific analytical objectives (van Caneghem et al., 2024). Polymer-based classifications (e.g., PET, HDPE, PP, PS) are essential for understanding chemical composition, degradation pathways, density-dependent transport, and toxicological behavior . Similarly, size-based frameworks, distinguishing macroplastics, mesoplastics, microplastics, and nanoplastics, are indispensable for assessing biological interactions, ingestion risks, and sampling strategies across environmental compartments (Elawady et al., 2026). These approaches provide standardized descriptors that support laboratory analysis, monitoring programs, and regulatory reporting, and their methodological value is well established (Rangel-Buitrago, 2025).

However, when applied in isolation, material- and size-based systems are conceptually limited in their ability to capture the full signal of plastic pollution (Arredondo-Navarro et al., 2024). By design, polymer classifications abstract plastic items from their functional form, production context, and socio-economic origin. For example, a PET fragment derived from a beverage bottle, a cosmetic container, or industrial packaging is treated equivalently at the polymer level, despite these items originating from distinct production systems, use pathways, and disposal behaviors. Similarly, size-based classifications emphasize the end state of fragmentation rather than the original identity of plastic objects, progressively erasing information as items degrade. A microplastic particle retains no formal link to its parent product, brand, or producer, limiting traceability and comparative analysis across regions (Vithanage and Prasad, 2023).

Moreover, these systems are inherently non-hierarchical and operate along single dimensions, preventing the integration of multiple layers of information within a unified framework (Shumway and Ward, 2025). As a result, material- and size-based classifications are poorly suited for addressing questions related to source attribution, market structure, or governance relevance. They describe what plastics are and how big they have become, but not where they come from, how they enter the environment, or why specific patterns occur across regions.

THCPL does not replace these established systems; rather, it complements them by entrenching material and size information within a broader hierarchical structure. By doing so, THCPL preserves the analytical strengths of existing approaches while overcoming their conceptual fragmentation, enabling plastics to be analyzed as structured anthropogenic entities rather than as isolated material descriptors.

### 7.3. Gains in analytical, forensic, and governance capacity

By integrating material properties, functional form, and socio-economic origin within a single hierarchical framework, the THCPL framework y expands the analytical, forensic, and governance capacity of plastic pollution studies. Unlike conventional classification systems, THCPL enables plastics to be examined as structured assemblages. This capability supports comparative studies among regions, coastal typologies, or time periods, revealing structured patterns that remain invisible under polymer- or size-only approaches.

At the forensic level, THCPL increases traceability by preserving links between environmental plastic items and their industrial origin. Family- and Genus-level classification enables the identification of producer- and brand-specific signatures within litter assemblages, even when product-level resolution is no longer possible due to fragmentation. For example, the recurrent dominance of specific corporate producers across multiple coastal sites can be detected and compared without requiring intact labels or species-level identification. This form of structured attribution provides a reproducible, evidence-based pathway for investigating sources and pathways of plastic inputs, particularly in regions influenced by mixed land-based and marine sources.

From a governance perspective, THCPL offers clear advantages by aligning environmental observations with existing regulatory and policy frameworks. Producer-level classification directly supports EPR schemes, which require robust mechanisms to associate environmental loads with market actors . By translating field observations into standardized producer and brand categories, THCPL enables policy-relevant analyses without introducing normative judgments or assumptions about responsibility. For instance, cross-regional comparisons of Family-level dominance can inform discussions on transboundary pollution, market penetration, or the effectiveness of packaging regulations, while remaining grounded in empirical evidence.

Recent large-scale brand audit initiatives (e.g., Break Free from Plastic) further demonstrate the importance of linking environmental plastic items to corporate and brand-level identifiers. These efforts, largely based on citizen science and global clean-up campaigns, have revealed consistent patterns of producer dominance across regions. THCPL provides a formal hierarchical structure that complements such initiatives by integrating brand-level observations within a broader, multi-level classificatory framework, enabling their incorporation into systematic scientific analysis.

The THCPL approach facilitates communication between scientific, regulatory, and management communities by providing a common classificatory language. This integrative capacity allows chemical, biological, and geological data to be contextualized within broader production and consumption systems, strengthening the relevance of plastic pollution research for decision-making. In this way, THCPL moves beyond descriptive categorization, offering a practical framework for linking environmental data to forensic investigation and governance processes.

## 8. Implications for monitoring governance, and the anthropocene record

### 8.1. Standardization and long-term monitoring

One of the principal contributions of the THCPL lies in its capacity to harmonize plastic litter data across regions, monitoring programs, and temporal scales. A persistent limitation in plastic pollution research has been the lack of a shared classificatory framework capable of integrating heterogeneous datasets produced under different methodological, cultural, and regulatory contexts (Corbau et al., 2025). The hierarchical structure with clearly defined taxonomic levels of the THCPL establishes a common language that enables direct comparison among studies without requiring methodological uniformity at the point of data collection.

