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# Riparian vegetation plastic monitoring: A harmonized protocol for sampling macrolitter in vegetated riverine habitats

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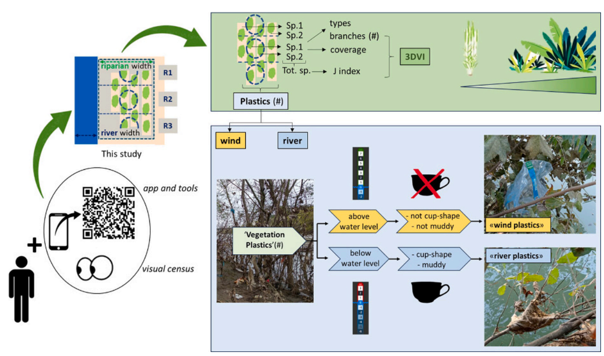
## HIGHLIGHTS

- We developed a harmonized protocol for sampling plastics in vegetation.
- We proposed vegetation tridimensional structure index (3DVI) related to plastics.
- We emphasize to use "Plastics Plants" app to survey plastics in vegetation.
- 3DVI correlated with the number of total and river plastics.
- The most dense and diverse community block more plastics.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Many studies highlighted that rivers transported land-based plastics to the sea. However, most of the litter remains stuck in the fluvial ecosystem, also blocked by vegetation. To date, research on riverine macrolitter focused on floating and riverbank monitoring, thus methods to sample riverbank and floating litter have been developed. Concerning rivers, few recent studies highlighted the role of riparian vegetation in entrapping plastics. Given that vegetation represents a large part of riverine ecosystems and that the dynamics of plastics entrapped by vegetation are neglected, it appears pivotal to study in more detail how vegetation contributes to plastic retention. However, as current protocols and guidelines considered only floating and riverbank plastics without providing standardized and updated strategies to monitor litter in vegetation, here we aimed to develop a new standardized protocol and tools to assess plastics in vegetation. Specifically, we focused on unveiling the three-tridimensional structure of vegetation in relation to plastic occurrence, while considering seasonal and hydromorphological aspects. To investigate the trapping effect of vegetation, we developed a three-dimensional vegetation structure index (3DVI) related to plastics. The 3DVI index considers plant structure (i.e., number of branches) and diversity (i.e., species). To test the 3DVI, we conducted an in-situ case study in central Italy. We found that both primary and secondary riparian vegetation blocked plastic litter. In detail, 3DVI correlated with the number of plastics, highlighting that the densest and most diverse communities trap more plastics. Furthermore, we provided for the first time the assessment of seasonality for the macroplastic entrapment by riparian vegetation and a preliminary quantification of wind-blown plastics. Our results should be of interest to

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promote the development of standardized and harmonized monitoring strategies for riparian habitat management and conservation.

## 1. Introduction

Plastics are widespread contaminants, ubiquitous in the environment and widespread from air to land systems passing through aquatic ones (Barboza et al., 2019; Picó and Barceló, 2022; Hurley et al., 2020; Battisti et al., 2023; Liro et al., 2023a). To date, most plastics are supposed to be accumulated in the aquatic environment (Meijer et al., 2021). The global plastics production increased to 390.7 million tonnes in 2021 (Plastics Europe, 2022). Given that plastics are highly produced every year and tend to double their production to more than one billion tonnes per year by 2050 (Thompson, 2022), a greater amount of consumed plastic will be discarded in the environment increasing plastic pollution (Thompson, 2022). Most of these plastics reach rivers and streams that will transport them to the sea (Meijer et al., 2021; Gallitelli and Scalici, 2022; González-Fernández et al., 2023). To date, studies on riverine plastic transport focused on floating macroplastic litter flowing downstream along rivers (González-Fernández et al., 2021). In this transport, hydrology is the main driver of floating river plastic transport (Van Emmerik et al., 2022a, b), which usually shows a seasonality (Van Emmerik et al., 2019). Moreover, floods and extreme events are responsible for carrying plastics on riverbanks (Roebroek et al., 2021; De Lange et al., 2022). Here, plastic litter can be stuck by sediments, organic wrack, and riparian vegetation (Van Emmerik et al., 2022a, b; Liro et al., 2023a; Gallitelli and Scalici, 2023). After being trapped in riverbank and vegetation, plastics can be remobilized by floods and extreme events (Van Emmerik et al., 2022a, b; Liro et al., 2023a). In this way, plastics will reach the sea contributing to enlarging the accumulation of litter in the marine environment (e.g., the "Ocean Garbage Patch" Lebreton et al., 2018 and coastal areas in Morales-Caselles et al., 2021).

Although guidelines and monitoring methods have been established for marine litter under the Marine Strategy Framework Directive implementation (MSFD, 2008/56/EC, Galgani et al., 2013), the monitoring of plastics in riverine systems is still under development, and research on certain aspects, such as accumulation of plastics in riparian vegetation is very scarce (Williams and Simmons, 1996; Cesarini and Scalici, 2022; Gallitelli and Scalici, 2023). According to these protocols, beach litter monitoring is achieved by sampling 100 m or for floating litter at sea. Then, the collected litter is classified considering size, shape, and type.

Compared to the marine environment, the understanding of river plastics is limited. Strategies and protocols should consider cost-effective tools with standardized and harmonized methods to mitigate plastic pollution. Although litter monitoring in riverine and riparian habitats has started recently, the research provided the first attempts to quantify sources and sinks of riverine litter in the River Taff in England (Williams and Simmons, 1996). In this case, litter on riverbanks and riparian vegetation has been described for the first time, also with the Christmas Tree effect (Williams and Simmons, 1996; Cesarini and Scalici, 2022; Gallitelli et al., 2022). However, protocols and guidelines for freshwater ecosystems have been adapted from the ones already existing for marine habitats. To our knowledge, standardized methods to sample riverine plastics are lacking and only a few have been developed – and adapted from marine systems (see Marine Framework Strategy, Galgani et al., 2013; OSPAR Beach litter, OSPAR, 2010). While marine litter data, although more numerous, is still limited and spotted, in time and space, there is a lack of data and harmonization of those for riverine plastics. The monitoring required for river litter should include methodological protocols and categories of items to be used for the assessment of litter on the surface water, water column, riverbank, riverbed sediment, biota (macroinvertebrates, fish, aquatic plants as macrophytes, riparian vegetation). In particular, floating plastic monitoring is based on the visual counting method (developed by González-Fernández and Hanke, 2017). Although drones and litter collection can be useful methods, the most effective still remains the visual counting one (Vriend et al., 2020).

Concerning the riverbank measurement, protocols were developed considering observations of plastic on riverbanks, beaches, and lake shores, based on the existing OSPAR Beach Litter (OSPAR, 2010), River-OSPAR (Schone Rivieren, 2017) and Plastic Pirates methods (Kiessling et al., 2019). Also, for CrowdWater, by using citizen science, data on riverbank plastics were collected (van Emmerik et al., 2020). Recently, monitoring strategies for riverbank plastic have been designed (Vriend et al., 2020). Particularly, Vriend et al. (2020) compared different protocols to sample and compare riverbank plastics, highlighting that methods to measure riverbank plastic vary greatly. Getting into details, both the OSPAR Beach Litter (OSPAR, 2010) and River-OSPAR (Schone Rivieren, 2017) studies sampled litter within a 100 m transect and then classified litter items into about 100 categories. Instead, the Plastic Pirates protocol by Kiessling et al. (2019) has been set to collect data by school children, spanning large areas and time scales along the Rhine, Danube, Weser and Elbe rivers in Germany.

To date, methods for sampling macrolitter in riverbanks neglected the role of vegetation in entrapping plastics (Gallitelli and Scalici, 2022). In fact, given that plants block litter, riverbank monitoring strategies should consider the contribution of riparian vegetation when the riverbank is vegetated. Although guidelines for monitoring plastics along rivers have been developed only recently (see United Nations Environment Programme, 2020), the monitoring of aquatic and riparian vegetation is still neglected. Consequently, protocols and guidelinesto monitor plastics in vegetation lack. Thus, we aim to provide a more comprehensive understanding of litter in riparian vegetation. To do so, we developed methods to sample litter in riparian vegetation by adapting parts from previously published methodology (Kiessling et al., 2019; United Nations Environment Programme, 2020; Vriend et al., 2020; Gallitelli and Scalici, 2023). Then, we also adapted the applicability of OSPAR and UNEP Methods for litter data collection in riparian vegetation during riverbank monitoring.

We aimed to develop new plastic monitoring tools for riverine macrolitter in view of riparian habitats management. To monitor plastics in vegetation, we set a novel protocol, considering the width of river and riparian areas as well as vegetation's tridimensional structure. Also, given that hydrology is the main driver in riverine plastics transport (Van Emmerik et al., 2022b), we split the plastics carried by rivers on vegetation from the ones carried by wind. Finally, we considered seasonality as plants undergo changes showing different habits according to the season. Considering seasonality, hydromorphological aspects, and tridimensionality of vegetation in relation to plastic entrapment in vegetation, we emphasize setting and promoting the development of a new standardized protocol to assess riverine plastics in vegetation related to plant tridimensionality. We also emphasized a new way of recollecting data through apps and tools (see "Plastic Plants") to propose a standardization for rivers, streams, and watercourses.

