RESEARCH ARTICLE



# Satellite monitoring of marine litter in the Adriatic Sea during 2015–2021

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Aim: To analyze the spatiotemporal distribution and accumulation patterns of floating marine litter in the Adriatic Sea from 2015 to 2021 using satellite observations, with particular focus on identifying regional variability and dominant transport mechanisms.

Methods: In this observational study, we used satellite data from the Copernicus Sentinel-2/MultiSpectral Instrument L1C system to estimate marine litter presence across the Adriatic Sea from July 2015 to September 2021. The dataset includes records of pixels per litter windrow (PLW), representing spectral reflectance indicators of floating plastic-like debris. We performed analyses on annual and monthly scales, focusing on four zones: Italy (zones A and B), Croatia (zone C), and Albania (zone D). We assessed variability using boxplot metrics and interpreted spatiotemporal patterns in the context of oceanographic features, wind patterns, and riverine inputs.

Results: Zone A had consistently higher PLW values across the study period, making it the most polluted area. Litter was probably transported along the western Adriatic coast by the Western Adriatic Current (WAC) toward the south, with partial redistribution toward the eastern coast. Zones B and D showed pronounced annual and seasonal variability, with peaks in 2017, 2019, and 2021, while zone C showed less consistent patterns. Monthly trends revealed increased litter presence in warmer months, coinciding with higher tourist activity and riverine discharges. There was a marked increase in the PLW difference between zones A and B in two periods, 2015–2017 and 2018–2021, potentially due to litter sinking, WAC meandering, or cleanup efforts.

Conclusions: Satellite remote sensing can help us identify marine litter hotspots and understand their seasonal and spatial dynamics. Our findings highlight persistent pollution in the northern Adriatic and the role of currents and riverine inputs in shaping litter distribution. Long-term monitoring and integrated waste management strategies are essential for effective mitigation.

Keywords: Adriatic Sea; marine litter; wind; sea currents; satellites

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## Introduction

Marine litter poses significant ecological and economic risks for society, impacting aquaculture, fisheries, and tourism (*1*). It enters the marine environment *via* rivers, runoff, sewage, wind, and ocean currents (*2*) and includes both anthropogenic waste (*e.g.*, plastics, rubber) and organic matter (*e.g.*, shells, dead marine organisms, tree branches, macro algae) (*3*). Aside from negative societal impacts, marine litter's harmful effects include entanglement, ingestion, bioaccumulation, and biomagnification in marine life (*4*).

Rivers are a major source of marine litter, as they transport waste from inland areas to the sea. Such is the case with the rivers Po, Adige, and Isonzo in the northwest Adriatic Sea, and the Neretva and Bojana rivers in its southeast (*5*). The Po River alone accounts for 28% of freshwater inflow into the Adriatic (*6*), influenced by nearby industrial zones (*7*), and drives the Western Adriatic Current (WAC), which strengthens during summer and flows toward southern Italy (*8*).

The northern Adriatic is characterized by lagoons (*e.g.*, Venice, Marano), dense populations, and industrial activity, making it a hotspot for litter generation and transport, especially in the Gulf of Venice (*7*). These processes are intensified by wind patterns and the Adriatic's cyclonic circulation, which includes gyres that retain floating debris (*5*, *8*).

The daily quantity of plastic waste on the islands of Mljet and Vis, which are located far from the mainland coast and account for 92% of the area's marine litter, ranges from 4 kg/km to 18.8 kg/km, with 57.7% of the plastic debris being unattributable to a specific source due to the small size of the particles (2.5–50 cm), which are subject to fragmentation and degradation as a result of hydrodynamic processes and ultraviolet radiation (*8*). Approximately 28% of marine litter originates from coastal activities (*e.g.*, inadequate waste management and tourism-related sources) and 12.3% comes from sanitary and medical waste (*e.g.*, cotton swabs and sanitary napkins), while other sources include illegal dumping (1.23%), maritime transport (0.6%), fisheries and aquaculture (0.10%), and agriculture (0.04%) (*5*).

