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Deep-sea marine litter from visual surveys: New findings from offshore Al Wajh, Red Sea (Saudi Arabia)

Giorgio Castellan [a,b], Fabio Marchese [c], Thomas Lüdmann [d], Marco Taviani [a,e], Hildegard Westphal [f,g,*]

[a] Institute of Marine Sciences, National Research Council (CNR-ISMAR), Bologna, Italy
[b] NBFC - National Biodiversity Future Centre, Palermo, Italy
[c] Biological and Environmental Science and Engineering Division, King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia
[d] University of Hamburg, Institute of Geology, Hamburg, Germany
[e] Stazione Zoologica Anton Dohrn, Naples, Italy
[f] Leibniz Centre for Tropical Marine Research (ZMT), Bremen, Germany
[g] Bremen University, Bremen, Germany

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ABSTRACT

Marine litter poses a critical threat to ocean health, yet deep-sea benthic macrolitter (> 25 mm in diameter) is still quite underassessed, mostly because of logistical and financial constraints to carry out research with camera-equipped devices for ocean floor surveys in the high seas. Despite growing research efforts on this crucial topic, our knowledge of the spatial distribution of deep-sea litter is still highly uneven. We have, therefore, summarized available data from the literature for a first synoptic view, documenting that most such studies are related to European seas, North America, and the Western Pacific. We have added also newly acquired information from a sector of the Red Sea basin that only recently has been targeted for deep-sea macrolitter, in view of its rapid coastal development and increasing tourism driven by giga-scale initiatives. In late summer 2023, the seabed off Al Wajh (Saudi Arabia) was explored using a Remotely Operated Vehicle (ROV) during mission M193 aboard the R/V *Meteor*. Analysis of the data collected provides new insights into the distribution of deep-sea benthic macrolitter in the region. Consistent with previous observations, litter density was low, with plastic items being the only recorded anthropogenic debris. Distribution patterns appeared to be influenced by geomorphology and hydrography, with debris accumulating in submarine canyons and topographic depressions, aligning with global patterns of litter deposition in complex seabed environments. The observed macrolitter is likely linked to maritime traffic, supporting literature findings that identify international maritime activities as the primary source of deep-sea macrolitter in the western Red Sea, with local sources playing a subordinate role. Differentiating between endogenous and exogenous litter sources is crucial for designing effective mitigation strategies, and requires long-term monitoring efforts integrating litter composition analysis, hydrodynamic modeling, and waste management assessments. This study aims to contributes establishing a baseline for future assessments of deep-sea marine litter in the northern Saudi Arabian Red Sea as basis for policies that balance economic growth with marine conservation.

1. Introduction

Litter in the marine environment is recognized as a major threat to ocean health (Galgani et al., 2022; Hajji and Lucas, 2024). Marine litter originates from offshore activities such as commercial and recreational shipping, fishing, maritime traffic, military operations, aquaculture, offshore infrastructure, and ocean dumping (Ramirez-Llodra et al., 2013), plus onshore sources such as agriculture, coastal recreational activities, ports, tourism, shipyards, sewage discharges, and riverine inputs (Angiolillo, 2019; Pham et al., 2014; Stefatos et al., 1999).

Research on marine litter has predominantly focused on its effects on beaches and shallow-water ecosystems (e.g., coral reefs) or commercially important biota (fish) as well as floating or coastal debris (Galgani et al., 2015). However, knowledge of benthic macrolitter beyond those

* Corresponding author at: Leibniz Centre for Tropical Marine Research (ZMT), Bremen, Germany.
E-mail address: hildegard.westphal@leibniz-zmt.de (H. Westphal).

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habitats remains scarce due to the challenges and high costs associated with deep-sea investigations (Haarr et al., 2022). In recent years, the increasing use of Remotely Operated Vehicles (ROVs) has provided new insights, particularly into the distribution of macrolitter in deeper environments (Galgani et al., 2000). Nevertheless, no comprehensive understanding of the distribution of macrolitter in the deep sea has been achieved.

