The shapes and sizes of macroplastics and other litter in rivers

James Lofty[1], Daniel Rebai[1*], Daniel Valero[2], Mário J. Franca[1]

[1]Institute for Water and Environment (IWU), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

[2] Department of Civil and Environmental Engineering, Imperial College London, London, UK

*Corresponding author

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Abstract

Limited data exists on physical and geometric properties of river macrolitter. To resolve this, we reveal the physical-structural relationships of river macrolitter, using two of the most comprehensive datasets generated to date. First, we dissect the properties of river litter using a detailed dataset of over 14,000 riverbank items, for which their dimensions (longest L_1, intermediate L_2, shortest L_3) and physical characteristics (mass, volume, density) are determined. These properties were then mapped onto a dataset of nearly 240,000 River-OSPAR items collected from 22 river and riverbank sites across four continents, using multivariate statistics and database density estimates. We then identify the most persistent River-OSPAR litter categories, together with kernel density estimations of their principal dimensions and geometries. Results show that only 25 River-OSPAR categories account for 80% of all river and riverbank litter, with soft plastic pieces/films and candy, snack, and crisps packaging being the most abundant. Flat, 2D shaped macrolitter are the most persistent litter items, with 48% of the top 25 items sharing similar geometric properties: L_1 between 1 - 10 cm, and a flatness ratio (L_3 / L_2) of < 0.4. In practice, these are flat objects with two larger dimensions and a third that is at least one order of magnitude smaller. This large, physically based dataset enables prioritisation of which shapes, sizes, and densities should be targeted by future plastic transport models, informing what plastics may be missing in current monitoring protocols, and the design of river clean-up technologies.

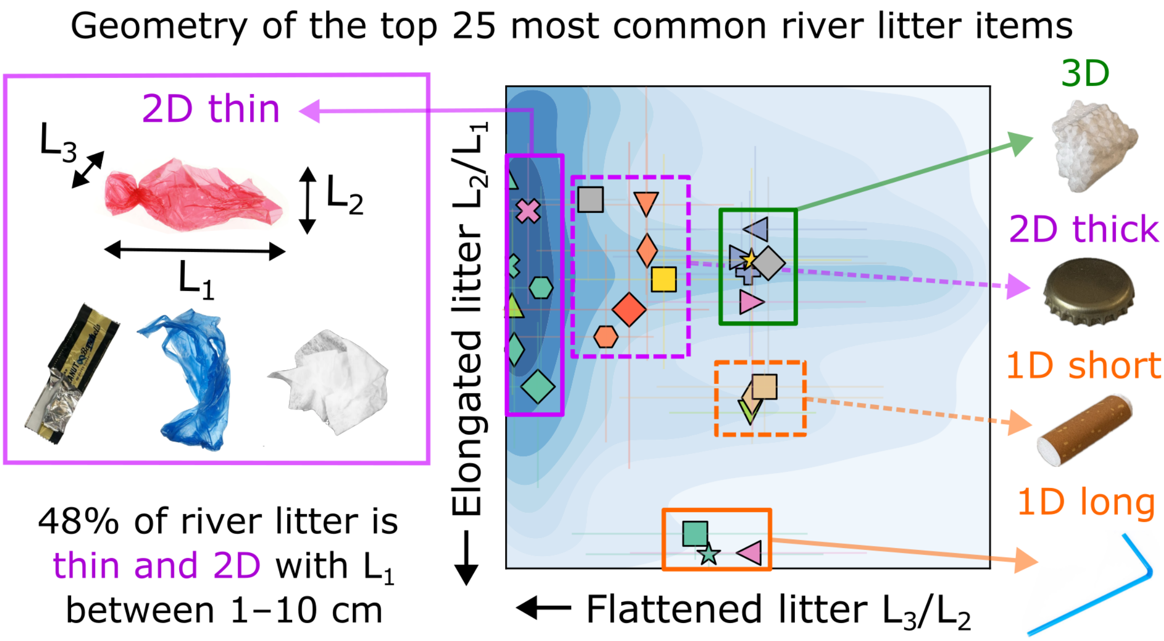
Keywords

Plastic pollution, Freshwater environments, Plastic inventory, Debris, River plastic transport, Plastics Treaty, Pollution modelling, OSPAR Commission.

Synopsis

This study demonstrates that just 25 River-OSPAR categories account for 80% of river litter, with 48% of items having the longest dimension of 1–10 cm and geometries that are flat 2D shapes.

Graphical abstract



1 Introduction

Plastic pollution is one component of the United Nations' triple planetary environmental crisis[1], owing to its environmental persistence and detrimental impacts on biodiversity[2], human health[3], infrastructure[4], and the economy[5]. Governments and international organisations are drafting a legally binding resolution in response to plastic pollution, which includes the development of strategies to monitor, manage, and remediate existing litter in the environment[6]. River systems are known conveyors and accumulation zones of macrolitter (litter items with a longest dimension > 1cm[7]) originating from land-based sources and are increasingly recognised in monitoring and clean-up efforts[8,9]. A critical step toward developing such solutions in rivers is identifying the most persistent polluting litter items and quantifying the physical properties that govern their mobilisation, movement and fate. This, in turn, will assist on clarifying which litter properties should be prioritised for the development of transport models, which litter items may be missed by current monitoring campaigns, or simply to inform the design of clean-up strategies in rivers.