## 2. Methods

### 2.1. Selection of methodological elements used to develop the new method

Regarding monitoring plastics in vegetation (see Fig. 1), as there is no standardized protocol for field sampling design, here we developed a new one considering the most common and important research design developed until now. To sample litter in riparian vegetation, we developed a new sampling design following the protocols by River OSPAR to adapt some parts (see van Emmerik et al., 2020). For observations of plastic on riverbanks, the existing OSPAR Beach Litter (OSPAR, 2010) has been used to standardize samplings by developing the River-OSPAR (Schone Rivieren, 2017) and Plastic Pirates methods (Kiessling et al., 2019). For the CrowdWater method, riverbank plastic is counted for a sampling stretch that is 1, 5, or 10 m long. The width extends from the water line to the high-water line or riparian vegetation (van Emmerik et al., 2020). Following these previous methods on riverine macrolitter, plastics in vegetation can be sampled in natural and urban areas, considering different land uses. To access vegetation, bridges and riverbank can be used to spot plastic in vegetation. To make the protocol more rapid, data can be collected by smartphone by using the "Plastics Plant" application (see QR Code in Fig. 2).

### 2.2. Design to select the study area for plastic monitoring in vegetation

Following the River-OSPAR (Schone Rivieren, 2017) and Plastic Pirates (Kiessling et al., 2019) protocols, we sampled vegetation in a 100 m river stretch. Also, different methods can be used to sample plastics in riverbanks and vegetation. As for mangroves, litter sampling was conducted by using a belt transect perpendicular to the shoreline as well as circular and quadrat plots (see Luo et al., 2021; Kesavan et al., 2021; De et al., 2023), we propose to use transect lines, circular plots, and nested plots. While transect lines and circular plots have been largely used until now (see Schone Rivieren, 2017; Kiessling et al., 2019; Cesarini and Scalici, 2022; Gallitelli et al., 2022), the nested plot approach is a new method that considers the circular plots as well as a larger plot based on the river and riparian area widths. This allows researchers to compare the results of plastic concentration in vegetation from a standardized method. In this regard, OSPAR methods sampled along the 100 m transect, with the width extending from the water line to riparian vegetation (van Emmerik et al., 2020) however this width can widely change due to local factors (i.e., in larger rivers vegetation strips might be narrow, agriculture crops might be widely extended in the riparian area). Thus, standardizing for the riparian area width and river width might be a trade-off that considers all those reasons (Fig. 1). In this way, the plot area can be calculated to sample litter in the vegetation plot (Fig. 1). To allow comparisons among rivers, we sampled riparian vegetation with standardized plots with a *minimum* area of 5 $m^2$ according to previous studies (Cesarini and Scalici, 2022; Gallitelli and Scalici, 2023). We developed this nested plot considering river width and riparian zone width for calculating the plot area and a 5 $m^2$ plot within the larger plot (see Fig. 1 and Table S2, according to the protocol in Gallitelli et al., 2022; Gallitelli and Scalici, 2023). River and riparian width can be calculated by using Google Earth or Google Maps. To calculate the plot area considering the riparian area, we divided the riparian width (rip) by the river width (riv) and then multiplied by 15 $m^2$ to obtain a *minimum* area of 5 $m^2$ - according to literature as (i) area used to sample plastics in vegetation (Gallitelli and Scalici, 2023) and (ii) common plot area used for sampling vegetation (Chytrý and Otýpková, 2003). So, the plot area is expressed as:

(1) $A = rip/riv * 15\ (m^2)$

This equation is valid also in urban or agricultural tract, where vegetation strip might be totally reduced, thus the area value results in <5 $m^2$. Thus, with the previous motivations, we keep a minimum of 5 $m^2$. In this regard, the sampling area ranges has been calculated with the riparian and river widths from other European rivers (i.e., such as Danube and Rhine) using Google Maps. The minimum-maximum values (i.e., 5–50 $m^2$) remain valid for Mediterranean and European rivers.

### 2.3. General approach to define sampling procedure

A summing up of the sampling procedure (Fig. 1) is here reported:

1. We might sample during two different periods. The first one is before the floods and the second one is after the floods (i.e., the end of spring for Mediterranean rivers, while the end of autumn for Alpine and Northern European rivers, see Blöschl et al., 2020). The period before the floods can be the initial period of flooding (i.e., winter season for Mediterranean rivers, while summer for Alpine and Northern European rivers, when ice melts).
2. To sample plastics in vegetation, the nested plot should be set where vegetation occurs.
3. Then, you calculate the sampling area. River and riparian width can be calculated by using Google Earth or Google Maps.
4. Adapt the area according to vegetation width, choosing the shape of a square or rectangle. If the riparian area has 2 m width and we need to sample 10 $m^2$, we will adapt a 2x5m rectangle to the area.
5. After calculating the vegetation sampling area, use this plot area to survey into 3 plots (i.e., replicates R1, R2, and R3, Fig. 1) and sample in each of those. The area of each plot is a minimum 5 $m^2$.
6. At the end sample in a 5 $m^2$ circle plot in the center of the nested plot (i.e., one circle per replica).

Vegetation and plastics were sampled both in each the nested plot (i.e., R sections) and in the circles. In detail, the area sampled for vegetation is given by riparian and river widths (eq. 1) and in this area plastic sampling are conducted. Precisely, the nested plots allow researchers to sample most rapidly and efficiently, to date, providing the plastic entrapment at species detail, however, the vegetation type is more generic but quicker to be used in the field as species identification is not needed. To bypass it and calculate the 3DVI index, we should use the vegetation type and note the number of species in the plot. To achieve the result comparability of plastics in riverine and riparian habitats, we encouraged them to follow those standardized methods.

The workflow of our new method design for plastics in vegetation is shown in Fig. 2. As citizen science allows scientists to have more data

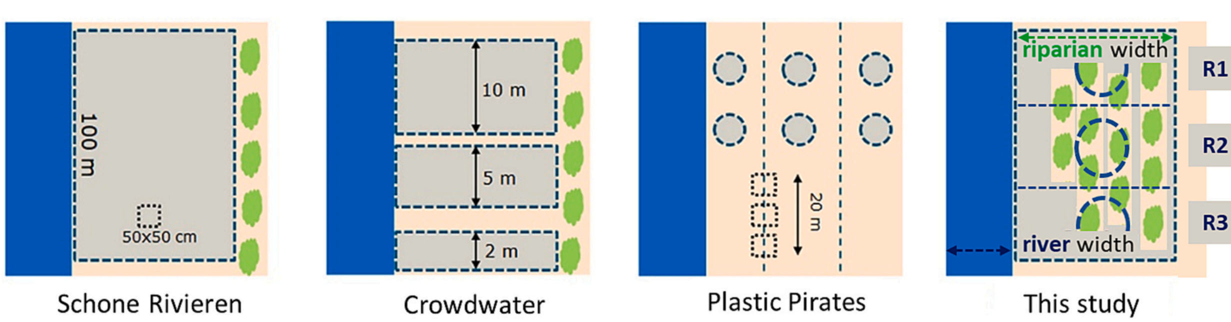


**Fig. 1.** Overview of riverine areas according to the NOAA beach litter protocol (Lippiatt et al., 2013) and Vriend et al. (2020). Sampling plots in the riparian area are shown in "This study", with green spots representing vegetation. Plot area was calculated considering river width and riparian vegetation width. The plot is divided into three replicates and the results were shown as average. This figure has been adapted by Vriend et al. (2020).

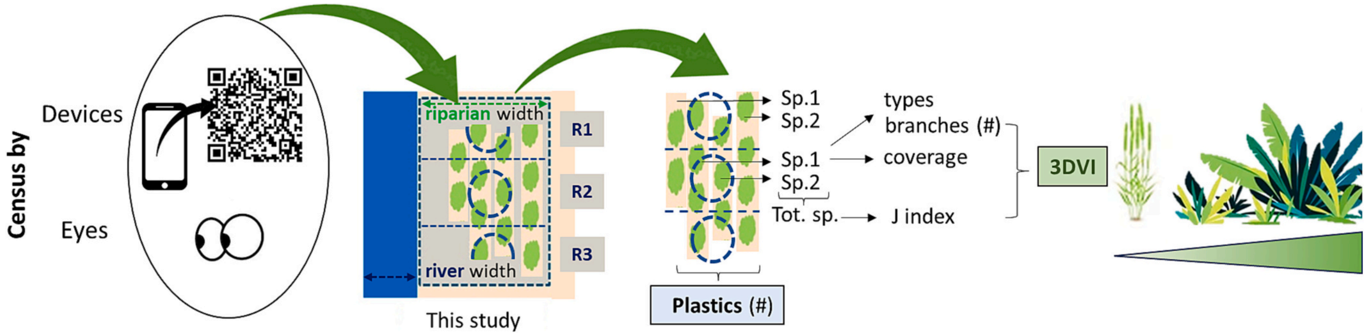


**Fig. 2.** Workflow for sampling plastics in riparian vegetation by visual and device census. The 3DVI index for the structure of vegetation is obtained by the collected data in the plot. The J index represents the evenness calculated on the total number of species (Tot. sp.) and the richness of species (Sp. 1, Sp. 2, etc.). The QR Code provides access to the "Plastics Plant" application.

and to engage people (being aware of the problem), the use of the "Plastics Plant" (https://eu.jotform.com/app/231882401150345) app could be used as potential tool to improve the sampling rapidity (QR Code in Fig. 2). This has recently been used with similar aims in riverine habitats (see Liro et al., 2023b).