Based on the scarce data available, the accumulation of deep-sea debris seems to be influenced by a combination of localized factors, including litter input pathways and volumes, marine environmental conditions, regional wind and hydrographic patterns, anthropogenic activities, population density, temporal environmental fluctuations, and extreme events (Hernandez et al., 2022). Additionally, debris tends to accumulate in areas with low circulation, high sedimentation rates, and complex seafloor topography, which function as natural retention zones (Woodall et al., 2015).

Despite increasing research efforts, available data on deep-sea marine litter remains highly uneven, with vast oceanic regions that remain largely understudied (Canals et al., 2021). Among these is the Red Sea, where benthic macrolitter was only recently documented (Martynova et al., 2024).

The Red Sea is a narrow semi-enclosed subtropical to tropical basin surrounded by largely desertic land with minimal riverine discharge. Spanning approximately 2000 km in N-S extension, it exhibits significant depth variation, ranging from shallow southern shelves to steep northern basins, reaching depths of nearly 3000 m in the axial trough (Rasul et al., 2015). Its climate is characterized by extreme aridity, leading to high evaporation rates, and pronounced seasonal variability, caused by the Indian monsoon (Aiki et al., 2006). Limited exchange with the Indian Ocean results in elevated salinity levels and a complex two-layer circulation system. Despite its oligotrophic nature, the Red Sea supports diverse and unique marine ecosystems, including extensive shallow-water, lush mesophotic, and scarce deep-sea coral communities (e.g., Berumen et al., 2013; Qurban et al., 2014; Roder et al., 2013; Nolan et al., 2024; Vicario et al., 2024; Westphal et al., 2025).

Over the past decade, the Red Sea coast of Saudi Arabia has experienced rapid population growth and accelerated residential, commercial, and industrial development, aiming at expanding key economic sectors such as tourism, infrastructure, and healthcare (http://vision2030.gov.sa). Planned sustainably, the increase in tourism and coastal development still could potentially lead to higher volumes of waste entering the marine ecosystem. Such pollution could extend environmental impacts to deep-sea habitats, posing significant risks to marine ecosystems and biodiversity. Thus, management based on monitoring is necessary to accompany developments and avoid any threat to the shallow marine as well as the deeper marine ecosystems.

In late summer 2023, the mesophotic to aphotic depths offshore Al Wajh (Saudi Arabia) were explored during mission M193 aboard the German R/V *Meteor*. The area offshore Al Wajh, located along the northeastern Red Sea margin, encompasses a highly heterogeneous seafloor shaped by salt tectonics, rift-related faulting, and sediment transport processes (Lüdmann et al., 2023). This morphologically complex region includes steep escarpments, isolated ridges, deep mini-basins, and canyon systems connected to the Al Wajh carbonate platform. These geomorphological features create conditions for the presence of a diverse array of benthic habitats, from those dominated by coralline algae, corals, and bryozoans at mesophotic depths to cold-water corals much deeper (Qurban et al., 2020).

Here, we report observations of benthic macrolitter from Remotely Operated Vehicle (ROV) dives conducted during the mission. Our study provides new data to assess the presence of benthic macrolitter in this region in the context of available studies on deep marine plastic litter compiled here. It also establishes a baseline for monitoring the impacts of increasing coastal development and tourism for the future. Ultimately, our contribution aligns with broader efforts to preserve the ecological integrity of the deep Red Sea while balancing economic growth with environmental sustainability.

2. Material and methods

2.1. Literature records

A bibliometric review was conducted using a quantitative methodology to identify and assess studies reporting seafloor litter in deep sea observed using ROV. The Scopus (scopus.com) and Web of Science (webofknowledge.com) databases were used, with the search query terms "litter" and "deep sea". Only studies based on ROV surveys were included. To ensure data accuracy, a cross-check was performed between the results from both databases to remove any duplicates. The study locations meeting the criteria were then extracted and transformed into spatial data using ArcGIS Pro software (© ESRI).

