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Computing riverine inputs of macrolitter into the Central Tyrrhenian Sea (Western Mediterranean Sea) from the Tiber River during the 1st post-pandemic year

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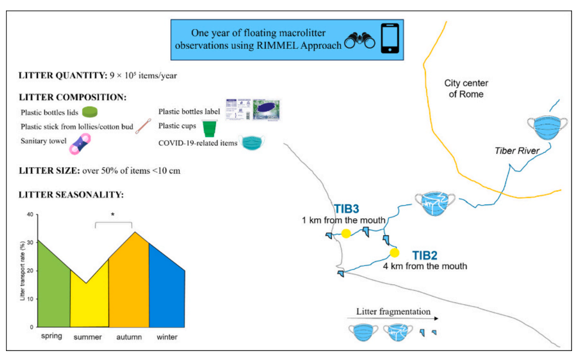
HIGHLIGHTS

- Addresses knowledge gap on riverine macroplastic input of a big capital city.
- Year-round macrolitter assessment at both Tiber River mouths using RIMMEL approach.
- Annual transport estimated at 9 × 10^5 items, peaking in autumn and lowest in summer.
- Post-pandemic reduction in macrolitter but increase in single-use plastic items.
- Over 50 % of items <10 cm, suggesting pre-sea fragmentation.

GRAPHICAL ABSTRACT



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ABSTRACT

This study addresses the critical knowledge gap on riverine macroplastic inputs to marine litter, focusing on changes in waste composition in a post-pandemic context. While marine plastic pollution has been widely documented, data on floating macrolitter from urban rivers remain limited. The first comprehensive, year-round assessment of floating macrolitter at both branches of the Tiber River mouth were conducted, using the harmonized RIMMEL approach using a dedicated android App. The simultaneous monitoring conducted at two sites (TIB2 and TIB3), recorded abundance, material composition, size and common item types, revealing an estimated annual transport rate of 9 × 10^5 items/year from the Tiber River to the Mediterranean Sea. Specifically, the transport rate was 104 ± 87 items/h and density of 1170 ± 151 items/km^2. The litter transport rate exhibited seasonal variability, with the highest peak observed in autumn and the lowest in summer. Findings reveal a post-pandemic reduction of <34 % in total macrolitter items, countered by a rise in single-use items, such as plastic cups, plastic bottles label and lids plastic stick from cotton bud and lollies, sanitary towel and condom. COVID-19-related items such as single-use face masks and gloves were also recorded. Over half of the items were under 10 cm, suggesting fragmentation before reaching the sea. This study enhances understanding of

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riverine litter in a big European capital, providing a post-pandemic dataset to identify pollution patterns and track the evolution of COVID-19-related waste.

1. Introduction

Plastic pollution has emerged as one of the most pressing global issues, with plastics entering all types of environments, including atmospheric, terrestrial, or aquatic ones (Jambeck et al., 2015; Windsor et al., 2019). Inadequate waste management is the primary driver of plastic spread in the environment, with urbanization level serving as a key indicator of the plastic pollution severity (Dikareva and Simon, 2019; Mihai et al., 2021). Once plastic enters the environment, they become extremely difficult to remove, leading to a range of negative consequences, including changes in carbon and nutrient biogeochemical cycles, habitat modifications, biological effects, ecotoxicity, and diverse societal implications (Arcangeli et al., 2019; MacLeod et al., 2021).

Despite the pervasive presence of plastic in freshwaters, research has traditionally focused on marine environments, with only recent attention directed at rivers and other freshwater systems (Blettler et al., 2018; Cera et al., 2020, 2022). Until recently, freshwaters, especially rivers, were mainly considered as pathways for transporting plastics from inland areas to the sea (Lebreton et al., 2017; Schmidt et al., 2017). However, awareness of the detrimental effects of plastic pollution on freshwater ecosystems has been increased (Blettler and Wantzen, 2019; Azevedo-Santos et al., 2021), shifting the perspective from rivers as plastic pathways to plastic reservoirs (van Emmerik and Schwarz, 2020; van Emmerik et al., 2022a).

Plastics can enter freshwaters through various pathways, including diffuse sources such as windblown debris and runoff, as well as point sources, like wastewater treatment plants and direct disposal (van Emmerik and Schwarz, 2020). The fate of plastics within river systems is influenced by hydromorphological factors such as river speed, flow dynamics, and water levels, which determine their transport pathways and final destinations (Liro et al., 2020; van Emmerik et al., 2022b). Plastics can become temporarily retained along riverbanks and subsequently re-enter the water during flood events (Cesarini and Scalici, 2022) or follow a “stop and go” pattern related to flow changes (Arcangeli et al., 2024). During their residence in freshwaters, plastic debris undergoes environmental stressors, including UV radiation, water currents, temperature fluctuations, and biofouling, which can lead to the breakdown of larger plastic items into smaller pieces (Andrady et al., 2022; Bocci et al., 2024).

