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Assessing marine litter and its ecological impact on the seafloor of Thermaikos Gulf (NE Mediterranean Sea, Greece): Insights from ROV and diver surveys

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ABSTRACT

This study investigates marine litter and its ecological impacts on the seafloor of the Thermaikos Gulf (NE Mediterranean Sea, Greece) for the first time, using data from 40 ROV dives (15–90 m depth) carried out between 2020 and 2024, and 11 scuba dives (0–5 m depth) conducted primarily at fishing ports during the same period. Plastics dominated the litter composition (80 %), with fishing-related activities contributing to 65 % of the litter at depths from 15 to 90 m, while single-use plastics comprised 46 % of the litter at nearshore locations. ROV surveys revealed litter densities decreased with depth and were likely influenced by water circulation patterns and human activities, particularly fishing. Shallow waters exhibited 50 times higher densities, highlighting the severe accumulation of litter in nearshore areas, particularly in ports. Benthic animals observed in ROV footage were identified, and their abundance was recorded, providing insights into the ecosystem's exposure to litter. Moreover, documented faunal interactions, including ghost fishing, entanglement, colonization, and the use of litter for shelter, highlight the ecological threats posed by marine litter. These findings surpass established Mediterranean litter density thresholds for the seafloor, underscoring the urgent need for stricter waste management at ports and offshore, stronger enforcement of EU directives, and targeted educational campaigns. This research establishes benchmark levels for setting environmental objectives under the Marine Strategy Framework Directive and for conducting targeted research to address litter pollution in the Thermaikos Gulf and similar coastal regions.

1. Introduction

Marine litter represents a major environmental issue in contemporary times (Ansari and Farzadkia, 2022; Löhr et al., 2024; Rangel-Buitrago et al., 2022; Werner and O'Brien, 2018; Williams and Rangel-Buitrago, 2019) and is found across all compartments of the marine environment (Addamo et al., 2017), from coastlines (beach stranded) (Ciufegni et al., 2024; Jokar et al., 2024) to the sea surface (floating) (Castro-Rosero et al., 2023; Pärn et al., 2023) and the seafloor (benthic) (Angiolillo et al., 2023; Cau et al., 2024; Gönülal et al., 2024). Once in the marine environment, most litter items degrade slowly (Ioakeimidis et al., 2016). Combined with their continuously increasing and improper disposal, this leads to a gradual worsening of pollution in marine and coastal zones (UNEP, 2021). This is especially true for plastics, which is by far the most frequently encountered material (Barboza et al., 2018; Barry et al., 2023). Plastic also breaks down into smaller pieces (Barnes et al., 2009) that cannot be easily retrieved from the environment (Loizidou et al., 2018), and even into particles smaller than 5 mm,

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known as microplastics (Arthur et al., 2009), which can be found even in supposedly pristine environments, such as Arctic sea ice, the Antarctic, remote mountain ranges, and deep ocean trenches (Hale et al., 2020). Through the International Negotiating Committee of the UNEP, 170 nations are engaged in ongoing negotiations to establish a global plastics treaty by 2025.

Marine litter originates from various sources. It may come from land-based activities and, due to poor waste management, be transported by rivers, runoff, or the wind into the sea. Frequently, litter originates from activities occurring within the marine environment, such as fishing, aquaculture, shipping, and cargo transportation (Madricardo et al., 2020). Some types of litter are indicative of their origin (e.g., fishing gear), yet distinguishing between various sources is not always straightforward (Cesarano et al., 2023; Koutsodendris et al., 2008; Veiga et al., 2016).

Research indicates that the seafloor accumulates a significant amount of litter (Cau et al., 2022), with densities varying according to distance from the shore, bottom topography, hydrodynamic aspects, shore use and maritime activities (Barnes et al., 2009; Bergmann et al., 2015; Melli et al., 2017). However, the study of benthic litter is quite challenging due to factors such as high costs, technological requirements, sampling methods, and inaccessibility (Miyake et al., 2011). The most common data collection methods involve bottom trawling and visual observation, which can be conducted either by divers or through seafloor imagery techniques using equipment such as Remotely Operated Vehicles (ROVs), Towed Underwater Cameras (TUCs) (Fakiris et al., 2022) and Unmanned Surface Vehicles (USVs) equipped with cameras. ROVs offer advantages such as enhanced operator safety, operation across a wide range of environments (including diverse water depths, complex rocky substrata, canyons etc.), and non-intrusive methods that are gentle on the ecosystem, allowing their use even in marine protected areas (Angiolillo et al., 2015; Costanzo et al., 2020; Madricardo et al., 2020). As technology advances, their manufacturing costs decrease (Brun, 2012), making them popular among researchers for marine environment studies (Angiolillo et al., 2023; Consoli et al., 2021; Ferrigno et al., 2021; Gimenez et al., 2022; Rendina et al., 2020; Rizzo et al., 2025).

