



Spatio-temporal dynamics of floating marine macro-litter in Italian waters (2018–2023): The impact of the COVID-19 pandemic

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ABSTRACT

Floating Marine Macro Litter (FMML) remains a pervasive threat in the Mediterranean Sea. This study assesses FMML across offshore and coastal Italian waters over a six-year period (2018–2023) to evaluate the impact of the COVID-19 pandemic. A total of 2111 standardized visual surveys were conducted from ferries and small vessels, with items recorded by trained observers under controlled sea-state conditions and classified according to MSFD protocols. Plastics dominated all surveys (81–87%), primarily comprising Single-Use Plastics (SUP) and Fishing Gear. Results show a distinct 'V-shaped' trend in the abundance of coastal SUP, which declined significantly during lockdowns before rebounding after the pandemic, whereas offshore levels remained stable, acting as a legacy reservoir. A unique pandemic pulse was observed for sanitary litter, which peaked during 2020–2021. Our results demonstrate that while socio-economic disruptions caused immediate shifts in Mediterranean coastal pollution, offshore environments exhibit greater resilience to short-term changes. These findings highlight the persistence of marine plastic pollution and underscore the need for integrated monitoring strategies combining FMML surveys with robust statistical approaches and remote sensing to support MSFD and IMAP targets for Good Environmental Status (GES).

1. Introduction

Marine litter is currently recognized as one of the most pervasive global pollution issues, listed among the eight contaminants of concern by the UNEP/GPA for the protection of the marine environment from land-based sources (Galgani et al., 2019; Erüz et al., 2023). Beyond being aesthetically detrimental, marine litter negatively impacts humans, wildlife, habitats, and coastal economies (Deudero & Alomar, 2015; Rochman et al., 2016). Documented harm to marine biota includes ingestion or entanglement, with at least 690 species reported to have encountered or ingested debris (Gall & Thompson, 2015; Ryan

et al., 2018). Crucially, larger macro-litter items generate vast amounts of secondary micro-litter through mechanical, photo-oxidative, and biological degradation, perpetuating the pollution cycle (Morales-Caselles et al., 2021; Thompson and De Falco, 2020).

Among the various materials (metal, rubber, paper, glass, etc.), plastics have become the most prevalent and widespread element of marine litter due to their lightweight nature, durability, and the modern societal dependence on single-use products (Zeri et al., 2018; Napper & Thompson, 2020). The Mediterranean Sea is particularly vulnerable to this pollution. Surrounded by industrialized countries and crossed by heavy shipping lanes, it records some of the highest municipal waste

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generation rates and is widely recognized as one of the most affected areas globally (Suaria & Aliani, 2014; Cózar et al., 2015). Furthermore, its hydrodynamics, characterized by a net surface inflow through the Strait of Gibraltar and limited outflow, cause the basin to act as an accumulator and retainer of floating material (Zambianchi et al., 2014; Suaria et al., 2016).

Recognizing these severe ecological and socio-economic impacts, international regulatory instruments, such as the Marine Strategy Framework Directive (MSFD, 2008/56/EC), list marine litter as a key Descriptor for achieving Good Environmental Status (GES). Specifically, under the UNEP/MAP Barcelona Convention, the Integrated Monitoring and Assessment Program (IMAP) obligates member states to quantify and characterize plastic debris to inform effective mitigation measures (Galgani et al., 2015). A crucial component of this assessment is monitoring Floating Marine Macro-Litter (FMML, items >2.5 cm). FMML serves as a timely indicator of overall pressure, representing the primary form of litter entering the sea before fragmentation or sinking (Morales-Caselles et al., 2021). While protocols for monitoring are established, understanding the pathways that govern litter distribution remains a major challenge. Recent studies have demonstrated that coastal litter pollution follows distinct seasonal and spatial pathways, often acting as a primary interface between terrestrial runoff and marine accumulation zones (Özşeker et al., 2024).

Despite these challenges, an even more critical gap exists in understanding how acute, large-scale socio-economic events influence litter composition and distribution over short time scales. The COVID-19 pandemic caused by SARS-CoV-2 is a prime example. The outbreak led to an immediate, dramatic surge in the use of Single-Use Plastics (SUP), particularly personal protective equipment (PPE) like masks and gloves, alongside increased demand for plastic packaging and disinfectants (Klemeš et al., 2020; Schlegel, 2020). The improper disposal of these items, compounded by short-circuited waste management systems during lockdowns, created an unforeseen pollution crisis (Silva et al., 2020; Erüz et al., 2023). By using the pandemic as a large-scale 'natural experiment,' this study assesses the sensitivity of coastal and offshore environments to rapid changes in land-based litter inputs. This provides a baseline for the effectiveness of future rapid-response mitigation measures required by the MSFD.

While the Mediterranean is a known plastic hotspot, there is a critical lack of multi-year, large-scale empirical data that tracks how sudden socio-economic shifts, like the global COVID-19 pandemic, interact with hydrodynamic processes to redistribute floating litter. The novelty of this study is to address this gap by providing an integrated analysis of a unique six-year longitudinal dataset with both coastal and offshore waters. Therefore, this work aims to quantify and characterize the floating marine macro-litter (FMML) (>20 cm) across offshore and coastal Italian waters of the Mediterranean Sea over an extended 2018–2023 period. By dividing the monitoring period into Pre-COVID (2018–2019), During COVID (2020–2021), and Post-COVID (2022–2023) phases, we hypothesized that (i) coastal litter composition would show immediate sensitivity to lockdown measures, specifically regarding consumer-related plastics, and (ii) offshore regions would exhibit a 'buffer effect,' acting as a stable reservoir for legacy litter despite temporary changes in human activity.

2. Materials and methods

2.1. Survey design and study area

Visual surveys were conducted between 2018 and 2023 across the Mediterranean Sea, following the standardized protocols described by Arcangeli et al. (2020, 2025). The survey design was based on a stratified sampling framework to capture sub-regional variability in both coastal and offshore areas using fixed transects. Offshore monitoring was performed from large ferries along five fixed routes (Livorno-Bastia, Civitavecchia-Barcelona, Ancona-Patras, Palermo-Tunis, and

Naples-Palermo). Conversely, coastal data were collected 3–6 nautical miles from shore using small-to medium-sized vessels across 68 fixed routes, spanning 14 Italian regions: Liguria, Toscana, Lazio, Campania, Basilicata, Calabria, Sardegna, Sicilia, Puglia, Molise, Abruzzo, Marche, Emilia-Romagna, and Friuli-Venezia Giulia.