Research on riverine macrolitter input to the sea has advanced across Europe (Schirinzi et al., 2020; González-Fernández et al., 2021; Tramoy et al., 2022), including studies conducted in Italy (Campanale et al., 2019; Palmas et al., 2022; Arcangeli et al., 2024, 2025). Since 2016, the input of riverine litter into the sea from the Tiber River has been investigated (Crosti et al., 2018; Cesarini et al., 2023a). However, these investigations were conducted separately on the two distinct branches of the river mouth, leaving a gap in the comprehensive understanding of macrolitter distribution and dynamics at the river mouth scale.

The existing research gap centres on the limited understanding of riverine macroplastic contributions to marine litter, especially in a post-pandemic context where waste composition could be changed significantly. While marine plastic pollution has been extensively studied, there is a lack of systematic data on the input and characteristics of floating macrolitter at river mouths, particularly for major rivers crossing densely populated cities like the Tiber, which flow through the capital of Rome. Recently, the COVID-19 pandemic has significantly impacted waste generation and disposal patterns, altering both the quantity and composition of litter entering the environment (Ormaza-González et al., 2021). Changes in citizen, tourist, and consumer behaviors, coupled with movement restrictions, have affected pollution levels in aquatic systems. While urban solid waste generation decreased due to reduced human activities, medical waste, including single-use masks, gloves, and other protective items, notably increased, contributing new pollution sources to the environment (Kazembeigi et al., 2022). Only recently, efforts to address standardized methods for characterizing plastics in freshwater systems have begun (González-Fernández and Hanke, 2017; González-Fernández et al., 2018).

This study addresses the research gap by providing the first comprehensive, year-round assessment of floating macrolitter at both branches of the Tiber River mouth, monitored simultaneously across an entire post-pandemic year. Using the harmonized RIMMEL approach (González-Fernández and Hanke, 2017), this research aimed at the entire river mouth scale to provide insight about the abundance, material composition, size distribution, and most common items of floating macrolitter, capturing seasonal variations.

2. Materials and methods

2.1. Study area

The research was conducted at the mouth of the Tiber River in Central Italy (Fig. 1; Fig. S1), chosen for its role as a major river crossing the city of Rome, the densely populated (approximately 4 million inhabitants) capital of Italy, and serving as a critical pathway for potential macrolitter transport to the Mediterranean Sea. The Tiber River is one of the most iconic rivers in Europe; it originates in the Apennine and, after approximately 400 km, ends into the Tyrrhenian Sea (Western Mediterranean marine-subregion, sensu MSFD).

In the last 50 km stretch,after the Castel Giubileo dam located on the outskirt of the city of Rome, the river crosses the whole city dividing itself, just 5 km from the sea, into two flow away branches of the delta: Fiumara Grande (natural branch) and Fiumicino Canal (artificial waterway dug in the 1st century B.C.) corresponding, respectively, to around 80 % and 20 % of the water flow. (Mikhailova et al., 1999). The width of the river at the division is approximately 2/3 for the Fiumara Grande and 1/3 for the Fiumicino Canal. In this stretch of the river, the water speed is slow with sandy-muddy substrates (Ceschin et al., 2010). The Castel Giubileo Dam helps regulate water flow to maintain a stable river level throughout the year, except during severe rainstorms or floods events.

Approximately 30 km upstream from the river mouth, after crossing the city, the riverbanks remain mostly natural with riverside vegetation.

Various anthropogenic pressures contribute to litter generation, including overtourism, dense suburban areas, informal settlements, agricultural activities, the maritime sector, improper waste disposal, and challenges in achieving efficient urban waste management, typical of big cities.

In addition it needs, to take into account that: the Castel Giubileo dam can intercept floating litter in the trash racks as described in Arcangeli et al. (2024) and that both branches before the monitoring sites host touristic marinas and to a lesser extent also part of the local fishing fleet.

2.2. Floating macrolitter monitoring

Two monitoring sites were located on two bridges on the two different branches at the river mouths (Fig. 1). One site, Ponte della Scafa (TIB2) was located at Fiumara Grande, approximately 4 km from the river mouth and the other one, Ponte pedonale (TIB3), was in Fiumicino, <1 km from the river mouth. Codes of bridge follow Cesarini et al. (2023a, 2023b). Monitoring simultaneously, within the same time period and with the same number of observations, the two branches of the river permitted the novelty of having for the first time data of Tiber River total macrolitter input to the sea.

Data collection followed the guidelines of the RIMMEL project (Riverine and Marine Floating Macro Litter Monitoring and Modelling of Environmental Loading) as outlined by González-Fernández and Hanke (2017) for analyzing floating macrolitter (>2.5 cm).

Data collection was based on visual observations from March 2021 to February 2022. At each site, six surveys were conducted per season, with four seasons per year (spring, summer, fall, and winter), ensuring at least one survey each month.

This resulted in a total of 48 surveys across the study period. The characteristics of the observation sites are reported in Table 1.

The bridges were divided into segments, termed as observation tracks to ensure a complete monitoring over the entire river (4 for TIB2 and 2 for TIB3). Monitoring surveys lasted a minimum of 60 min for each observation track and covered the entire river width or, when fewer observers were available, only half of it. In the latter case, the monitoring took into consideration the section from the riverbank to the centre of the river. Data from these partial surveys were successively extrapolated to estimate values across the total width of the river, doubling the transport rate while keeping the density consistent. Observers were provided with a wide-angle binocular to better identify objects when needed.