One methodology currently adopted to characterise macrolitter collected from rivers and riverbanks is the River-OSPAR (Oslo-Paris Convention) litter index, which is an adaptation of the OSPAR Guidelines[10] originally developed for monitoring marine litter on beaches but modified to include categories common to riverine environments (see[11] for an evaluation of the River-OSPAR litter index in rivers). The River-OSPAR litter index comprises 109 unique litter categories and provides a harmonised framework for data collection across different basins and river compartments (i.e. riverbanks, water column and riverbed). This enables a consistent record of river litter by volunteers, researchers, and stakeholders. While this approach has enhanced public awareness and, in some cases, influenced policy decisions, such as the European Union's directive on single-use plastics[12], the River-OSPAR classification system primarily provides qualitative information on the types of litter common in rivers, without their geometric or material properties.

By employing the River-OSPAR litter index, or through similar methodologies, previous studies have quantified and catalogued the different types of litter found in both the active channel (the river)[13–15] and the adjacent low-lying floodplains (the riverbank)[16–18]. The quantitative characteristics of these items, such as their dimensions, shape, flexibility and density, require intensive efforts and are typically overlooked by many monitoring campaigns. To the knowledge of the authors, there is no single real-world dataset of individual river litter items, which include their principal dimensions, as well as their volume, mass and density. These properties are nonetheless fundamental parameters for determining when macrolitter is mobilised, how they are predominately transported and where they ultimately end up[19,20]. Furthermore, simplifying the wide diversity of river litter into their statistical distributions provides useful information[21], for instance, inputs for population balance models[22] that can predict transport in fluvial environments for continuous distributions of litter.

This study conducts a meta-analysis compiling published research that have sampled and categorised macrolitter items from rivers and riverbanks using the River-OSPAR litter index. This allows us to establish the top 25 most persistent litter items across global river systems, building on a dataset of 239,290 litter items from 22 study sites across four continents. Using multivariate statistics, we then map their physical properties from a more detailed dataset of 14,052 litter items collected from riverbanks[23]. This statistical analysis allows us to characterise the complete geometric and material properties of river macrolitter, including their shortest dimension and volume, which are absent from the dataset of de Lange et al. (2023) and most other studies. This delivers a comprehensive description of the most persistent types of river litter and helps to prioritise which shapes and sizes should be targeted by future plastic transport models, monitoring protocols, and clean-up technologies.

2 Methods

2.1 Literature search and meta-analysis

First, we identify and compile into a database studies that report and categorise litter collected from in-stream sampling of active channels (rivers) and litter collected from adjacent floodplains (riverbanks) using the River-OSPAR litter index[11]. Using a Scopus-keyword search, a total of 14 research studies were suitable for meta-analysis: eight studies which focused on sampling litter in rivers and six studies that sampled litter from riverbanks. The studies investigated are displayed in Table 1 and include eleven different rivers from Europe, Central America, Africa and Asia, covering varying social-economic levels, land usages and sampling flow conditions. Table 1 shows the selected studies, the geographical locations of the river, the study area (river or riverbank), collection method and the total number of

River-OSPAR items categorised, and TablesS1 presents further information on each study location's social-economic status, land usage, sampling frequency and seasonality.

While several litter classification schemes exist[24–27], of which none have been widely accepted as a standardised method, we focused on the River-OSPAR index for three main reasons. First, it was specifically developed for categorising litter items in fluvial environments and has a detailed hierarchical structure that allows finer discrimination between item types, sizes, and materials. Second, studies applying the River-OSPAR index tend to report full item-by-item inventories rather than aggregated categories, improving data harmonisation and comparability across sites and studies. Third, extensive item-by-item datasets containing size and mass information for River-OSPAR-indexed items are available, such as de Lange et al. (2023), of which comparable datasets are not available for the other litter indexes.

Table 1. Selected studies for meta-analysis, river location, study area (river or riverbank), collection method, River-OSPAR items considered and total number of plastics collected in the study.

Study	Rivers sampled	Location	Study area	Collection methodology	River-OSPAR items considered	Total number of categorised River-OSPAR items
van Emmerik et al. 2020b	Meuse, Waal and Rhine Rivers	The Netherlands	Riverbank	River-OSPAR protocol [11]	All items	152,415
Ballerini et al. 2022	Durance River	France	Riverbank	Beach-OSPAR protocol[10]	All items	25,423
Tramoy et al. 2019	Seine River	France	Riverbank	Visually using a $1\ m^2$ quadrat	All items	20,259
de Lange et al. 2023	Rhine, IJssel, and Meuse Rivers	The Netherlands	Riverbank	River-OSPAR protocol[11]	All items	16,488
Oswald et al. 2023	Waal River	The Netherlands	River (water column)	Anchored stow net covering entire water column	64 plastic items (no glass or metal)	12,832
Oswald et al. 2025	Rhine, Waal and IJssel Rivers	The Netherlands	River (surface, suspended and near-bed)	Larve and trawl nets at three depths (surface, suspended, near-bed)	64 plastic items (no glass or metal)	11,153
Vriend et al. 2023	Rhine River	The Netherlands	River (surface, suspended and near-bed)	Trawl net at three depths (surface, suspended and near-bed)	All items	6,684
Pinto et al. 2024	Odaw River	Ghana	Riverbank	$5\times2\ m^2$ riverbank survey	All items	3,802
Tramoy et al. 2022	Huveaune River	France	River (water column)	Grab sampling from bar screens	All items	3,147

Silburn et al. 2023	Belize River	Belize	Riverbank	Beach-OSPAR protocol [10]	All items	2,505
Tasseron et al. 2024	Rhine, IJssel, and Meuse Rivers	The Netherlands	Riverbank	Battulga [26], CrowdWater[33], Plastic Pirates[25], and NOAA beach protocol [34].	All items	1,865
Nguyen and Bui 2023	Saigon River	Vietnam	Riverbank	River-OSPAR protocol[11]	All items	713
van Emmerik et al. 2018	Saigon River	Vietnam	River (surface load)	Trawl net from bridge	All items	614
Bardenas et al. 2023	Mahiga Creek	Philippines	River (surface and suspended load)	Trawl net at surface	32 plastic items (no glass nor metal)	124

