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Conceptual model of global plants entrapping plastics

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Abstract

Aquatic plants, seagrasses, macrophytes, mangroves, and riparian vegetation are responsible for some of the most important ecosystem services provided on the Earth. Given their role in trapping plastics along rivers, we propose a new ecosystem service of plastic entrapment by global plants. Although research started recently to study vegetation trapping plastics, little is known about the global patterns of plastic retention and remobilization by vegetation through different habitats. Given those gaps, we synthesize global data on plastic entrapment in plants providing a conceptual model to describe processes for plastic retention by vegetation. Our results demonstrate how vegetation has a pivotal role in entrapping plastics across spatial and temporal scales, finding the higher density of plastics on plants rather than in the adjacent water area. Furthermore, we proposed a conceptual model (i.e., Plant Plastic Pathway) of plants entrapping plastics, highlighting spatial and temporal scales of plastic retention and release processes in different habitats. Thus, we anticipate our conceptual model to be a starting point for more sophisticated future studies, putting effort into looking at plastic–vegetation dynamics. Our conceptual model may have a crucial effect if applied to plastic hotspot area detection with clean-up and mitigation actions in riverine ecosystems.

Highlights:

- We synthesize global data on plastic entrapment in plants providing a conceptual model to describe processes for plastic retention by vegetation.
- Vegetation has a pivotal role in entrapping plastics through spatial and temporal scales, finding the higher density of plastics in plants rather than in water.
- We proposed a conceptual model (i.e., Plant Plastic Pathway) of plants entrapping plastics, highlighting spatial and time scales of plastic retention and release processes in different habitats.
- Our conceptual model may have a crucial effect if applied to plastic hotspot area detection with clean-up and mitigation actions in riverine ecosystems.

Key words: plastic hotspot, global pollution, plastic trapper, ecosystem service, plastic plants

1. Introduction

Plastic pollution is an emergent contemporary well-investigated issue due to the risk that it poses to the environment (van Emmerik and Schwarz 2020; Azevedo-Santos et al. 2021; Lavers et al. 2022; Ryan and Chitaka 2022). Mismanaged waste is largely accumulated in aquatic ecosystems, ubiquitously persisting in the ocean (van Sebille et al. 2012) and lakes (Cera et al. 2023), as well as in rivers (van Emmerik et al. 2022). Although rivers are considered the main carrier of land-based plastics to the sea (Gasperi et al. 2014; Tramoy et al. 2020; González-Fernández et al. 2021; Gallitelli and Scalici 2022), plastics can also be retained in watercourses (Gallitelli et al. 2022; van Emmerik et al. 2022) and estuaries (Simon-Sánchez et al. 2019; van Emmerik et al. 2020; López et al. 2021; Wang et al. 2022). Plastic input in rivers may be transported downstream, reaching the sea as a final output (González-Fernández et al. 2021). However, during its way, plastics are blocked by bridges, infrastructure, sediments in the rivers, as well as riverbanks (Liro et al. 2020; Roebroek et al. 2021; van Emmerik et al. 2022; de Lange et al. 2023; Liro et al. 2023). Apart from artificial factors blocking plastics, plants occurring in these systems may block plastic litter. Floating and submerged aquatic vegetation standing on the river water surface and column (i.e., macrophytes) may act not only as a (temporary) sink for macroplastic litter (Gallitelli et al. 2023a), but also as a carrier along rivers (Schreyers et al. 2021). Moreover, riparian vegetation on the riverbanks may entrap plastics coming from land as well as plastics transported by the river. At the same time, mangroves on coastal and estuarine habitats entrap plastics coming from rivers. Together with other understudied habitats, riparian ecosystems, as well as coastal systems (with mangroves and dune plants), might have a key role in the plastics that do not reach the ocean. For these reasons, the entrapment of plastics by plants might influence the flux, distribution, and accumulation of plastics along watercourses (see Gallitelli and Scalici 2022). Also in the coastal and marine systems, plastics can be entrapped by plants (see Ivar do Sul et al. (2014), Martin et al. (2019), Kesavan et al. (2021), and Luo et al. (2021) for mangroves, Sanchez-Vidal et al. (2021) for marine plants, Andriolo et al. (2021), Gallitelli et al. (2021), and Ouyang et al. (2022) for dune coastal plants). From this framework, the output of plastics from rivers to the sea can be one of the main sources for plastics entrapped in dunes, mangroves, seagrass, salt marsh, or coral ecosystems.

Vegetation provides us with many ecosystem services (i.e., benefits and well-being obtained by ecosystems according to MEA 2005), such as oxygen production, nutrient cycling, habitat provisioning, or water purification (Chambers et al. 1987; Scott et al. 2018; Riis et al. 2020; Thomaz 2021). Among this latter, given that plastics accumulate in seagrasses, macrophytes, mangroves, dune plants, and riparian vegetation, this could be seen as a new ecosystem service provided by plants (Gallitelli et al. 2021; Kerpen et al. 2024). Indeed, plants (temporarily) block plastics from the surrounding environment offering us the possibility of recollecting plastics and disposing them of properly. Entrapped micro and macroplastics (items < 0.5 cm and items > 0.5 cm, *sensu* Gallitelli and Scalici 2022) may be harmful by entering the food chain (Setälä et al. 2018; Provencher et al. 2019; D'Souza et al. 2020), damaging plants (Rillig et al. 2019; Parkinson et al. 2022), and impacting the nursery function (Goss et al. 2018; Bonanno and Orlando-Bonaca 2020). Given these reasons, understanding the entrapment dynamics of plastics in plants might be important. Thus, we pose our emphasis on the plastic entrapment process by global plants.

Recent research has started to study vegetation trapping plastics, therefore little is known on (i) which plants more accumulate plastics, (ii) the processes that bring plastics to be retained and released by vegetation, (iii) global patterns of plastic accumulation in vegetation, and (iv) pathways of plastics entrapped by vegetation through different habitats (i.e., from terrestrials to marine and coastal ones via rivers). Given those gaps, we synthesize global data from 115 papers on plastic entrapment in plants providing a conceptual model to describe processes for plastic retention by vegetation. Specifically, we (i) reviewed the vegetation archetypes and structures in relation to the plastic entrapment in different habitats. Then, we (ii) assessed if global plants act as plastic trappers with a focus on plastic types and sizes entrapped by plants. We compared plastic density within vegetation to that outside vegetation in the same habitat and then investigated which plastic types and sizes were mostly blocked by global vegetation. We (iii) proposed a conceptual model (i.e., Plant Plastic Pathway, PPP hereafter) of plants entrapping plastics, highlighting spatial and time scales of plastic retention and release processes in different habitats. Details on spatial and time scales need to be investigated to understand plastic accumulation in plants. Given that mechanisms and processes of plastics entrapped in vegetation are neglected, the goal of this conceptual model is to shed light on the processes of plastic retention by plants. While research in this area is still in its early stages, we seek to identify which plant type and species have a greater propensity to accumulate plastics. By understanding this, we can discern the structure and traits that make certain plants more effective at trapping plastic debris than others. Furthermore, we address the underlying mechanisms that contribute to the entrapment and subsequent release of plastics by vegetation. Additionally, we attempt to establish global patterns of plastic accumulation in vegetation. This involves examining plastic entrapment across diverse habitats, spanning from the fluvial ecosystems to the marine and coastal ecosystems, acting as the main link of plastics between these habitats. The PPP model hypothesizes the spatial and temporal scales at which plastic retention and release occur in various habitats. Moreover, the PPP model should help in understanding and spotting the 98% of plastics that remain stuck in the fluvial system (Meijer et al. 2021), acting as a tool to prevent and mitigate plastic pollution. By providing a comprehensive framework for understanding plastic retention by vegetation through aquatic ecosystems, our study seeks to contribute valuable insights to the field of plastic pollution research and inform strategies for mitigating the environmental impacts of plastic debris.