### 2.3.1. *Vegetation sampling design*

According to the precise riparian vegetation occurring in your study area, in each plot dominant species are investigated for evaluating their suitability as mechanical traps for plastics. In doing this, we considered the *minimum* of 5 % coverage in a plot to define the presence of a species adapting it from phytosociological methods (see Braun-Blanquet, 1932) and contributing to the dominance or evenness indexes. To perform a large-scale and more affordable and feasible protocol, we propose to adapt from the phytosociological approach, choosing only the dominant species allowing researchers to be more smart, precise, and quick with fieldwork. To investigate whether the spatial occupation by vegetation (i.e., vegetation structure) is pivotal in the plastic entrapment process, vegetation cover and density in the surveyed area were sampled. To report the results with vegetation types and species, we suggest indicating the vegetation type with the dominant species, i.e., trees with *Salix* sp. dominance, and shrubs with *Rubus* sp. dominance. Only species with >5 % cover in the plot were considered.

### 2.3.2. *A new developed index to detect vegetation structure*

In each plot, we detected the coverage of vegetated and unvegetated parts. Then, for the vegetated part, we assessed the cover of each plant type (i.e., trees, shrubs, grasses, reeds) and species. For each species, we counted the number of individuals and branches. This allows to have a proxy for the structure of riparian vegetation. To investigate the structure of riparian vegetation in entrapping plastics, we analysed the habitus – or 'spatial organization' – of the riparian local communities. In detail, data on plant structures (i.e., the number of individuals and the number and height of branches per species) was sampled and then used to develop the 3D vegetation index (i.e., 3D Vegetation Index, 3DVI, see Fig. 2) considering tridimensionality and diversity index. Concerning the three-dimensionality index of vegetation (i.e., 3D Vegetation Index, 3DVI) about the community structure, we calculated considering tridimensionality (3D) and diversity index (i.e., Shannon and Evenness indices based on the number of species). The 3D value was calculated by considering (i) the number of basal branches counted for each individual and (ii) the area of the plot. The diversity is given by the number of species and their occurrence considering all the total species occurring within the surveyed plot. Given that (i) plastics are mostly carried by river currents, depending on flood events, and (ii) plastics have been observed to be blocked on vegetation branches and different species possess several structures to block plastics (Gallitelli and Scalici, 2023), we selected the number of species and the number of branches as criteria for the 3DVI related to plastic occurrence. To explain the role of the plant structure in entrapping plastics, the obtained 3D index (3DVI) is correlated with the number of plastics entrapped by vegetation – to be used as a tool to sample and detect plastics in vegetation in relation to the plant structure.

To consider the structure for each individual, the area has been addressed by modifying the previous calculations. The 3D value is given by adding the sum of branches for all the species per site area.

Thus, the 3D index now results as:

(2) $3D = n^\circ \text{ of total branches/plot area } (m^2)$

The number of branches ranges between 1 and 300. Although the branch number may widely vary among individuals and species, reeds (*Phragmites australis*) and grass (Poaceae) have only 1 main branch, while shrubs (*Rubus ulmifolius*) have 20–50 branches per plant and trees (*Alnus glutinosa*, *Platanus* sp., *Salix* sp.) have 100–300 branches (Gallitelli L., pers. obs., 2021; Gallitelli and Scalici, 2023). The plot area ranges between 5 $m^2$ and 50 $m^2$, according to eq. (1). This formula has been tested also with riparian and river widths by other European rivers (i.e., Danube and Rhine rivers). Given that, 3D index gets maximized with a high branch number and a small area, while 3D gets minimized with low branch number and big area. Thus, 3D ranges between 0.02 and 60.

Then, to consider the role of each species in a community, the Evenness index (J) has been used rather than the number of species. In order to determine species diversity - important measure of community structure - species evenness is combined with the number of species in the community. In this index, the number of plant species and individuals for each species in the plot is also considered. The Evenness index (Pielou, 1966) indicates which species are more abundant than others. Now, given that the J index is:

(3) $J = H' / H_{max} = H' / \ln S$,

where $H'$ is the Shannon Index (Shannon, 1948) and S is the number of species. The maximum evenness is obtained in a community in which all species have the same number of individuals. If $J = 0$, it means that there are some dominant species in the community, while if $J = 1$, each species has an equal role. The Shannon Index ranges between 1 and $H'_{max}$, potentially the number of maximum species. The standardized structure index (i.e., 3DVI) results to be:

(4) $3DVI = 3D/J$,

where 3D is given at (2) and J at (3).

The 3DVI ranges between 0 and 600. The 3DVI is zero if $J = 0$, while it gets minimized when $J = 1$ (i.e., species with equal role) and maximized when $J = 0.1$, and so there are some very dominant species. Considering the same diversity (i.e., the same J' index and so number of species), a multi-species assemblage or a community may show different values of branch number (i.e., 3D index). Thus, the higher the branch number, the lower the J' index and the higher is the 3DVI value. This results in a more complex structure of vegetation, that could trap more plastics, so plastic entrapment might be higher. Regarding the correlation of 3DVI and plastics, a higher value of 3DVI can result in (i) a high quantity of plastics blocked by the community with many species entrapping litter, and (ii) few quantities of plastics efficiently blocked by only few species. Given that, we expected that bigger concentration of plastics could be found where 3DVI has a higher value.

### 2.4. Plastic sampling in vegetation

To investigate further macroplastic distribution along rivers in relation to the riparian vegetation structure in entrapping macroplastic litter, surveys of riverine macroplastic litter entrapped in riparian vegetation may be carried out in summer for two main reasons. The first is to consider the low water level after flood time and thus have the *maximum* number of plastics on vegetation (Cesarini et al., 2023), and the second is given by the presence of the densest vegetation canopy in summer in which species can be better identified (Gallitelli and Scalici, 2023). Considering that floods are the most important driver of plastic transport and distribution in rivers (Van Emmerik et al., 2023), those events are considered for our samplings. Furthermore, extreme events (i.e., unexpected floods) could be of large interest to be studied in relation to the plastic entrapment in vegetation.

#### 2.4.1. Plastics screening in vegetation: wind and river plastics

After calculating the 3DVI, this index is correlated with the total number of plastics found in vegetation. Given that plastics entrapped by vegetation are carried both by river current and wind, we distinguished the contribution of wind plastics (i.e., plastics carried by the wind on vegetation) from river plastics (i.e., floating plastics carried by the river) following a two-step verification process (Fig. 3).

First, all the plastics above the water level were selected as plastics carried by the wind. The water level value depends on the previous flood and the height reached by the water. To have a proxy of the water level, we detected the maximum level of flood after intense rains. In this case, we noted the maximum level height during the fieldwork, by using the discharge taken by staff gauges (Seibert et al., 2019) or the noticeable sign of increased flow by river current on the riverbanks as a proxy for water level. Moreover, the leaves, organic and plastic on leaves and branches are used as a proxy of the maximum level with the flood. After choosing this *criterium* to collect data on the water lever, we noted the maximum height to which plastic was deposited due to water contributing accounting also the wind role. Above the maximum height of river water level, plastics are carried by the wind. All the plastics entrapped in plants over the line of the floods were considered to calculate the effort of the wind in transporting plastics (Fig. 4). In general, for the European contexts with smaller or greater rivers, the height of the water level should be adapted as 2.0 m and 5.0 m, respectively. Secondly, the other step is to check plastics below water level considering their shape and the presence of organic. The presence of sandy-muddy substrate on the litter as well as its not cup-shaped form (e.g., a plastic bottle) was used as screening to discard these plastics from riverine transport and entrapment in plants (Fig. 3). Thus, river-transported plastics presented the cup-shape form modelled by river current and/or were dirty with river sediment and mud showing plant and organic encrustations on it. Wind-blown plastics, on the other hand, are plastics like bags and soft plastics. These plastics are lighter fitting with the right shape to get trapped in the vegetation, as opposed to bottles and glasses that can be carried by the wind but then do not fit in vegetation (Fig. 4).

About the seasonal dynamics of litter on plants, in winter with floods and high water level, litter approach plants as well as it can remobilise litter. In summer, during the dry season, the water level decreases leaving litter on plants. Our hypothesis as a first attempt to evaluate wind plastics is that with the high discharge, rivers might carry more plastics (Roebroek et al., 2021), and thus vegetation could block more macrolitter. Then, during spring, the river water level decreases and macrolitter carried by the river remains on vegetation (Fig. 4).

Considering that floods increased water levels in winter in temperate rivers (see Rood et al., 2007; Hayes et al., 2018), more river plastics were transported (see Roebroek et al., 2021) with all plastics without a cup shape and placed in a high part of the tree above flood levels to be considered carried by the wind. In summer, all the classic river-transported plastics until the winter flood line were counted as plastic transported by the current, while the non-cup-shaped plastics are carried by the wind. In winter, on the other hand, the water is high and (Fig. 3; Fig. 4).