2.2 Identifying prevalent litter items in rivers and on riverbanks

From the studies selected, we extracted data on either the total count or the percentage of each River-OSPAR item identified in the selected rivers or riverbanks. This database was constructed by manually extracting reported litter data and metadata from 14 published studies. When numerical data were only available as figures, we digitised the graphs to obtain the counts or relative proportions of the most common River-OSPAR items. Some investigations reported only the top 10 or 20 River-OSPAR litter items found in the sampled river or used a shortened River-OSPAR list only considering items composed of plastic (Table 1). As a result, the total amount of each litter item was sometimes not available from each study and subsequently resulted in a total of 239,290 litter items from the selected studies. In order to remove bias towards studies with larger samples, we first compute the relative occurrence of each River-OSPAR litter category. We then calculate the average relative occurrence, considering the 14 studies selected (Table 1), allowing us to establish a global rank of most prevalent litter items

We classify each River-OSPAR category based on their potential material composition. These include soft polyolefin (PO soft) plastics, which consist of flexible plastics likely composed of low-density polyethylene (LDPE) or polypropylene (PP) and include plastics like bags, films and wrappings. Hard polyolefin (PO hard), which consist of plastics that are rigid and are likely composed of polymers such as high-density polyethylene (HDPE) and PP and include items such as bottle caps, lighters and hard containers. We also assign River-OSPAR categories to polymers which are typically composed of only one polymer, which include polystyrene (PS), expanded polystyrene (EPS), polyethylene terephthalate

(PET). We also include multilayered items, where multiple materials are combined in their composition, such as crisp packets made from laminated plastic films with a thin aluminium layer, cigarette filters typically composed of cellulose acetate wrapped in paper, and Tetra Pak juice cartons consisting of paperboard and polyethylene. Other materials included glass, metal, paper, wood, rubber and textiles. Table 2 displays the materials assigned to each River-OSPAR item collected from rivers and on riverbank with their common usage as well as a density (ρ) lower and upper limit based on the polymers included in that category, based on densities provided by Kooi et al 2019

We further flag each River-OSPAR category by whether the item is flexible and will deform under typical river hydrodynamics or will remain rigid in structure (Table 2). This classification is of interest since the dimensions and geometry of flexible elements can change during river transport, which may influence how they are mobilised, deposited, or retained.

Table 2. Material classifications assigned to each River-OSPAR litter item, their common usage, density range[21] and flexibility.

Material category	Common usage	Density range (ρ) (g/cm^3)	Rigid/flexible
Soft polyolefin (PO soft)	Flexible plastics: plastic bags, films, foils and wrappings	0.83 – 0.98	Flexible
Hard polyolefin (PO hard)	Rigid plastics: bottle caps, lighters and hard containers	0.83 – 0.92	Rigid
Polystyrene (PS)	Plastic cutlery, food containers, straws and cups	1.04 – 1.10	Rigid
Expanded polystyrene (EPS)	Foams, packaging, takeaway containers	0.01 – 0.04	Rigid
Polyethylene terephthalate (PET)	Plastic bottles	1.35 – 1.45	Rigid
Multilayer	Cigarettes, crisp packets, candy bar wrapper, juice or milk cartons	0.89 – 1.45	Rigid/Flexible
Other plastics	Plastic items not described in the River-OSPAR litter index	0.89 – 1.45	Rigid/Flexible
Glass	Glass bottles and jars	2.20 – 2.80	Rigid
Metal	Beverage cans, glass bottle caps, scrap metal	2.70 – 8.00	Rigid
Rubber	Tyres, balloons and condoms	1.10 – 1.20	Rigid/Flexible
Paper	Cardboard packaging, toilet paper, newspaper and cups	0.60 – 1.20	Rigid/Flexible
Textiles	Clothing, carpets, fabrics	1.30 – 1.80	Flexible
Wood	Pallets, corks, ice cream sticks	0.30 – 1.00	Rigid

2.3 Shape and size statistical description

To characterise the dimensions and shapes of litter in rivers and on riverbanks, we start by dissecting the dataset of de Lange et al., (2023), which reports the mass (M) (to a limit of 0.01 g), the two largest dimensions (L_1 and L_2) (to 0.1 cm accuracy), and the River-OSPAR ID for 14,052 litter items collected from riverbanks along the Dutch Rhine, IJssel, and Meuse rivers. Further details regarding the collection methodology of the litter items and uncertainties can be found in the relevant publication [23]

We first computed the Pearson coefficient for the de Lange et al. (2023) dataset (Figure S1), which showed positive correlations, indicating that larger values in one variable are generally associated with larger values in the others, which aligns with the expectations (i.e. larger dimensions typically contribute to a greater particle mass). Correlations were non-negligible, suggesting that the statistical dependence among mass and size variables must be explicitly accounted for in the statistical modelling process.

For each River-OSPAR category, we next model the joint probability distribution using empirical copulas[38], a tool which enables the separate modelling of the dependence (correlation) structure among multiple random variables.