2. Approach

To summarize the process, first, the literature search allowed us to unveil how different plants entrap/release plastics in different habitats globally. Then, data extraction from those searched papers highlighted the plastics entrapped by each plant type and species. Lastly, the PPP model wrapped all that information with a conceptual view of the plastic entrapment process, also highlighting temporal and spatial scales.

2.1. Vegetation structures in relation to the plastic entrapment in different habitats

In this overview, we quantified the number of studies on vegetation entrapping plastics ($n = 115$, Table S1). To achieve it, the process was (i) data collection, (ii) data extraction and harmonization, and (iii) data analysis and comparisons.

First, (i) to collect data, we conducted a precise search on Web of Science and Scopus (hereafter WS and SC, respectively) until the 15th of May 2023. We searched the keywords "vegetation" and "plant" AND "microplastic" and "macroplastic" together with "marine, macrophyte, dune, mangrove, and riparian" ecosystems. We searched for those habitats AND plant, vegetation AND block, trap AND plastic. Those papers and the data extracted from the literature search were used to understand the entrapment of plastics in global vegetation. The similar papers obtained from both the search engines (WS and SC) were deleted if similar. Then (ii) data were extracted from the papers that reported them ($n = 11$). Second, to compare literature findings, we processed data based on metrics such as the number of plastic items per m^2 or the number per item standardized on the area reported in the sampling design of the paper. More information was reported at the beginning of the next paragraph. Third, to assess if plastic quantity is higher in vegetation than in the environment, we compared plastic density within patches of vegetation to that outside vegetation in the same habitat/compartment.

Before comparing plastic density within vegetation, we discussed (a) the different plant types and species considered per ecosystem and (b) the characteristics of these types (i.e., traits and structure).

Concerning the (a) different plant types and species in each ecosystem (Table 1), aquatic moss, marine, and freshwater algae are the main vegetation occurring in marine and riverine ecosystems (Tyler 1996; Dawes 1998; Chambers et al. 2007; Bornette and Puijalon 2009). In marine ecosystems, aquatic vegetation is submerged and mainly composed of algae, seaweeds, and seagrasses, while in freshwater mosses, algae and macrophytes are the main widely distributed vegetation (Tyler 1996; Dawes 1998; Chambers et al. 2007; Bornette and Puijalon 2009). While for marine ecosystems, the coastal habitats host dune plants, riverbanks along rivers have riparian vegetation in the ecotone. Aquatic vegetation plays an important role in both marine and freshwater ecosystems providing several ecosystem services such as being a food source for organisms, contributing to carbon sequestration and releasing oxygen, and absorbing pollutants (Chambers et al. 1987; Krause-Jensen and Duarte 2016; Scott et al. 2018; Thomaz 2021). Vascular plants are important primary producers representing food for fish and birds in aquatic ecosystems, serve as a nursery habitat for many species, and offer both protection from predators and enhanced feeding opportunities (Likens 1975; Lazzari and Stone 2006; O'Hare et al. 2018). Among those several ecosystem services, plants also entrap plastics (Gallitelli et al. 2022; van Emmerik et al. 2022). Related to the plastic entrapment, in this paper, all the vegetation types and species are reported in Table 1.

Regarding the (b) plant traits and structure, moss, marine, and freshwater algae possess thallus and leaves as structures to entrap plastic in marine environments (Cozzolino et al. 2020). On the other hand, marine macroalgae (i.e., seagrass, *Posidonia oceanica*), freshwater macrophytes, mangroves, and riparian vegetation have a well-developed radical apparatus, branches, and leaves that can block plastic debris. Also, other peculiar structures (i.e., pollons in riparian vegetation and pneumatophores in mangroves) are involved in plastic retention. Due to the occurrence of plants, these latter blocked the water body leading to increased energy dissipation (induced by flow or waves) and the formation of wake regions where sediments (and plastics) in general accumulate (Kerpen et al. 2024). More information on the trap efficiency of species in different habitats is provided in Table S2 according to the published literature until now (Supplementary Table S2). Thus, leaves, roots, or branches together with plant density drive the plastic entrapment process by plants. All these traits provide the main structure of plants. For our aim, the concept of "plant structure" related to plastic entrapment has not been well described, and the processes and mechanisms are not so investigated and understood. In botany and plant ecology, plant structures are defined as part of vascular plants with vital functions (see soft traits, Lavorel et al. 2007; Kattge et al. 2011). For this reason, we will examine leaves, roots, and branches—the primary part of vascular plants with primary functions for plant growth and survival. In our view (i.e., plastic entrapped by plants), structure comprehends morphological plant traits (i.e., leave shape, roots, and branches) as well as community structure (i.e., the structure given by the different species living in a specific habitat). Many structures may help to entrap litter. We should consider that at a specific level, plants possess different typologies of leaves, roots, and branches—apt at blocking different sizes and types of plastics.

To better understand the architecture of vegetation, we discussed the retention and release processes of vegetation archetypes and provided a basic introduction to plant archetypes and their traits. Regarding (iii) data analysis and comparison, data on plastic density in plants were obtained from the literature. We extracted the metadata representing plastic density (items per m^2, hereafter it/m^2). Data on plastic density were extracted by the sampled area occupied by plants reported in the literature (e.g., 10 plastic items found in 200 m^2 of mangroves) and standardized on the area occupied by the plants in the plot site. To make all the results comparable, we harmonized data to items/m^2, so we divided by 100 when data were expressed as items/100 m^2. Also, to be harmonized with others, data expressed as items could be converted to items/m^2 if the area is reported in the study. To assess differences in entrapment levels between plant species, we calculated the plastic density found for each plant (see Gallitelli et al. 2024). This density provides the quantity of plastics trapped by a specific plant in a certain area (reported as items per m^2) in a precise habitat. As data were collected by literature, when more papers were available, an average between the plastic density in plants was calculated. The plastic density in plants (ρ_{plant}) has been calculated as follows:

(1) $$\rho_{\text{plt}} = N_{\text{plant}}/A_{\text{plant}}$$

where plastic density in plants is given as items/m^2 and indicates the number of plastics found per plant habitat (N_{plant}) in the sampled area (A_{plant}). Then, to obtain a global harmonization among plastics trapped by all types of vegetation, we calculated values for the plastic trap efficiency, expressed as % of E_{trap}.

(2) $$E_{\text{trap}} = \rho_{\text{plt}}/\rho_{\text{env}} \times 100$$

These results on plastic density were plotted in a global figure with all vegetation types. The higher to lower plastic density among all types of vegetation has been shown. The global map for plastics in vegetation for each type of vegetation has been created with metadata by literature. Those available metadata were obtained by the literature and extracted to obtain the average plastic concentration as items/m^2. To visualize the results, a final map has been created with Datawrapper.com.

2.2. Plants as plastic trappers

We compared plastic density within vegetation to that of outside vegetation in the same habitat from the same geographical region and then investigated which plastic type is mainly retained by global vegetation. To assess whether

Table 1. Overview of retention and release dynamics related to plastic entrapment by plants divided per habitat.