To obtain the number of plastics carried by the river, we subtracted the number of plastics above the maximum water level due to flood and that are not cup-shaped, as follows:

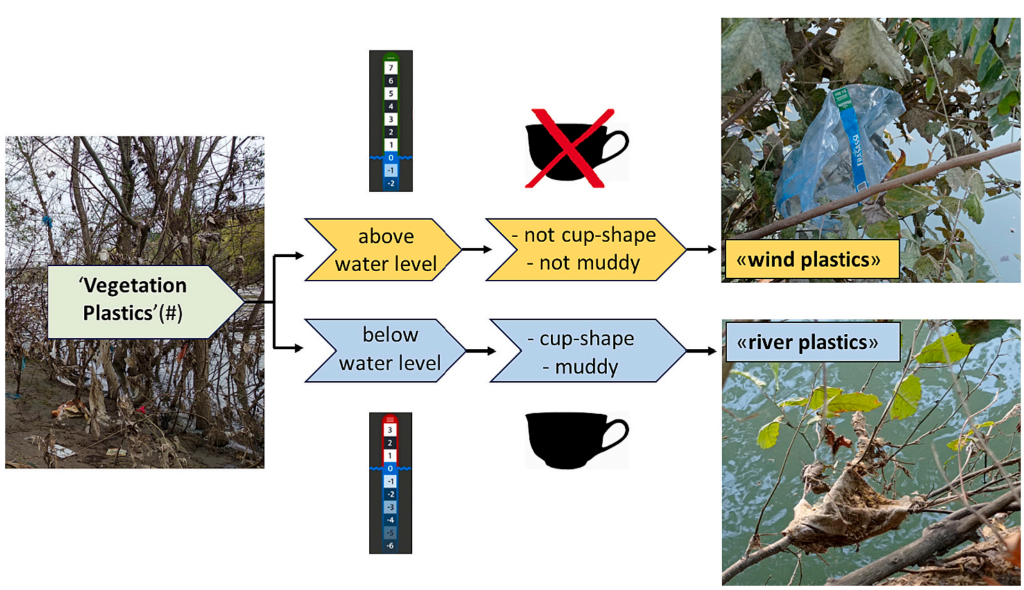


**Fig. 3.** Workflow for screening plastics in vegetation. Screening of plastics follows the two-step verification process considering water level and cup-shaped/muddy elements on plastics. The visual staff gauges (water level) are taken from Seibert et al. (2019).


**Fig. 4.** The high water level is represented in this picture. The contribution of wind is considered above the ordinary high water level (blue line). Below this line, most plastics are carried by water current (i.e., "river plastics"), while above ordinary water level, there are "wind plastics".

(5) $P_r = P_{tot} - P_w$,

where $P_r$ is plastics carried by the river, $P_{tot}$ is the total amount of plastics blocked by riparian vegetation, and $P_w$ is the plastics carried by the wind.

#### 2.4.2. Riparian plastic classification

To quantify the trap efficiency of macroplastics by riparian plants, we performed fieldwork along rivers sampling MA in each river in riparian habitats considering the number of items, litter type (plastic, paper, etc.), item type (bottles, cups, etc.), polymer (e.g., polystyrene, polyethylene, etc., Table S1), size (2.5-5 cm, etc) and colour (white, transparent, etc). Plastic litter has been removed from plants and riverbanks to then be disposed of properly. For more information on litter and item type, we followed Galgani et al. (2013) and González-Fernández et al. (2021), while for the specific sampling and plastic standardization see van Emmerik et al. (2020) and Gallitelli and Scalici (2022). We tried to harmonize our data according to the OSPAR beach litter protocols (Van Emmerik et al., 2020a) and the relative identity-based classification by Schone Rivieren, 2017 and the RIMMEL project (González-Fernández et al., 2018). To have faster and more precise results, reducing the number of categories will avoid misclassification and biases by observers (González-Fernández et al., 2018; Kiessling et al., 2019; van Emmerik et al., 2020). Then, to check for a harmonized comparison with studies in the literature, we compared results from identity-based categorization (González-Fernández et al., 2018) and 7 polymer categories (van Emmerik et al., 2020; Gallitelli and Scalici, 2022), as the most common classification used in the literature (see Table S1).

Then, we collected macroplastic litter and we counted and classified it for type, size, colours, and polymers. Then, the macrolitter present in each of the species was scored considering the main characteristics following the classifications by Galgani et al. (2013) and González-Fernández et al. (2021). After that, we analysed the plastic trap efficiency by vegetation (i) type (trees, shrubs, grass, reeds, according to Raunkiaer, 1934 and Lavorel et al., 2007) and (ii) species. The value of the plastic trap efficiency was calculated considering the number of plastic items occurring in the plant plot (P) and the area occupied by the plants ($A_p$) as follows:

(6) Plastic trap efficiency by a certain species $= P\ (\#)\ /A_p\ (m^2)$

### 2.5. Application of the general approach to our case study

#### 2.5.1. Study area

To achieve our aims, we selected the Tiber and Aniene Rivers as our study area. The Tiber River represents the 2nd longest river in Italy, with the Aniene River as the main tributary of the Tiber River, so their plastic output to the sea might be fundamental (González-Fernández et al., 2021; Cesarini et al., 2023). To investigate plastics in vegetation following our new methodology, we sampled three sites for two rivers in summer 2021 and winter 2022. In each river, we performed three replicates per site for both seasons, sampling 405 $m^2$ for plots on the Tiber River and in Aniene River.

Regarding hydromorphology features, we selected the water level and the river width as proxies for the hydromorphological features. Indeed, the wider the river, the more it takes on characteristics typical of a lowland watercourse (according to Vannote et al., 1980). Because of how riparian vegetation is structured in southern European latitudes with particular hydromorphology and Mediterranean river flow regimes (Stella et al., 2013), we set 2 m as a water level measure relative to our study area. Above that water level, plastics are carried by wind, and the number of plastics decreases during spring when the river carries fewer plastics due to fewer floods and seasonality (Van Emmerik et al., 2019; Roebroek et al., 2021).

#### 2.5.2. Vegetation sampling

To assess which type and species of vegetation most efficiently retain plastics, vegetation type and dominant species were sampled in the plots. In our study area, the riverbank is mainly inhabited by riparian vegetation with mixtures of riparian trees dominated by elder (*Acer* spp.), willow (*Salix* spp.) and poplar (*Populus* spp.). Practically, according to Siligardi et al. (2007) definition of vegetation, we indicated when riparian vegetation is primary or secondary (i.e., takes root on a natural or artificialized bank, respectively). The former is characterized by vegetation that has evolved naturally, preserving conditions of permeability to flows between the riverbed and the surrounding area. On the other hand, the latter is the strip formed within an artificial riverbed (i.e., embankments, bank defences, or other anthropogenic buildings). Those cause an evident interruption of the link between the riverbed and the surrounding area (Siligardi et al., 2007).

For the phytosociological analysis in the Rome area, more information is provided by Fanelli (2002), Celesti-Grapow et al. (2013) and Fratarcangeli et al. (2022). To understand the role of occurring alien species, we divided species into native and alien species, according to Cao Pinna et al. (2021). Native species contains also plants naturalised before 1500 CE (i.e., archeophytes). To assess if a species was alien we checked on The Euro+Med Plantbase Project (http://ww2.bgbm.org/EuroPlusMed/query.asp).

Considering that floods increased water levels in winter in temperate rivers (see Rood et al., 2007; Hayes et al., 2018) transporting more plastics (see Roebroek et al., 2021), then in summer all the classic river-transported plastics until the winter flood line were counted as plastic transported by the current. Given these reasons, to better understand the seasonality of litter in vegetation, we sampled during both seasons (i.e., summer 2021 and winter 2022). For the Tiber River, the mean value for wind was 4.2 m/s and 4.6 m/s in summer 2021 and winter 2022, respectively. In the Aniene river, the mean value for wind was 2.9 m/s and 6.2 m/s in summer 2021 and winter 2022, respectively. In general, wind speed never exceeds the speed of 9 m/s in our study areas (Windy.app, 2023).

We sampled riverine macroplastic litter entrapped in riparian vegetation in summer 2021 and winter 2022. Although flood intensities and flood-rich periods were found higher in other Italian and European Rivers (Blöschl et al., 2020), the hydrology in the Tiber River as well as the Mediterranean Rivers remains unaltered. Thus, we considered summer and winter periods to sample plastics in vegetation.

### 2.6. Data analysis

To unveil the relationship between the structure of vegetation (i.e., 3DVI) related to wind and river plastics occurring in vegetation, we carried out a regression analysis. Wind and precipitation data can be requested by National and Regional agencies and downloaded by administrative websites. To obtain data on precipitation in the Tiber and Aniene Rivers in Rome, we used https://meteonetwork.eu/. Moreover, imageries and datasets available on worldClim can be used through GIS software (see Fick and Hijmans, 2017; Harris et al., 2020). Furthermore, to consider a possible influence of environmental constraints on plastic occurrence in riparian vegetation, correlations with precipitation and wind speed were performed (see here with zoom to Italy for European Drought Observatory and Monthly Precipitation: https://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1145).

To investigate the difference between the found different polymers and types of plastics, we performed a Kruskal-Wallis test (H′). If the results were significant, a pairwise post-hoc was conducted.

To understand the seasonality of litter in vegetation, we found that higher precipitation data showed high plastic occurrence in vegetation (i.e., winter vs. summer seasons). The role of wind on plastic transport has been assessed by comparing data in two seasons. In the linear regression 3DVI has been considered as independent variable.

On comparing two different ways of sampling plastic in vegetation, nested plots better consider the study area (i.e., river and riparian widths) while single circular or quadrat plots are most prone to be under representative of the surrounding area. The linear transect considered is the same as reported in the Crowdwater procotol (van Emmerik et al., 2020) and United Nations Environment Programme (2020), in our protocol also considering river and riparian widths. Although that, the number of plastic categories in both 5 $m^2$ circle and nested plot was quite similar. Considering our findings, we suggested that nested plots could be used for any kind of vegetation, while the circular plot could be more useful to sample secondary vegetation as this vegetation is usually characterized by a narrow strip. All data analyses were performed by using GraphPad software. The alpha test level was set at $<0.05$ for the statistical analyses.