A total of 2111 surveys were completed, categorized into offshore ($n = 355$) and coastal ($n = 1756$) assessments. For both survey types, a frequency of 3–5 surveys per season was maintained to ensure comprehensive seasonal coverage; monitoring was conducted along portions of the whole transects, to maximise spatial coverage within each sampling season.

Data collection was designed to ensure high-quality observations while accounting for key factors influencing sighting probability and statistical representativeness, including vessel speed, sampling width, minimum detectable object size, observer experience and environmental conditions.

Surveys were conducted by dedicated trained observers under optimal daylight and sea-state conditions (Beaufort ≤ 2). Observations were performed along fixed strip transects, with widths of 5 m for small-to medium-sized vessels and 50 m for large vessels. All observations were made with naked eye and, when necessary, supported by binoculars and digital cameras to verify item classification. Data were recorded using standardized observation sheets.

The identification and categorisation of items were based on the type of material categories (Artificial polymer materials, Glass, Processed wood, Metal, Textile, Paper, Rubber, Natural debris) and assigned to subcategories ("General names"), according to the Joint List of Litter Categories for Marine Macrolitter Monitoring developed under the MSFD (Fleet et al., 2021). For each item, other characteristics were recorded when possible: source (Land–Sea); activity (Food–Fishing–Maritime–Cosmetic–Sanitary–Other); size classes (20–30; 30–50; >50; >100 cm); colour (White–Transparent–coloured); buoyancy (positive–neutral–negative) and physical state (entire–fragmented). Buoyancy was assigned based on the observed position of the object in the water column (Positive: floating/mostly or entirely above the sea surface; Neutral: items at the sea surface, or only partially submerged; Negative: objects entirely sunken or below the surface). Fragmentation was assessed by identifying whether an item was a recognizable whole object (e.g., a complete bottle) or a 'fragment' lacking identifying morphological features of its original form, provided the piece was still >20 cm in size. Items were further grouped as Single-Use plastics (SUP) (e.g. bottles, bags, packaging, tableware, etc.), or Fishing Gear (FG) (e.g. nets, lines, floats, fish boxes, etc.), according to the MSFD masterlist (Fleet et al., 2021). Polymer composition was also inferred based on the same FMML reference masterlist, enabling consistent classification across surveys. Top 20 items were evaluated for each survey type.

To account for the effects of the COVID-19 pandemic, data were grouped into three temporal periods: 2018–19 (Pre-COVID), 2020–21 (During COVID) and 2022–2023 (Post-COVID). This temporal classification allowed the assessment of how pandemic-related changes in human activities and waste management influenced coastal and offshore litter distribution and composition. For regional analysis, the "Western Mediterranean" (WMED) included offshore tracks from LIBA, CBAR, PATU and NAPA routes, while the "Adriatic-Ionian" (AdrIon) comprised the ANPA tracks. For coastal surveys, the Tyrrhenian regions were assigned to the WMED region, and the Adriatic and Ionian regions to the AdrIon region. Data from Sicilia and Calabria were subdivided accordingly between their Tyrrhenian and Adriatic/Ionian sectors (Fig. 1).

2.2. Statistical analysis

To characterize compositional shifts in litter categories across periods, inferential statistical analyses were applied to relative abundance, expressed as percentage composition. All analyses were conducted on aggregated data at the spatio-temporal group level, obtained by pooling

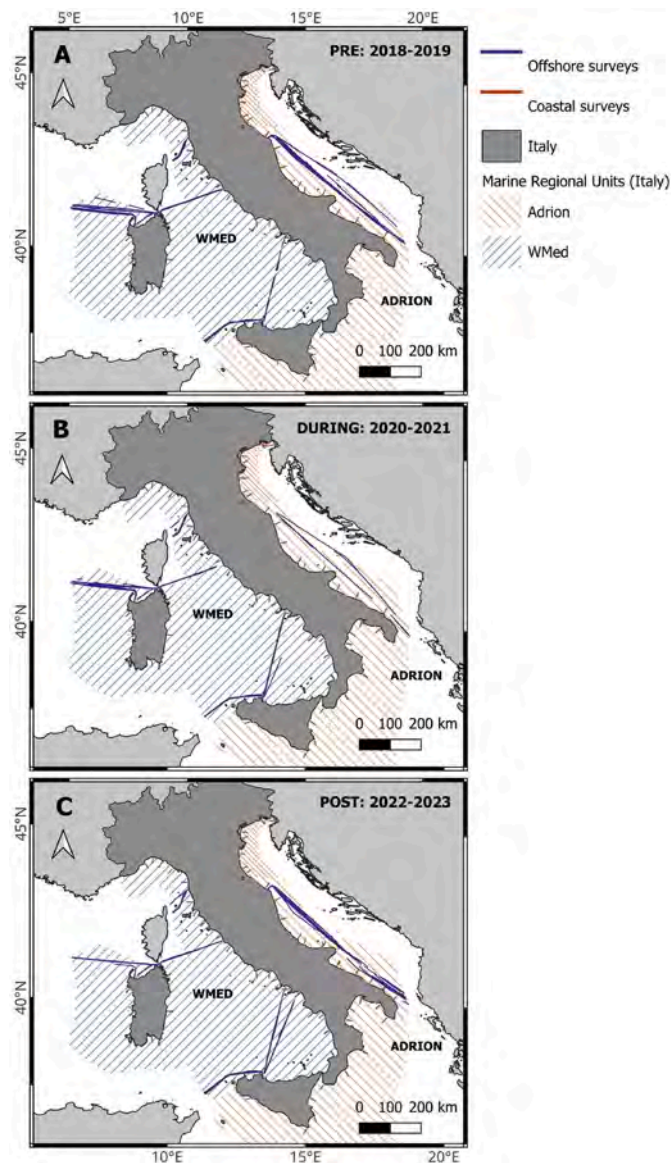


Fig. 1. Spatial distribution of monitored transects during 2018-2023 period divided in PRE (2018-19), DURING (2020-21) and POST (2022-2023) in consideration of COVID-19 pandemic outbreak. Coastal fixed transect monitoring (red lines) and offshore fixed transects monitoring (blue lines). Gridded sea areas, Italian Marine Reporting Units (MRU): Western Mediterranean (WMed, blue), Adriatic-Ionian (AdrIon, orange). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