Plant habitat	Retention dynamics		Release dynamics		References
	Timescale	Main mechanisms	Timescale	Main mechanisms	
Riparian	Continuous accumulation	River transport and floods	Seasonal cycle	Floods	Cesarini and Scalici (2022), Gallitelli et al. (2022, 2024), and Gallitelli and Scalici (2023)
Macrophytes	Continuous accumulation	Water current, tides, and wind	Daily to monthly	Floods and river current	Schreyers et al. (2021), Gallitelli et al. (2023a), Tan et al. (2023)
Mangroves	Continuous accumulation	Sea waves, river transport, and tidal currents	Monthly to annual to decadal	Sea storm events, increased hydrology level, and tidal currents	Martin et al. (2019), Luo et al. (2021), and De et al. (2023)
Dune plants	Continuous accumulation	Sea waves, river transport, and wind	Seasonal cycle	Wind and sea storm events	Gallitelli et al. (2021), Andriolo et al. (2021), Ben-Haddad et al. (2023)
Marine plants	Continuous accumulation	Sea waves, marine transport, and tidal currents	Daily to decadal	Sea extreme events and sea waves, and tidal currents	Cozzolino et al. (2020) and Sanchez-Vidal et al. (2021)

Note: According to transport, storage, and remobilization, plants may act as a sink for plastics (i.e., storage period), as well as a source of them (i.e., remobilization period).

plastics entrapped in plants were more abundant than plastics occurring in the adjacent environment (i.e., PLANT and ENVRN, with ENVRN as control), we performed a Wilcoxon matched-pairs signed rank test between plant and control matrices using plastic density (i.e., plastic trap efficiency). Although there is no standardized protocol to monitor plastics in and out of vegetation, the area of the adjacent environment sampled as control is reported only a few times (i.e., check Gallitelli et al. 2021; Schreyers et al. 2021; Battisti et al. 2023; Ben Haddad et al. 2023). If not reported, the plastic items sampled were divided for the same area sampled for plastics in vegetation (following Gallitelli et al. 2021). When the value of plastic in the environment is not available, it has been calculated by adapting metadata on plastic occurrence in rivers according to Meijer et al. (2021) and https://ourworldindata.org/plasticpollution. Data from Meijer et al. (2021) were reported as million metric tons (MT) per year. To obtain plastic density in the environment (i.e., ρ_{env} expressed as items/m^2), we used the plastics in the environment expressed by MT per year (N_{env}) by dividing it by the area occupied by plants (A_{plant}) found in the papers. When results were expressed as MT per year, we converted them into number of items per year. To obtain the mass of the litter, we calculate an approximate average weight of the most occurring plastic item in tonnes. By dividing this latter, we obtained the number of items for the MT. To compare plastics in plants with plastics in the environment, we considered the areas of plants (A_{plant}) and environment (A_{env}) as the same. Then, as we are focusing on rivers near the sea, we multiplied those values by the probability that the litter must reach the sea (P_{sea}), provided by https://ourworldindata.org/plasticpollution. All that information is reported in Supplementary Table S2. By following eqs. 1 and 2, the plastics in the environment were calculated by this equation:

$$\rho_{env} = (N_{env}/A_{env}) \times P_{sea} \quad (3)$$

Our main hypothesis is that plants may block different types of plastics in relation to their structure complexity. Based on the habitat in which they occur, plants show their own morphology and structure (i.e., soft traits, see Lavorel et al. 2007; Kattge et al. 2011), which here we highlighted to be crucial for plastic entrapment. To highlight the effects of plant characteristics on entrapment, we based on well-established plant trait databases (TRY database, see Kattge et al. 2011). In detail, due to their structure, different types of vegetation could block different types of plastics. Plastic polymers and types were obtained from the literature and classified according to van Emmerik et al. (2018) and Gallitelli and Scalici (2022). The list of polymers and types is shown in Supplementary Table S3. Then, to understand which plastic types were dominantly blocked by a certain type of vegetation, data were divided for each vegetation and the output can be seen in Supplementary Table S4.

2.3. The "Plant Plastic Pathway": a conceptual model of plants entrapping plastics

To summarize all the findings on plants entrapping plastics, we developed the PPP model to understand where plastic stuck, given that most plastics are retained by fluvial ecosystems. To date, given that data sampling in each kind of vegetation does not follow a unique protocol, it is impossible to convert the conceptual model into a mathematical and numerical model. The present conceptual model is discussed as a synthesis of the plastic entrapment process, and it will be applied in future research.

To show the conceptual model of plastics entrapped by plants, we discussed the process and mechanisms of trapping plastics by plants according to the five phases identified by Liro et al. (2020). Our "Plant Plastic Pathway" links the retention, remobilization, and transport of plastics by plants in different habitats (Gallitelli et al. 2021, 2024; Schreyers et al. 2021). The plastic entrapment by plants in different habitats moves from the river to the coast and marine ecosystems.

Regarding the type of plants, floating and submerged vegetation in rivers and seas has been included in macrophytes and marine plants, respectively. Dune plants, mangroves, and riparian vegetation were included in the other respective groups (see Fig. 1).

Although precise and meticulous protocols to sample plastics in vegetation lack, literature reported that several vegetation types have been sampled using transects and plots of various measures (i.e., meters and square meters). Thus, the different methodologies do not allow results to be compared and to extrapolate a variable from another one (e.g., if plastics in vegetation are reported as items but, in the paper, the area of the plot or the weight of litter sampled in vegetation is not reported, it is difficult to obtain the result expressed as items/kg, items/m, and items/m^2).

In our paper, we will look at plastic entrapment at three different spatial scales: (i) the local (plant) scale that considers how many plastics are entrapped/released in a single plant, then (ii) the landscape (river) scale that pointed out how much plastic is entrapped within a river system, and (iii) the global scale that considers how vegetation and plastic entrapment vary over the globe.

All data analyses were performed by using GraphPad software. The alpha test level was set at <0.05 for the statistical analyses.

3. Findings

3.1. Plant structures in relation to plastic entrapment in different habitats

In this section, we summarized the main structures (i.e., plant traits) and the processes that impact plastic entrapment by plants. We proposed a conceptual model to highlight those trapping processes and structures (see Figs. 1 and 2). We highlighted the time and spatial scales that lead to the retention and release of plastics in vegetation. We emphasized the plant structure related to those processes and how the different vegetation types affect the plastic entrapment (Fig. 1).

Regarding plant traits, we discussed the main organs of plants related to plastic entrapment.

Although literature well reported that plants trap plastics (Williams and Simmons 1996; Ivar do Sul et al. 2014; Martin et al. 2019; Schreyers et al. 2021; Gallitelli et al. 2021; Cesarini and Scalici 2022; Gallitelli et al. 2022; Gallitelli and Scalici 2023), plants possess different typologies of leaves, roots, and branches—apt at blocking different sizes and types of plastics.

An important structure pivotal in the entrapment process is related to branches and roots. In the first case, more articulated and composed branches form a sort of net that retains certain types of litter (such as bags and foils, see Martin et al. 2019; Gallitelli et al. 2022). In the second case, roots may form a "basket"—that can entrap plastics. In this regard, these structures are characterized by more elements that entangle each other, thus plastics transported by water or wind can be deposited on them. In this process, force (of water or wind) could press plastics into the vegetation structure, making it a suitable trap (see pneumatophores in mangroves, Srikanth et al. 2016). In particular, the mangrove aerial root called pneumatophores (see *Avicennia* spp., *Laguncularia* spp., and *Sonneratia* spp.) might be temporary traps for plastic debris (see Martin et al. 2019; Duan et al. 2021; Kesavan et al. 2021) and particularly blocked film-like plastics such as plastic bags (Debrot et al. 2013; Ivar do Sul et al. 2014; Martin et al. 2019), as well as also large containers and big-sized plastics (see Martin et al. 2019 and Kesavan et al. 2021). In addition, foam spherical smaller plastics (e.g., PS foam) can be trapped by algae for their shape. The structure of dune vegetation (i.e., prostrate shape, with a dense core area) is key in blocking macrolitter coming from the shoreline (Gallitelli et al. 2021). Considering riparian vegetation, trees, shrubs, and reeds form basal shots that act as a net for plastics (see Cesarini and Scalici 2022; Gallitelli et al. 2022; Gallitelli and Scalici 2023). Also, roots and abaxial leaf surfaces in floating duckweed allow microplastics to remain attached to the plants (Mateos-Cárdenas et al. 2019; Dovidat et al. 2020).