Litter observed passing by was recorded using the JRC Floating Litter Monitoring App (version FLM 2.3, Android system-2015; Fig. S2). This app allows the recording of the material type (e.g., plastic, paper, rubber, metal, cloth/textiles, processed wood), type of items, and size (e.g., 2.5–5 cm; 5–10 cm; 10–20 cm; 20–30 cm; 30–50 cm; > 50 cm). Also, river surface speed was recorded based on the mean speed of 5 items, passing by two points along a stretch of known distance (i.e. 10 m) divided by the time taken.

Also, additional items, not included in the App list, were recorded as "other object", according to the material. These items were both logged in the app under the 'other object' category and also noted on a paper survey sheet, where also additional details such as their condition (entire or fragmented) were recorded (Fig. S3). This approach was used to capture information on whether the item could be identified as belonging to a specific recognizable item, even if it was fragmented. While the APP included the term "pieces" referring to a piece of unrecognizable item. Among the 'other object', the main part was categorized as 'other plastic.' Within this group, we also identified a subcategory of 'Covid-19 items', which included single-use plastic face masks, or part of it, (J253) and single-use plastic gloves (J252), categorized as 'indicators' of sanitary/medical waste.

These items were recorded to compare records with the available dataset from 2016 to 2019 on macrolitter surveys in the Tiber River (Crosti et al., 2018; Arcangeli et al., 2024). However, it is important to note that such items were never recorded in previous field surveys. Additionally, information on whether an object was single use was also recorded.

In this investigation, the first version of the JRC App was used, which included fewer item categories -$N = 42$- compared to the new JRC Joint List for Litter Categories -$N = 186$-(Fleet et al., 2021). When referenced, the 'J' codes correspond to the categories listed in this more recent publication.

2.3. Data analysis

Data collected from the two sites were aggregated in order to have an estimate of the total input of riverine litter from Tiber River to the Mediterranean Sea.

Two different units were used as indicators of river floating macrolitter abundance:

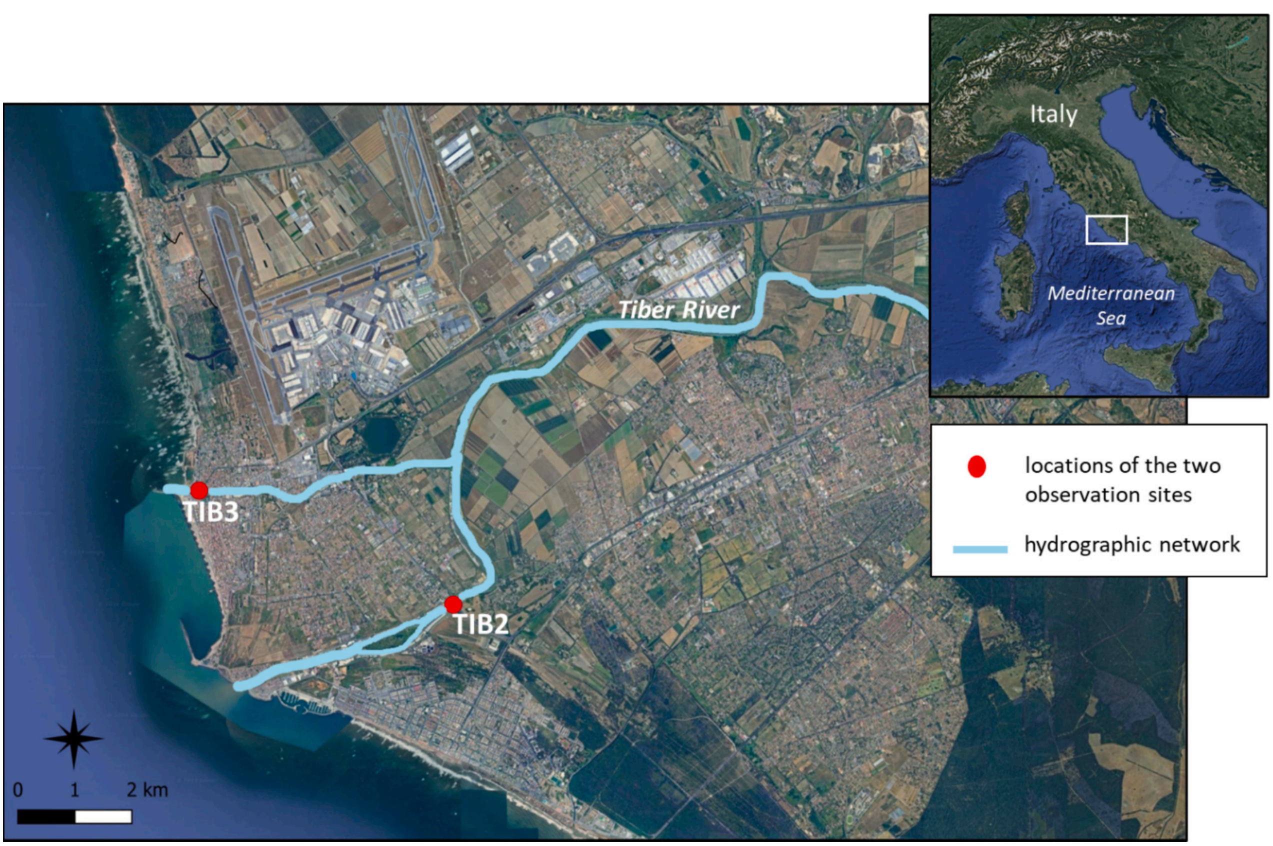

Fig. 1. Map showing the Tiber River mouth composed by the two branches after crossing through the city of Rome, Italy. TIB2 is located 4 km upstream from the river mouth at Fiumara Grande, while TIB3 is situated 1 km from the river mouth at Fiumicino.

Table 1
Characteristics of the observation sites. Observation height of the site (vertical distance between observer eye and river surface); observation track width (section observed for litter identification); total river width (width of the river from riverbank to riverbank).

Observation site	Observation height	Observation track width	Total river width	Observation tracks	Surveys per season			
					Spring (March–May)	Summer (June–August)	Autumn (September–November)	Winter (December–February)
TIB2 (Scafa bridge)	9 m	20 m	80 m	4	6	6	6	6
TIB3 (Pedestrian bridge)	4 m	15 m	30 m	2	6	6	6	6

- Litter transport rate (measured as frequency): number of items/1 h
  Data were normalised taking into consideration observation tracks width and length in time of the survey.
- Litter density: number of items/km^2
  Data were normalised taking into consideration: observation tracks, length in time of the survey, river speed, river width.

To assess potential significant differences in composition by material and size of floating macrolitter across the four seasons, nonparametric Kruskal-Wallis tests were applied. Differences between two seasons were assessed with the Mann-Whitney *U* Test to evaluate whether there was a difference between litter transport rate among two samples. The same analysis was conducted separately at the two observation sites to examine seasonal differences in the litter transport rate.

Moreover, the relationship between litter transport rate and river speed for each observation site was tested by non-parametric Spearman's (R) correlation. The *p*-value for statistical tests was set at <0.05, and the analyses were performed using Past version 4.02.

3. Results

During the monitoring year, the abundance of the floating macro litter at the Tiber River mouth was as follows: transport rate of 104 ± 87 items/h and density of 1170 ± 151 items/km^2. Overall, the transport rate of floating macrolitter in a year was estimated at 9 × 10^5 items/year. A reduction in total macrolitter items of <34 % was observed compared to the data previously the pandemic (Crosti et al., 2018).

Floating litter was composed mainly of plastic (90.3 %), followed by paper (4.1 %), rubber (2 %), textile (1.5 %), metal (1.1 %), and processed wood (1.0 %) (Fig. 2A). Taking seasonality into account, plastic comprised over 80 % of litter in all seasons. During the summer, plastic relative abundance was at its lowest (83 %), while the presence of paper (6 %) and textiles (4 %) increased (Fig. 2B). However, no statistical differences were observed between the four seasons by Kruskall-Wallis test (P = ns).

Most of the items (70 %) were under 10 cm (Fig. 3A). Specifically, the frequency of items, in terms of litter size, decreased as size increased: 36 % of the items were in the smallest range 2.5–5 cm and 34 % were 5–10 cm. In contrast, fewer items were found in the larger size ranges, with 16 % in the range 10–20 cm, 10 % in the range 20–30 cm, 3 % in range 30–50 cm, and only 1 % were > 50 cm. This size distribution pattern, characterized by a higher abundance of smaller sizes compared to larger ones, remained consistent across the four seasons. This was confirmed by the Kruskal-Wallis test, which showed no significant differences (P = ns; Fig. 3B).

The five most abundant items detected are shown in Table 2 and comprise other plastic/polystyrene items, plastic pieces, polystyrene pieces, plastic bottles and bags. These top five items represent 80 % of the total litter observed from the Tiber River (thus the group “other plastic” aggregated many different types of items). Overall, the fragmented state, which includes both “pieces” and fragmented, accounted for 48 % of total recorded items.

The five most recorded items in the “other plastic” group are reported in Table 2 which included plastic bottles lids (J 21); plastic cups (J227); plastic bottles label (not in the new Joint list); plastic stick from cotton bud (J95) and lollies (J31); sanitary towel (J96).

During this post-pandemic investigation both plastic single-use facemask (J253) and single-use plastic gloves (J252) were detected as Covid-19 items, with 3 % and 2 % respectively. However, these items were less frequent compared to those listed among the top five items in Table 2.

Compared to the 2016–2019 dataset there was an increase (>10 %) of single use containers, both plastic and paper (PE coated) mainly related to food consumption; transport rate of fisheries related items, instead remained similar (1.5 %).