observations within each period and subregion (as described above). Pearson's Chi-Square (χ^2) Test of Independence was used to evaluate associations between categorical variables, i.e., to test whether litter characteristics (e.g., buoyancy, fragmentation state) and material composition were independent of the sampling zone (Coastal vs. Offshore) or temporal period. Degrees of freedom are reported for all Chi-square analyses to specify the parameters of the underlying distribution used for p-value calculation. Two-Proportion Z-tests were conducted to detect significant differences in the relative abundance of specific litter categories from the Joint List of Litter Categories for Marine Macrolitter Monitoring between independent groups (e.g., SUPs, FG, Sanitary items). These tests were applied to (i) Spatial Comparisons, comparing the prevalence of specific categories between Coastal and Offshore environments, and (ii) Temporal Pairwise Comparisons, evaluating shifts in abundance among specific study periods (e.g.,

comparing 2018–19 baseline levels vs. 2020–21 pandemic levels) to determine the statistical significance of observed temporal variations. The null hypothesis (H_0) for all tests assumed that no significant difference existed in litter proportions or distribution between compared groups. Statistical significance was established at $\alpha = 0.05$ (95% confidence level). All P-values were two-tailed, and analyses were all performed using R studio v4.3.1 (R Core Team, 2022).

To address the pronounced spatial heterogeneity of marine litter distributions, variability was estimated using non-parametric bootstrap resampling. For each spatio-temporal group, data were resampled with replacement to generate the distribution of the mean and calculate 95% confidence intervals (CI) for the relative abundance of key litter categories (e.g., Single-Use Plastics, Fishing Gear) and source activities (e.g., Sanitary, Recreation, Agriculture). A total of 2000 iterations were applied for general litter categories and 10,000 iterations for source-related analyses to generate robust mean estimates using R (rsample package and custom scripts, Frick et al., 2026). Bootstrap methods were preferred over standard deviation because they make no assumptions about data normality and provide robust estimates of variability in highly heterogeneous datasets. Temporal shifts were deemed statistically significant when the 95% CIs of the compared periods did not overlap.

2.3. Quality assurance and quality control (QA/QC)

Quality Assurance and Quality Control (QA/QC) were ensured by using only data collected by trained observers who participated in training and intercalibration exercises prior to the study. Data were all filtered to include only observations made under optimal weather and visibility conditions (Beaufort scale ≤ 3) to minimize detection bias caused by sea state.

3. Results

3.1. Offshore

3.1.1. Material composition and temporal variations

During the six-year monitoring period, 355 offshore surveys yielded 13,559 total observations of floating objects. Litter-specific data accounted for the majority of these records ($n = 11,655$), representing approximately 86% of the total observational effort. Plastics dominated the offshore litter assemblage across all monitoring years (2018-2023), contributing an average of 81% of total items. The highest plastic proportion occurred during 2020-21 (86%), coinciding with the COVID-19 period, while the lowest was recorded in 2018-19 (75%, Fig. S1). Natural matter (average 12%), and minor fractions of Paper/cardboard (2.7%) and Processed wood (1.7%) followed, although natural matter was excluded from subsequent analysis.

Among artificial materials, Single-Use Plastics (SUP) represented the largest component. Robust bootstrap analysis ($n = 2000$ iterations) indicated a remarkable stability in SUP abundance between the Pre-COVID (Mean: 23.0%; 95% CI: 18.9–27.1%) and During-COVID (Mean: 22.9%; 95% CI: 20.6–25.8%) periods (Fig. 2), confirming that offshore accumulation of consumer plastics persisted independently of pandemic restrictions. In the Post-COVID phase (2022–23), mean SUP abundance decreased to 18.1% (95% CI: 12.4–23.4%); however, the overlap between this confidence interval and the pre-pandemic baseline suggests that this reduction was not statistically significant at the regional scale, likely due to high spatial variance in litter distribution. Fishing-related items (FG) displayed a similar pattern of high variability. While raw counts suggested a decline in total abundance, bootstrap analysis revealed extensive overlap in confidence intervals across periods. Mean FG prevalence dropped from 12.8% (95% CI: 8.2–18.3%) in 2018–19 to 9.6% (95% CI: 4.7–15.1%) during the pandemic, stabilizing at 10.1% (95% CI: 7.6–12.7%) thereafter. The substantial breadth of these confidence intervals indicates that while sea-based inputs may

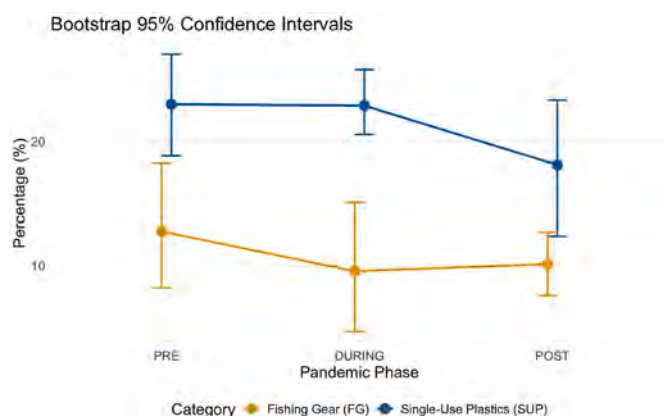


Fig. 2. Temporal trends of Single-Use Plastics (SUP) and Fishing Gear (FG) in offshore waters across pre-, during-, and Post-pandemic phases. Points represent the bootstrap mean percentage, and error bars indicate 95% Confidence Intervals (CI) derived from 2000 resamples.

have decreased on average, the signal was modulated by significant spatial heterogeneity, with some offshore transects retaining high densities of fishing debris despite the general reduction in maritime activity. Both SUP and FG contributions remained consistently highest in the Adriatic-Ionian region (AdriIon).