In the entrapment process, the number of individuals and species as well as the type and species of vegetation are also pivotal characteristics (Gallitelli et al. 2022). While plant density increases the plastic entrapment (see Gallitelli et al. 2023*a* on aquatic macrophytes), different types and species of vegetation with their complex aerial roots and branches provide high structural complexity (Martin et al. 2019; Gallitelli et al. 2024). Vegetation characterized by more individuals and higher density (i.e., a more complex and denser structure, namely plant structure complexity) could act as a net blocking more litter (Martin et al. 2019), as well as a filter that blocks the bigger plastic items sieving the smaller ones (Andriolo et al. 2020; Gallitelli et al. 2023*b*). The plant canopy seasonality might be pivotal for plastic entrapment; however, further research should be done to investigate the interaction of plant metabolism and plastics. In this regard, plastic release in relation to seasonality is a topic to be further investigated. Furthermore, plant diversity may play a role in terms of entrapping plastics; as the structural complexity of plant roots and branch architecture vary across species, it could create various scenarios in which tree communities act as trappers as more intricate ecosystems formed by various species and plant types (Luo et al. 2021; Gallitelli et al. 2022). A conceptual figure (Fig. 1) shows the location of the vegetation in the riverscape and the traits within the vegetation, pivotal to blocking plastics from the environment.

Regarding the plastic entrapment by plants along different habitats, we assessed the efficiency of entrapment in different taxonomical groups (Supplementary Table S2; Figs. 1 and 2). The plastic trap efficiency ranged from 0 to 17 items/m^2, calculated using literature metadata (see Supplementary Table S2). Aquatic moss, marine, and freshwater algae possess thallus and leaves as structures to entrap plastic in marine environments (Cozzolino et al. 2020). On the other hand, marine macroalgae (i.e., seagrass, *Posidonia oceanica*), freshwater macrophytes, mangroves, and riparian vegetation have a well-developed radical apparatus, branches, and leaves that can block plastic debris. Also, other peculiar structures (i.e., pollons and spines) are involved in plastic retention. In detail, while pollons may create a net effect blocking macroplastics (Gallitelli et al. 2022), spines may degrade macroplastics into

Fig. 1. The basic structural traits of vegetation along riverscape. The different plant archetypes are here represented by leaves, roots, and branches. The most common plastic types are shown on vegetation in the following literature (see Supplementary Table S4, Fig. 2). Along the riverscape, the average plastic trap efficiency per each vegetation is shown. The legend indicates the plastic trap efficiency ranging from 0 to 17, calculated using literature metadata (see Supplementary Table S2). The five coloured dots indicate plastic concentration trapped by plants. Figures have been taken from https://www.pngegg.com/it and iStockphoto.com.

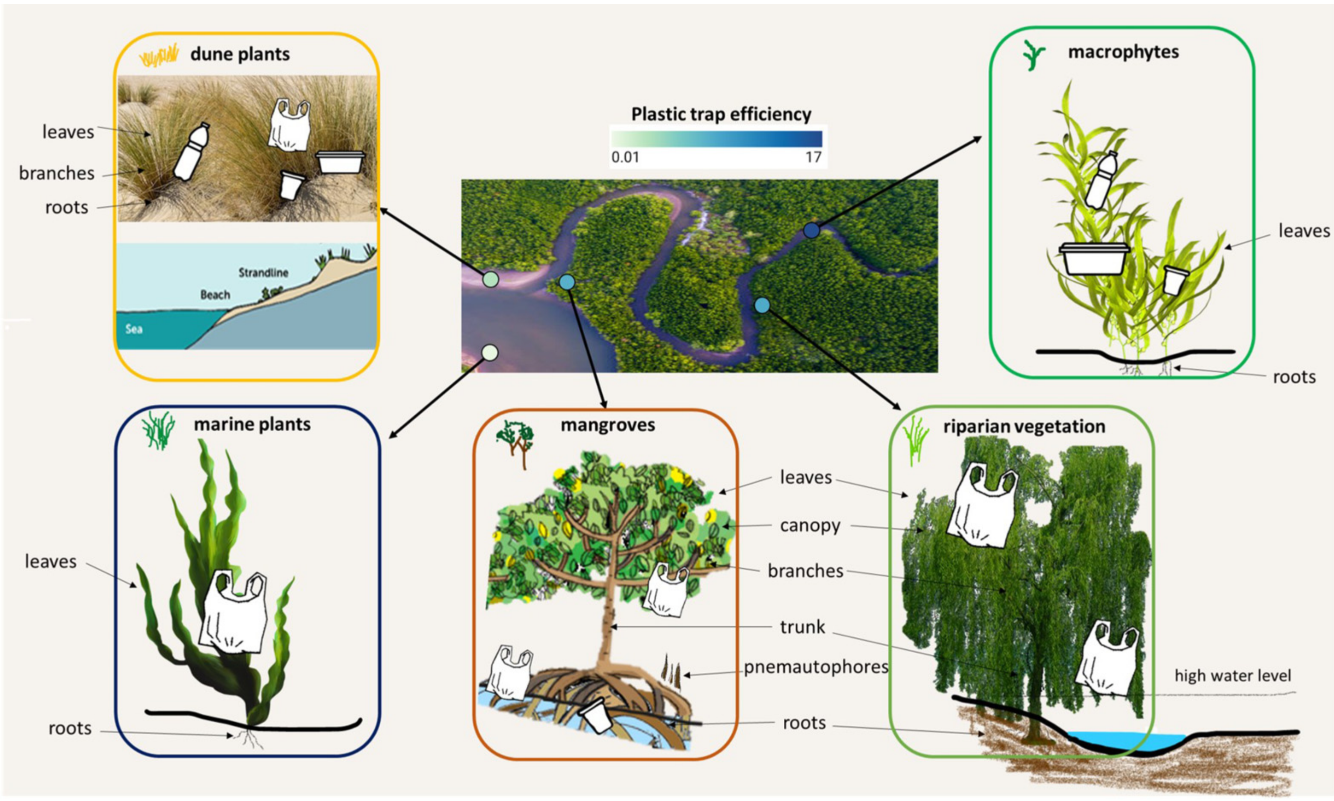
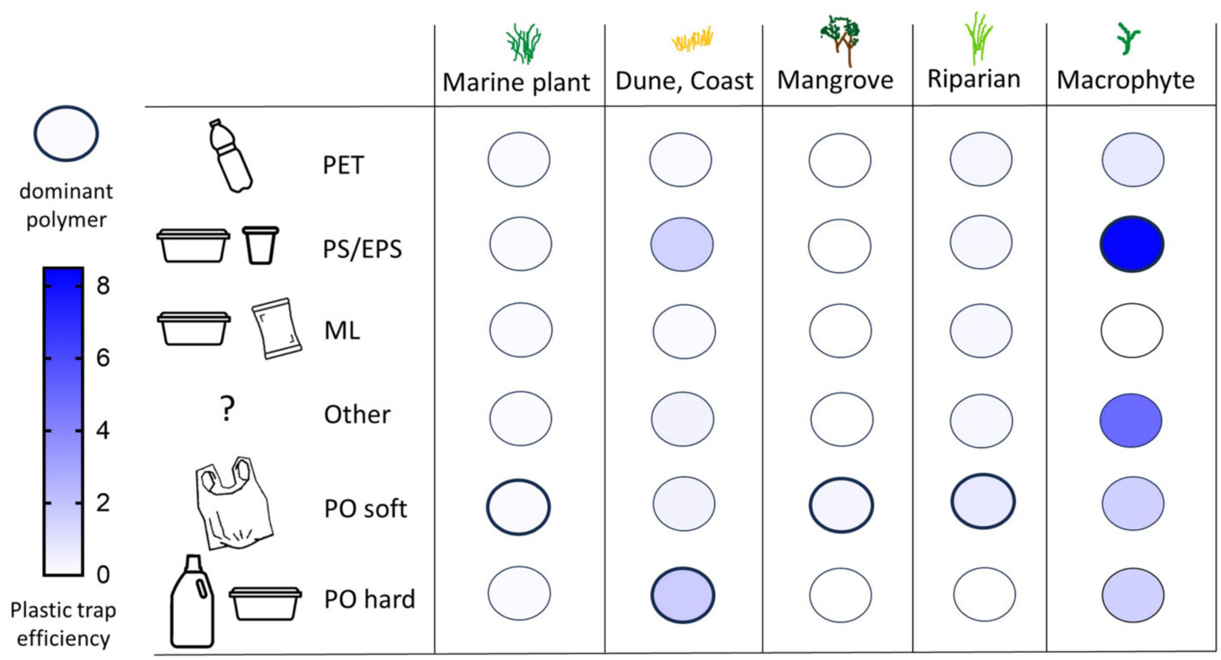