2.2. Data collection

Cruise M193 took place in September-October 2023 focusing on marine carbonate sedimentation in the Saudi Arabian Northern Red Sea onboard the German R/V *Meteor* (Lüdmann et al., 2023). In particular, the cruise investigated the deeper waters around the Al Wajh carbonate platform by means of seismics, hydroacoustic bathymetry mapping, and sediment sampling (Fig. 2), including a deep-sea fan to the north of the platform fed by one of the largest onshore drainage systems on the Arabian Peninsula during Quaternary pluvial phases, and several isolated mini basins related to salt tectonics, and mesophotic reefs. Sea-floor footage was recovered by means of ROV surveys undertaken with the MARUM Squid of Bremen University.

2.3. Geophysical data collection

The hydroacoustic dataset was acquired using the Kongsberg EM122 multibeam echosounder system, as well as the Teledyne PARASOUND, at survey speeds ranging from 5.5–6 knots to 7–9 knots, depending on operational constraints. To minimize noise at the outer edges of the swath, a swath sector of 140–100° was applied. Both echosounders were configured with equidistant beam spacing for all survey lines, and the EM122 was primarily operated in deep-ping mode to minimize artifacts in the backscatter signal compared to auto-ping mode.

The EM122 and PARASOUND systems operated continuously throughout the survey area, while the EM710 was primarily used in shallower waters (< 700 m, with occasional operations down to 1000 m) due to high noise levels, largely attributed to interference from the PARASOUND and seismic activities. Sound velocity profiles were derived from CTD casts and an XSV probe deployed during reflection seismic blocks.

Sub-bottom profiling was conducted using the Teledyne PARASOUND, operating at a low frequency of 2 kHz and a high-frequency range of 19–23 kHz. The variable high-frequency range was specifically employed to reduce noise interference with the EM710 system, particularly in shallow water regions (< 100 m depth).

2.4. Video collection and analysis

The MARUM Squid, a light work-class ROV of Bremen University, manufactured by SAAB Seaeye (UK), was utilized for operations reaching depths of up to 2000 m. The vehicle was equipped with a SULIS Z70 4 K UHD resolution camera operating at 30 fps, featuring a hemispherical dome port and a fully corrected optical lens with 12x optical zoom. Additionally, the HD Lookdown camera, a prototype developed at MARUM, provided full HD resolution imaging from a quasi "top-down" perspective to monitor the area directly in front of the ROV. High-resolution still images (14 Megapixels) were captured using the IMENCO TIGERSHARK camera, mounted on an auxiliary Pan & Tilt unit on the upper port side of the ROV. An external flashgun, angled at 45°,

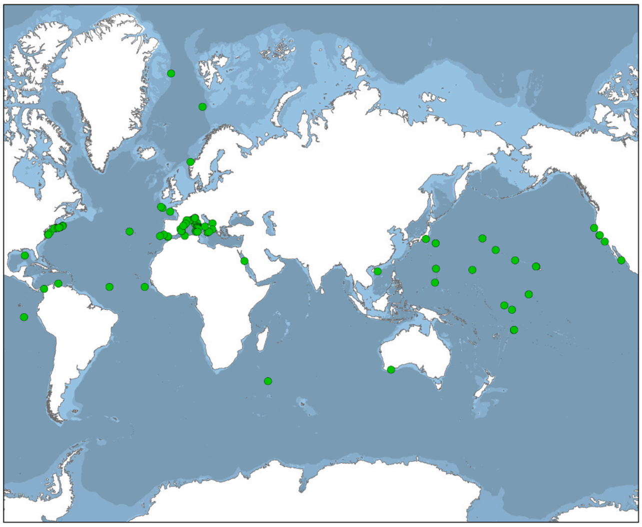

Fig. 1. Global distribution of studies in literature documenting macrolitter in the deep sea using ROV. List of references is reported in Tab. S1.

was installed on the ROV's upper porch for enhanced illumination during still image capture with the TIGERSHARK. Further details on the ROV can be found in Lüdmann et al. (2023).