Tutman *et al.* (*1*) analyzed marine debris collected from four locations along the Croatian Adriatic coast: Omiš (Punta), the Neretva Delta, Mljet (Saplunara), and Vis (Zaglav) from November 2014 to March 2016. Using eight 15-meter trawlers, one ton of waste was retrieved, consisting of 470 kg of plastic (39,399 items), 275 kg of processed wood (399 items), 90 kg of metal (414 items), 55 kg of textiles (384 items) and 25 kg of rubber (193 items), predominantly footwear, 20 kg of glass and ceramics (656 items), and 5 kg of paper (226 items). In a waste removal campaign implemented near the island of Hvar from November 2014 to May 2015, seven trawlers removed a total of 7,034.29 kg of marine debris; an estimated 50 to 100 kg of seabed waste was collected monthly per trawler, amounting to a total of 30.8 tons of waste, with plastic comprising approximately 42% of the total mass (*9*).

Ciappa (*10*) reported that the Po River exhibits a stratified estuarine system from May 2020 to September 2020, during which freshwater disperses horizontally across the surface layer. In this period, sea currents and wind patterns play a significant role in facilitating the accumulation of floating litter. Conversely, during the winter months, vertical homogenization of the water column occurs, reducing the thickness of the surface layer and subsequently diminishing the capacity for surface litter accumulation, leading to drops in amounts of floating debris at sea during winter and increases in coastal accumulation. The highest concentrations of marine litter in the northern Adriatic within this study were recorded in August 2020, likely due to hydrological and meteorological conditions that favored litter retention and accumulation.

According to Prevenios (*11*), the Ionian Sea exhibits similar levels of marine debris to the Adriatic Sea, which is why these two regions are often collectively referred to as the Adriatic-Ionian Basin. The average density of marine litter in this basin ranges from 0.22 to 2.9 items/m$^2$ (*5*). National-level results from surveys carried out between 2014 and 2016 showed that Croatia (island of Vis) had the highest litter density with 11 items/m$^2$ (1,055 items/100 m), followed by Greece (Ipsos) with 0.91 items/m$^2$ (455 items/100 m), Slovenia (Strunjan) with 0.83 items/m$^2$ (828 items/100 m), Italy (Foce Bevano) with 0.55 items/m$^2$ (549 items/100 m) and Montenegro (Kamenovo) with 0.52 items/m$^2$ (524 items/100 m). Other significant sites included Bele Skale (Slovenia) with 0.49 items/m$^2$ (490 items/100 m), the Neretva River delta (Croatia) with 0.48 items/m$^2$ (479 items/100 m) and Thesprotia (Greece) with 0.43 items/m$^2$ (426 items/100 m), while lowest litter densities were recorded on beaches in Greece (Issos, Mega Ammos, Chalikounas, and Kalamas), ranging from 0.08 to 0.09 items/m$^2$ (92–177 items/100 m).

Kolitari *et al.* (*12*) reported on data collected in 2015 within the MEDITS program, focusing on marine litter in the Drin and Vlora Bays along the Albanian coastline. They found wooden materials to be the most prevalent at depths of 290–298 meters, with an average mass of 0.96 kg. At shallower depths of 112–116 meters, significant quantities of discarded fishing nets were recorded (0.85 kg). Various items such as clothing, footwear, and paper, totalling approximately 1.1 kg, dominated litter at greater depths of 568–584 meters. The average total mass of marine litter was 0.7 kg, with plastic accounting for 0.2 kg at depths of 241–244 meters, marking this area as the most polluted.

An analysis of waste originating from marine activities (*e.g.*, maritime transport, fisheries, and aquaculture), land-based activities (*e.g.*, agriculture, tourism, and recreational activities), and mixed sources (*e.g.*, sewerage systems and hospitals) has demonstrated that the origin of most collected waste cannot be definitively attributed to either marine or terrestrial sources (*5*). For instance, plastic bottles may originate from both land and sea-based sources, while sanitary waste such as cotton buds can be traced to hospital systems or tourism-related activities. As a result, the proportion of waste classified as originating from mixed sources ranges from 15.3% to 66.4%. The relative contribution of marine- *vs.* land-based activities to the overall waste composition varies between countries within the Adriatic-Ionian basin, such as Montenegro (1.5% *vs.* 74.1%), Bosnia and Herzegovina (1.9% *vs.* 82.8%), Italy (14.8% *vs.* 27.0%), and Greece (13.2% *vs.* 48.0%) (*5*).