We generated a synthetic dataset by aggregating item counts reported from each of the 14 investigations in Table 1. In these studies, the authors provide the total number of litter and River-OSPAR ID of each item. For each site, we created a dataset of $N = 10^4$; which is large enough to be statistically meaningful. Take Nguyen and Bui (2023) as an example: the study found that 12.34% of litter in the Saigon River consisted of plastic bags (e.g., shopping bags) (River-OSPAR ID = 2). Accordingly, this study contributes 1,234 synthetic items with River-OSPAR ID = 2. For each of these 1,234 synthetic elements, we assign M, L_1 and L_2 by randomly drawing from the corresponding category from de Lange et al. (2023), following the observed distribution. For example, this implies that we assume a plastic bottle found in the Rhine River is comparable to a plastic bottle found in the Saigon River, or in any other river worldwide. For certain River-OSPAR categories, no objects were found in the de Lange dataset. In these cases, it was not possible to apply this category-based procedure. Then, we use the all-categories distribution.

To validate this approach, we compared the item masses in the generated synthetic dataset to two independent datasets from the Seine River (France)[18] and the Saigon River (Vietnam)[35]. Figure S2 shows that both studies report the average mass per River-OSPAR category, and the results are analogous to those from the generated synthetic dataset

2.4 Completing volume and shortest dimension

The mass of an object is related to the density and the volume by $M = \rho V(L_1, L_2, L_3)$. We nonetheless lack prior information on the density of individual plastic litter items from the original studies. To address this, we adopted a statistical modelling approach. We first treat density as a random variable by assigning a triangular symmetric distribution using the ranges of Table 2. This is then transferred to object volume through $V = M/\rho$.

However, in some cases, the measured volume of the item does not correspond directly to the polymer material volume. A typical example is beverage bottles > 0.5 L, where the PET polymer makes up only about 2% of the object's total volume. For such categories, the volume of the object would be incorrect. To address this, we instead calculated effective density ranges (defined as the mass of the item divided by its total measured volume, which includes voids). This adjustment was applied to categories where the material density does not represent the bulk density of the object, which included plastic bottles, metal beverage cans, glass bottles, plastic cups and straws.

We next modelled the volume term $V = kL_1L_2L_3$, as a random function where k is an unknown parameter, based on the shape. As litter items can be found in a large diversity of shapes, we assigned a shape selected at random and in equal proportions from a set of common geometric approximation: cuboid ($k = 1$), ellipsoid ($k = \pi/6$), elliptical cylinder ($k = \pi/4$), triangular prism ($k = 1/2$), elliptical cone ($k = \pi/12$), tetrahedron ($k = 1/6$), rectangular pyramid ($k = 1/3$), elliptical pyramid ($k = \pi/12$), and wedge ($k = 1/2$). Under these assumptions, it is possible to estimate the unmeasured third dimension, $L_3 = V/kL_1L_2$.

By estimating the shortest dimension (L_3) of each litter item, we can infer key shape parameters. For every litter item in the synthetic dataset, elongation ($EL = L_2/L_1$) and flatness ($FL = L_3/L_2$) ratios were calculated, as well as Corey shape factor[39] ($CSF = L_3/\sqrt{L_1 L_2}$). These shape descriptors enable a detailed characterisation of the size and shape of litter items based on their dimensions and geometric approximations and have been used previously to quantify sediment [39–41] and plastic transport formulae [42–44].

To validate the chosen approach, we performed three sensitivity tests surrounding assumptions made regarding material density and litter shape, which affect the estimation of L_3. First, we assumed that the distribution of the material density for each River-OSPAR category was uniform, instead of triangular. Second, we considered the density as triangular distribution but doubling the density range (e.g., for the material densities ranges for PET we used 1.25 - 1.55 g/cm instead of 1.35 - 1.45 g/cm^3, as in Table 1). Third, since all shape factors (k) are bounded within the interval between 0 and 1, in the alternative scenario, we assumed a uniform distribution over this interval, $k \sim$U(0,1). The resulting cumulative distribution functions of L_3, shown in Figures S3, do not change significantly under these different scenarios, confirming the robustness of the proposed approach.

3 Results

3.1 The most persistent macrolitter items in river environments

The meta-analysis covers a total of 34,296 and 204,994 litter items in rivers and riverbanks, respectively. Figure 1 shows the top 25 most persistent River-OSPAR items, separated by their study area (river or riverbank), and coloured by their material composition.