Fig. 2. Plastic polymers and types are entrapped by the different global plants. The circle dots indicate the % of trapping efficiency based on the average values available from the literature (see Supplementary Table S4). The circles in bold represent the specific dominant polymer trapped by each vegetation. The scale shows the plastic trap efficiency. PET, polyethylene terephthalate; PS/EPS, polystyrene/expanded polystyrene; ML, multilayer; PO, polyolefin.



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smaller particles, enhancing microplastic pollution in watercourses (Cesarini and Scalici 2022; Gallitelli et al. 2022). More information on the plastic trap efficiency of species in different habitats is provided in Supplementary Table S2 according to the published literature until now (Supplementary Table S2). Thus, leaves, roots, or branches together with plant density drive the plastic entrapment process by plants. Although first attempts showed that the more complex the plant shape and tridimensionality the more efficient in entrapping plastics (see Gallitelli et al. 2021; Ben-Haddad et al. 2023), difficulties in comparing 1 m^2 of mangroves in India with 1 m^2 of riparian vegetation in Italy yet subsist. This is mostly due to the use of different protocols and thus a lack of method harmonization (see also the Method section). However, literature data show that a certain type of vegetation blocked more plastics than others, probably due to a higher and more complex plant structure (Gallitelli et al. 2024). Moreover, indoor experiments proved that the trapping efficiency might be directly related to the biomass per square meter or to the number of plants per area (de los Santos et al. 2021; Kerpen et al. 2024). The entrapment efficiency of plastics is also driven by leaf morphology in freshwater macrophytes (Gallitelli et al. 2023a; Tan et al. 2023). While articulated leaves in aquatic macrophytes lead to blocking more plastics than linear and long leaves (see Gallitelli et al. 2023a), tridimensionality structure in other plants is mostly given by high spatial complexity. In this view, dune plants show prostrate shape, articulated leaves, and branches that make them able to filter, sieve, and trap litter (see Gallitelli et al. 2021, 2023b). Mangroves and riparian vegetation forests are characterized by patches with different species and plant types. Mangroves seem to block one of the highest plastic abundances, and this could be mainly due to their aboveground root structures (Fig. 1). Pneumatophores, plank, stilt, and knee roots are the best traps for plastics (Martin et al. 2019; Luo et al. 2021; De et al. 2023; Okuku et al. 2023) as these roots decrease tidal flow and consequently wave energy, creating a lotic environment in which plastics can accumulate easily. Precisely, the pneumatophores of the white mangrove (*Avicennia marina*) in the Arabian and Red Seas efficiently trap macrolitter (Martin et al. 2019). Also, in the landward zone, mangrove roots entrap efficiently hard plastic and clothing, allowing soft plastics to pass and be trapped by mangroves in the middle zones between seaward and landward zones (Okuku et al. 2023). In the seaward zone, mangrove forests mainly trap fishing gear (Okuku et al. 2023). Instead, riparian vegetation species do not possess aerial roots; however, they efficiently entrap macroplastic litter with pollons, branches, and canopy (see Cesarini and Scalici 2022; Gallitelli et al. 2022, 2024; Gallitelli and Scalici 2023).

In marine ecosystems, seagrass and macroalgae have blades and leaves that trap microplastics. Literature pointed out that macroalgae blocked more plastics than seagrasses. This could be mostly due to the denser meadow that characterizes those plants (Cozzolino et al. 2020; Esiukova et al. 2021; Sanchez-Vidal et al. 2021; Navarrete-Fernández et al. 2022). Regarding macro-algae, seaweeds may block plastics following several pathways of entrapment (Li et al. 2022, Table 1; Supplementary Table S2). Plastics might result entrapped or attached within the air sac structure (Datu et al. 2019; see Li et al. 2022). More in detail, the seagrass blade of the smooth ribbon seagrass (*Cymodocea rotundata*) showed having wrapped microfibers and microfragments (Datu et al. 2019). These are characteristic structures that are not so common in plants and given the higher sea current, it might be slightly difficult to entrap an efficient quantity of plastics. In the same manner, the Mediterranean seagrass (*Posidonia oceanica*) entraps plastics in meadows (i.e., leaves block up to 1470 plastic particles per kg, Sanchez-Vidal et al. 2021), egagropilae balls, and stolons (i.e., specific roots) according to Sanchez-Vidal et al. (2021) and Navarrete-Fernández et al. (2022). Microplastics were found attached to the underwater canopy of seagrasses (Cozzolino et al. 2020; de los Santos et al. 2021; Kerpen et al. 2024). In the entrapping process, bioadhesion is also an important interaction between MPs and aquatic macrophytes (Kalčíková 2023). Among all these studies, only Cozzolino et al. (2020) quantified the role of seagrass plastic entrapment in the field. In detail, macroplastics and microplastics have been found in the canopy and superficial sediment of seagrasses (two intertidal: seagrass *Zostera noltei* and saltmarsh *Sporobolus maritimus*; and the two subtidal: seagrass meadows of *Cymodocea nodosa* and *Zostera marina*, and rhizophytic macroalga *Caulerpa prolifera*) (Cozzolino et al. 2020). Regarding the trapping effect in marine plants (see Supplementary Table S2), intertidal and subtidal seagrasses entrap few macroplastic items per 100 m^2 (1.3 ± 2.1 and 1.4 ± 2.2 items 100 m^{-2}, respectively), while the macroalga and the saltmarsh resulted to be more efficient (4.2 ± 5.3 items 100 m^{-2} and 17.3 ± 13.3 items 100 m^{-2}, respectively, see Cozzolino et al. 2020). In this regard, seagrass beds act as a trap of microplastics—mostly when the bed is vegetated (Jones et al. 2020; Cozzolino et al. 2020; Sanchez-Vidal et al. 2021; Navarrete-Fernández et al. 2022; Gaboy et al. 2022; Boshoff et al. 2023; Huang et al. 2023).

Both freshwater and marine vegetation may block litter actively (i.e., when living) or passively (i.e., when dead and occurring as vegetal wracks and woody jams accumulating in rivers and coasts). In these latter cases, vegetal wracks and woody jams have been discovered to entrap large quantities of plastic litter (Burlat and Thorsteinsson 2022; Liro et al. 2022).