3.1.2. Source and activity

Litter originating from land-based sources was predominant throughout the survey, increasing gradually from 2018 to 19 to 2022–23 (Fig. 3). Conversely, sea-based sources peaked during the 2020–21 pandemic period. The main contributing activities (>1% among all the activities taken into account) were Fishing/Aquaculture (F/A) and Food-related items. F/A litter reached its maximum in 2018–19 (61%) but declined markedly thereafter, while food-related debris peaked in 2022–23 (45%). Sanitary items displayed a distinct "pandemic pulse". Their contribution increased four-fold from 0.6% in 2018–19 ($n = 20$) to 2.3% in 2020–21 ($n = 41$; $Z = 5.38$, $p < 0.001$) and remained elevated at 1.7% in 2022–23, significantly higher than the pre-pandemic baseline ($p < 0.001$). To account for spatial variability between monitoring

routes, a non-parametric bootstrap analysis ($n = 10,000$) was performed. This confirmed the robustness of the sanitary shift: the 95% Confidence Intervals (CI) for the pandemic period [1.38, 3.53] did not overlap with the pre-pandemic baseline [0.27, 1.34], confirming that the increase was not driven by outliers but was a consistent trend across the region. Regarding recreational activity, the bootstrap analysis revealed an emerging upward trend. The mean proportion of recreational items more than doubled from the pre-pandemic baseline (0.98%) to the post-pandemic period (2.10%). However, unlike sanitary items, the confidence intervals for recreational items overlapped (Pre: [0.63, 1.32] vs. Post: [0.71, 3.78]), suggesting that this increase was highly variable and driven by specific local hotspots rather than a uniform regional rise. Both Food and F/A litter contributions were more abundant in the AdriIon region (Table 1).

3.1.3. Offshore litter buoyancy, size, colour, physical state and top items

Artificial offshore items were primarily neutrally buoyant (51%), with the highest proportion recorded in 2020–21 (58%), followed by positively buoyant items (32%), which peaked earlier in 2018–19 (41%, Fig. S2A). Excluding items smaller than 20 cm, most debris were between 20–30 cm and 30–50 cm (together >80%, Fig. S2B). White (55%) and transparent/opaque (21%) were the dominant colours (Fig. S2C). The majority of items were fragmented (67%), reaching 79% in 2022–23 (Fig. S2D). Generic waste items were the most frequent overall, with common specific items including Industrial sheets (J67), rigid pieces (J79), shopping bags (J3), and polystyrene boxes (J58) (Table S1). Frequently found fishing gear included floats for nets (J62) and fishing

Table 1

Relative contribution (%) of litter source activity of the offshore observations in the two surveyed Italian Marine Reporting Units (MRU): Western Mediterranean (WMed) and Adriatic-Ionian (AdriIon).

Activity source	WMed (%)	AdriIon (%)
Fishing/Aquaculture	51,1	49,7
Food	36,3	38,8
Sanitary	6,4	5,4
Recreation	3,4	0,9
Other	0,0	2,3
Activities <1% (sum)	2,5	2,9

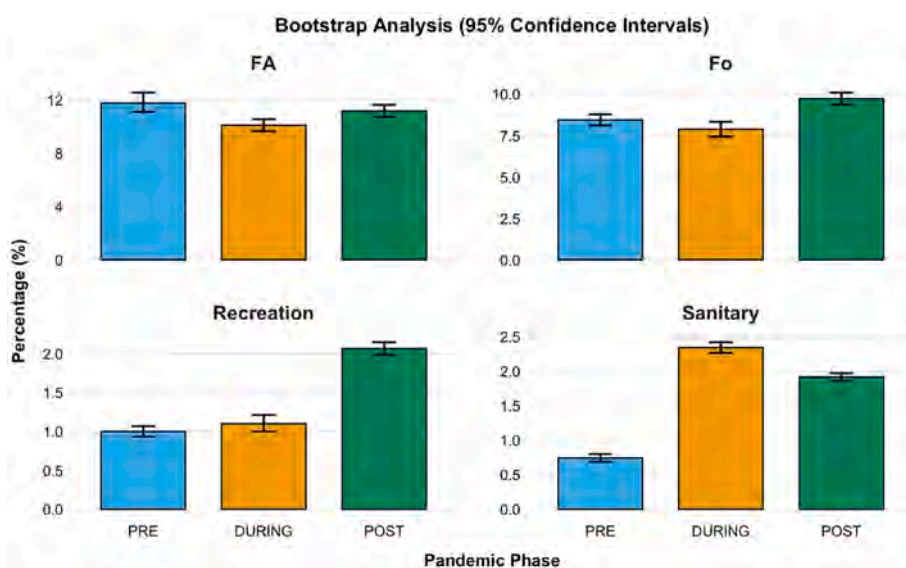


Fig. 3. Bootstrap analysis of offshore litter source activities (>1%) across Pre- (Blue), During- (Orange), and Post-Pandemic (Green) periods. Bar heights represent the mean percentage contribution of each category, and error bars indicate the 95% Confidence Intervals (CI) derived from 10,000 bootstrap iterations. Non-overlapping error bars (e.g., Sanitary items between Pre and During) indicate statistically significant differences at $\alpha = 0.05$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

lines (J59), alongside not fishing gear items like plastic bottles (J7-J8). The dominant polymers were PE, PP, PS, and PET, on the basis of the used FMML protocol, which is consistent with common consumer items and packaging plastics.

3.2. Coastal

3.2.1. Material composition and temporal variations

During the monitoring period, 1756 coastal surveys yielded 1924 total floating objects. Litter-specific data accounted for the majority of these records ($n = 1846$), representing approximately 96% of the total observational effort. Plastics also dominated, averaging 87% of total litter (Fig. S3). Plastics abundance was highest in 2018-19 (90%), and lowest during 2020-21 (83%). Processed wood was the second most abundant material (average 5%). SUP constituted 56.9% of artificial litter in 2018-2019, but declined significantly to 41.0% in 2020-21 ($Z = 5.56$, $p < 0.001$) and remained at similar levels in 2022 (40.6%). FG items also decreased from 25.7% (2018-19) to 16.4% in 2020-21 ($Z = 3.96$, $p < 0.001$), showing a modest rebound to 18.5% in 2022, though it remained below pre-2020 levels. SUPs were most abundant in the Western Mediterranean (WMED), while FG peaked in the Adriatic region.

Bootstrap analysis ($n = 2000$) revealed distinct patterns for coastal litter (Fig. 4). SUP displayed a marked decrease during the pandemic, dropping from a mean of 41.5% (95% CI: 30.6–52.9%) in the Pre-COVID period to 25.9% (95% CI: 18.6–33.8%) during 2020–2021. Although a slight overlap in confidence intervals reflects high regional heterogeneity, the strong downward trend aligns with reduced tourism and mobility during the pandemic period. However, this effect appeared transient, with SUPs rebounding to 33.7% (95% CI: 22.5–45.1%) in the Post-COVID phase. Conversely, FG temporal variations were characterized by high variability. While mean abundance declined gradually from 33.4% (Pre-COVID) to 26.2% (Post-COVID), the extensive overlap in confidence intervals indicates that these shifts were not statistically significant at a regional scale, suggesting that coastal fishing litter accumulation is driven by localized factors rather than a uniform temporal driver.