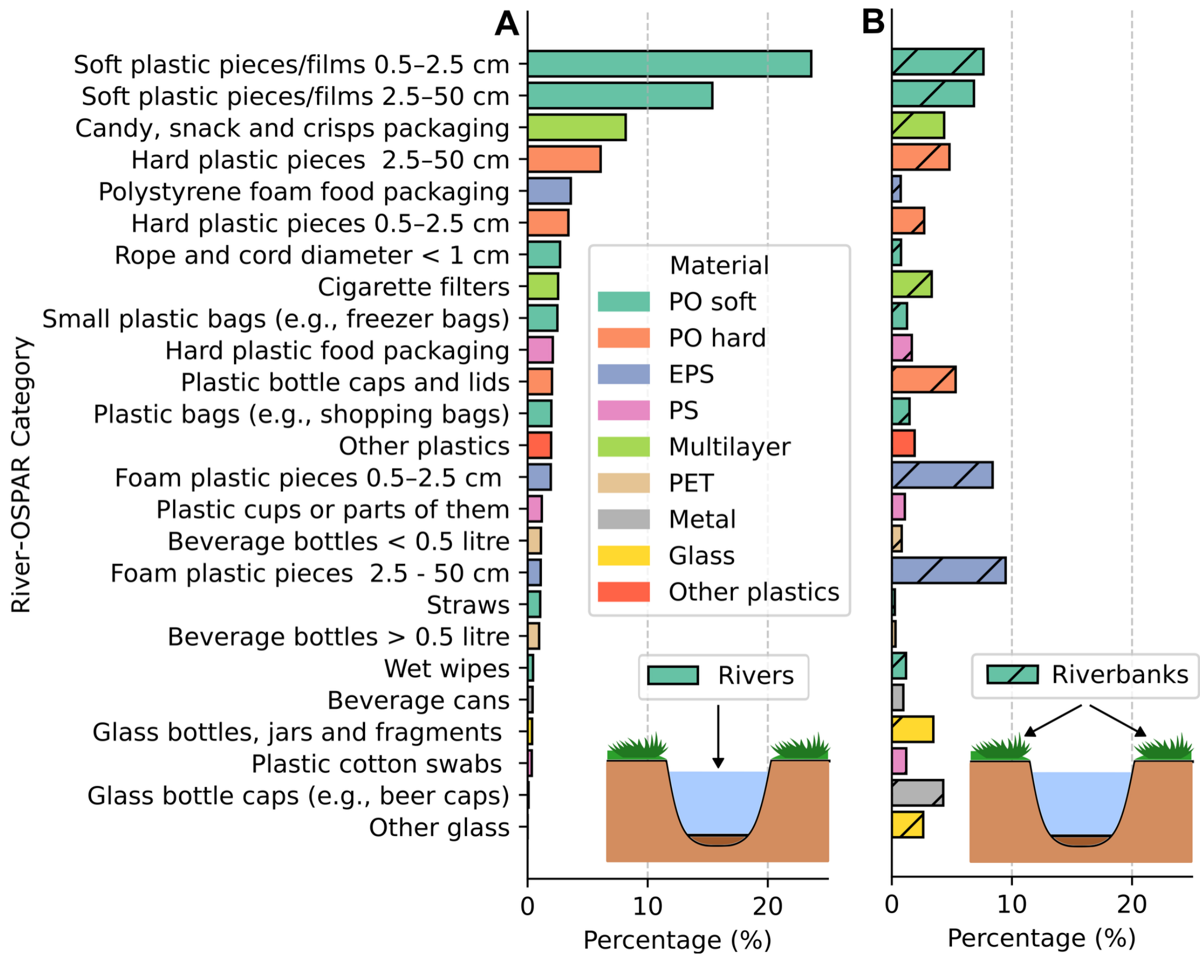


Figure 1. Top 25 most persistent River-OSPAR items in A) rivers (*N* = 34,296 items) and B) on riverbanks (*N* = 204,994 items), separated by their study area (river or riverbank) and coloured by their typical material composition.

The top 25 items shown in Figure 1 represent 80% of the most persistent litter items found in riverine systems. The data reveals distinct differences in the composition of litter found between rivers and riverbanks. In rivers, soft plastic pieces/films 0.5–2.5 cm (River-OSPAR ID 117.2) (23%), soft plastic pieces/films 2.5–50 cm (River-OSPAR ID 46.2) (15%) and candy, snack and crisps packaging (River-OSPAR ID 19) (8%) were the most commonly identified items. Over half the litter items identified in rivers were composed of PO soft plastic (54%), with a typical material density close to that of water (ρ = 0.89 – 0.98 g/cm^3) (Table 2). In contrast, on riverbanks the most common items were foam plastic pieces 2.5–50 cm (River-OSPAR ID 46.3) (9%) and foam plastic pieces 0.5–2.5 cm (River-OSPAR ID 117.3) (8%). These materials are commonly composed of highly-buoyant EPS (ρ = 0.01 – 0.04 g/cm^3) (Table 2) and were predominantly found on riverbanks and less frequently in water samples.

Variations in litter composition between the river and riverbanks can be attributed to differences in hydrodynamics between river compartments. In rivers, litter is transported from upstream sources, while on riverbanks, litter is introduced either through direct human activity or via overbank flooding events that occur a few times each year. Unlike in rivers, where continuous transport is likely for litter with a density similar to water, litter deposited on a riverbank typically remains stationary until it is re-mobilised by another bank-overflow event. The likelihood of different types of litter being deposited on riverbanks during high-flow events depends largely on their buoyancy. Highly buoyant items, such as EPS, which float on the water surface are more likely to be deposited on the banks after a high flow event and retained by vegetation as water levels recede[45,46]. In contrast, litter with a density closer to that of water, such as PO soft litter, are likely to be submerged and mix within the active channel, making them less likely to be deposited on riverbanks[46]

Alternatively, differences in litter composition can arise from the sampling methodology. Most in-stream river litter collections from the meta-analysis (Table 1) have focused on sampling the surface or suspended layers of the river. For instance, six studies sampling the surface layer, which hold a bias for buoyant items or items that are hydrophobic, stabilised by surface tension [47]. Four studies sampled the suspended layer, capturing items whose transport is governed by turbulence, and only three studies targeted the near-bed region (5 – 10 cm above the riverbed). Notably, none of the studies in this meta-analysis employing the River-OSPAR litter categories conducted direct sampling of the riverbed or sediments, where dense materials such as glass and metal would be transported as bedload or deposited in the riverbed. Consequently, reported riverine litter compositions may be biased toward floating and suspended materials, underestimating the contribution of high-density items deposited in sediments or transported as bedload.

3.2 Size distributions of macrolitter in rivers

Figure 2A-C presents Kernel Density Estimation (KDE) plots of the longest (L_1), intermediate (L_2), and shortest (L_3) dimensions, of the top 25 River-OSPAR items, ranked by their prevalence in rivers. Data presented in Figure 2 and from this point onwards, correspond to the dataset described in Section 2.3

and 2.4, which is available at Lofty (2025). KDE plots of each River-OSPAR litter category's volume, mass and density are available in Figure S4.