The increasing body of scientific literature documents the threats posed by marine litter pollution to wildlife and ecosystems, with impacts ranging from entanglement and ingestion to the bioaccumulation and biomagnification of toxic substances. These substances are either released from plastic litter or absorbed and accumulated in plastic particles, causing damage to benthic habitats and communities (Angiolillo and Fortibuoni, 2020; Fossi et al., 2018; Galgani et al., 2019; Gall and Thompson, 2015; Rochman et al., 2016). Marine life entangled in litter often faces significant mortality risks, which can lead to declines in biodiversity. One of the most concerning types of marine litter is abandoned, lost or otherwise discarded fishing gear (ALDFG), such as nets, fishing lines, ropes and pots. These items continue to trap marine life for extended periods after their abandonment, a phenomenon known as "ghost fishing" (Galgani et al., 2013). Over 200 species, including marine mammals, turtles, and birds, have been recorded as being entangled in or having ingested debris (Kühn et al., 2015). Additionally, an increasing number of studies highlight the significant impacts of marine pollution from litter on economic sectors such as tourism and recreation, fishing and aquaculture, transportation and shipping, as well as on infrastructure and services, local communities, and businesses (Aretoulaki et al., 2021; Brouwer et al., 2017; Leggett et al., 2018; McIlgorm et al., 2011; Mouat et al., 2010; Vlachogianni, 2017; Watkins et al., 2016).

In recent years, numerous studies have been published examining pollution in the Mediterranean caused by marine litter and its impacts on organisms, using ROV technology. For example, Costanzo et al. (2020) investigated the coralligenous habitat of a Marine Protected Area (MPA) in Sicily, Italy, for the presence of litter and potential impacts on the biotic community. Consoli et al. (2020a) analyzed the quantity of marine litter and its impact on benthic fauna in an area of the central Mediterranean Sea, off the southwest coast of Malta. Vigo et al. (2023) investigated, among other parameters, the presence of litter in a no-take area in the northwestern Mediterranean. Higueruelo et al. (2023) assessed the impacts of litter on benthic communities in the Cap de Creus MPA, Spain. More recently, Rizzo et al. (2025) included marine litter assessments in their research on a protected Mediterranean bank in the Gulf of Taranto, Italy. In addition, the study of very shallow waters often involves the use of divers. Such research has been conducted at 172 coastal locations in the Mediterranean as part of the Dive Against Debris® citizen science initiative (Consoli et al., 2020b), at two Natura 2000 sites in the Adriatic Sea (Stagličić et al., 2021), and at the Cabrera MPA in the Balearic Islands (Compa et al., 2022).

According to the Marine Strategy Framework Directive (MSFD), EU member states are required to assess the composition, quantity, and spatial distribution of litter, ensuring they remain at levels that do not cause harm to the marine environment. Due to their inherent characteristics, gulfs and bays often accumulate a high volume of human activities, and in combination with low circulation, they become hotspots for marine litter (Galgani et al., 2015). In compliance with the European directive, the primary aim of this study was to examine, for the first time, the macro-litter burden in the Thermaikos Gulf. This gulf was chosen due to its diverse potential sources of litter, including urban, industrial, and port-related activities, river inflows, and various fishing operations. Instances of animal-litter interactions were also documented where observed. Furthermore, an inventory of the organisms observed on the Gulf's seafloor was conducted, along with an assessment of the benthic, epi-benthic and demersal animal population. Simultaneously studying the distribution of litter and organisms, particularly commercially exploitable species, provides a picture of exposure levels and the risk of ingestion (Darmon et al., 2017). Previous research on the Thermaikos Gulf (Androulidakis et al., 2024) has highlighted the need for monitoring and managing litter pollution in this area to address existing knowledge gaps about the region's environmental condition, preserve its ecological integrity, and uphold its crucial role in marine biodiversity and sustainability within the Mediterranean basin. This research contributes to gathering the necessary knowledge, enabling the relevant authorities to establish a detailed set of environmental objectives and threshold values for their marine ecosystems, with the aim of achieving Good Environmental Status (GES).