3.2.2. Source and activity in coastal waters

Land-based litter was most abundant in 2022, while the lowest contribution occurred in 2018–19, with consistently higher values in the Adriatic region. In contrast, Sea-based litter contributions peaked in 2022–23 (21%) and reached their minimum during 2020–21.

Among the most relevant source activities (>1% of the total activities), the category "Other" dominated overall (26.3%), followed by Food-related and Fishing/Aquaculture (F/A) debris. Bootstrap analysis

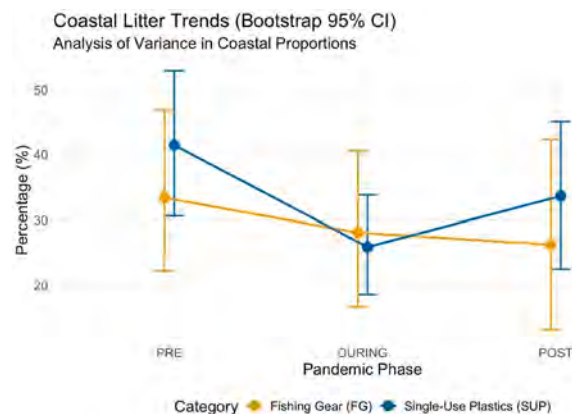


Fig. 4. Temporal trends of Single-Use Plastics (SUP) and Fishing Gear (FG) in coastal waters across Pre-, During-, and Post-pandemic phases. Points represent the bootstrap mean percentage, and error bars indicate 95% Confidence Intervals (CI) derived from 2000 resamples.

indicated that the contributions of these primary sources were largely stable over time due to high spatial variability. Both F/A and Food items were most prevalent in 2018–19 (27% and 12%, respectively; Fig. 5), particularly in the Adriatic-Ionian Mediterranean (Table 2). Although Food-related litter appeared to increase again in 2022 (12%) after a dip in 2020–21 (9%), the overlapping confidence intervals (Pre: [5.6, 14.9] vs Post: [6.4, 21.1]) suggest this fluctuation was not statistically significant.

A clear temporal anomaly was, however, observed for sanitary waste. Such items were virtually absent before the pandemic (Bootstrap Mean = 0.00%; 95% CI [0.00, 0.00]) but rose sharply to 1.7% during 2020–21 (Bootstrap Mean = 1.09%; 95% CI [0.20, 2.49]). Their contribution then declined to 0.5% in 2022. Crucially, the bootstrap confidence interval for the post-pandemic period returned to a lower bound of zero ([0.00, 1.63]), rendering the values statistically indistinguishable from the pre-pandemic baseline. This pattern statistically confirms that the surge in coastal sanitary pollution was a short-lived event linked to the pandemic, rather than evidence of a lasting shift in litter composition. Additionally, a minor but significant emergence of agricultural waste was detected exclusively during the pandemic period (Mean 0.88%; 95% CI [0.08, 1.83]), likely reflecting localized shifts in land-use or waste management.

3.2.3. Coastal litter buoyancy, size, colour, physical state and top items

Coastal debris was dominated by positively buoyant items (77%), peaking in 2022 (81%, Fig. S4A). The most frequent size classes were again 20-30 cm and 30-50 cm (Fig. S4B). White items were the most common (Fig. S4C), and entire items predominated (Fig. S2D). The leading items were Shopping bags (J3), industrial sheets (J67), rigid pieces (J79), and polystyrene boxes (J58, Table S2). Fishing gear such as fishing lines (J62) and mussel/oyster socks (J45) were frequently found, especially during 2018-19. Sanitary-related items, notably cleaning products containers (J9), were most abundant during 2020-21, while Food-related items, like food wrappers (J30) and plastic bottles (J7-8), increased in 2022. Polymer composition mirrored offshore observations and was dominated by PE, PP, PS, and PET, based on the FMML list.

3.3. Sanitary assemblage and spatial-temporal distribution

Given the clear link between sanitary litter and the COVID-19 period, these items were examined in greater detail. A total of 281 sanitary-related objects were identified across all surveys. The combined (offshore + coastal) assemblage was dominated by cleaning product containers (J9, $n = 83$, 29.5%), sanitary towels (J96, $n = 56$, 19.9%), tampons (J144, $n = 44$, 15.7%), and single-use face masks (J253, $n = 22$, 7.8%) (Table 3). Overall, 43% of the sanitary items were classified as Single-Use Plastics (SUP); however, this aggregate value hides a pronounced contrast between offshore ($n = 169$) and coastal ($n = 114$) zones.

Statistical tests confirmed a significant dependence between zone and temporal accumulation pattern. Coastal sanitary pollution peaked early, with 61% of all coastal items recorded during 2020–2021, largely concentrated in the Adriatic-Ionian (77%). Offshore observations displayed a delayed accumulation, with 85% of items recorded after 2018-2019 and a distinct peak in 2022–2023 (59%), consistent with gradual offshore drift. Spatially, most offshore items occurred in the Western Mediterranean (57%), underscoring a contrasting distribution relative to the coast.