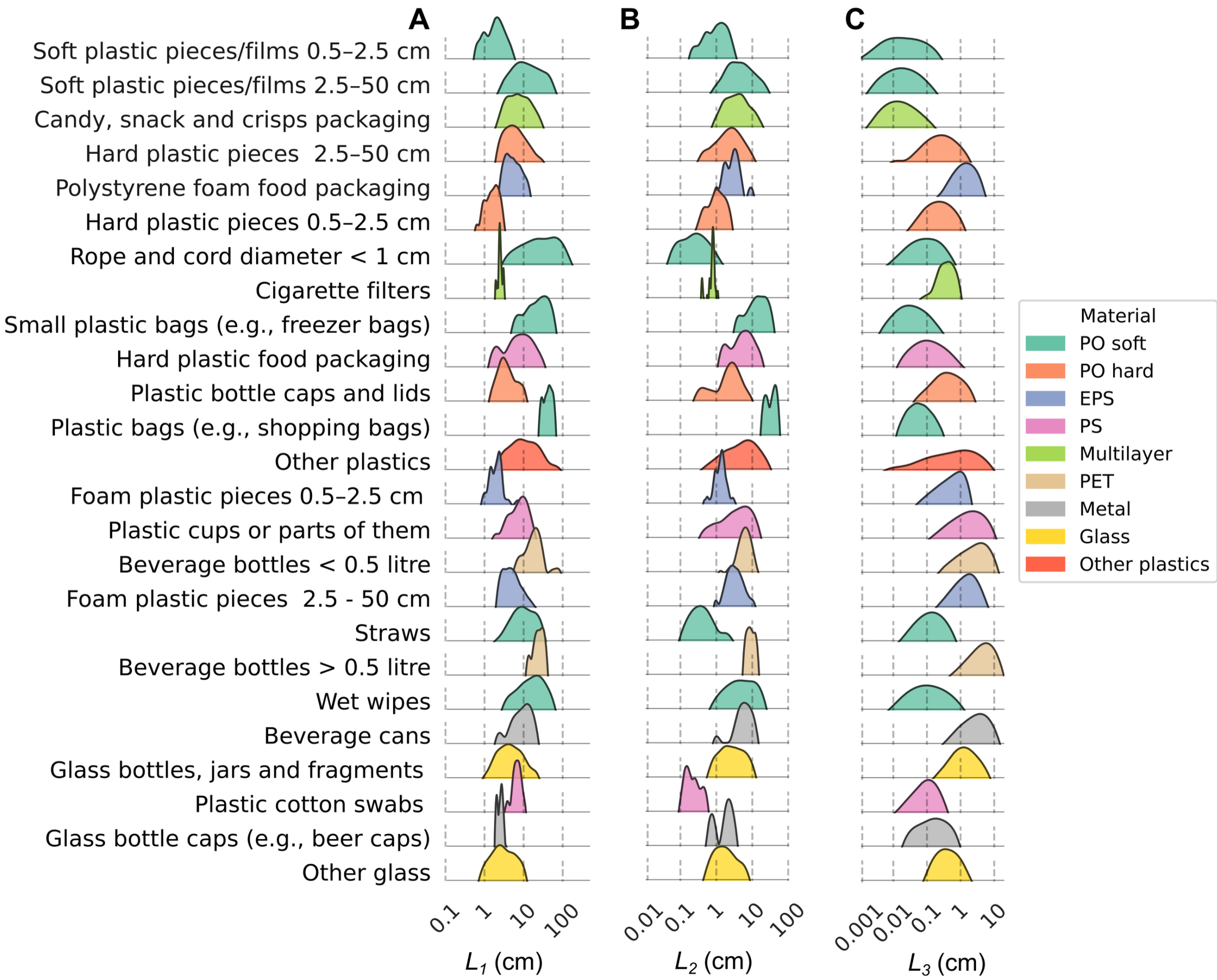


Figure 2. KDE plots for the top 25 most common River-OSPAR litter A) longest (L_1), B) intermediate (L_2) and C) shortest (L_3) dimensions. Litter items are ranked by their prevalence in rivers (Figure 1) and coloured by their material composition.

We begin with a qualitative inspection of the results obtained from the built dataset to support the validity of the proposed approach. Consider, for example, a River-OSPAR category with which we are familiar — candy, snack, and crisp packaging. The median values of L_1 and L_2 are on the order of 10 cm, while L_3 is on the order of 0.01 mm, aligning with our expectations of such category and consistent with the typical thickness of food wrapping materials (approximately 0.05 - 0.12 mm). For completeness, statistical comparisons of the L_1 dimensions of the top 25 litter items between the full dataset and measured litter items reported by de Lange et al., (2023) are available in Figure S5.

Across the top 25 River-OSPAR litter categories, L_1 typically ranges from 1 to 50 cm, with 60 % of all items measuring between 1 and 5 cm. The intermediate dimension, L_2, is generally one order of magnitude smaller, ranging from approximately 0.1 to 10 cm, with exceptions observed for small and large plastic bags. While the long and intermediate dimensions generally span two orders of magnitude, the shortest dimension L_3 exhibits the greatest variability—spanning up to three orders of magnitude and typically ranging from 0.01 to 10 cm. 98% of top 25 River-OSPAR litter items have a L_1dimension > 1 cm suggesting that the majority can be classed as macrolitter, as defined by Hartmann et al. (2019).