## 3. Results

### 3.1. Plastic occurrence and vegetation structure (3DVI)

The total 3DVI was 285.7 ranging between 7.2 and 45.3 per site (mean: 23.8) on a sampled total area of 405 $m^2$. Primary vegetation shows a better structured vegetation than secondary vegetation (3DVI: 167.0 vs 118.7, respectively). Also, primary vegetation blocked more plastics than secondary one (509 items vs 414 items, respectively, see Fig. 5 and Fig. 6). Overall, plastics blocked by vegetation ranged between 12 and 178 MA items with the plastic concentration (i.e., entrapping efficiency by plants) between 1.2 MA/$m^2$ and 21.7 MA/$m^2$. In detail, trees showed higher plastic trap efficiency than grasses, shrubs, and reeds (37.4 MA/$m^2$, 6.9 MA/$m^2$, 3.8 MA/$m^2$, and 1.5 MA/$m^2$, in %: 75.4 %, 13.9 %, 7.6 %, and 3.1 %, respectively, see Table S4). Overall, the top-3 plants blocking most MA were: (i) *Acer negundo* (21.1 MA/$m^2$), (ii) *Populus alba* (6.3 MA/$m^2$), and (iii) *Robinia pseudoacacia* (6.2 MA/$m^2$, Fig. 5, Fig. 6). Standardized to the area covered in the plots, the tree *Acer negundo* blocked most of plastics with the higher value of plastic trap efficiency than other species (Fig. 6, Table S4). Regarding the Aniene River, trees entrapped most plastics than other plant types in both seasons (Fig. 6A). For the Tiber River (Fig. 5B), in summer, grasses (i.e., *Erigeron karvinskianus* and *Urtica dioica*, 3.1 MA/$m^2$) blocked more than trees (i.e., *Alnus glutinosa, Platanus hybrida, Robinia pseudoacacia*, and *Ficus carica*, 1.8 MA/$m^2$), while in winter trees blocked more than grasses (1.8 MA/$m^2$ vs 0.9 MA/$m^2$). Regarding native and alien species, riparian vegetation along the Aniene and Tiber areas was characterized by higher plastic trap efficiency in alien species than native ones (i.e., 29.5 MA/$m^2$ vs. 20.1 MA/$m^2$, respectively). On 13 species occurring in the plots, 4 species (30.8 %) were exotic and alien species (i.e., *Robinia pseudoacacia*, *Acer negundo*, *Platanus hybrida*, *Erigeron karvinskianus*). These alien species covered about the same as the native (208.7 $m^2$ vs 196.3 $m^2$).

Overall, the most entrapped items were soft, PS, and multilayer elements, such as plastic bags and sanitary/hygienic towels (see Fig. 7).

### 3.2. Plastic entrapment, vegetation structure, and environmental constraints

Concerning the structure of vegetation related to plastic occurrence, plastics occurring in vegetation were significantly related to vegetation structure. In detail, the number of total and river plastics correlated with the 3DVI value ($r = 0.72$, $p = 0.007$ and $R^2 = 0.51$, $p = 0.0088$, $Y = 5.497*X - 56.92$). Thus, the most dense and diverse community blocks more plastics. Also, we found that the wind plastic amount and concentration were not related to the 3DVI ($r = 0.52$; $p = 0.08$ and $r = 0.51$, $p = 0.09$).

Regarding river plastics (Fig. 8, Fig. 9A), we found different polymers of plastics (Fig. 8A), with a maximum in the Aniene River ($H (4, 48) = 33.93$, $p < 0.0001$). Among the pairwise, EPS/PS and PO soft resulted significantly different ($p = 0.0001$), as well as EPS/PS and other ($p = 0.01$), PO soft and multilayer ($p < 0.0001$), and multilayer and other ($p = 0.001$).

For wind plastics (Fig. 8 B,D), we found mainly PO soft and other items without a significant difference ($H (4, 48) = 6.451$, $p = 0.09$, see Fig. 9B). Concerning the wind contribution, we provided a preliminary


**Fig. 5.** Topmost occurring plastic items in the Tiber and Aniene River's riparian vegetation. (A) An *Alnus glutinosa* tree blocked hygienic towel and COVID face mask. (B) *Robinia pseudoacacia* blocked sanitary towels. (C) *Populus* spp. entrapped a plastic cup. (D) Scan the QR code to access to all the pictures and videos of plastics entrapped by vegetation. The link is here: Plastics in riparian vegetation.

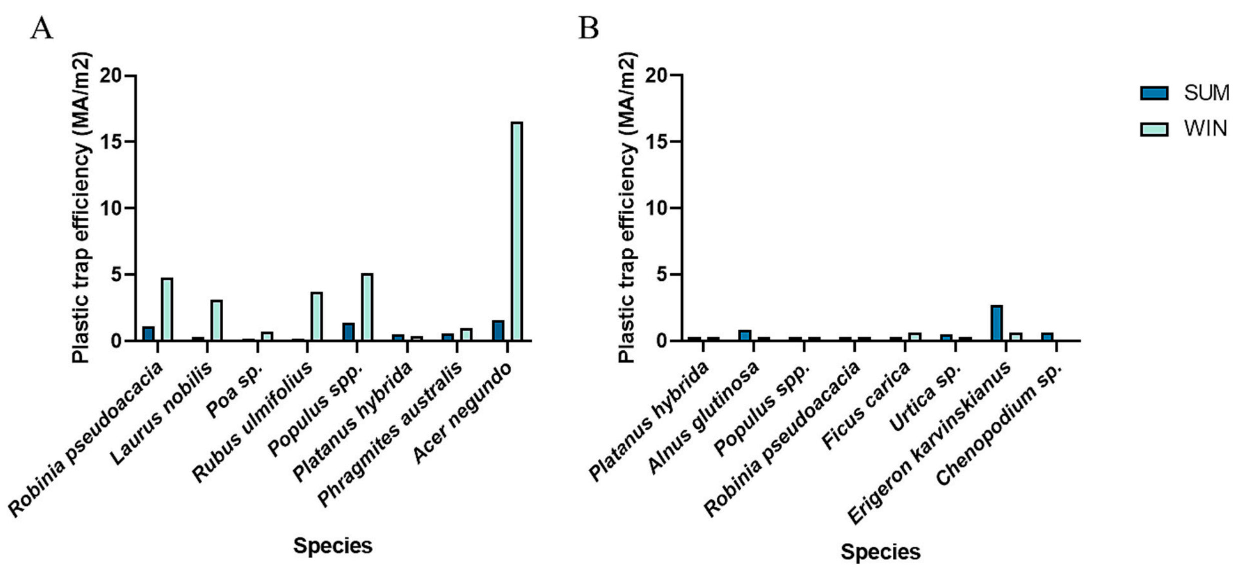


**Fig. 6.** Plastic trap efficiency (MA/$m^2$) in summer and winter seasons for each species sampled in the Aniene (A) and Tiber (B) Rivers. MA = macroplastics.

assessment of wind role (Fig. 3). For the first time, we characterized the riverine macrolitter transported by river current (i.e., cup-shape macroplastics) and the wind transported macroplastic items (Fig. 4). The wind showed a minor role in transporting plastics, accounting for 3.8 % of total litter, while most of the litter was transported by water (96.2 %, see Fig. 9B).

For both the rivers, plastic bags (28.3 %) were the most occurring plastic types (Fig. 8B), together with plastic pieces (22.5 %), and hygienic towels (21.7 %) ($H (11) = 76.47$, $p < 0.0001$). Precisely, in the Tiber River, plastic pieces (33.8 %) were the most dominant plastic types with plastic bags (24.6 %), hygienic towels (15.1 %), while in the Aniene River, while plastic bags (31.1 %), followed by hygienic towels (26.9 %), and sanitary towels (16.9 %). From the correlation matrix, the r coefficient for significant pairwise ranges between 0.61 and 0.80. In detail, we found that plastic cups are highly related to hygienic towels ($r = 0.80$, $p = 0.003$) and plastic bags ($r = 0.78$, $p = 0.004$). Plastic pieces were highly correlated with plastic bags ($r = 0.61$, $p = 0.04$), face masks ($r = 0.68$, $p = 0.02$), and plastic packaging ($r = 0.62$, $p = 0.03$). Following seasonality, plastic trap efficiency in plants changes according to different seasons (Fig. 10), with plastic bags, hygienic towels, and plastic pieces as the most occurring items. Across seasons, although wind speed and precipitations were not significantly correlated to the plastic amount and concentration ($r = 0.43$, $p = 0.18$; $r = 0.44$, $p = 0.19$), we found that higher precipitation data showed high plastic occurrence in vegetation (i.e., winter vs. summer seasons).