An analysis of the composition of 70,851 marine litter items in the Adriatic-Ionian Basin revealed that 74–92% of the waste consists of plastic, confirming the predominance of plastic materials in the marine environment (*5*). The most commonly encountered items include plastic fragments measuring 2.5–50 cm (19.89%), polystyrene (11.93%), cotton swabs (9.17%), plastic caps (6.67%), cigarette butts (6.60%), mussel farming nets (2.43%), candy and snack wrappers (2.11%), straws (1.80%), plastic cups (1.65%), plastic bottles

(1.13–1.24%), plastic bottle cap rings (1.09%), wires with a diameter of less than 1 cm (1.06%), glass/ceramics (3.2%), metal (1.5%), paper (14%), textiles (1.1%), and rubber (0.6%). Approximately 0.1% of the litter could not be classified by material type.

Here, we aimed to analyze the spatiotemporal dynamics and retention zones of marine litter in the Adriatic Sea using satellite-derived data from July 2015 to September 2021.

## Methods

We obtained satellite observations of floating marine litter from the dataset described by Cózar *et al.* (*13*) developed as a proof of concept for spaceborne monitoring of marine litter using Copernicus Sentinel-2 MultiSpectral Instrument (MSI) Level-1C products. The dataset spans the period from 4 July 2015 to 21 September 2021 and covers the entire Mediterranean Sea. Each detection includes spatial and temporal information and the number of pixels per litter windrow (PLW), which represents surface aggregates of plastic-like floating debris identified through their spectral reflectance signatures.

A total of 14,374 litter windrow detections were reported for the Mediterranean basin, of which 5,035 were located within the Adriatic Sea domain (40.5–45.7° N and 12.0–19.4° E). Here, we conducted analyses at annual and monthly temporal scales. For the regional assessment, we subdivided the Adriatic Sea into four zones corresponding to major coastal sectors: the northern Italian coast (zone A), the southern Italian coast (zone B), the middle Croatian Adriatic coast (zone C), and the Albanian coast (zone D).

All descriptive statistics were performed and all figures generated in *R* (R Foundation for Statistical Computing, Vienna, Austria), within the RStudio environment (Posit, Boston, Massachusetts, USA).

## Results

We analysed 5,035 satellite records from the four above-mentioned zones across the Adriatic Sea (**Figure 1**). Zone A recorded the most observations (n = 4,108), with consistent detection and abundance of marine litter throughout the seven-year study period (2015–2021). Fewer observations were recorded in zones B (n = 57), C (n = 34), and D (n = 148). Most areas across the Adriatic Sea are characterized by low litter density, except for a few localized zones of higher density in zones A and D.

Annual distributions of PLW revealed significant regional differences (**Figure 2**). The northern Adriatic (zone A) displayed small differences in median values, with annual variability. Conversely, the southern Italian coast (zone B) exhibited substantial variability, with the highest values observed in 2021. The Croatian coast (zone C) showed a significant peak in litter presence in 2017, whereas the Albanian coast (zone D) demonstrated pronounced alternating yearly patterns, with peaks in 2017, 2019, and 2021. The annual distribution of marine litter in the northern Adriatic (zone A) from 2015 to 2021 exhibited relatively consistent median values, although annual variability exists, with the highest values recorded in 2016 and the lowest in 2017. Zone B exhibited lower values and vari-