3.2. Plants as plastic trappers

Here we discuss if plants were able to entrap plastics, and what plastic sizes and types are mainly blocked by different types of vegetation. First, we quantified the number of studies on vegetation entrapping plastics ($n = 115$, Supplementary Table S1). Overall, plastics in marine plants (53.0%) resulted to be more studied than macrophytes and dune vegetation (15.7% both), as well as mangrove plants and riparian vegetation (9.6% and 6.1%) (see Supplementary Table S1). In the next paragraph, we describe the process of plastic entrapment by plants. Plastics freely move in the environment, transported by water or wind (Gallitelli and Scalici 2022; Mellink et al. 2022). When litter is near a plant patch, litter hits on plants and embeds in vegetation due to plant structure and reduced hydraulic energy. We also highlight that plastic density within vegetation is more abundant than plastics outside vegetation in the same habitat ($W = 21.00$, $p = 0.03$; Supplementary Tables S1 and S2), meaning that several plastics occurring in the surrounding environment would stick in vegetation. Considering the habitat, plastic concentration in plants ranged from 0.1 items/m^2 and 1.6 items/m^2 in marine and dune vegetation to 24.2 items/m^2 and 25.5 items/m^2 in mangroves and macrophytes, passing through 14.5 items/m^2 for the riparian vegetation. Secondly, we also found that there could be a relation between plastic type and vegetation structure involved in the entrapment effect using literature metadata (Supplementary Tables S3 and S4).

Concerning the size of plastics, plants with long leaves should allow small plastic items (i.e., 5–10 cm) to pass more easily, while plants with composed and serrated margins could help in entrapping bigger plastics (20–30 cm and 30–50 cm, Gallitelli et al. 2022). Macrophytes may block different sizes of plastics (i.e., micro-, meso-, and macro-plastics) within the water column (Schreyers et al. 2021; Gallitelli et al. 2023a). Moreover, independently of plastic size, the higher the plant density the higher the entrapment of plastics by macrophytes (e.g., the spike watermilfoil *Myryophyllum spicatum* and the curly-leaf pondweed *Potamogeton crispus*): macro-, meso-, and microplastics were trapped similarly by aquatic plants (Gallitelli et al. 2023a). Furthermore, the common reed (*Phragmites australis*) reedbed and dune plants blocked small and medium macrolitter items (e.g., 2.5–5 cm and 5–10 cm) in the foredune area, allowing a higher number of larger items (e.g., >10 cm) to back dune habitats (Andriolo et al. 2020; Cresta and Battisti 2021; Gallitelli et al. 2023b). Overall, the plastic size range for each vegetation type is 0.1–132 cm for marine plants, 0.5–50 cm for dune plants, 1–10 cm for macrophytes, and 0.5–50 cm for riparian plants (Supplementary Table S5). Data on plastic size range in mangroves lack.

Concerning the plastic type entrapped by plants (see Supplementary Table S4), according to the ongoing literature, marine plants, mangroves, and riparian vegetation trapped mainly PO soft, while dune plants are able to trap PO soft, as well as expanded polystyrene/polystyrene (EPS/PS) and PO hard. Likewise, macrophytes trap EPS, polyethylene terephthalate (PET), and PO hard (Fig. 2). In this view, it is crucial to investigate the type of litter found trapped by plants, as the retention dynamic depends also on the type of litter (Fig. 2). Across different types of vegetation, given to their structure, vegetation blocked plastic litter with different ways (see the plant structure and the plastic trap efficiency among all types of vegetation). Among different habitats, dune plants in the foredune blocked more plastic lids and cotton buds, while plants in the back dune mainly entrapped polystyrene pieces (Cresta and Battisti 2021; Gallitelli et al. 2023b). Moreover, the smallest litter items (i.e., 0.5–5 cm) were mostly trapped by the foredune plants, while the largest items were blocked by shrubs in the back dune (Andriolo et al. 2020; Gallitelli et al. 2023b). While composed leaves occupy a greater surface as well as more elements to block hard plastics such as bottles (Luo et al. 2021), linear and simple leaves are apt at blocking more plastics that are soft elements, such as foil and bags (Ivar do Sul et al. 2014; Gallitelli et al. 2022). For instance, when leaves are thin and flexible (i.e., the ones of the seagrass *Zostera capensis*) they tend to move with current and to bend, thus it may decrease their trapping abilities (see Cozzolino et al. 2020). In this way, also the characteristic of the plastics might be pivotal in the plastic entrapment: indeed, a flexible plastic bag can get caught in a single branch, while a rigid cup can be held up by a basket-like mesh. More in detail, plastic foils, PET bottles, and plastic bags are mostly blocked by roots and branches (i.e., pneumatophores in mangroves, pollons in riparian vegetation, and prostrate branches in dune plants). To understand the trapping efficiency of the dominant polymer trapped by a certain type of vegetation, we calculated a mean of trapping efficiency for each vegetation (Supplementary Table S2) and then multiplied by the % of the dominant polymer to obtain the "dominant polymer trapped". Figure 2 and Supplementary Table S4 emphasize the different plastic types blocked by global vegetation and the percentage of trapping efficiency specific to the dominant polymer trapped by each vegetation.

3.3. The Plant Plastic Pathway: a conceptual model of plants entrapping plastics

Concerning the transport, storage, and remobilization of plastics, plants may act as a sink for plastics (i.e., storage phase) as well as a source of them (i.e., remobilization phase) (Fig. 3). We identified five main phases for plastics entrapped in plants (Fig. 3). The main mechanisms of the trapping plastics by plants process are identified in Fig. 3A as (i) input of plastics in the environment, (ii) transport in the environment such as a river, then (iii) storage in vegetation (i.e., blocked within the individuals or stuck on the branches of vegetation), that (iv) can be released to the environment with remobilization, and consequently be free in the environment (v) as final output. According to Liro et al. (2020), our model described the process of plastic entrapment by each plant in light of the five phases observed. By proposing the "Plant Plastic Pathway" we attempted to link the retention of plastics by plants in different habitats: the plastic entrapment by plants in different habitats is highlighted from the river to coast and marine ecosystems (Fig. 3B). At the river catchment level, the transported riverine plastics may be blocked by aquatic and riparian vegetation along the riverbank when water level increases (Williams and Simmons 1996; Schreyers et al. 2021; Cesarini and Scalici 2022; Gallitelli et al. 2022; Gallitelli and Scalici 2023). *Ergo*, in a highly vegetated catchment, the chances of plastic mobility are lower because plastics can be retained mainly by vegetation. Instead, in a lowly vegetated system (i.e., urban canalized river), there might be much more likelihood of plastic release and transport downstream. Thus, the more the vegetation occurrence, the higher the probability of entrapping plastics, so the likelihood of entrapping plastics by plants would increase with fewer plastics now available to be transported by rivers to the sea (i.e., only about 2% of plastics carried by rivers reach the ocean, see van Emmerik et al. 2022). The model should help in spotting the 98% of plastics that remain stuck in the fluvial system, with the plants blocking it together with substrate, wrack, and infrastructures.