Considering vegetation height, plants blocked macroplastics mostly

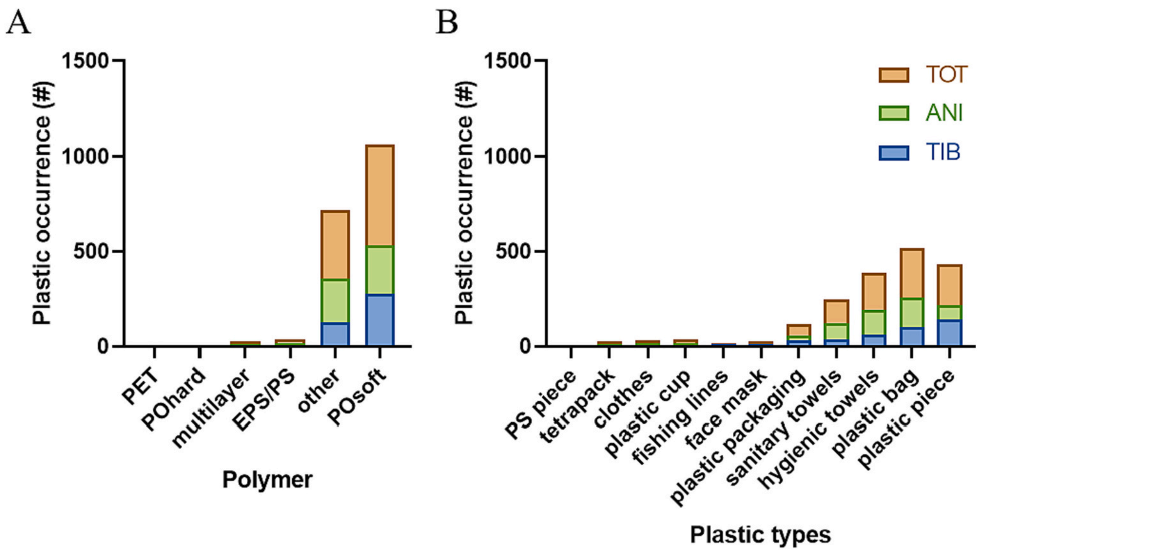


**Fig. 7.** Plastic occurrence (#) in primary and secondary vegetations (ANI and TIB, respectively). Plastic polymers (A) and types (B) are shown in the legend.

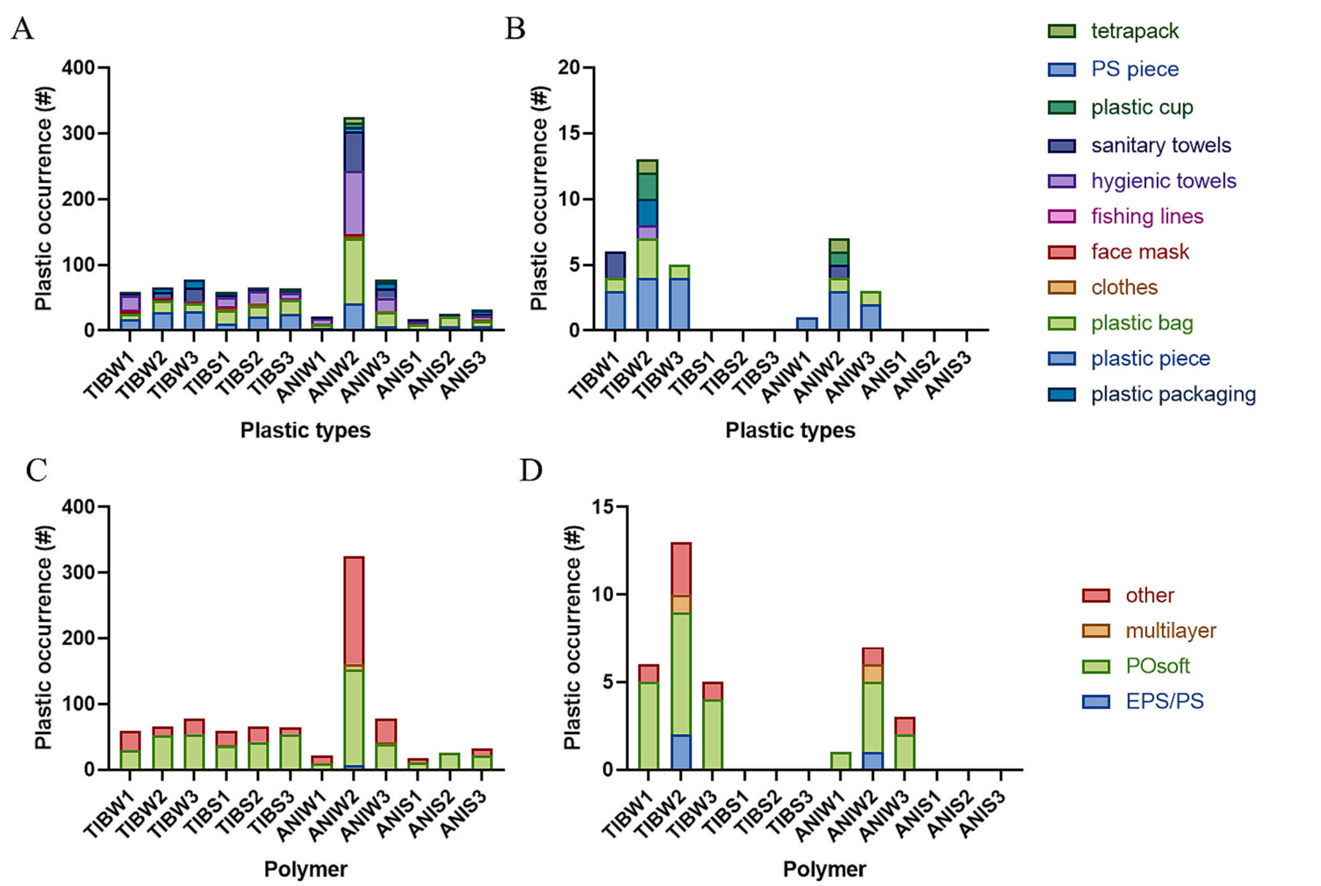


**Fig. 8.** Polymers and types of river (A, C) and wind (B, D) plastics occurring in the Tiber and Aniene River's vegetation. TIBW1 indicates the first station of the Tiber River sampled in the winter period, while ANIS3 is the third station of the Aniene River sampled in the summer period. ANIW = Aniene river sampled in the winter season, ANIS = Aniene river sampled in the summer season. In both the panels the same colours highlighted the same plastic polymers and types.

below water level (i.e., <2 m, Fig. 11).

## 4. Discussion

In our research, we emphasize setting the development of a new standardized protocol to assess plastics in vegetation related to plant tridimensionality. Particularly, we investigated that primary and secondary riparian vegetations blocked plastics. Particularly, trees showed higher plastic trap efficiency than grasses, shrubs, and reeds. We also emphasized the role of native and alien species in entrapping plastic litter. For the first time, we provided an index to consider the structure of riparian vegetation (i.e., 3DVI). Then, we assessed the trapping of

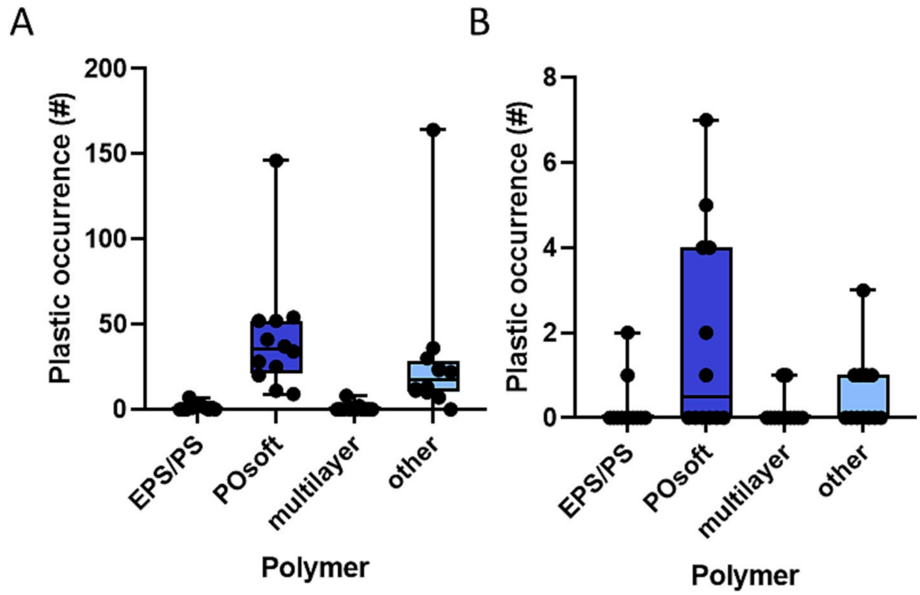


**Fig. 9.** Polymers for river (A) and wind (B) plastics. Note the different y-axis values.

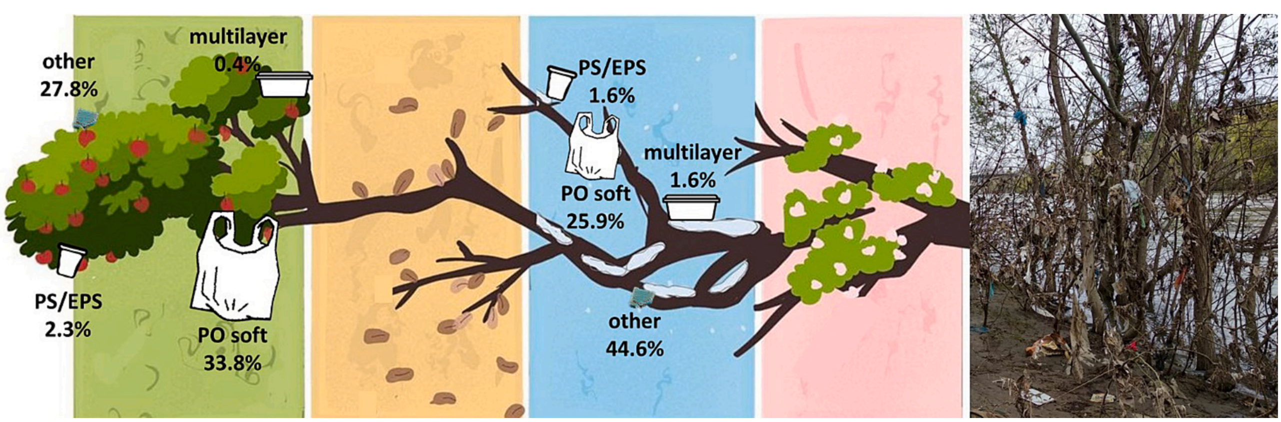


**Fig. 10.** Seasonality of plastics in vegetation. From left to right, summer, autumn, winter, and spring seasons. The plastic trap efficiency changes according to different seasons. Moreover, vegetation foliage and metabolisms change according to seasons. The image was adapted by Shutterstock (https://www.shutterstock.com/es/image-vector/simple-cute-vector-4-seasons-tree-2304292881).

plastics in relation to the index values obtained finding that more plastics were trapped by the most dense and diverse community. Also, we provided a preliminary assessment of the wind role characterising the riverine macrolitter transported by the river current (i.e., cup-shape macroplastics) and the wind-transported macroplastic items. Finally, considering different vegetation heights, plants blocked macroplastics mostly below water level (i.e., water level < 2 m).