The composition of sanitary litter differed sharply between zones ($\chi^2 = 44.06$, $df = 4$, $p < 0.0001$). The coastal assemblage was dominated by absorbent hygiene products, primarily tampons (J144, 37%) and sanitary towels (J96, 18%), while cleaning containers (J9) were scarce (<10%). Consequently, coastal environments contained a higher proportion of SUP-classified items (69%). In contrast, the offshore assemblage was dominated by J9 containers (44%), resulting in a lower SUP proportion (18%). This difference was highly significant ($\chi^2 = 74.22$, df

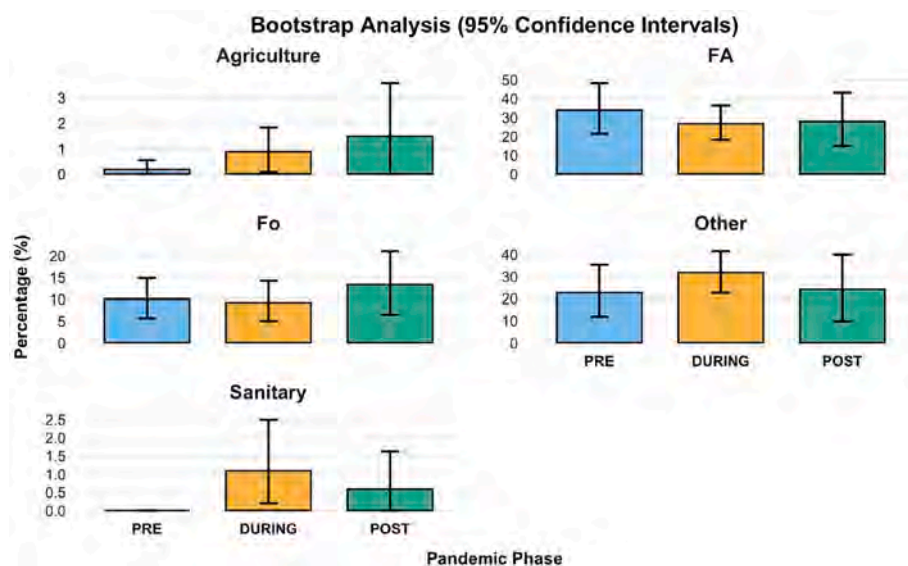


Fig. 5. Bootstrap analysis of coastal litter source activities across Pre- (Blue), During- (Orange), and Post-Pandemic (Green) periods. Bar heights represent the mean percentage contribution of each category, and error bars indicate the 95% Confidence Intervals (CI) derived from 10,000 bootstrap iterations. Non-overlapping error bars (e.g., Sanitary items between Pre and During) indicate statistically significant differences at $\alpha = 0.05$. Note the significant emergence of sanitary and agricultural waste during the pandemic period compared to the zero-baseline in the pre-pandemic phase. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2

Relative contribution (%) of litter source activity of the coastal observations in the two surveyed Italian Marine Reporting Units (MRU): Western Mediterranean (WMed) and Adriatic-Ionian (AdriIon).

Activity source	WMed (%)	AdriIon (%)
Agriculture	0,8	1,3
Fishing/Aquaculture	29,0	42,0
Food	15,5	19,5
Other	49,0	34,7
Sanitary	2,8	0,9
Activities <1% (sum)	3,7	1,5

Table 3

Top 5 sanitary items (% and number of items) found in both coastal and offshore observations during surveys performed in the period 2018-2023. J codes are provided according to the Joint List of Litter Categories for Marine Macrolitter Monitoring developed under the MSFD (Fleet et al., 2021).

Sanitary items	Coastal (%) (n tot = 91)	Offshore (%) (n tot = 132)	Total (%) (n = 281)
Plastic tampons and tampon applicators (J144)	36,8 (n = 42)	1,2 (n = 2)	15,7 (n = 44)
Plastic bottles and containers of cleaning products (J9)	7,0 (n = 8)	44,4 (n = 75)	29,5 (n = 83)
Plastic sanitary towels/panty liners/backing strips (J96)	17,5 (n = 20)	21,3 (n = 36)	19,9 (n = 56)
Plastic single-use face-mask (J253)	9,6 (n = 11)	6,5 (n = 11)	7,8 (n = 22)
Other identifiable non-foamed plastic items (J241)	8,8 (n = 10)	4,7 (n = 8)	6,4 (n = 18)

$= 1, p < 0.0001$), confirming that offshore waters preferentially accumulate buoyant packaging debris, whereas coastal zones act as sinks for heavier composite sanitary products.

Despite the global surge in Personal Protective Equipment (PPE) usage during the pandemic, single-use face masks (SUFM) comprised only a minor fraction of sanitary litter: 10% of coastal and 7% of offshore observations, contributing 8% overall. Unlike other sanitary categories, mask distribution showed no significant spatial difference, indicating a more homogeneous dispersion. This pattern suggests that while SUFMs

are reliable indicators of pandemic-related pollution, they represent a secondary component of the sanitary waste burden in both coastal and offshore environments.

4. Discussion

The present study confirms the persistent and critical status of marine litter in the Mediterranean Sea across both offshore and coastal environments. Plastics were by far the most abundant material in both offshore and coastal surveys, consistent with previous large-scale Mediterranean assessments (Suaria & Aliani, 2014; Arcangeli et al., 2018; Campanale et al., 2019). This consistent prevalence of plastics in both environments underscores the pervasive nature of macro-plastic pollution and supports its designation as a core indicator under MSFD Descriptor 10 (D10C1) (Galgani et al., 2013; Arcangeli et al., 2025). The agreement between datasets collected through independent surveys demonstrates the robustness of FMML monitoring and validates its capacity to deliver reliable regional-scale assessments despite methodological and logistical constraints (Arcangeli et al., 2018; Gonzalez-Fernandez et al., 2021).

4.1. Spatio-temporal divergence and socio-economic influence

Comparative analyses revealed both shared regional pressures and distinct spatio-temporal responses, clearly linked to socio-economic dynamics. The response of marine litter to the COVID-19 pandemic differed markedly between coastal and offshore domains, a distinction effectively captured by robust bootstrap resampling. The significant reduction in coastal SUP during the lockdown phase suggests a high sensitivity of nearshore environments to immediate land-based input changes. Crucially, this reduction appeared transient; post-pandemic levels rebounded to 33.7%, with confidence intervals trending back toward baseline values. This pattern strongly supports the hypothesis that the coastal "clean-up" effect was directly linked to temporary restrictions on tourism and mobility. This coastal "lockdown effect" was further evidenced by the emergence of agricultural waste, which appeared as a statistically significant, albeit minor, fraction exclusively during the pandemic, likely reflecting localized shifts in land use or rural waste management while tourism was suppressed (Dalias et al., 2018).

In contrast to the coastal response, offshore sectors exhibited remarkable stability in litter composition and abundance throughout the study period. These open-sea areas appear to function as legacy reservoirs, where the litter burden is governed by long-term accumulation and basin-scale hydrodynamic retention rather than short-term fluctuations in land-based sources (Onink et al., 2019). This decoupling of offshore and coastal dynamics implies that once plastic reaches the open sea, it becomes part of a persistent pool of debris that is shielded from the immediate impacts of terrestrial policy shifts or lockdowns. The observed variability in Fishing Gear (FG), underscore a decoupling between regional fishing effort and localized litter accumulation. Although a large-scale reduction in Mediterranean fishing activity was documented during the study period (Russo et al., 2021), our analysis suggest that FG distribution is characterized by high spatial patchiness rather than a uniform basin-wide decline. This implies that FG hotspots, associated with specific bathymetric features or traditional fishing grounds, may act as persistent sources of plastic input that are less sensitive to short-term fluctuations in maritime traffic.