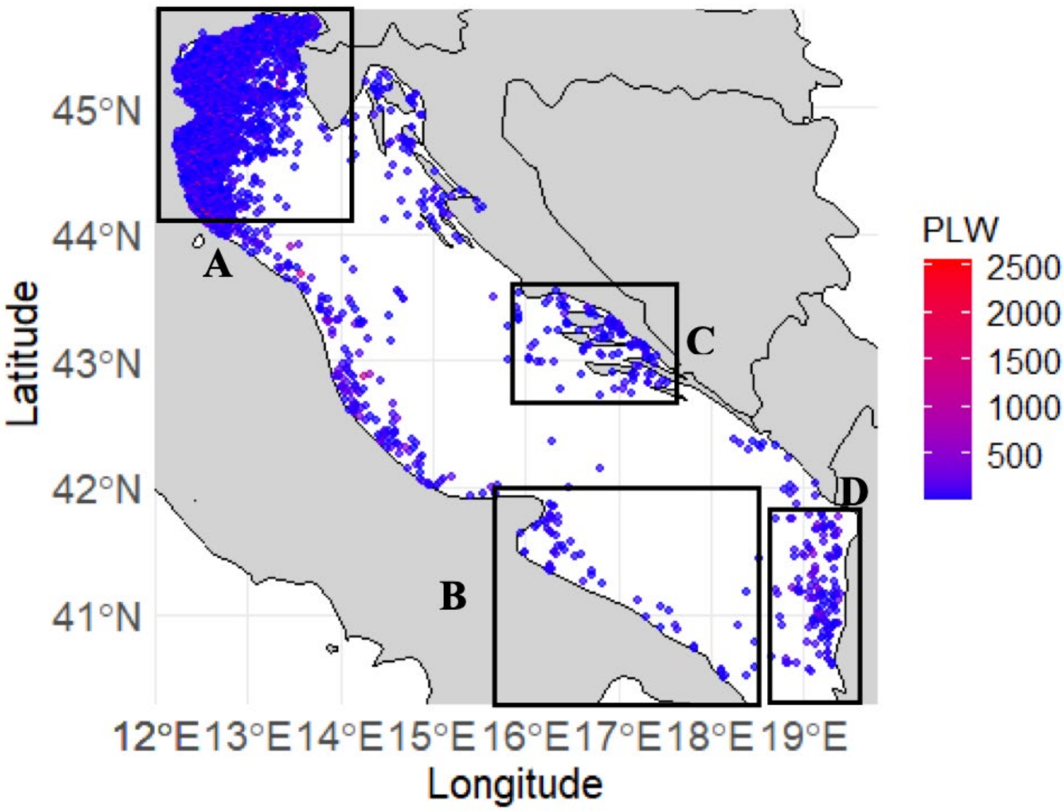


**Figure 1.** Distribution of marine litter across the Adriatic Sea and the zones A–D during 2015–2021.

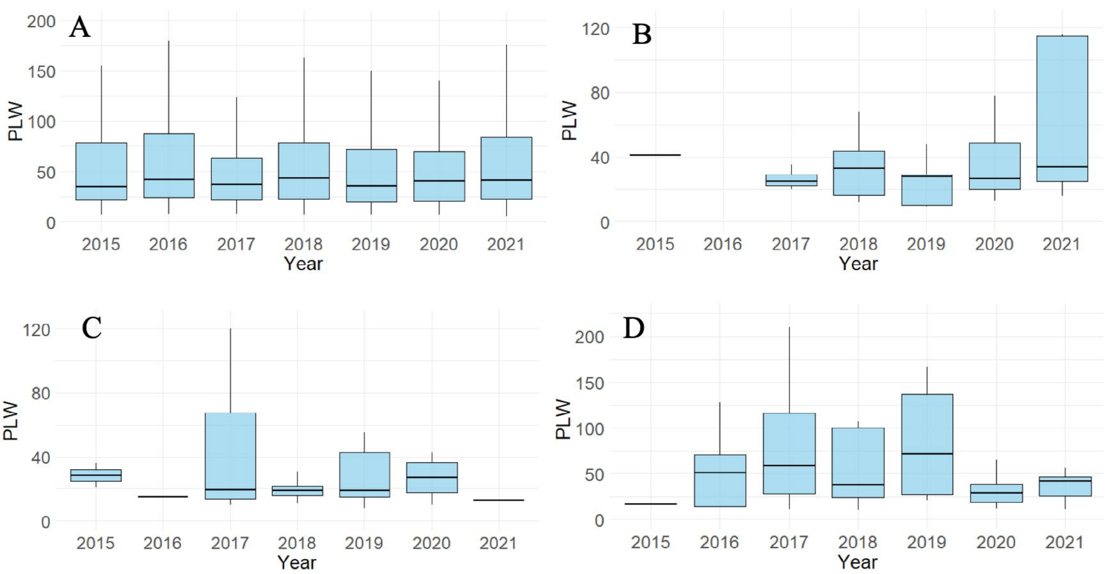


**Figure 2.** Boxplots showing the annual distribution of marine litter zones A–D during 2015–2021, shown in pixels per litter windrow (PLW).

ability than zone A. No data were recorded for 2016, while the highest variability was noted in 2021. Elevated levels of marine litter were recorded along the middle Croatian Adriatic coast (zone C) in 2017 and 2019, both accompanied by high variability. Although we noted an increased presence of litter in 2020, the distribution remained more stable compared to 2019 and 2017. In contrast, 2015 and 2018 were characterized by lower levels of marine litter and low variability. The Albanian coastline (zone D) demonstrated marked alternations between litter accumulation and dispersal, with evident peaks in 2017, 2019, and, to a lesser extent, 2021. In comparison, we noted generally lower quantities of litter 2016, 2018, and 2020.