2. Methodology

2.1. Study area

The study area for this research is the Thermaikos Gulf in Greece, situated in the northwestern Aegean Sea in the eastern Mediterranean (Fig. 1). It covers an area of approximately 3300 km^2 and is a relatively shallow embayment with flat and featureless seabed (Androulidakis et al., 2024; Karageorgis et al., 2005). At south, it communicates with the deep Sporades basin. The seabed is characterized by mixed soft substrates and some areas featuring patches of *Posidonia oceanica* and *Cymodocea nodosa* seagrass meadows (Dimarchopoulou et al., 2024; Panayotidis et al., 2022), sponges, corals and shells of *Pinna nobilis* (Ganias et al., 2023). Previous research (Androulidakis et al., 2024) morphologically divides the gulf into three sections—inner, central, and outer—characterized by distinct hydrography, water column structures, and regional hydrodynamic circulation, which are primarily influenced by wind-driven currents, freshwater inflow from rivers, and water mass exchanges with the open Aegean Sea. The inner section has depths of <40 m, the central reaches around 50 m, and the outer deepens to approximately 200 m toward its shelf break (Androulidakis et al., 2024). Dominant north-northwestern winds induce a cyclonic circulation pattern in the inner gulf. These winds drive near-surface waters southward toward the outer section, while near-bottom currents flow northward. Simultaneously, they facilitate the inflow of denser Aegean Sea