The Mann-Whitney U Test showed a statistical difference between litter transport rate in summer and autumn ($P < 0.05$); no statistically significant differences were observed between the other seasonal pairs (Fig. 4). Fig. 5 shows the temporal, and seasonal, variation of floating macrolitter transport rate in relation to river speed recorded at the two river mouths. In this case, no significant differences were found in the seasonality of the transport rate when the two observation sites were

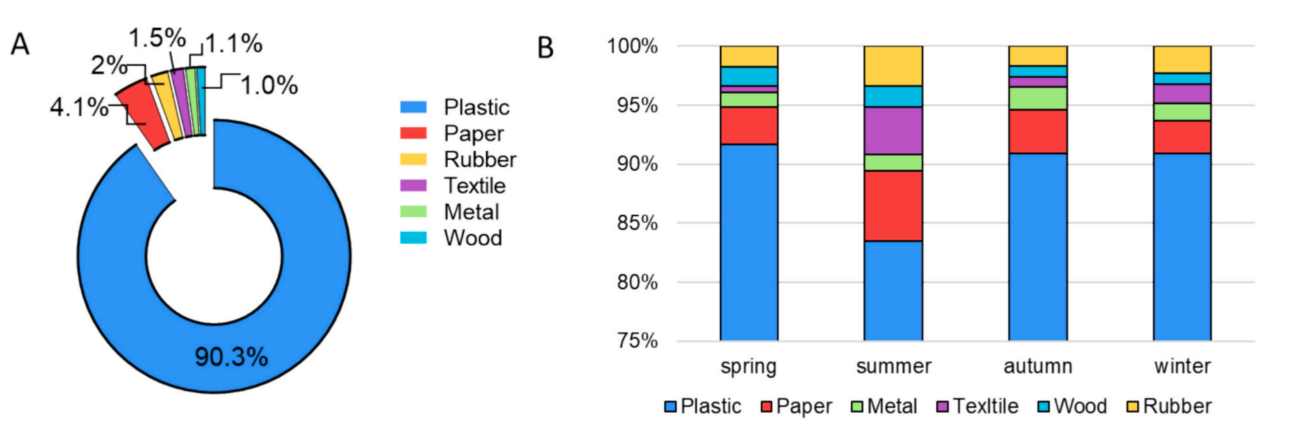

Fig. 2. Composition of floating litter (%) by material type discharged from the Tiber River into the sea: (A) overall distribution, and (B) seasonal variations.

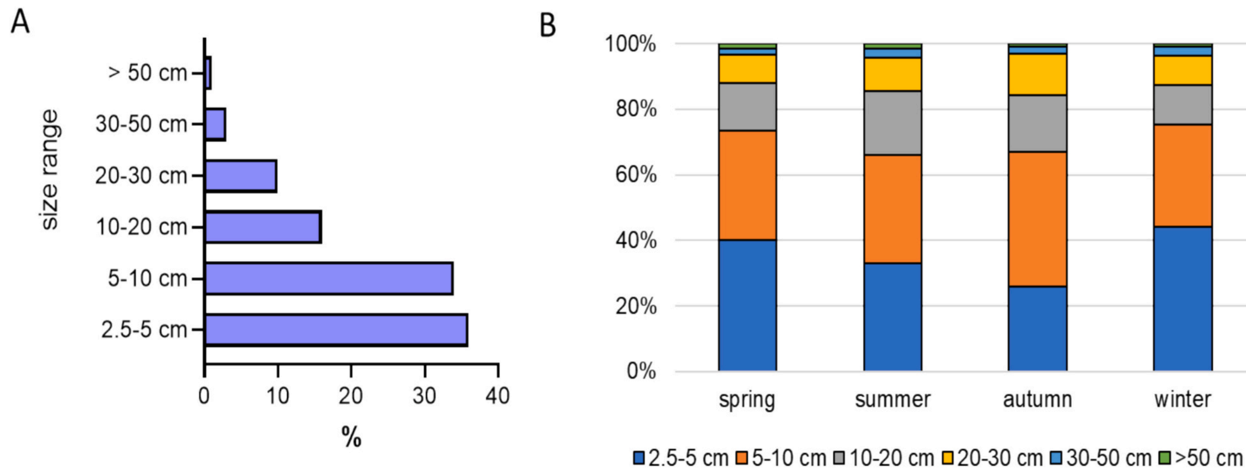

Fig. 3. Composition of floating litter (%) by size range discharged from the Tiber River into the sea: (A) overall distribution, and (B) seasonal variations.

Table 2
Top 5 items of riverine floating litter (left) and of "other plastic items" category (right) from Tiber River. Percentage values for the two classifications are reported in the brackets.