We found significant spatial and temporal variability in monthly patterns of marine litter distribution for individual locations (**Figure 3**). In zone A, litter levels gradually increased from February to July, except for a decline in May, followed by a decrease in August until December. In zone B, annual variability was pronounced, with peaks in April and October. For zone C, litter peaks were most prominent in March, July, and August; March displayed the greatest variability within the upper quartile range; while other months recorded lower values, with January, June, October, and November showing low variability around the median range. In zone D, the highest observations of marine litter were recorded in September and December. April, May, and December exhibited high variability in the upper quartile range, while February, September, and October demonstrated balanced variability throughout the data range.

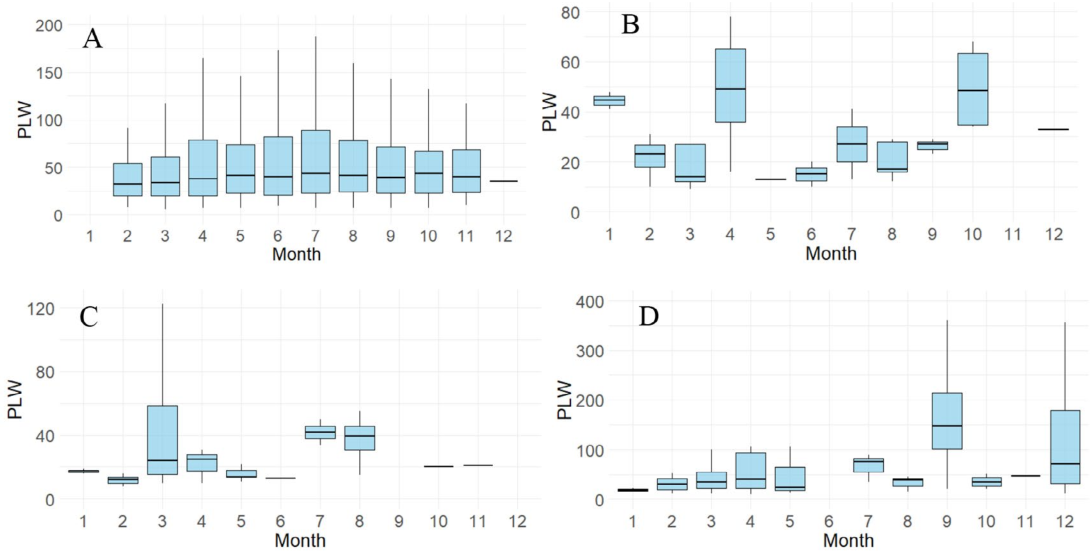


**Figure 3.** Boxplots showing the monthly distribution of marine litter for zones A–D during 2015–2021, shown in pixels per litter windrow (PLW).

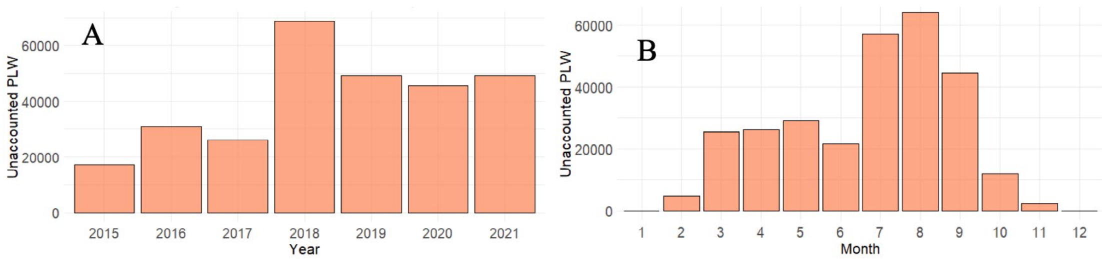


**Figure 4.** The total annual difference (**Panel A**) and the monthly difference (**Panel B**) in floating marine litter between northern (zone A) and southern (zone B) Italian coast during 2015–2021, shown in pixels per litter windrow (PLW).