### 4.1. Plastic occurrence and vegetation structure (3DVI)

To date, the first attempts and protocols to monitor river plastics have been developed, but they need to be highly implemented. Given that plastic pollution is part of the "Sustainable Development Goals" (SDGs) in the 2030 Agenda for Sustainable Development (https://sdgs.un.org/goals), however, plastics are not yet introduced in national and international directives, such as the Water Framework Directive (WFD 2000/60).

As studies used different protocols to sample different kinds of vegetation (e.g., mangroves, dune plants, seagrass, macrophytes, riparian plants, check Williams and Simmons, 1996; Cozzolino et al., 2020; Luo et al., 2021; Gallitelli et al., 2021; Schreyers et al., 2021; Cesarini and Scalici, 2022; Gallitelli and Scalici, 2023), a unified protocol is a need to sample plastics in plants with standardized methods. This would increase result comparison to drive data to policy-making decisions for plastic mitigation. Here we put our emphasis on the tridimensional structure of vegetation, creating a new index to address it and then relate the structure to plastic occurrences. We adapted from River OSPAR protocols following van Emmerik et al., 2020, and Vriend et al., 2020.

On comparing two different ways of sampling plastic in vegetation, nested plots better consider the study area (i.e., river and riparian widths) while single circular or quadrat plots are most prone to be under representative of the surrounding area. The linear transect considered was the same as reported in the Crowdwater procotol (van Emmerik et al., 2020) and United Nations Environment Programme (2020), in our protocol also considering river and riparian widths. We found that the number of plastic categories in both 5 $m^2$ circle with nested plots was quite similar. Considering our findings, we suggested that nested plots could be used for any kind of vegetation, while the circular plot could be more useful to sample secondary vegetation as this vegetation is usually characterized by a narrow strip (Ricotta et al., 2001; Gallitelli and Scalici, 2023). Also, this method could fit the secondary vegetation as it is difficult to measure the vegetation width given the distribution of this

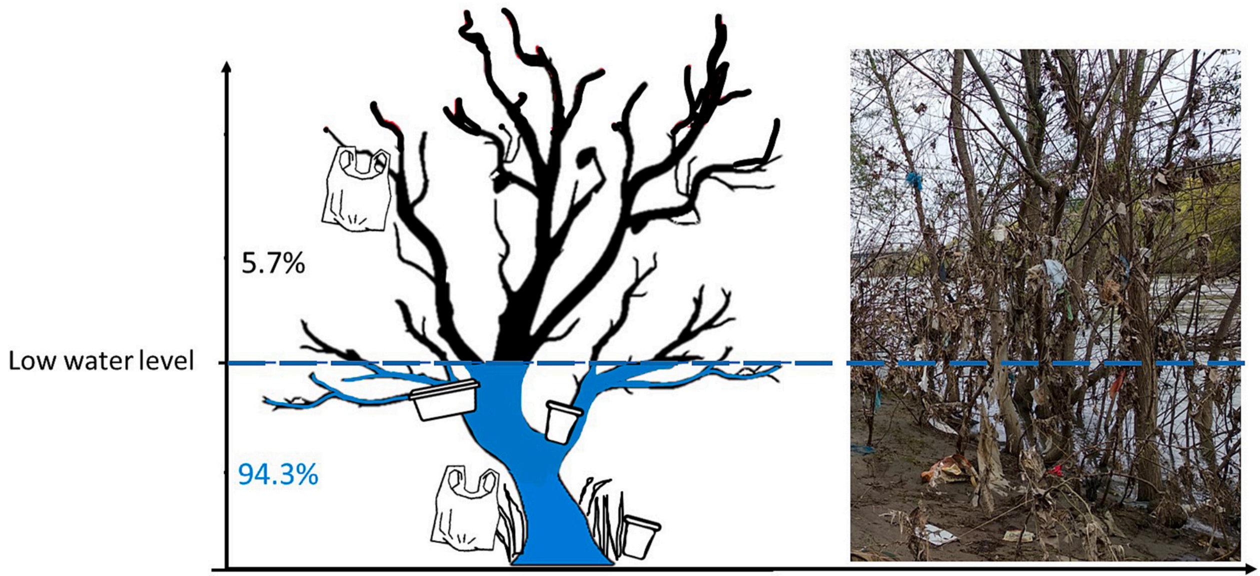


**Fig. 11.** Occurrence of river and wind plastics at two different vegetation heights considering the low water level (i.e., 2 m). For other contexts with smaller or greater rivers, the height (m) should be revised (i.e., about 2.0 m and 5.0 m, respectively, for instance).

vegetation in urban areas (see Badino et al., 2004; Fratarcangeli et al., 2022; Gallitelli and Scalici, 2023). Although literature used different transects and quadrats (e.g., 50x2m or 20x2m transects and 5x5m, 10x10m, or 0.5 × 0.5 m plots) to sample plastics in vegetation (see Kesavan et al., 2021), for rivers the length of the riparian areas should be taken into account as it can be narrow as a strip due to agriculture or wide in more natural site (Gallitelli and Scalici, 2023).

Concerning the vegetation tridimensionality and structure (i.e., 3DVI), we developed for the first time a vegetation index to describe the structure and diversity of the plant community – and then relate it to the plastic entrapment process. The higher the 3DVI value, the more complex the vegetation (i.e., characterized by a lot of individuals, species, and branches). From the index, we should consider that, with the same value of diversity (J' index), a multi-species assemblage may have a higher number of branches (i.e., 3D). Furthermore, the most dense (i.e., branched) and diverse communities (or multi-species assemblage) block more plastics. This could be due to the different traits occurring in riparian plants from trees to shrubs, reeds, and grasses (Raunkiaer, 1934). To date, literature has not focused deeply on unveiling vegetation structure in relation to plastic entrapment. In this way, research only reported the type of vegetation with specific organs that blocked plastics. For instance, Martin et al. (2019) and Kesavan et al. (2021) pointed out that pneumatophores are key in entrapping plastics in mangroves, while vegetation traits (i.e., spines, pollons, see Lavorel et al., 2007) were reported to be pivotal in plastic entrapment by riparian vegetation (Cesarini and Scalici, 2022; Gallitelli et al., 2022). Furthermore, we found that alien species contribute to blocking plastics. In highly disturbed urban environments (i.e., our study area), the dominance of exotic and alien species (i.e., *Robinia*, *Acer negundo, Platanus hybrida, Erygeron*) is expected as these are species that might tolerate disturbance. Although alien species distribution has increased also in riparian areas (Praleskouskaya and Venanzoni, 2021), due to warming and eutrophication, these species could also benefit us with the new ecosystem service of trapping plastics (see also Gallitelli et al., 2021). In this case, the presence of alien species could make the structure of the vegetation community more intricate, resulting in a higher 3DVI index. Given the spread of alien species in Mediterranean areas as well as in other parts of the world (see Cao Pinna et al., 2021), their use as "ecosystem services" to block plastic and then mitigate plastic pollution could be an interesting trade-off as if we remove alien vegetation then we also could remove plastic stuck on them. However, to better do it, appropriate protocols and management plans should be developed and applied.

### *4.2. Plastic entrapment, vegetation structure, and environmental constraints*

Concerning the structure of vegetation related to plastic occurrence, plastics occurring in vegetation were significantly related to vegetation structure with the number of total and river plastics related to the 3DVI, however wind plastics amount and concentration were not related to the 3DVI. This explains how hydrology is key for river plastic transport (Van Emmerik et al., 2022b), and for carrying plastics on riverbanks and vegetation. In all this process of carrying plastics, wind has a small and neglected role in our study area. Concerning the wind contribution, we provided a preliminary assessment of the wind role, considering that the wind never exceeds the 9 m/s speed in our study area during samplings (Windy.app, 2023). For the first time, we characterized the riverine macrolitter transported by river current (i.e., cup-shape macroplastics) and the wind transported macroplastic items (Fig. 3 and Fig. 4). The wind showed a minor role in transporting plastics, indeed most of the litter was transported by water. The contribution by wind could be higher in bigger rivers (i.e., Tiber River) as they are wider while small rivers (i.e., Aniene River) are narrower and so vegetation here close the environment and river is less subject to wind and plastics carried by the wind. Few studies investigate the role of wind in literature. In particular, the role of plastic transport by wind is *minimal* as provided by Garello et al. (2021) for the Paraná River (Argentina). Moreover, extreme wind speeds do not necessarily result in transporting waste (Mellink et al., 2022). Thus, splitting the contribution of plastics carried by the river current from the one due to the wind is fundamental to better understanding the role of vegetation in entrapping riverine plastics. We should consider that plastics in vegetation are mainly due to (i) plastics transported by the river as floating plastics, (ii) plastics coming from the metropolis, and (iii) dumping or tourism activities. Also, litter input by citizens in riverbank can be a local input as well as the wind could play an important role (see Garello et al., 2021; Roebroek et al., 2021; Mellink et al., 2022). Although a clear link between trapping litter in vegetation and floating plastics has not been studied, hydrology is the most important factor in carrying plastics to riverbanks and, consequently, to riparian vegetation (Gallitelli and Scalici, 2023).