4.2. Transport, retention, and degradation dynamics of floating marine litter

Our findings support a conceptual model where coastal zones serve as the primary interface for fresh anthropogenic inputs, while offshore convergence zones act as long-term reservoirs. This observed coastal accumulation reflects the role of the Italian shelf as a primary retention zone. Similar dynamics have been documented in other semi-enclosed basins, such as the Southeastern Black Sea, where 'source-to-sink' investigations revealed that the composition of streamside litter and beach litter are closely coupled (Erüz et al., 2023). These findings suggest that in basins with restricted water exchange, rivers and coastal streams serve as the primary conduits for anthropogenic debris, leading to high-retention zones on the inner shelf before potential offshore export (Erüz et al., 2022).

On the other hand, the stability of the offshore legacy reservoir during the pandemic suggests that the residence time of floating macro-litter in the open Mediterranean exceeds the duration of temporary socio-economic shifts. This highlights the necessity of differentiated management strategies: coastal measures should focus on reducing immediate pulses of consumer waste, whereas offshore strategies must address the removal of existing legacy plastic that continues to circulate regardless of current land-based activity (Morales-Caselles et al., 2021; Özşeker et al., 2024). A notable inversion in the prevalence of Single-Use Plastic (SUP) underscores this mechanism: SUP abundance was highest in Western Mediterranean (WMED) coastal waters but peaked in Adriatic-Ionian (AdriIon) offshore zones. This pattern supports the hypothesis that positively buoyant SUPs are efficiently advected offshore through wind-driven drift and surface current transport (Cózar et al., 2015; Liubartseva et al., 2018). The simultaneous depletion of SUPs in coastal waters during 2020–2021, coinciding with pandemic lockdowns, and their subsequent enrichment offshore in 2022–2023, further suggest active offshore displacement and accumulation within convergence zones of the AdriIon basin. Such redistribution highlights how transient socio-economic perturbations, coupled with hydrodynamic forces, can reshape surface litter pathways over relatively short timescales.

The physical characteristics of the debris provide complementary evidence of these processes. Offshore environments contained a higher proportion of fragmented items, particularly during 2022, consistent with longer residence times and progressive mechanical and photo-oxidative degradation (Andrady, 2011; Lebreton et al., 2019). This delayed fragmentation pattern underscores the persistence of macro-debris at the sea surface (Geyer et al., 2017) and its key role as a continuous source of secondary microplastics (Ter Halle et al., 2016; Koelmans et al., 2017). In contrast, coastal litter typically comprised more intact and recently released items, reflecting proximity to input sources and shorter exposure durations (Thiel et al., 2013; Pedrotti et al.,

2016; Morales-Caselles et al., 2021).

Material buoyancy also emerged as a critical factor governing vertical and horizontal transport. The scarcity of textiles and clothing items in surface observations suggests that denser materials are underrepresented, as these items tend to rapidly lose buoyancy through water absorption and biofouling (Kukulka et al., 2012). Consequently, surface-based surveys capture primarily buoyant polymers such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET), emphasizing the need for complementary subsurface monitoring to capture the full spectrum of polymer types (Arcangeli et al., 2018; Suaria et al., 2020).

Spatially, the AdriIon region consistently emerged as a hotspot for both fishing-related litter and fragmented debris (i.e. polystyrene fish boxes), reflecting the region's combined influence of intensive fishing activity, confined circulation, and limited outflow (Pasanisi et al., 2023; Corbau et al., 2025). These findings reinforce the importance of integrating hydrodynamic modelling with empirical monitoring to identify accumulation zones and design targeted mitigation strategies for sea-based litter sources (Carlson et al., 2017). Collectively, the results demonstrate that transport mechanisms, buoyancy properties and degradation dynamics are tightly interlinked drivers shaping the persistence, composition, and spatial fate of floating marine litter in the Mediterranean Sea. This reinforces the need for targeted management of marine-based sources in this region.

4.3. Sanitary waste as a transient pandemic signature

A critical finding of this study is the bifurcated behavior of sanitary litter, which exhibited two distinct spatio-temporal trajectories: 1) A 'pulse-and-recovery' pattern in coastal waters versus a 2) 'pulse-and-persist' pattern in offshore sectors.

In coastal environments, the surge in sanitary items recorded during the lockdown phases, characterized here as a 'pandemic pulse', was remarkably transient, with a statistical return to baseline levels in the post-pandemic phase. This high responsiveness to immediate shifts in consumer behavior and municipal waste management efficiency identifies nearshore zones as active, sensitive sinks. This rapid recovery is likely driven by the physical properties of the litter; the prevalence of absorbent hygiene products and textile-based sanitary towels, items that lose buoyancy upon water saturation, facilitates quick sequestration from the surface layer. Such findings align with observations in other semi-enclosed basins, such as Turkish inland and coastal ecosystems, where COVID-19-induced shifts led to measurable increases in medical and personal protective equipment (PPE) waste (Özşeker et al., 2022). Furthermore, the transience observed in our data suggests that without structural improvements in land-based waste management, socio-economic disruptions provide only a temporary hiatus in the overall trend of marine pollution (Özşeker et al., 2025). This segregation provides empirical evidence of how material buoyancy and hydrodynamic sorting govern the fate of land-based pollution pulses during major socio-economic disruptions. In contrast, offshore sectors exhibited a sustained accumulation of sanitary litter that failed to return to pre-pandemic baselines. We attribute this "pulse-and-persist" behavior to the dominance of positively buoyant polymers, specifically cleaning and disinfectant containers. Unlike saturated textiles, these rigid plastic objects are highly susceptible to wind-driven transport (Stokes drift) and surface currents (van Sebille et al., 2020). The observed temporal lag, a coastal peak during the 2020–2021 lockdowns followed by a delayed offshore maximum in 2022–2023, aligns with estimated surface transit times (12–24 months) toward convergence zones in the Western Mediterranean (Carlson et al., 2017). This indicates that the open sea acts as a legacy reservoir for high-buoyancy pandemic waste, shielding it from the immediate recovery observed at the coastline.