During Cruise M193, seven dives were successfully conducted to investigate the deep and mesophotic benthic environments surrounding the Al Wajh carbonate platform. All ROV dives maintained an approximately constant altitude of ~ 2 m above the seafloor, ensuring a relatively stable field of view throughout the transects. Videos were georeferenced using ROV positioning provided by USBL system and analyzed to identify marine macrolitter. Items were classified using nomenclature in Butterworth et al. (2012) that distinguish bags, glass bottles, cans, ropes, as well as abandoned or derelict fishing gear. The litter items were counted, and density was calculated as the ratio between items and dive lengths (item km^{-1}), considering the entire set of dives performed in the area. We transformed the .xls files into point shapefile (.shp) to be further analyzed in GIS software (ArcGIS Pro). A map was then compiled showing all classified benthic marine litter items observed in the area surveyed.

3. Results

3.1. Global deep-sea macrolitter recorded in ROV surveys

The global distribution of studies on deep-sea marine litter observations conducted using ROVs shows a strong geographic bias (Fig. 1). A total of 114 literature records were identified (Tab. S1). The data reveal the highest concentration of studies in the Mediterranean Sea and the northeastern Atlantic Ocean, with a few additional sites scattered across the Pacific and Indian Oceans, while only one previous study of the Red Sea has been identified. A notable gap is evident in the Southern Hemisphere, particularly in the South Atlantic and the Antarctic region.

3.2. Deep-sea macrolitter offshore Al Wajh

The ROV dives conducted during the expedition explored diverse environments in the Red Sea, spanning from mesophotic to aphotic zones. In total, seven dives were performed providing images of 21.45 km of sea bottom transects from 92 to 1337 m water depth (Table 1). Dives M193_59-1, M193_71-1, and M193_89-1 investigated the steep vertical walls of platform fragments related to the Al Wajh platform (Petrovic et al., 2022). Other dives targeted diverse features, including deep-sea coral ecosystems (M193_10-1), the lava fields on

Table 1
List of ROV dives performed during the M193 cruise reporting dives metadata, marine macrolitter items observed and density.

Dive	Date	Start location Latitude Longitude (ddeg)	End location Latitude Longitude (ddeg)	Depth (m)	Length (km)	Duration (hh:mm:ss)	Num. items	Density (items km^{-1})	Item location Latitude Longitude (ddeg)	Item depth (m)
M193-10-1	14/09/2023	26.3936 36.0706	26.4023 36.0693	678–744	3.56	07:32:58	0	0		
M193-044-1	27/09/2023	25.4518 36.1172	25.4544 36.1085	1207–1337	5.15	06:17:16	0	0		
M193-051-1	28/09/2023	25.5815 36.3544	25.5913 36.3518	673–1060	3.86	06:53:54	2	0.52	25.5815–36.3544	1059
									25.5818–36.3543	1053.6
M193-059-1	29/09/2023	25.9072 36.3912	25.9098 36.3951	110–678	4.24	07:37:22	0	0		
M193-071-1	30/09/2023	25.3212 36.8605	25.3209 36.8619	117–490	1.53	06:53:08	0	0		
M193-085-1	02/10/2023	25.1596 36.9636	25.1566 36.9579	570–631	1.98	05:57:39	2	1.01	25.1596–36.9624	617.4
									25.1592–36.9615	620.9
M193-089-1	03/10/2023	25.1479 36.9267	25.1481 36.9275	92–380	1.13	05:58:11	0	0		
Tot.				92–1337	21.45	23:10:28	4	0.19		