The variability in object sizes differs significantly across River-OSPAR categories. Litter items with a highly standardized geometry and size, such as cigarette filters and plastic bottles, exhibit a very narrow size distribution, while litter items with a consistent geometry, but a range of possible sizes, such as plastic cups, present a broader distribution with a clear peak around the median value. On the other hand, some categories group together less well-defined items, such as those labelled "Other plastics." In these cases, the variability is much higher, and the resulting distribution is considerably broader, reflecting the heterogeneity of the objects within the category.

3.3 Shape distribution of macrolitter in rivers

Figure 3 plots the average elongation (EL) and flatness (FL) ratios of the top 25 litter items found in rivers and on riverbanks. Figure 3 represents the bivariate KDE map for the plastic frequency based on elongation and flatness across the synthetic dataset, while marginal KDE plots for elongation and flatness are shown above and to the right of the main plot. Dashed lines in Figure 3 delineate the boundaries between different shape categories: *spheres* (EL > 0.66, FL > 0.66), *rods* (EL < 0.66, FL > 0.66), *disks* (EL > 0.66, FL < 0.66), and *blades* (EL < 0.66, FL < 0.66) - following the shape classifications proposed by Zingg (1935). Spherically shaped particles have all three axes of similar length (i.e. $L_1 = L_2 = L_3$). Disk-shaped particles have two equal longer axes and one shorter axis (i.e. $L_1 = L_2 \neq L_3$). Rod-shaped particles have one longer axis with the other two equal shorter axes (i.e. $L_1 \neq L_2 = L_3$). Blade-shaped particles have all three axes of different lengths (i.e. $L_1 \neq L_2 \neq L_3$). KDE distributions for EL, FL and the CSF each River-OSPAR category is available in Figure S6, while bivariate KDE maps each River-OSPAR category are available in Figure S7.

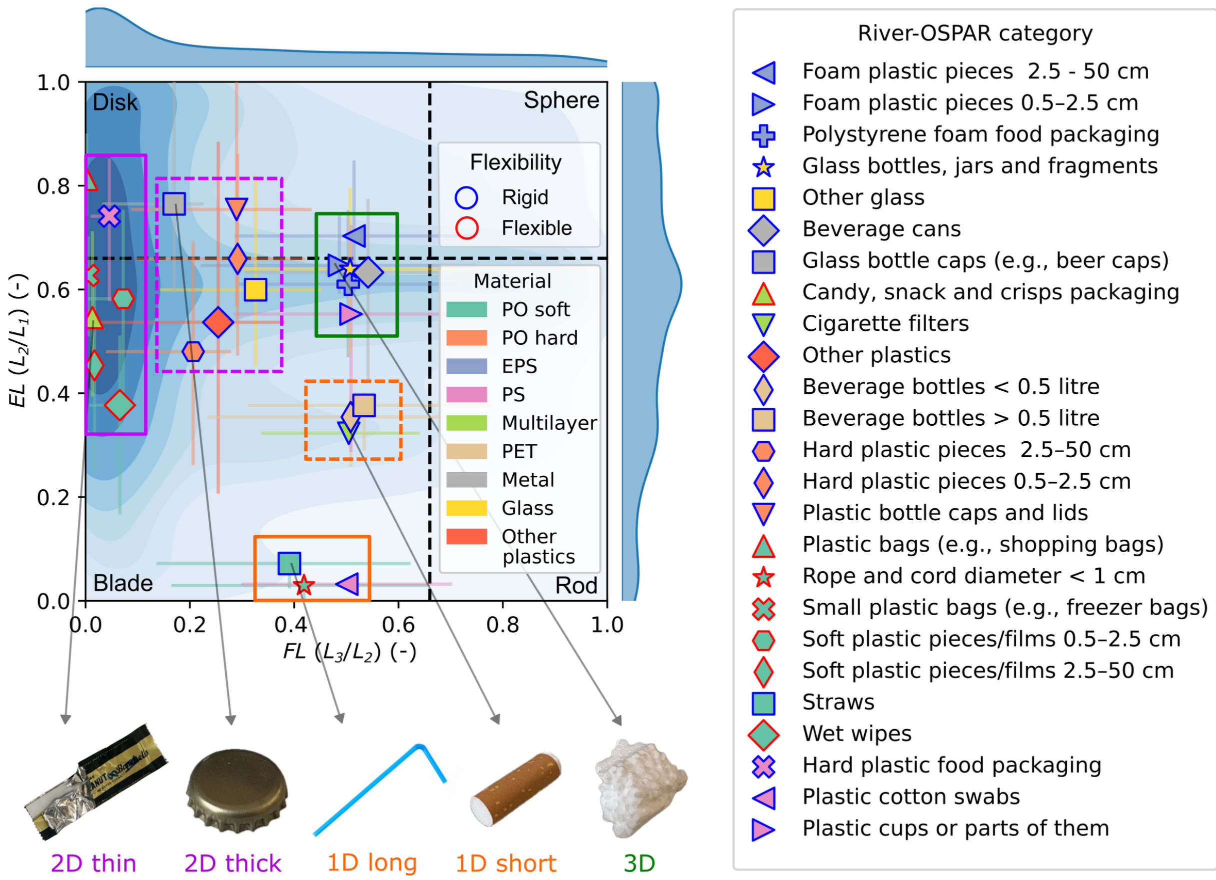


Figure 3. Geometric elongation (EL) and flatness (FL) ratio for the top 25 litter items found in rivers and on riverbanks. Markers indicate the average geometrical parameter, with horizontal and vertical lines representing the interquartile range (25th – 75th percentiles). The face colour of each marker indicates the material composition (Table 2), while the edge colour indicates whether the item is flexible (red) or rigid (blue). The background colormap shows the bivariate KDE map for the synthetic dataset, with colour intensity indicating low (light) to high (dark) occurrences. Marginal KDE are also included for El and Fl ratios. Coloured boxes delineate five distinct shape regions: 2D thin (pink solid), 2D thick (pink dashed), 1D long (orange solid), 1D thick (orange dashed) and 3D (green solid) geometries.