THCPL is explicitly designed to work under variable data resolution. Items can be consistently classified at higher taxonomic levels even when fine-scale identification is constrained by fragmentation or weathering. This feature is particularly advantageous for long-term monitoring, where changes in sampling intensity, personnel, or environmental conditions often introduce inconsistencies (GESAMP 2019; Smith and Turrell, 2021). By preserving information at the highest confidently identifiable level, THCPL permits historical and contemporary datasets to be reinterpreted within the same analytical framework, supporting temporal trend analysis and retrospective synthesis.

Producer-level (Family) classification can be applied consistently across decades, even as product designs or brand portfolios change (i.e., the Coca-Cola company). This allows long-term tracking of shifts in industrial signatures within coastal litter assemblages, independent of short-lived packaging changes. Similarly, Order-level functional categories allow monitoring programs to assess changes in the functional composition of plastic debris, such as transitions from rigid containers to flexible films, with clear implications for transport and ecological interaction.

Through this hierarchical flexibility, THCPL supports scalable monitoring strategies that can be updated over time without sacrificing comparability. As such, it provides a optimal foundation for regional, national, and international monitoring initiatives seeking to integrate plastic pollution data across space and time.

### 8.2. Corporate accountability and policy relevance

This framework also provides a direct and scientific bridge between environmental observation and policy-relevant governance frameworks. By incorporating corporate producers, brands, and specific marketed products within a hierarchical classification, THCPL allows plastic pollution data to be aligned with regulatory instruments that operate at the level of producers and markets, most notably EPR schemes. This alignment addresses a long-standing gap between how plastic pollution is monitored in the environment and how responsibility is assigned in policy contexts.

Under conventional monitoring frameworks, plastic litter is typically reported in aggregated material or size categories, which limits its relevance to governance mechanisms that require traceable links to economic actors (Williams and Rangel-Buitrago, 2019 and 2022). THCPL overcomes this limitation by allowing environmental plastic assemblages to be described in terms of identifiable producer and brand signatures, without introducing normative judgments or assumptions of liability. In this sense, THCPL increases transparency by making industrial and market structures visible within environmental datasets, while preserving scientific objectivity.

For example, Family-level classification allows monitoring programs to document the relative contribution of major producer groups within coastal litter assemblages across regions and time periods. This type of information can support evidence-based discussions on packaging policy, product stewardship, and the effectiveness of regulatory interventions, while remaining descriptive rather than prescriptive (Johnson et al., 2025). Importantly, THCPL does not assign responsibility or evaluate corporate behavior; it provides a structured evidentiary basis upon which governance decisions may be informed.

Beyond EPR, THCPL also supports broader environmental governance objectives by facilitating cross-jurisdictional comparison and harmonized reporting. A shared taxonomic framework enhances the comparability of national and regional datasets, strengthening international cooperation and supporting policy evaluation at multiple scales (Seo et al., 2026). Translating complex environmental observations into structured, traceable categories, THCPL increases the policy relevance of plastic pollution research and contributes to more transparent, accountable, and coherent environmental governance.

### 8.3. Stratigraphic, geological and archaeological implications

Beyond its relevance for monitoring and governance, THCPL has direct implications for the interpretation of plastics within the stratigraphic, geological and archaeological record. As plastics become progressively incorporated into soils, sediments, coastal deposits, and anthropogenic strata (Rangel-Buitrago et al., 2022; Russell et al., 2025), their classification as discrete, hierarchically organized entities provide a structured framework for interpreting future technofossil assemblages. THCPL offers a means to translate heterogeneous plastic deposits into analytically meaningful units that reflect both material properties and socio-economic origin.

THCPL will be essential for comparative reference that will support future archaeological research. As ubiquitous materials of the modern world, plastics will serve as key chronological and cultural markers of the Anthropocene. THCPL enables accurate identification and provides a framework for establishing chronologies linked to technological change and consumption patterns, offering future archaeologists a solid basis for interpretation.

At higher taxonomic levels, THCPL categories such as Class and Order correspond to broad material and functional signatures likely to persist in sedimentary archives, influencing preservation pathways, fragmentation patterns, and lithification potential. At finer levels, Family- and Genus-level attribution preserves information on industrial systems and consumption structures, which may remain identifiable through diagnostic forms, composite materials, or distinctive manufacturing features embedded in future deposits. In this sense, THCPL facilitates the interpretation of plastic-bearing strata not merely as accumulations of synthetic polymers, but as stratigraphic expressions of specific phases of industrial production and market organization.

By linking material persistence with production and consumption systems, THCPL provides a conceptual bridge between environmental observations and the emerging geological archive of the Anthropocene. This framework supports the systematic interpretation of plastics as technofossils, reinforcing their role as durable markers of human transformation of the Earth system and contributing to a more structured understanding of the Anthropocene sedimentary record.