Top	Litter	Other plastics
1	Other plastic/polystyrene items (32 %)	Plastic bottles lids (16 %) Plastic stick from lollies and cotton bud (13 %) Sanitary towel (12 %) Plastic bottles label (10 %) Plastic cups/ Condom (6 %)
2	Plastic pieces 2.5 cm - 50 cm (28 %)	
3	Polystyrene pieces 2.5 cm - 50 cm (9 %)	
4	Plastic bottle (7 %)	
5	Bag (4 %)	

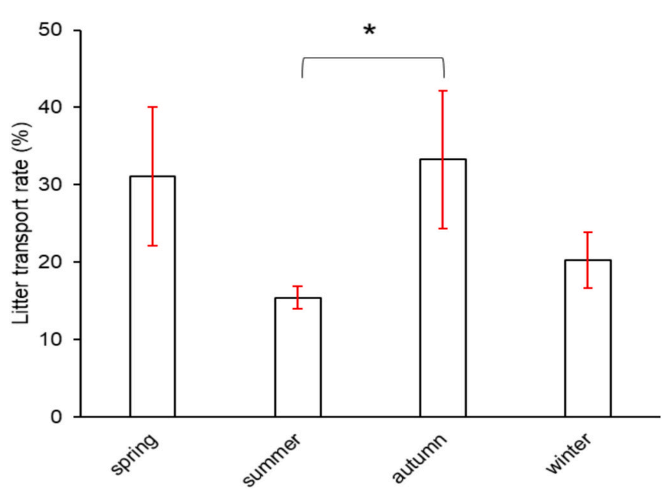

Fig. 4. Seasonal relative abundance in transport rate (items/h) in percentage expressed as mean value and standard error, for the entire Tiber River. Asterisks indicate *p*-values (*≤0.05).

analyzed separately using Kruskal-Wallis and Mann-Whitney *U* tests (P = ns). About the relationship between litter transport rate and river speed, no significant correlations were found at both observation sites (P = ns).

4. Discussion

This study, conducted just at the end of the pandemic restriction on population movements, is the first attempt to comprehensively assess the input of riverine macrolitter from both branches of the Tiber River into the sea. Using the harmonized RIMMEL approach, the study provides a post-pandemic baseline dataset on the abundance, material composition, size distribution and seasonal trends of floating macrolitter. The findings reveal a post-pandemic reduction in macrolitter, accompanied by an increase in single-use plastic items. The quantity of macrolitter exhibited a seasonal variation, with higher levels observed in autumn and lower levels in summer. However, no significant seasonal differences were found in the composition or size of the macrolitter. This distinction highlights that while seasonal changes influence the overall amount of macrolitter entering the river system, they do not significantly affect their composition or size distribution.

4.1. Flux of riverine macrolitter discharged into the sea

Several studies conducted during or shortly after the pandemic restriction period showed a decrease in environmental litter (Ormaza-González et al., 2021; Van Fan et al., 2021; Darabi et al., 2023; Souza Filho et al., 2023). The findings of this study align with the previous investigations that focused on the two river branches separately (Crosti et al., 2018; Cesarini et al., 2023a). The reduction in macrolitter at the Tiber River mouth compared to pre-pandemic years, is noteworthy. Based on monitoring a single branch (Crosti et al., 2018), the estimated floating litter transport rate was 85.4 items/h, with a density of 1270 items/km^2. This reduction can be attributed to decreased activity along the riverbank and the overall restricted movement within the city of Rome during the pandemic lockdown. As expected, most of the litter consists of plastic, making the terms "litter" and "plastic" nearly synonymous in terms of quantity.

The litter transport rate showed a seasonality pattern with the highest peaks during autumn and the lowest peak in summer, considering the entire Tiber River. The same seasonal trend of litter flux was observed for the Tiber River in 2017 (Crosti et al., 2018), and in other European rivers (Lebreton et al., 2017). Stagnitti and Musumeci (2024) highlighted that peak beach litter cleaning operations should be carried out in autumn, as rivers play a significant role in the distribution of plastic litter during this season. This recommendation aligns with our findings, which also show a higher quantity of litter transported by rivers in autumn, confirming that autumn is the most effective period for beach cleaning efforts focused on riverborne debris. Seasonal variation in plastic transport in rivers is influenced by multiple factors, with river discharge and wind jointly playing key roles (van Thi et al., 2024). As