From Figure 3, it is evident that the majority of litter items found in rivers and on riverbanks are flat 2D objects, with a longest dimension (L_1) that is approximately double the size of the intermediate dimension (L_2), with significantly smaller third dimension (L_3). This is indicated by a high-probability region at FL < 0.2, and at EL between 0.4 – 0.8. Specifically, 50% of the top 25 River-OSPAR items have a FL value of < 0.2. The marginal FL KDE peaks at $FL \approx 0.05$, while the KDE of EL appears approximately uniform, suggesting that the ratio between the L_2 and L_1 is distributed evenly. 70% of litter items appear to be rigid, while the majority of flexible litter items tend to be flat in shape with a FL value < 0.1.

Most OSPAR items can be classified as either blade- (EL < 0.66, FL < 0.66) or disk-shaped items (EL > 0.66, FL < 0.66). Notably, no River-OSPAR items within the top 25 have geometries that are spherical- (EL > 0.66, FL > 0.66) or rod- shaped (EL < 0.66, FL > 0.66). Five distinct regions can be identified in Figure 3 (delineated as boxes), in which litter items cluster in similar geometries. Some items exhibit a more three-dimensional rigid geometry (3D), with $EL \approx 0.6$ and $FL \approx 0.5$, meaning that the intermediate dimension is half the length of the longest, and the shortest is half of the intermediate. Within this category includes polystyrene foam pieces, polystyrene food packaging, metal beverage cans, and plastic cups.

Other items exhibit a more two-dimensional geometry - where their long and intermediate axes are approximately half the size as each other ($EL \approx 0.6$), while the shortest axis is significantly smaller. These items can be further subdivided into two groups: thick two-dimensional rigid objects (2D thick), such as plastic bottle caps, with FL ratio between 0.1 – 0.4, and thin, flexible, two-dimensional objects (2D thin) with $FL < 0.1$, such as candy, snack and crisp packaging.

Finally, some litter items present a one-dimensional geometry, where the shortest dimension is about half the size as the intermediate dimension ($FL \approx 0.6$), while the long dimension is significantly larger. Similarly, these objects can be subdivided into two groups: short, rigid one-dimensional items (1D short), with $EL \approx 0.4$, such as cigarette filters and long one-dimensional items (1D long), with $EL < 0.1$, such as plastic straws. Other examples for 1D short items include beverage bottles, while examples for 1D long items include ropes, chord and cotton swabs.

4 Discussion

The results of this study reveal that only 25 River-OSPAR litter categories cover 80% of all macrolitter items in rivers and riverbanks, with the most prominent being soft plastic pieces/films (River-OSPAR ID 117.2 & 46.2) and candy, snack and crisps packaging (River-OSPAR ID 19). Buoyant, flat-shaped macrolitter items dominate the physical properties of the top 25 litter items. Specifically, 48% of the top 25 litter items share similar geometric properties; they have a longest dimension in between 1 and 10 cm, a flatness ratio of < 0.4 and an elongation ratio of any value between 0 and 1. In practice, these are flat objects with two larger dimensions and a third that is at least one order of magnitude smaller.

The generated dataset provides a clear and empirically grounded basis for prioritising monitoring protocols capable of effectively quantifying the diversity of plastic shapes and sizes identified in this meta-analysis. The dominance of small, flat, 2D-shaped macrolitter highlights the need for methods that can accurately quantify these plastics in rivers. Current, visual based monitoring of surface litter items using volunteers counting from bridges[36,50], UAVs[51] or cameras[52,53] report that they have a reliable detection limit for items between 2.5 and 5 cm, while controlled bridge field tests show detection rates between 23 – 83 % for items with an L_1 dimension between 1 – 3 cm [54]. Based on this analysis, 34% of litter items have an L_1 < 2.5 cm, indicating that potentially more than a third of litter may go undetected using these visual-based protocols. Therefore, water column monitoring methods capable of detecting small plastics (< 2.5 cm) such as net-based sampling[13,14,28,55] or emerging techniques such as sonar[56] or echo sounding[57], may be more favoured for quantifying the litter items identified in this study.

The dataset generated in this study[48] may also be used as an input for the numerical modelling of plastic transport in aquatic environments, for instance, into population balance models, introduced by Shettigar et al[22]. The results indicate that plastic transport models should largely prioritise the dynamics of flat-shaped litter items, rather than adapting traditional sediment transport frameworks, which are typically calibrated for near-spherical particles. For such flat litter items, their drag coefficient may vary significantly even at equivalent Reynolds numbers[58,59].

To date, many laboratory and field experiments have focused on litter items represented by 3D geometries, such cups[47,60], bottles[20,61] and rigid items[19,62,63]. However, these geometries are not typically observed in river systems (Figure 3). Therefore, future experimental work should refocus on realistic particle geometries, which is essential for the development of representative transport processes and for the calibration and validation of hydrodynamic models.

Finally, knowledge of the physical characteristics of dominant litter items should also inform the design and optimisation of clean-up technologies, such as floating booms[64], barriers[53], interceptors[65] and traps[66]. These technologies should be designed with suitable grid or mesh sizes or positioned in the river to target these most frequently observed items.

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Data availability statement

Meta-analysis and synthetic datasets, as well as corresponding codes are provided in an open access external repository: https://doi.org/10.5281/zenodo.17632202

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