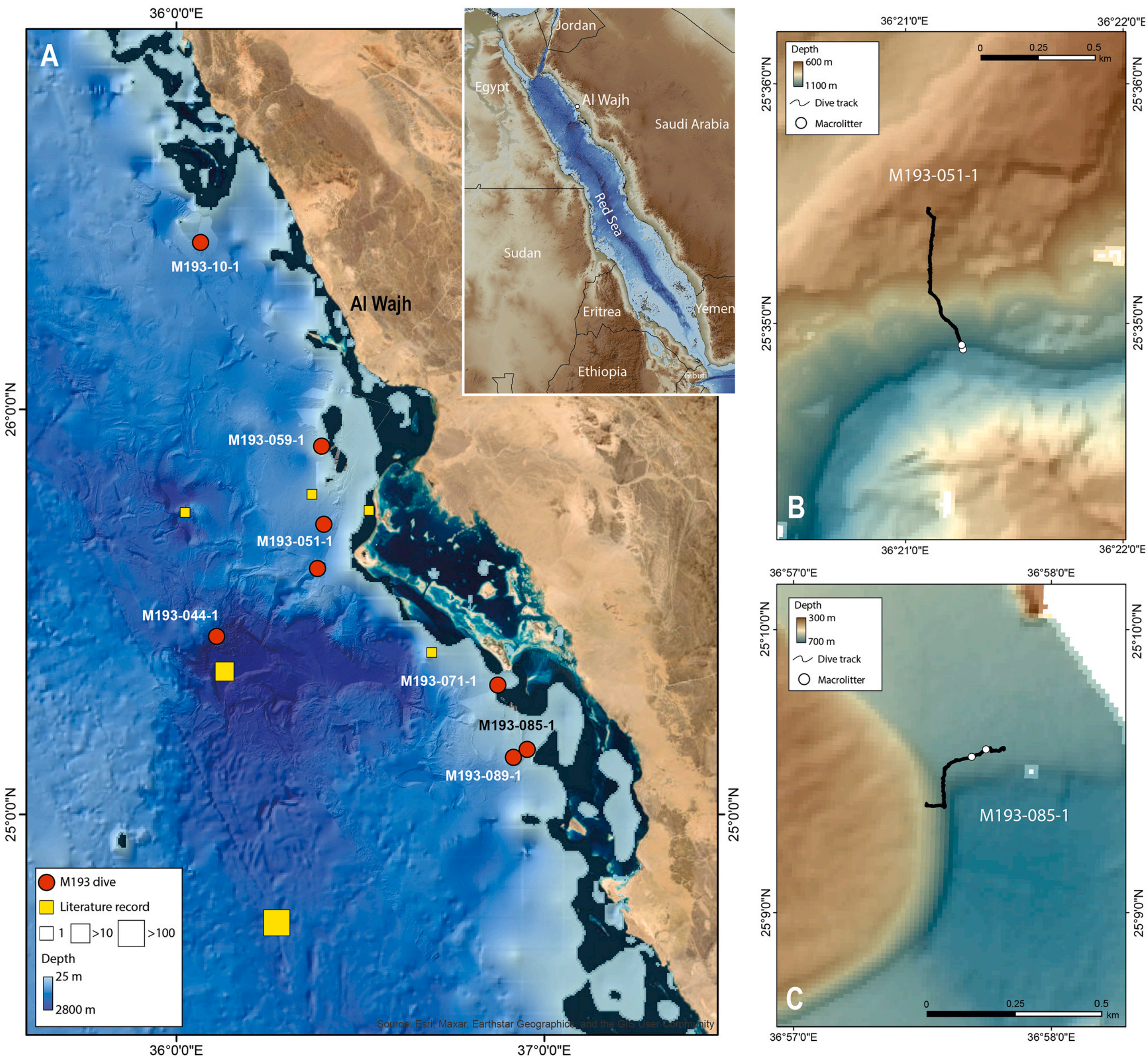

Fig. 2. (A) Location of ROV dives performed during the M193 cruise and literature records with symbology proportional to litter density; (B) Tracks of dive M193-051-1 and (C) M193-085-1 with occurrences of macrolitter items observed. Digital terrain model from GEBCO 2024 Grid.

the southern flank of the submarine Mabahiss Volcano (M193_44-1), a submarine canyon system (M193_51-1), and a recently discovered brine pool (M193_85-1; Stuhr et al., 2025). ROV observations revealed complex morphologies, including steep walls, volcanic pillow lava fields, intricate stair-like features and slumped blocks at depths > 200 m ca, as well as carbonate platforms in the mesophotic zone above, with biogenic carbonate concretions and algal nodules, supporting a diverse array of marine life spanning from corals (Scleractinia, Antipatharia, and Octocorallia), sponges, and algae.