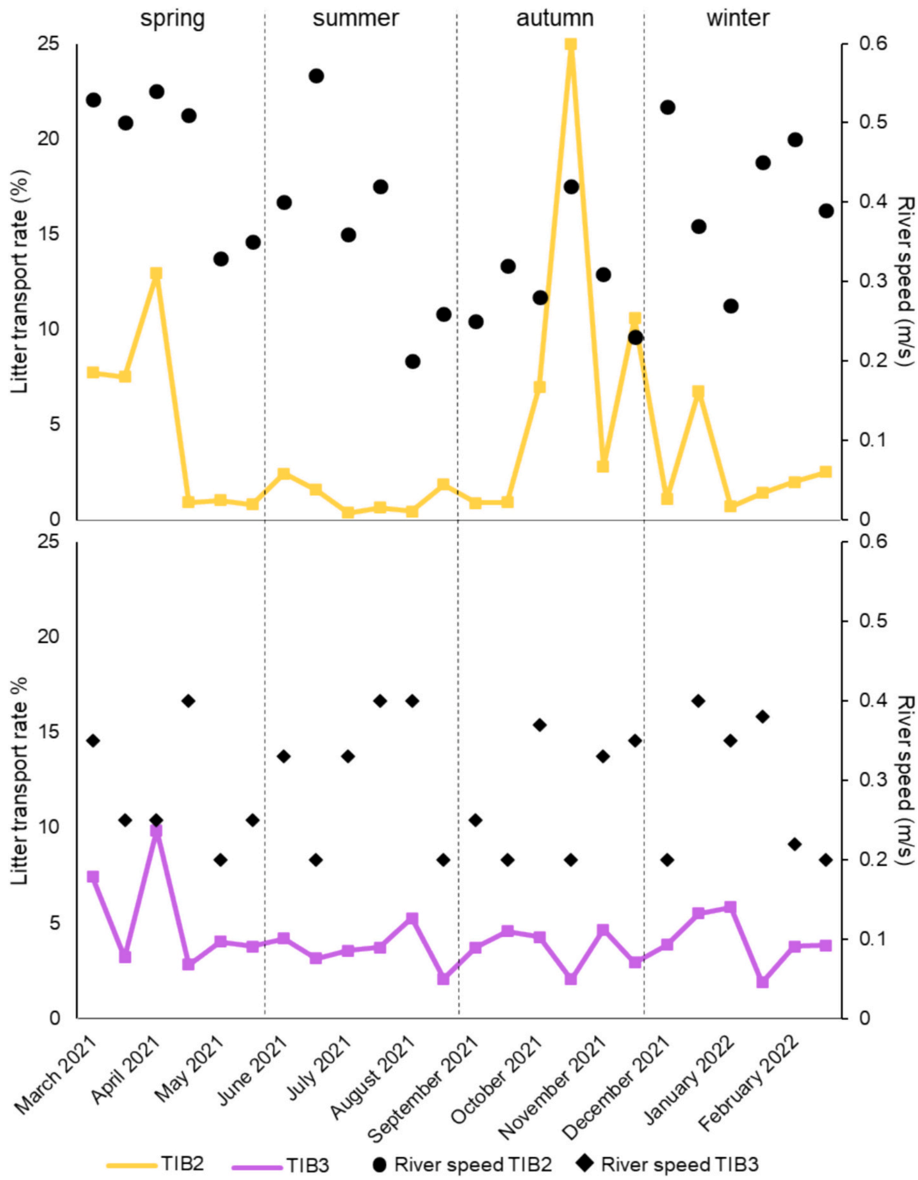

Fig. 5. Temporal and spatial variations of the litter transport rate (items/h) as percentage for TIB2 (A) and TIB3 (B), and river speed (m/s) recorded during the monitoring surveys.

previously investigated, the influence of litter transport in Tiber River was related to rainfall (Cesarini et al., 2023a). Litter transport rate is strongly influenced by water levels globally, as rising water can remobilize litter temporarily deposited on riverbanks and the riverbed (Liro et al., 2020; Cózar et al., 2024).

Our findings indicate that seasonal differences in litter transport rates at the Tiber River mouth are influenced not only by river water speed (as shown by the correlation analysis) but possibly also by factors such as seasonal riverbank attendance and rain washout from the main river and its tributaries. At the Tiber River mouth, water levels (and consequently river speed) are regulated by the dam, except during severe rainstorms or floods, when surveys cannot be undertaken. This regulation further adds complexity to understanding the relationship between river speed and litter transport. This aligns with the observations of van Emmerik et al. (2019), who reported no clear relationship between plastic transport and factors such as water discharge, rainfall, or tidal range in the Saigon River. They hypothesized that plastic transport is influenced by the interplay of these multiple factors, including wind, which requires further investigation.

In comparison with other post-pandemic studies, the macrolitter levels observed in the Tiber River are generally lower compared to other rivers. Specifically, other European rivers showed concentration slightly higher. For example, the Rhine River reported rates between 1.9×10^6 and 4×10^6 items/year, and the Meuse River in Netherlands between 1.3×10^6 and 3.8×10^6 items/year of macrolitter (van Emmerik et al., 2022b). In comparison, African and Asian rivers have been observed to carry significantly higher levels, reaching up to two orders of magnitude. Notable examples include the Odaw River in Ghana, with 3×10^7 items/year (Pinto et al., 2023), and the Saigon River in Vietnam, with 2×10^7 items/year (Schreyers et al., 2024); thus item/year should be normalised with water speed and river width for proper comparison.

4.2. Composition of macrolitter by item category with a focus on Covid-19 related items

Plastic was the most abundant material at both river mouths throughout the entire year of observation, as expected. However, although not statistically significant, it is interesting to note that only during the summer the percentage of plastic decreased, while paper and textile materials increased. This finding may be linked to an influx of tourists during the summer, leading to increased consumption of items like paper (e.g., napkins, takeaway containers) and textiles (e.g., disposable towels or clothing). These materials, which typically have lower buoyancy than plastics, are likely discarded near the river and introduced recently, as they remain floating rather than settling on the riverbed (Rech et al., 2014; Crosti et al., 2018). This suggests that the rise in paper and textile materials is driven by short-term tourist activities rather than a significant reduction in plastic use. The pandemic has increased the presence of single-use items, significantly enhancing the production and consumption of single-use plastics, notably including personal protective equipment such as masks and gloves (Facciolà et al., 2021; Silva et al., 2021). This study recorded for the first time, during systematic surveys, plastic single-use facemask (J253) and single-use plastic gloves (J252) which were, however, never detected in the Tiber River during the previous 2016–2019 surveys. The research, conducted during the pandemic (March 2021–February 2022), highlights not only the increase in the presence of such items in rivers but also how macrolitter river surveys can effectively detect indicators related to consumption patterns and inadequate waste management practices, which together drive the production and accumulation of waste in the environment. These findings underscore the relevance of monitoring 'Covid-19 items' during that period, as they serve as indicators of behavioral shifts and environmental pressures caused by the pandemic. Moreover, tracking this category remains crucial even years later to assess the long-term environmental impact and persistence of these materials after the emergency phase of Covid-19. Given that personal protective equipment is still in use in many parts of the world, continued monitoring can provide valuable insights into the ongoing effects of the pandemic on waste production and the accumulation of such items in aquatic ecosystems.