Despite the global proliferation of Personal Protective Equipment (PPE), SUFMs remained a minor and spatially undifferentiated fraction of the floating macro-litter. This lack of a significant surface signal,

despite high production volumes, is likely explained by rapid biofouling. Microbial colonization and the trapping of mineral particles have been shown to increase mask density within weeks of seawater exposure, leading to premature sinking (Shen et al., 2021). This suggests that the "missing fraction" of pandemic PPE is likely sequestered on the benthos, further highlighting that the surface-floating component of medical waste is a transient indicator rather than a long-term reservoir.

4.4. Methodological considerations and future perspectives

In this work, we provide evidence that floating marine macro-litter (FMML) serves as a critical and timely indicator of anthropogenic pressure, directly reflecting the effectiveness of land-based waste reduction measures and signaling risks of entanglement and ingestion for marine megafauna. The sampling design implemented in this study was optimized for maximum spatio-temporal coverage, proving effective for monitoring highly variable phenomena across large scales. However, to ensure the robustness of future monitoring frameworks and address the inherent challenges of ship-based surveys, several methodological considerations must be addressed.

- 1) A primary consideration in ship-based monitoring is the diversity of observation platforms. In this study, offshore data were collected from commercial ferries (height ~15–20 m), while coastal data were obtained from smaller motorboats (height ~2–4 m). Such differences in vantage points can influence the detection probability of smaller or submerged items. While focusing on items >20 cm effectively harmonized the dataset across both platforms, as this size class remains identifiable even from high command bridges, future applications would benefit from the inclusion of specific detection functions (e.g., Distance Sampling) to further minimize potential platform-induced bias (Vighi et al., 2022).
- 2) The coastal dataset exhibited a characteristic zero-inflated distribution, highlighting the extreme spatial "patchiness" of marine litter. Our analysis suggests that when logistic constraints limit transect length, the single transect may not be sufficient as a standalone statistical unit to represent coastal variability. To mitigate this, we employed a bootstrap-based resampling architecture ($n = 2000-10,000$). This approach proved essential, as it allowed for the estimation of robust confidence intervals and significant differences between periods without the assumptions of normality required by parametric tests. Furthermore, we recommend that future studies consider the use of weighted means or medians when area coverage varies significantly between transects, ensuring that smaller, highly-impacted regions are accurately represented (Gonzalez-Fernandez et al., 2021).
- 3) Although the 20 cm size threshold excludes the smaller macro-fraction, the detected concordance in size-class distributions between coastal and offshore environments validates the use of items >20 cm as an efficient indicator for long-term monitoring. Specifically, the 20–30 cm category emerged as a high-fidelity proxy for monitoring the effectiveness of the Single-Use Plastics Directive (EU, 2019/904), as it captures the most common identifiable objects such as drink bottles, food packaging, and sanitary waste. By identifying large fragments, items lacking primary morphological features but remaining within this size class, we can monitor the initial stages of the plastic "fragmentation cascade" before litter enters the micro-plastic cycle.
- 4) While the "V-shaped" recovery of coastal plastics observed in this study perfectly aligns with the socio-economic lockdown cycle, we acknowledge that hydrodynamic forcing (e.g., riverine discharge and wind-driven currents) plays a secondary role in litter redistribution. Future monitoring efforts should integrate "event-based" sampling following extreme weather to decouple these natural pulses from anthropogenic signals.

- 5) In conclusion, the continued inclusion of the 20–30 cm size class in standardized protocols is highly recommended to avoid underestimating primary source categories and to track progress toward Good Environmental Status within the MSFD and IMAP frameworks.

5. Conclusion

The present study utilizes the socio-economic disruptions of the COVID-19 pandemic as a natural experiment to characterize the spatio-temporal drivers of floating marine macro-litter (FMML) in the Mediterranean Sea. Our data demonstrate a clear spatial divergence in litter dynamics. Coastal accumulations showed high sensitivity to fluctuations in land-based emissions, evidenced by the significant reduction in Single-Use Plastics (SUPs) during lockdown periods. Offshore densities, on the other hand, remained stable, acting as persistent reservoirs of legacy debris. This decoupling suggests that while coastal pollution is driven by immediate terrestrial input, offshore distribution is governed by the interplay between polymer buoyancy and basin-scale Lagrangian transport. Specifically, our findings indicate a progressive sorting mechanism that facilitates the transboundary movement of buoyant items from high-input Western coastal areas toward Eastern offshore convergence zones. For future monitoring, the synergy between ship-based visual observations and remote sensing remains essential for reconciling local variability with basin-wide trends (Cózar et al., 2024).

Scientifically, these results emphasize that achieving Good Environmental Status (GES) necessitates a multi-scalar governance approach: targeting immediate land-based source reduction at the national level, while establishing international frameworks to manage the long-term transport and accumulation of persistent debris in offshore Mediterranean basins.

Ultimately, the monitoring framework presented here serves as a scalable model for future MSFD-oriented management strategies. By providing a high-resolution, longitudinal baseline, this approach enables the refinement of indicators for Descriptor 10 and supports the development of adaptive policies capable of evaluating the long-term efficacy of regional mitigation efforts across the Mediterranean basin.

CRedit authorship contribution statement

V. Donnarumma: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **G. Suaria:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Paluselli:** Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **S. Aliani:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **E. Pasanisi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **F. Maffucci:** Supervision, Methodology. **M. Azzolin:** Methodology, Data curation, Conceptualization. **I. Campana:** Methodology, Investigation, Data curation, Conceptualization. **A. Castelli:** Project administration, Methodology, Investigation. **M. Costantino:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation. **R. Crosti:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **M. Farina:** Methodology, Investigation. **M. Gregoriotti:** Methodology, Investigation. **E. Pignata:** Methodology, Investigation. **E. Santini:** Methodology, Investigation, Formal analysis. **G. Sarà:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Investigation, Data curation, Conceptualization. **R. Teti:** Methodology, Investigation. **A. Arcangeli:** Writing – review & editing, Writing – original

draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used ChatGPT in order to check the English grammar. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article. The graphical abstract for this study was generated using FigureLabs.ai. The authors reviewed and edited the final output to ensure scientific accuracy.

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.envpol.2026.128391>.

Data availability

Data will be made available on request.

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