## 9. Conclusions

This paper introduces the THCPL as a conceptual and operational framework designed to classify plastic litter as structured anthropogenic entities within the Earth system. By moving beyond material- and size-based descriptors, THCPL establishes a hierarchical taxonomy that integrates material composition, functional form, industrial origin, market identity, and product-level specificity. This approach responds directly to the conceptual fragmentation that has characterized much of the plastic pollution literature and provides a coherent structure capable of capturing the full signal of plastics across environmental compartments.

The primary conceptual innovation of THCPL lies in its explicit recognition of plastics as coupled socio-material entities. By incorporating corporate producers, brands, and specific marketed products as taxonomic levels (while clearly defining ontological and epistemological boundaries) THCPL enables plastics to be analyzed not only as pollutants, but as material expressions of industrial systems, consumption patterns, and long-term Earth system transformation. The framework preserves analytical rigor by maintaining a strict separation between classification and normative evaluation, ensuring that THCPL remains a scientific tool rather than a supporting instrument.

The empirical application of the THCPL across six coastal study areas in Brazil, Colombia, Italy, Morocco, Panama, and Spain demonstrates the operational feasibility and analytical coherence of the framework under real-world field conditions. A total of 912 plastic items were classified using THCPL, encompassing a wide range of coastal typologies, accumulation intensities, and socio-economic contexts. Across all datasets, items were consistently resolved at the Phylum, Class, and Order levels, confirming the robustness of material- and function-based classification. At finer resolutions, THCPL enabled the identification of 314 distinct corporate producers (Families) and 455 brands or product lines (Genera) across countries, with Species-level resolution achieved where preservation allowed. Family-level dominance patterns varied markedly among regions, with highly diversified producer assemblages in Colombia and Brazil, more concentrated profiles in Morocco and Spain, and lower-abundance, flatter distributions in Italy and Panama.

From a scientific perspective, THCPL enhances analytical capacity by enabling cross-scale comparison, diversity and dominance assessments, functional composition analysis, and forensic source attribution under real-world field conditions. Its hierarchical flexibility allows items to be classified at the highest reliable resolution, ensuring comparability across regions and time even when fragmentation constrains fine-scale identification. The empirical application across six countries demonstrates that THCPL is operational, transferable, and robust across contrasting coastal typologies, accumulation regimes, and socio-economic contexts.

Beyond research applications, THCPL holds significant societal and governance relevance. By aligning environmental observations with producer- and market-level identifiers, the framework provides a transparent bridge between monitoring data and policy instruments such as EPR schemes. THCPL supports harmonized reporting, cross-jurisdictional comparison, and evidence-based policy evaluation without assigning responsibility or imposing value judgments. In parallel, its structured approach contributes directly to the interpretation of plastics as technofossils, providing a systematic and reproducible lens through which future sedimentary records of the Anthropocene may be read. By preserving information on material properties, functional form, and socio-economic origin, THCPL enables plastic-bearing strata to be interpreted not merely as accumulations of synthetic polymers, but as stratigraphic expressions of specific industrial systems, consumption regimes, and historical phases of human activity. In this sense, THCPL contributes to the development of a readable Anthropocene stratigraphy, in which plastics function as culturally and industrially encoded material markers.

THCPL establishes the necessary foundation for quantitative extensions through the development of Anthropocene Taxonomy of Plastics Indices (ATPI), which will formalize metrics of diversity, dominance, and functional structure across taxonomic levels. Future research should also explore the application of ATP to additional environmental compartments, including river systems, urban environments, and deep-sea settings, as well as its integration with chemical, biological, and socio-economic datasets. By providing a stable classificatory framework, THCPL opens new ways for interdisciplinary research, long-term monitoring, and policy-relevant analysis of plastic pollution.

## CRediT authorship contribution statement

**J.A.G. Cooper:** Writing – original draft, Investigation. **Martin Juan Guillermo:** Writing – original draft, Investigation. **Francois Galgani:** Writing – original draft, Investigation. **William J. Neal:** Writing – original draft, Investigation. **Alex Paternina-Ramos:** Writing – original draft, Investigation. **Tommaso Giarrizzo:** Writing – original draft, Investigation, Conceptualization. **Nelson Rangel-Buitrago:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francisco Jailton Silva Filho:** Writing – original draft, Investigation, Conceptualization. **Lucio Brabo:** Writing – original draft, Investigation, Conceptualization. **Leví García-Romero:** Writing – original draft, Investigation. **Mohamed Ben-Haddad:** Writing – original draft, Investigation. **Carolina Peña-Alonso:** Writing – original draft, Investigation.

## 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. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ancene.2026.100561.

## Data availability

Data will be made available on request.

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