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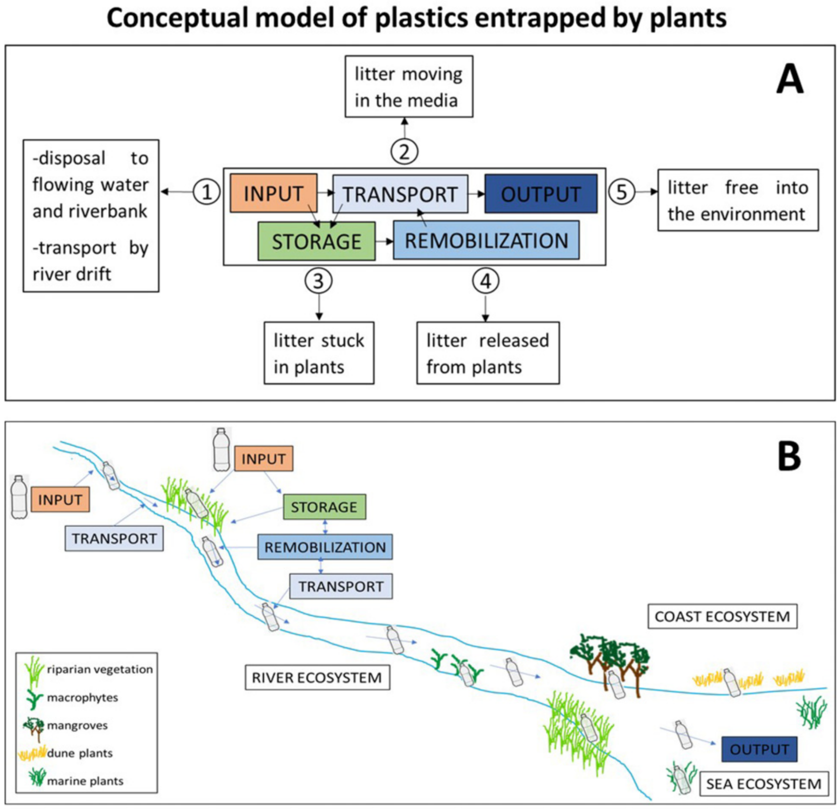
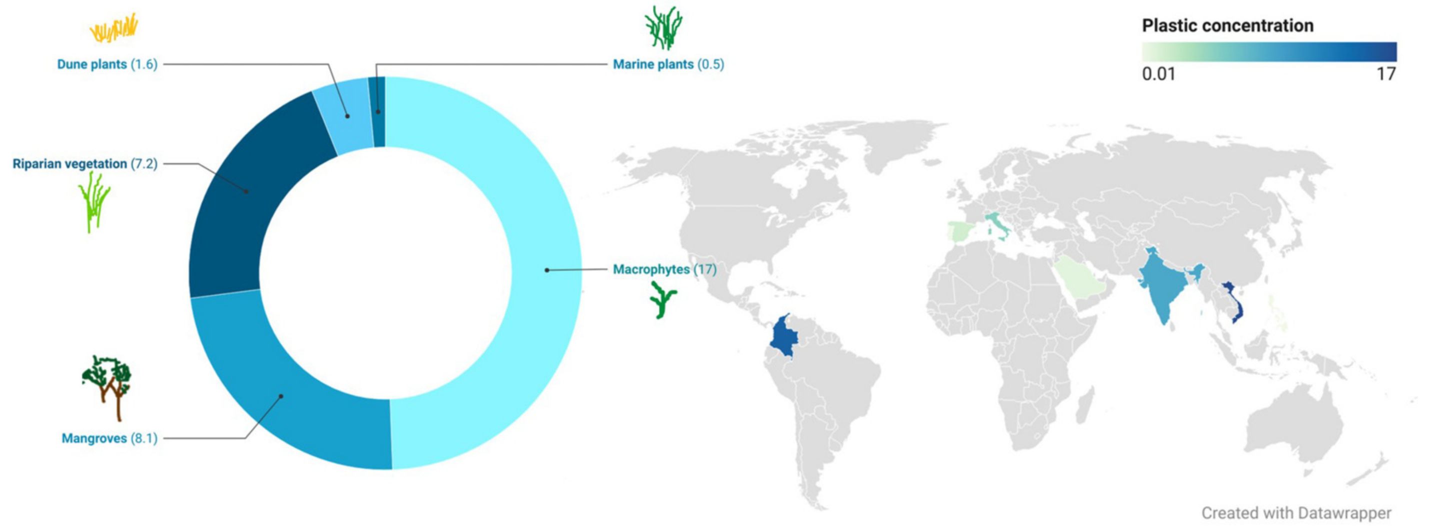
Fig. 3. Conceptual model of plastics entrapped by plants. (A) Process and mechanisms of trapping plastics by plants according to the five phases identified by Liro et al. (2020). Although we referred to the study of Liro et al. (2020), for the first time, the innovation is to consider a model only with vegetation entrapping litter. (B) "Plant Plastic Pathway" linking the retention of plastics by plants in different habitats: the plastic entrapment by plants in different habitats is highlighted from the river to the coast and marine ecosystems. The arrows in the figures indicate the fate of macroplastics from one process to another one.



3.3.1. Spatial and temporal scales of the entrapment process

On the spatial scale of processes driving plastic entrapment in plants (defined in Methods, also see Table 1, Figs. 3 and 4), the plastic entrapment *phenomenon* is still neglected. However, literature needs different studies focusing on various scales from the ecosystem global scale (i.e., catchment, ocean, and coast) to a local one (i.e., river stretch, sea spot, and coast plot). In this view, plastic entrapment by plants can be understood considering variables that change when changing the spatial scale. While general factors might patrol the global scale, the more the research goes to the local scale, the increasing number of factors affecting plastic occurrence in plants. For instance, based on the spatial scale considered, factors such as floods and heavy rain are the main responsible factors of plastic remobilization from plants to the environment indicating a temporary plastic entrapment (see Navarrete-Fernández et al. 2022). On a global scale, each ecosystem occurs in a specific biome characterized by common factors. The most important factor that affects a biome is given by precipitations (Fang et al. 2005; Jiang et al. 2017), and these latter determine floods. On a global scale, floods and discharge seasonality are important factors in delivering plastics along rivers and so on vegetation (Roebroek et al. 2021; Gallitelli et al. 2023a). At the catchment scale, river regimentation (e.g., dams and weirs) influences rainfall and river flow, and thus plastic transport (Liro et al. 2020). At the local (plant) scale, mowing of vegetation and habitat alteration result in the near disappearance of the plant that can no longer block plastic at that time after mowing. In general, at the local level, plastic trapping by vegetation may be due more to human activities, while at the global level to more extensive natural events (e.g., precipitations). At a local scale, water level, hydrology, and meander presence are pivotal factors for stucking plastics in plants (Table 1). Moreover, seasonal influences and extreme events (e.g., droughts and floods) may affect the plant density or the plastic blocking ability. As the influence of abiotic factors on the plastic entrapment by plants is still not well investigated, studies on the entire catchment (three river zones in Gallitelli et al. 2022), on the whole coast for mangroves or dune plants, and large areas in ocean and seas lack. To date, the entrapment of plastics by plants has been observed in small plot areas in freshwater, marine, and coastal habitats (Cozzolino et al. 2020; Schreyers et al. 2021; Ben-Haddad et al. 2023). On a global scale (Fig. 4), research on macrophytes mainly focuses on Vietnam (Schreyers et al. 2021), while riparian vegetation has been studied in Italy (Cesarini and Scalici 2022; Gallitelli et al. 2022; Gallitelli and Scalici 2023). Research on

Fig. 4. Global maps for plastics in vegetation for each type of vegetation. The average plastic concentration is given as items/m^2. This map has been created with Datawrapper.com.



mangroves was conducted in Kenya, Saudi Arabia, Brazil, and China, while studies on dune plants entrapping litter have been carried out in Mediterranean areas (Gallitelli et al. 2021; Andriolo et al. 2021; Ben-Haddad et al. 2023; Battisti et al. 2023; Gallitelli et al. 2023b; Calderisi et al. 2023).