Marine macrolitter was identified, categorized, and mapped during the M193 cruise, documenting direct evidence of human imprints on the deep-sea bottom off Saudi Arabia. The explored area was rather pristine in terms of human impacts, with no fishing impacts (dredging marks, nets) observed during our ROV dives and a very little presence of marine macrolitter. Four items were identified in total (Fig. 2), making up an overall macrolitter density of 0.19 items/km. Items were identified as bags and cups composed of plastic material lying on soft substrate (Fig. 3, Table 1).

In dive M193-051-1 that explored more than 3 km of sea bottom within a canyon system between 673 and 1060 m, two items were identified at the base of canyon wall (ca. 1050 m), resulting in a density of 0.52 items/km. A slightly higher macrolitter density (1.01 items/km) was observed in dive M193_85–1, surveying a brine pool between 570 and 631 m, where two plastic bags were documented at 617.4 and 620.9 m depth.

4. Discussion

Our global review of deep-sea macrolitter observations highlights significant geographic disparities in research efforts. Most studies are concentrated in the Mediterranean Sea and the northeastern Atlantic Ocean, while notable gaps remain in the South Atlantic, the Antarctic region, and the Pacific and Indian Oceans. This hinders an understanding of sources (offshore versus onshore) and transport mechanisms (surface currents versus mass flow) of macrolitter on a global scale. Within these underrepresented areas, data on deep-sea litter in the Red Sea are extremely recent and indicate a variable distribution of litter both geographically and bathymetrically (Martynova et al., 2024),