The average difference between zones A and B from 2015 to 2021 was approximately 21,000 PLWs (**Figure 4**). This increased significantly to around 52,000 PLWs in the 2018–2021 period. The smallest differences (<5,000 PLWs) occur in winter months – January, February, October, November, and December. The difference rises to about 22,000 PLWs from March to June, with the highest values recorded in July, August, and September.

## Discussion

Using Copernicus Sentinel-2/MSI L1C satellite data, we analyzed floating marine litter in the Adriatic Sea for the 2015–2021 period. We observed the highest amount of floating litter along the northern Italian coast (zone A), with relatively consistent values. This pattern is likely influenced by high population density, intense industrial activity (*7*), and the northern Adriatic Sea cyclonic circulation, as well as the Po, Adige, and Isonzo rivers, which transport waste from inland areas to the northern Adriatic Sea and further along the western Adriatic coast *via* the WAC towards the southern Italian coast (*5*). We detected most of the marine litter during the summer months in the northern Italian coast, probably due to increased tourism followed by sea stratification that prevents vertical mixing and keeps litter at the surface (*10*). We further noted an extreme increase in litter presence along the Albanian coast during December compared to other zones, coinciding with a documented flooding event (*14*). Additionally, litter from the Albanian coast may be carried to the southern Italian coast or to the Croatian middle Adriatic coast *via* the South Adriatic Gyre (*8*).

The southern Italian coast (zone B) and the Albanian coast (zone D) are characterized by variability in floating litter distribution, which may be influenced by fluctuations in the strength of the Eastern Adriatic Current, WAC, and South Adriatic Gyre and the Bojana River, as well as by the absence of islands that would obstruct and retain litter, facilitating its accumulation (*5*, *8*). The middle Croatian Adriatic (zone B) coast also shows irregular litter distribution. Despite the presence of numerous islands that could potentially trap floating litter along the coastline (*8*) and the influence of a strong southerly wind (*jugo*) common in this region, the absence of higher litter concentrations may be explained by litter sinking below the surface (*15*) or by local cleanup actions that reduce the amount of visible floating debris.

We found that marine litter is predominantly concentrated along the northern Italian Adriatic coast, rather than the southern Italian Adriatic. This is particularly evident in the 2018–2021 period, while in 2015–2017, the two regions encountered relatively similar amounts of litter. However, this does not necessarily imply that the litter observed in the southern Adriatic originates solely from the northern Adriatic; it may also be transported from the Albanian coast and/or the middle Croatian Adriatic coast *via* the South Adriatic Gyre (*5*, *8*) and may come from the Ionian Sea. During the summer months, increased amounts of litter are likely transported from the northern Italian Adriatic due to the strengthening of the WAC, while during the winter months, litter is more likely to originate from the Albanian coast and/or the middle Croatian Adriatic coastline, and potentially from the Ionian Sea, when the Eastern Adriatic Current becomes more pronounced

(*8*). It is also possible that some litter sank during transport *via* currents (*15*), resulting in reduced detectability and consequently less available data.

Our study has some limitations. While satellite monitoring offers broader spatial coverage than traditional vessel-based or drone surveys, which often lack adequate spatial resolution and data coverages and enables the identification of source regions and transport pathways of marine litter (*13*), it is constrained by cloud cover, ship wakes and oceanographic conditions, which may lead to data gaps and/or reduced accuracy of detections. Another challenge is the limited spectral range of the multispectral sensor onboard Copernicus Sentinel-2, which reduces its ability to discriminate between different materials (*13*). A super-spectral sensor has been proposed as a way of enhancing detection accuracy, as it offers a broader spectral range that enables more precise discrimination, particularly between plastic litter and other materials such as driftwood and algae. However, detection in this case is only possible when debris forms on surface aggregates longer than ~70 meters (*13*). Lastly, satellite data need to be complemented by *in situ* litter observations, which are currently limited in the Mediterranean and other marine and inland waters, and without which satellite imagery cannot be properly validated or cross-referenced with field data, which reduces its reliability (*13*).

Solving the issues observed in our analysis requires systematic and efficient land-based waste management, as well as greater ecological awareness within society. There is also a need for increased efforts to collect *in situ* observations in marine and inland waters, as this is essential for cross-referencing with satellite imagery to ensure the validity and reliability of litter data.

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