The composition of the top litter items observed in this study was consistent with other studies examining riverine litter discharge into the Mediterranean and various European seas (Castro-Jiménez et al., 2019; Schirinzi et al., 2020; González-Fernández et al., 2021), with the most common items being other plastic/polystyrene pieces and single-use plastics. In particular, there was an increase in single use plastic containers mostly related to food consumption. The category "Other plastic/polystyrene items" also included sanitary towels and items related to COVID-19 prevention. The environmental impact of plastic pollution deriving from the COVID-19 pandemic is extensively documented, highlighting the necessity to designate "Covid-19 related items" as a distinct category of litter (Ammendolia et al., 2021; De-la-Torre et al., 2021; Cesarini et al., 2022).

4.3. Composition of macrolitter by size range and fragmentation process

The smaller size (< 10 cm) was more abundant compared to the bigger one, and most of these were found to be plastic fragments. This trend was confirmed along the entire year of the study, without significant differences between the four seasons. However, the number of items in the size classes <10 cm is likely underestimated due to perception bias (floating item present and "visible" but not detected) at TIB2, due to the architecture of the bridge. This is in line with previous studies (Crosti et al., 2018) that previously observed a similar composition of litter by size at the mouth of the Fiumicino Canal in the Tiber River. This suggests that litter fragmentation likely starts within the river when items are trapped into the vegetation or covered by sediments leading to detrimental effects on the ecosystem Many factors due to environmental exposure can generate fragmentation of macrolitter such as UV exposure, change in temperature, turbulence, biofouling, generating also secondary microplastics (Tsiaras et al., 2021). Conversely, the lower proportion of larger litter items, is possibly due to their lower buoyancy and greater likelihood of becoming entangled in riparian vegetation, where they remain trapped on the riverbanks until flood events (Williams and Simmons, 1996; Cesarini and Scalici, 2022), during which accurate detection of floating items is unlikely to occur. In this sense, rivers should not be considered merely as a pathway for litter dispersion into the sea but as reservoir systems where the fate and dynamics of litter of litter is complex and influenced by various factors. Each size category of plastic poses its own set of hazards and impacts at a different scale in riverine systems. For instance, larger plastics can cause entanglement and pose choking hazards for freshwater biota (Blettler and Mitchell, 2021), whereas smaller ones can be ingested and accumulate within organisms, leading to toxicological effects (Ribeiro et al., 2019; Cesarini et al., 2023b). Additionally, plastics, including macro size, can serve as carriers for environmental contaminants, pathogens, and invasive species (Amaral-Zettler et al., 2020). The colonisation of macroplastics by endemic freshwater biota can also negatively impact them when these plastics are flushed into water conditions that are not optimal for their survival (Gallitelli et al., 2023).

5. Conclusions

This study represents the first joint monitoring of both branches of the Tiber River, providing a comprehensive assessment of floating macrolitter input to the sea. It contributes valuable insights into riverine litter, including its transport rate, density, composition, and seasonal variation within a major city during the first post-pandemic year.

Key findings include the significant seasonal variation in litter flux, with higher peaks observed during the autumn, likely influenced by water runoff. Notably, the study identifies an increase in single-use items, particularly personal protective equipment such as masks and gloves, which were recorded, during systematic surveys, for the first time in the Tiber River. This highlights the impact of the COVID-19 pandemic on litter composition and the need for timely indicators of waste production and littering behavior. Tracking this category is crucial to evaluate the long-term environmental impact and persistence of these items. With personal protective equipment still in use globally, continued monitoring is essential to understand its ongoing effects on waste accumulation in aquatic ecosystems. The observed reduction in litter flux post-pandemic suggests that human activity and river usage, which were reduced during the health emergency restrictions, play a significant role in litter dispersion.

Smaller-sized litter items were found to be more abundant than larger ones, indicating that the process of fragmentation begins within the river basin, with degraded items reaching the sea. These findings highlight the importance of addressing litter management directly within river basins, where the fragmentation process begins and the efficiency of removal is higher compared to the marine environment, where floating litter density decreases due to sinking and distance from the river source.

CRediT authorship contribution statement

Giulia Cesarini: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Antonella Arcangeli:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Massimiliano Scalici:** Writing – review & editing, Supervision, Resources. **Roberto Crosti:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.178669.

Data availability

Data will be made available on request.

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