On the time scales for the plastic entrapment by plants, temporal scales (Table 1) are essential to understand how long they can retain plastics and when plastic will be released into the environment. To date, this topic is completely understudied, so we might hypothesize that plastic entrapment could act in a matter of days or for a month to annual period. Given that long-term data on plastic retention by plants are not still available, we considered field observation by Cozzolino et al. al (2020) and Gallitelli et al. (2022). Moreover, we considered the time of the factors influencing plastic entrapment, such as hydrology (van Emmerik et al. 2022). This could be due as it follows the seasonality of climate, such as aquatic and riparian vegetations when undergoing floods and water levels increasing in the temperate or tropical region during winter and summer wet seasons, respectively (Schreyers et al. 2021; Gallitelli et al. 2022; Fig. 1). To date, literature assessed plastics in vegetation in a one-shot sampling; thus, we can assert that those plants entrap plastics daily. The only study that indicates a longer trapping timescale is by Cozzolino et al. (2020), which reports that seagrasses may retain plastic litter for 42 days. Another study pointed out that mangroves could retain plastics for years although this has not been checked (Kesavan et al. 2021). To date, long-term studies have still not been conducted; however, the effort was on the seasonal entrapment of plastics by plants (Gallitelli et al. 2024). Thus, we could define all these vegetation types as temporary (i.e., daily plastic storage) or non-temporary (i.e., month to possible annual or decadal plastic storage) sinks of plastics (see Table 1). Although we speculated a possible long-term retaining of plastics by plants, future studies should assess this *phenomenon* as timescale between the succession of storage and remobilization phases (Fig. 3).

4. Impacts and future perspectives of plastics trapped by vegetation

Although plants block plastics (Maghsodian et al. 2022; Okuku et al. 2023), the latter undergo deterioration due to abiotic and biotic factors. For this reason, macroplastic items will fragment into microplastics being easily used by biota and entering the food web (D'Souza et al. 2020; O'Connor et al. 2022). Even though plastics represent a high risk to aquatic ecosystems (Wang et al. 2019; Kukkola et al. 2021; Koelmans et al. 2022), in literature the effects of these newly formed microplastics and nanoplastics on plants remain largely unknown. During the ecosystem service of entrapping plastics, plants may receive several negative effects from plastics (Ciaralli et al. 2024), posing at risk the ecosystem services provided by itself when it is in a healthy *status*. Plastics may interact with plants (Battisti et al. 2020) as well as interfere with the ecosystem services that plants provide (e.g., photosynthesis and primary production, essential for ecosystem functioning). Recently, macroplastics have been found to cover vegetation branches threatening the emission of buds and flowers (Gallitelli and Scalici 2023). Notwithstanding all the threats due to plastics, only recently a plastic treaty has been stipulated to fight plastic pollution (Velis 2022; Bergmann et al. 2022). Given that the development of effective and harmonized monitoring strategies still remains a big challenge, to limit the impact of plastics on ecosystems and human health, the inclusion and integration of (riverine and vegetation) plastic litter monitoring in the European and global directives (e.g., Water Framework Directive 2000/60/EU) should be a key starting point. However, global, international, and national Directives (e.g., Water Framework Directive 2000/60/EU) still lack the introduction of plastics in their monitoring and prevention programmes.

This conceptual model provided the pathway of plastics in plants linking the retention of plastics by plants in different habitats. The plastic entrapment by plants in different habitats is highlighted from the river to coast and marine ecosystems. Concerning this pathway, there might be a relationship between plastics in plants and (environmental) plastic transport emissions. For example, in estuaries with mangroves (if the likelihood of entrapment by plants is high), there may be less plastic transported in the river, hence less mobility of plastics reaching the ocean. To investigate whether different river types (e.g., tropical or temperate, and intermittent or free running) act similarly as sinks for plastics in vegetation, further research should consider the differences among several rivers as they differ each one from the other for the abiotic and biotic factors such as river width, water flow and discharge, and vegetation communities (see Kellman and Tackaberry 1993; Heartsill-Scalley and Aide 2003; Tockner et al. 2009; Tiegs et al. 2019; Riis et al. 2020). However, to perform feasible comparisons, data on plastics in vegetation should be harmonized according to similar and common standards. First, the method design for sampling plastics in vegetation should be similar considering a vegetated patch as well as an unvegetated control patch (following Gallitelli et al. 2021; Battisti et al. 2023; Gallitelli et al. 2024). After sampling plastics in vegetation, the concentration unit for plastics in vegetation should be standardized as several items in vegetation patches in a certain sampled area or a transect (i.e., it/m^2 or it/m). To monitor plastics in vegetation, plastics in the surrounding environment without vegetation (i.e., control) should be considered. Given that vegetation entraps plastic litter, these guidelines on plastics in vegetation should be considered when monitoring litter to provide information on plastic pollution in the environment surrounding the vegetation. Considering that our aim is a conceptual model with rivers where all the vegetation types are contributing to entrapping all the plastics carried by rivers and remaining in the fluvial ecosystems (i.e., missing plastics), our research highlights the role of plants in entrapping a part of the plastics that are flowing into the ocean. So, in providing this first novel conceptual model about plants entrapping plastics, we are not modelling statistically but in a conceptual way. Future studies will try to consider all the lacking information to fill the gap in this recently born area.

5. Conclusions

Mangroves, dune plants, riparian vegetation, macrophytes, and seagrasses, as the only flowering plants which grow in aquatic and semiaquatic environments, are responsible for some of the most important ecosystem services, among which also may retain plastics. Our key finding is that terrestrial ecosystems can reduce marine pollution by retaining plastics. With the evidence of significantly higher concentrations in vegetation than in water, we highlighted that future studies should focus on vegetation as it is a valuable plastic trapper (Figs. 1 and 3) and thus it could be used to collect temporarily plastics and then remove it from the environment (without removing plants).

However, future multidisciplinary studies should develop guidelines apt for taking plastics out of vegetation (e.g., trees, flat riverbanks, and mangroves). To advance in science, research should consider vegetation and all the processes linked to plastic transport for a better understanding of the effect of the ecosystem service of entrapping plastics by plants. Given that the development of effective and harmonized monitoring strategies still remains a big challenge, to limit the impact of plastics on ecosystems and human health, the inclusion and integration of (riverine and vegetation) plastic litter monitoring in the European and global directives (e.g., Water Framework Directive 2000/60/EU) should be a key starting point to monitor plastic pollution with harmonized protocols to then tackle the problem. Given that, we propose some pragmatic suggestions and operational implications for the management of plastic entrapped by plants—useful for conservation managers and land planners.

1. Find the accumulation areas! Our findings might be crucial in investigating more regarding the pathway of plastics entrapped by plants, given that terrestrial ecosystems contribute to polluting rivers and marine ecosystems as one of the most polluted habitats. Thus, more data on plastics in plants might be collected by scientists and local community engagement. The use of the "Plastic Plant app" (Gallitelli et al. 2024, https://eu.jotform.com/app/231882401150345) to sample could make it easier!
2. From hotspot areas to clean-up actions: after quantifying plastic in plants, let us remove it! Thus, proper guidelines should be given on how to remove litter from plants (e.g., by nets). Then, the engagement of the community in cleanup efforts helps remove plastic accumulation areas and also prevents future plastic pollution.
3. Updating field observations, datasets, and models is pivotal for litter removal! Our conceptual model may have a crucial effect if applied considering which plant species to remove plastic pollution in situ. The model should help in spotting the 98% of plastics that remain stuck in the fluvial system, with the plants blocking it together with substrate, wrack, and infrastructures. Future studies might focus on time and space scales for vegetation retaining plastics, highlighting macroplastic litter hotspots and how to remove them from plants using valuable policy-making decisions.

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Data availability

All the dataset is available in the whole manuscript and Supplementary Materials.

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Validation: LG, MS
Visualization: LG, MS
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Writing – review & editing: LG, MS

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Supplementary material

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