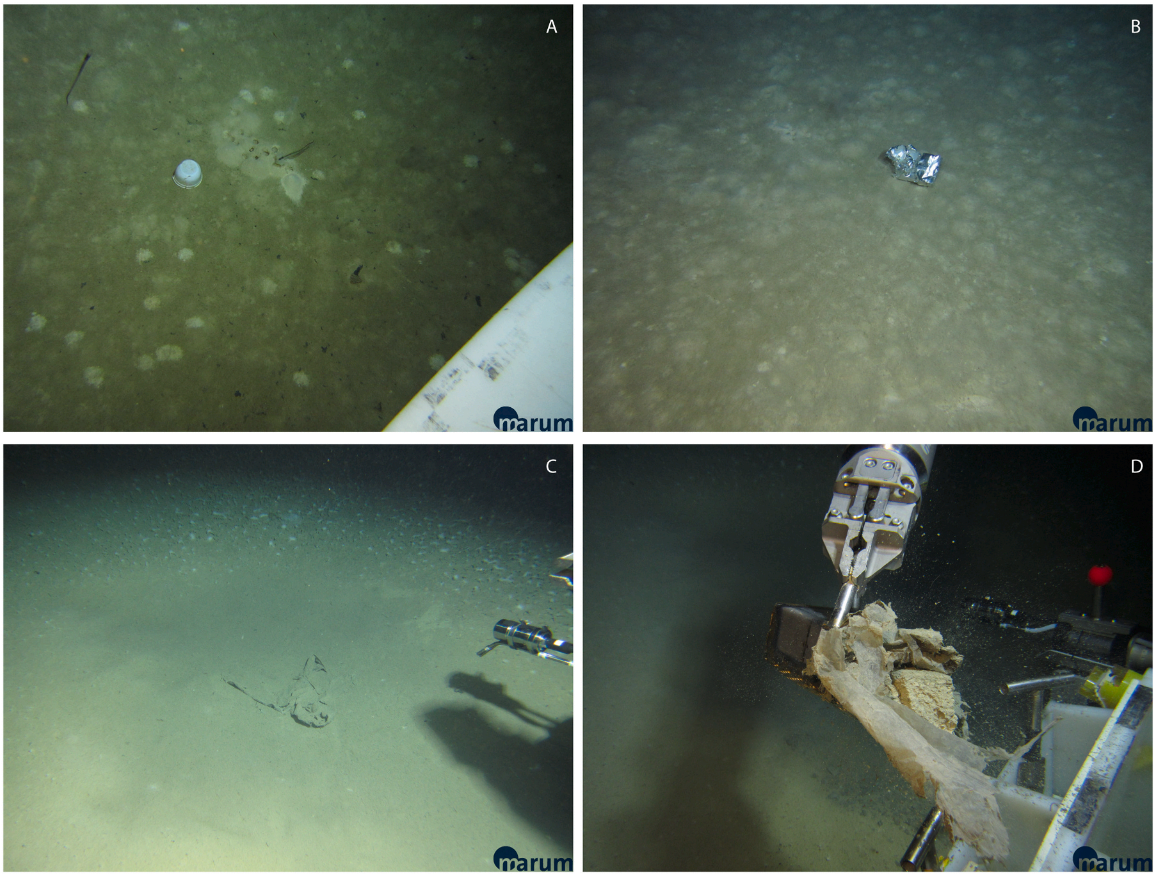

Fig. 3. Marine macrolitter items observed in ROV dives. A) Plastic cup in dive M193-051-1 at 1059 m depth; B) Aluminum/plastic bag at 1053.6 m in dive M193-051-1; C-D) Plastic bags at in dive M193-085-1 at 617.4 m and 620.9 m, respectively.

implying the need of recording more data to achieve an understanding of litter density, sources, transport mechanisms, and sinks in the Red Sea specifically.

Our ROV surveys corroborate previous observations in the area offshore Al Wajh (Martynova et al., 2024). The overall litter density observed was low (0.19 items/km), with only four plastic items recorded across the surveyed area. These included plastic bags and a cup found on soft substrates at depths exceeding 600 m. No evidence of fishing-related debris was detected, suggesting minimal current physical impacts from fisheries in the region on the deep-sea floor.

The geomorphology of the surveyed seabed likely played a crucial role in influencing the observed litter distribution. Two out of four of the identified macrolitter items were concentrated within a submarine canyon system at approximately 1000 m water depth, and near a brine pool at 600 m. Submarine canyons are well-documented pathways for the transport of sediments and anthropogenic debris from coastal and shelf regions to the deep sea, acting as efficient conduits due to their steep topography and strong down-slope currents (Galgani et al., 1996; Ramirez-Llodra et al., 2011; Schlining et al., 2013; Pierdomenico et al., 2020; Taviani et al., 2023). This mechanism has been confirmed in multiple studies, which found that litter densities are typically higher in submarine canyons compared to other physiographic settings, such as continental shelves, seamounts, banks, and mounds (Pham et al., 2014). The predominance of plastic items in these environments is particularly noteworthy, as most plastics are lightweight and are more readily transported by bottom currents and can accumulate in topographic depressions (Mordecai et al., 2011; Tubau et al., 2015). The totality of litter items observed in ROV dives were, indeed, composed of plastic, suggesting a similar process in explored sites. The persistence of plastic in deep-sea environments, combined with its potential to fragment into microplastics, raises concerns about long-term ecological impacts. Similarly, the macrolitter observed near the lava fields of Mabahiss Volcano suggests that such geomorphological features may function as localized retention zones for anthropogenic waste. The hydrodynamic characteristics of the site may contribute to the trapping and long-term deposition of debris.

It is important to note that the ROV transects in this study primarily followed sloping features, meaning that only a limited portion of the flat seafloor was surveyed. Previous studies indicate that higher litter densities tend to be found in depositional areas at the base of canyons, where weaker currents facilitate accumulation (Pham et al., 2014).