In the optic of climate change, sampling plastics should consider collecting data on environmental hydrologic factors (see Van Emmerik et al., 2022b). As climate change could alter the water cycle (Zaitchik et al., 2023), river plastic transport could be influenced as well by extreme events (Roebroek et al., 2021). Because of how riparian vegetation is structured in southern European latitudes with particular hydromorphology and river flow regimes of our latitudes, we have that most plastics are under 2 m in our study area. This also depends on the slope of the riverbank and the variation of water level during floods. Hydrology acts as the main driver of floating plastics in the river (Van Emmerik et al., 2022b), being a source for plastics on riverbanks and riparian vegetation. Small rivers with low discharge and water levels could have a limited output of plastics to the vegetation, although González-Fernández et al. (2021) identified small and medium-sized rivers as the major carriers of plastics. Furthermore, seasonality could be another important factor that should be considered in river plastic transport as well as for plastic in vegetation. First, vegetation undergoes to a seasonal pattern due to the habitat in which occurs. For instance, in the temperate climate, we usually have a cold and hot season, while in tropical areas there are wet and dry seasons (Whittaker, 1970). Due to this seasonal pattern, plants change their foliage and morphology during the year (Janzen, 1975). From our findings, if we match vegetation seasonality with hydrology seasonality, river plastics are most prone to be blocked by vegetation during high water levels. Then, plastics entrapped by vegetation could be remobilised by floods (see Gallitelli et al., 2022) and flow downstream with river current. In detail, river plastics (i.e., plastics carried by water on vegetation) are more active during winter with floods, while in the summer and dry season river plastics are less active, so there could be an increase in the wind plastic transport (Gallitelli et al., 2022). Although the plastic entrapment by plants could be affected by flash floods after summer storms - that are sudden events in Mediterranean areas (see Gaume et al., 2009), in our study areas these were absent when sampling, however these events should be considered.

Regarding plastic polymers and types, we mostly found that vegetation blocked plastic bags, hygienic towels, and packaging. Considering the polymers, vegetation entrapped mostly PO soft items. Given that the results regarding plastic entrapment by vegetation are similar if showing polymers or litter types, we might recommend using the classification of plastic polymers (i.e., PS/EPS, PO soft, PO hard, multilayer, and other as described in Methods) to have smart and rapid fieldwork.

### 4.3. *Methodology application to other context*

Some limitations should also be highlighted in this study. We should keep in mind that this is the first study to perform this kind of analysis and findings, so we do not have a large dataset to be used as it is for marine litter or riverine plastic transport (see Roebroek et al., 2022). In detail, the reasons for the neglect of monitoring aquatic and riparian vegetation could be due to the focus to microplastics in marine ecosystems by researchers (see Gallitelli and Scalici, 2022). However, as recently researchers understood that freshwaters are highly polluted by plastics and that most plastics remain in the fluvial ecosystems (Van Emmerik et al., 2022a; Gallitelli and Scalici, 2022), the focus and efforts moved to river transport of plastics to prevent the plastic outflow to the sea. As future perspectives, we encourage the expansion of the datasets, from a (i) spatial and (ii) temporal point of view. (i) Firstly, this preliminary dataset were collected in a restricted small area as these results were used to set and apply the protocol. Indeed, although we considered environmental drivers (i.e., hydrological, seasonality, and vegetation factors) to better understand the plastic entrapment by vegetation, however our study wants to set a protocol to provide with data standardization for plastics entrapped in vegetation. This would allow to compare results from different rivers in the world and understand issues related to biota (i.e., see plastics on vegetation hindering buds and flower emission and also pollination in Gallitelli and Scalici, 2023). To date, monitoring of litter in vegetation has been neglected and not considered in standardized guidelines. Thus, when applied internationally across the whole of European rivers, our methods should challenge the river ecosystem heterogeneity and different vegetation types. Indeed, European rivers vary significantly in terms of their size, flow dynamics, and ecosystems. A standardized method may account for these variations by considering regional differences and seasonality in river ecosystems. Moreover, riparian vegetation along European rivers includes a wide range of plant species and habitats, thus a standardized method might integrate it in order to consider the diversity of these ecosystems and perform valuable plastic data collection. To tackle plastic pollution (United Nations Environment Programme, 2020), we need good estimates by field and modelling data to then drive decisions for plastic mitigation, so we should promote method standardization and harmonization. Proposing riverine and riparian clean-up initiatives for the removal of macroplastics along these habitats might be the first effort to reduce their occurrence in these environments. By addressing these limitations, European countries might monitor more effectively plastics in riverine habitats, facilitating joint efforts to combat plastic pollution in their rivers. Given the importance of vegetated areas in influencing plastic transport to the sea, future research should consider studying this topic – benefitting from our findings. In this way, more data will be available to understand where plastics accumulate in rivers – as only 2 % is predicted to reach the ocean (see Meijer et al., 2021). (ii) Secondly, in view of long-term monitoring, the large dataset could use remote sensing and high technologies to detect macroplastic litter in riparian and riverine habitats (Geraeds et al., 2019; Broere et al., 2021; Tasseron et al., 2022). In this regard, only recently riparian habitats started to be studied by remote sensing (Pace et al., 2021; Larsen et al., 2023), thus future research could investigate the *phenomenon* of plastics in riparian habitats by integrating remote sensing. Future perspectives can develop applications to sample more easily and smartly plastics within vegetation. As future perspectives, the creation and implementation of applications with a section for plastics in vegetation could also provide precious data (e.g., for instance, the implementation of the CrowdWater application with a section on plastics in aquatic and riparian vegetations).

In all this framework, to better improve ecosystem functionality, it is also important to match the management of ecosystems (e.g., management of plants in rivers and canals, Caneva et al., 2021) with plastic removal. In this view, plants provide a further ecosystem service, i.e., entrap plastics. Thus, if plants block plastics, we should propose correct management of mowing activities as if we mowe, so we take care of plants and we remove plastics from plants. Also, taking care of plants might allow plants to be stronger to trap more other plastics. For this, we need new protocols and implementation of current laws and directives to better manage plastic pollution in riverine habitats. Thus, in light of resolving the plastic problem, given the importance of plants entrapping plastics from rivers, future efforts should focus on that research. The lack of consistent and long-term observations to monitor plastics in aquatic ecosystems could be fixed by more intense collaborations between all parts of the European plastics system and policymakers. Also, to meet our 2050 net zero and circularity targets sustainability, there is a need for a new and enabling policy framework that could pose the basis for a comprehensive global treaty on riverine plastics (United Nations Environment Assembly of the United Nations Environment Programme, 2022; United Nations Environment Assembly of the United Nations Environment Programme, 2023). In this view, this global treaty will need harmonized and standardized methods to recollect precise datasets to solve plastic pollution (see Hurley et al., 2023).

## 5. Conclusions

Riverine and riparian habitats are important habitats providing many ecological services. Among these, the new one of trapping plastics by plants could be key to spotting plastic accumulation areas – for then mitigating plastic pollution. In this optic, as rivers carry most of the plastics, riverine plastic transport needs to be understood also in view of the riparian vegetation's role in entrapping macroplastics. Although the role and structure of vegetation started to be investigated recently (Gallitelli et al., 2021, 2023), here we emphasized the riparian vegetation three-dimensional structure for the first time. We emphasized that plant structures are important variables for understanding the entrapment efficiency of macrolitter, highlighting that the complexity of vegetation structure is key for the trapping net effect. Riparian vegetation is threatened by several disturbances (i.e., contaminants, habitat loss, agriculture, etc.) but at the same time, it traps plastics allowing the development of remedial designs through the removal of plastics. In this regard, it appears pivotal to further study how vegetation contributes to the retention of plastics. Before solving the plastic problem, one must find ways to assess plastics in vegetation, given the problem posed by plastic on vegetation (see plastic effects on blooming and pollination in Gallitelli and Scalici, 2023). As plants trap plastics, vegetation can contribute to plastic remediation, so once a protocol to sample plastics in vegetation is proposed, then environmental drivers (e.g., seasonality, hydromorphological aspects, wind, and vegetation structure) on plastic deposition in vegetation can be further understood - to better analyze areas of plastic accumulation. As vegetation retains plastics efficiently in watercourses providing us the ecosystem service of trapping macrolitter, these preliminary guidelines on plastics in plants could be key to standardizing data collection and comparing results. We encouraged them to follow those standardized methods to achieve result comparability. Then, following previous research (Battisti et al., 2020), those data could be used in future research to detect plastic hotspot areas and, consequently, for future solutions such as mitigation and clean-up activities.

## CRediT authorship contribution statement

**L. Gallitelli:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **M. Cutini:** Methodology, Supervision, Validation, Visualization, Writing – review & editing. **M. Scalici:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

## 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.

## Data availability

All data are present in the manuscript and Supplementary Materials.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.169570.

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