The findings from our study align with global patterns of deep-sea macrolitter distribution, where submarine canyons and other complex topographic features serve as accumulation zones for plastic debris. Understanding the interactions between seabed geomorphology and litter transport dynamics is essential for developing targeted mitigation strategies, particularly in regions experiencing rapid coastal development. Future research should focus on expanding spatial coverage and integrating hydrodynamic modeling to better predict litter dispersal and deposition in deep-sea environments. Establishing systematic monitoring programs will be critical for assessing the long-term impacts of coastal expansion and maritime activities on deep-sea ecosystems. The application of ROV technology, as demonstrated in this study, provides a valuable tool for monitoring macrolitter distribution and evaluating human-induced changes in deep-sea environments. A broader initiative should be established whereby all expeditions utilizing ROVs systematically report any observed macrolitter, even when such observations fall outside the primary objectives of the mission. In cases where only small amounts of macrolitter are recorded, as in M193, these data risk being overlooked, but they may still contribute to a more comprehensive global assessment of macrolitter distribution.

While our study provides insights into deep-sea macrolitter distribution offshore Al Wajh, a crucial next step is to determine whether deep-sea litter in the Red Sea originates primarily from local sources, such as tourism, urban expansion, and industrial development along the coast, or from international maritime activities, including shipping and cargo loss. Differentiating between these sources is essential to evaluate the true impact of regional economic growth and to implement effective mitigation strategies.

Studies suggest that maritime traffic plays a dominant role in seafloor litter accumulation in the eastern Red Sea, with higher densities recorded farther from the shore, near major shipping routes (Jeftić et al., 2009). However, in a rapidly developing region like the Red Sea, the increasing presence of tourism and infrastructure projects could alter this balance. A long-term, systematic monitoring approach should integrate quantitative assessments of litter composition, hydrodynamic modeling of debris transport, and regional waste management analyses. By establishing whether deep-sea macrolitter is primarily of endogenic (locally generated) or exogenic (externally introduced) origin, it will be possible to refine conservation strategies and enforce targeted regulations to mitigate pollution at its source. If international maritime traffic will remain the primary source of marine litter in the deep Red Sea, stricter enforcement of the International Convention for the Prevention of Pollution from Ships (MARPOL) regulations, improved waste reception facilities at ports, and enhanced monitoring of illegal waste disposal at sea may be essential to mitigate further pollution. Should local sources become more prominent, future policies should focus on strengthening waste management infrastructure, implementing stricter regulations on coastal industries, and launching public awareness campaigns.

Furthermore, climate change could impact the balance between locally generated and externally introduced sources of deep-sea macrolitter. Specifically, the expected increase in the frequency and intensity of flash floods resulting from shifting precipitation patterns (Youssef et al., 2016) has the potential to move large amounts of coastal debris. These extreme weather events can quickly transport waste from urban, industrial, and tourism hotspots directly into the ocean, significantly boosting the accumulation of locally sourced litter in deep-sea ecosystems. Incorporating climate forecasts and flash flood behavior into hydrodynamic models will be essential for enhancing predictions of litter movement and deposition, ultimately improving mitigation strategies and aiding the creation of targeted, effective waste management and conservation policies.

The relatively low litter densities observed offshore Al Wajh offer a unique opportunity to implement sustainable development practices that align with conservation objectives. By integrating ecological preservation into economic initiatives, it is possible to safeguard the Red Sea's unique deep-sea habitats while advancing economic development. Long-term monitoring and the cumulative effects of human activities would be useful to ensure the protection of this ecologically significant region.

Author statement

GC, MT and HW conceived the research. GC wrote the initial draft of the manuscript. GC analysed the ROV footage. FM created the bathymetric maps. GC, FM, TL, MT and HW contributed to the collection and compilation of data. All authors revised and approved the final text. HW and TL wrote the proposal and secured the funding for the research cruise RV Meteor 193.

CRediT authorship contribution statement

Hildegard Westphal: Writing – original draft, Project administration, Investigation, Funding acquisition, Conceptualization. **Marco Taviani:** Writing – original draft, Methodology, Investigation, Conceptualization. **Thomas Lüdmann:** Project administration, Investigation, Funding acquisition. **Fabio Marchese:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Giorgio Castellan:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization.

Data management statement

Oceanographic and multibeam seafloor data collected during the cruise are upon reasonable request to Th. Lüdmann. The video footage from the ROV survey is stored at ZMT and can be made available on reasonable request to H. Westphal.

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. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rsma.2025.104357.

Data availability

Data will be made available on request.

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