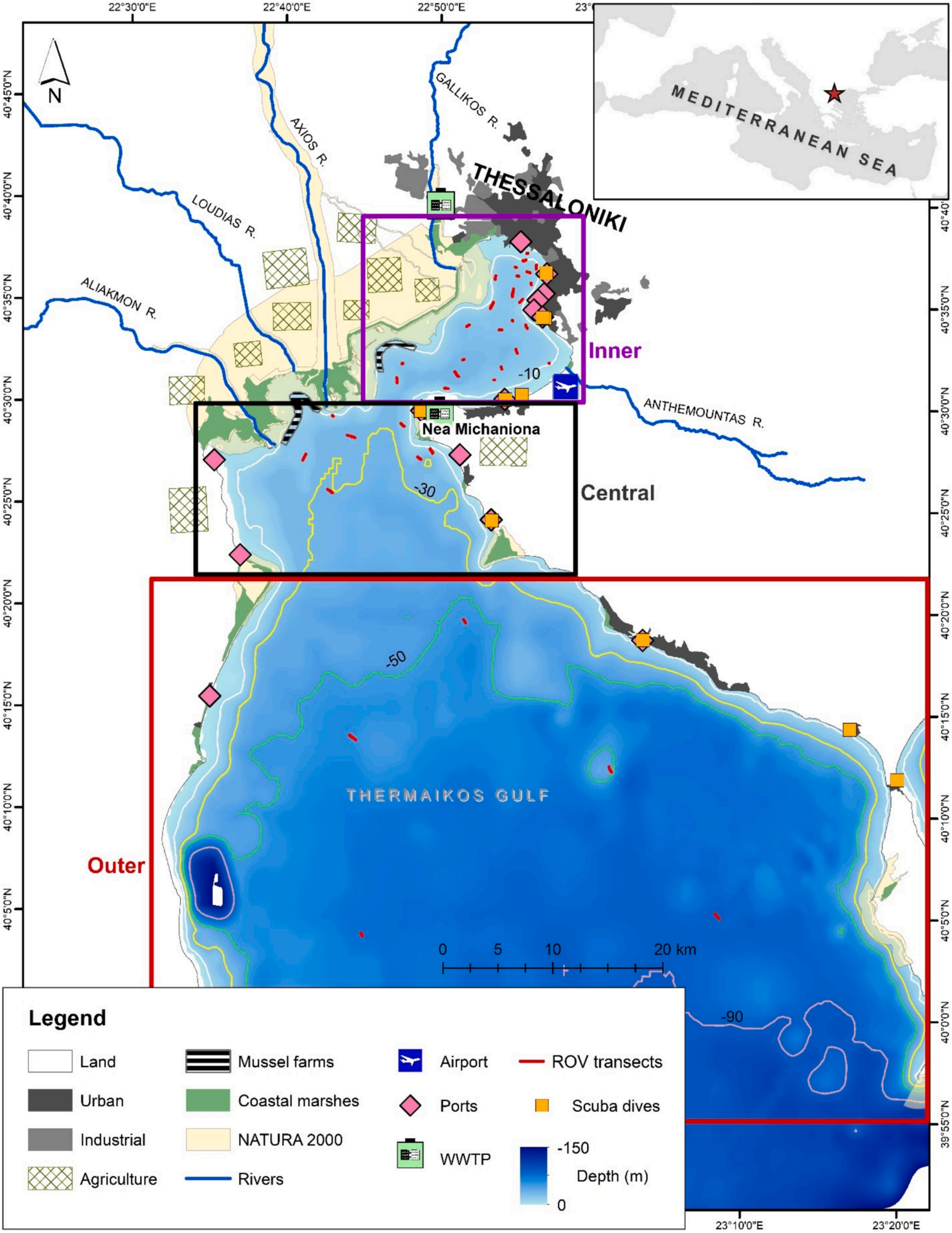

Fig. 1. Map of the study site (Thermaikos Gulf) and sampling locations of the ROV transects and scuba dives.

waters into the deeper layers, contributing to the renewal of the inner gulf with clearer waters (Androulidakis et al., 2023). Various nutrient-rich rivers flow into the Thermaikos Gulf, the most significant being the Axios River (providing 50 % of the fresh water) and the Aliakmonas River, which discharge into the western section of the gulf (Karageorgis and Anagnostou, 2003; Krestenitis et al., 2012). These rivers, along with some smaller ones (e.g., Loudias), form a wetland that encompasses ecologically significant areas and protected zones that belong to the Natura 2000 network and some of which are designated as Ramsar Sites (Vokou et al., 2018).

The gulf experiences intense human activity. Numerous agricultural and livestock farming facilities are located along its western coast, leading to a reduction in freshwater supply from the rivers (Kourafalou et al., 2004). Additionally, the most important mussel cultivating facilities in Greece are located in this area (Kalaitzidou et al., 2022). It is expected that pollutants such as fertilizers, pesticides, antibiotics, and possibly litter from these human activities enter the gulf (Christophoridis et al., 2009). Nutrient overload from the aforementioned activities leads to eutrophication events, which constitute a major water quality issue in Thermaikos, sometimes indicated by harmful algal blooms (Androulidakis et al., 2021; Nikolaidis et al., 2006). On the northern side of the gulf is the densely populated metropolitan area of Thessaloniki, the second-largest city in Greece, with a population of over 1,000,000 inhabitants (Hellenic Statistical Authority, 2021). This area hosts significant industrial activities and a major port, where various seaport operations and heavy maritime traffic are observed. As a result, Thermaikos receives pollutants from urban and industrial wastewater, including heavy metals, organic contaminants, and microplastics, degrading water quality. Two discharge points for treated wastewater are located in the gulf (Petala et al., 2018) (Fig. 1). Extensive fishing activity occurs throughout the Gulf, as the Thermaikos Gulf is one of the most important fishing grounds in the northeastern Mediterranean Sea (Voultsiadou et al., 2011). However, in recent decades, fish stocks have declined due to overexploitation (Dimarchopoulou et al., 2022), along with disturbances to benthic communities caused by heavy trawling (Dimitriadis et al., 2014). Management measures for fisheries in this area involve an 8-month trawling season, running from October to May (Dimitriadis et al., 2014). The eastern and southwestern parts of the gulf host several fishing ports and intense tourist activity. Regarding the marine litter pollution status of the gulf, Kermenidou et al. (2023) assessed microplastic concentrations in surface water, sediment, and fish for the first time, reporting alarming quantities. It is noteworthy that they identify the breakdown of large plastic objects, which accidentally entered the marine environment, as the primary source of microplastics. However, no research on macro-litter abundances has been published to date.

2.2. Fieldwork

Visual footage for investigating marine litter in Thermaikos Gulf was collected during five (5) expeditions carried out in 2020, 2021, 2022, 2023 (September) and 2024 (October) during daylight hours (9:00 to 17:00 h). These expeditions were conducted aboard the vessel *Typhoon* (IMO: 9303481), managed by the Athanasios C. Laskaridis Charitable Foundation (aclcf.org). The vessel operates throughout the year, cleaning the Greek coastline and delivering the recovered waste to recycling centers or suitable disposal sites, while also being equipped to support research initiatives.

A BlueRobotics BlueROV2 was used (Fig. 2), equipped with a high-definition (1080p) underwater camera facing downward with a slight tilt, protected via a 300 m depth rated casing. The BlueROV2 also included a jaw grabber for sample collection, a compass, a depth sensor,

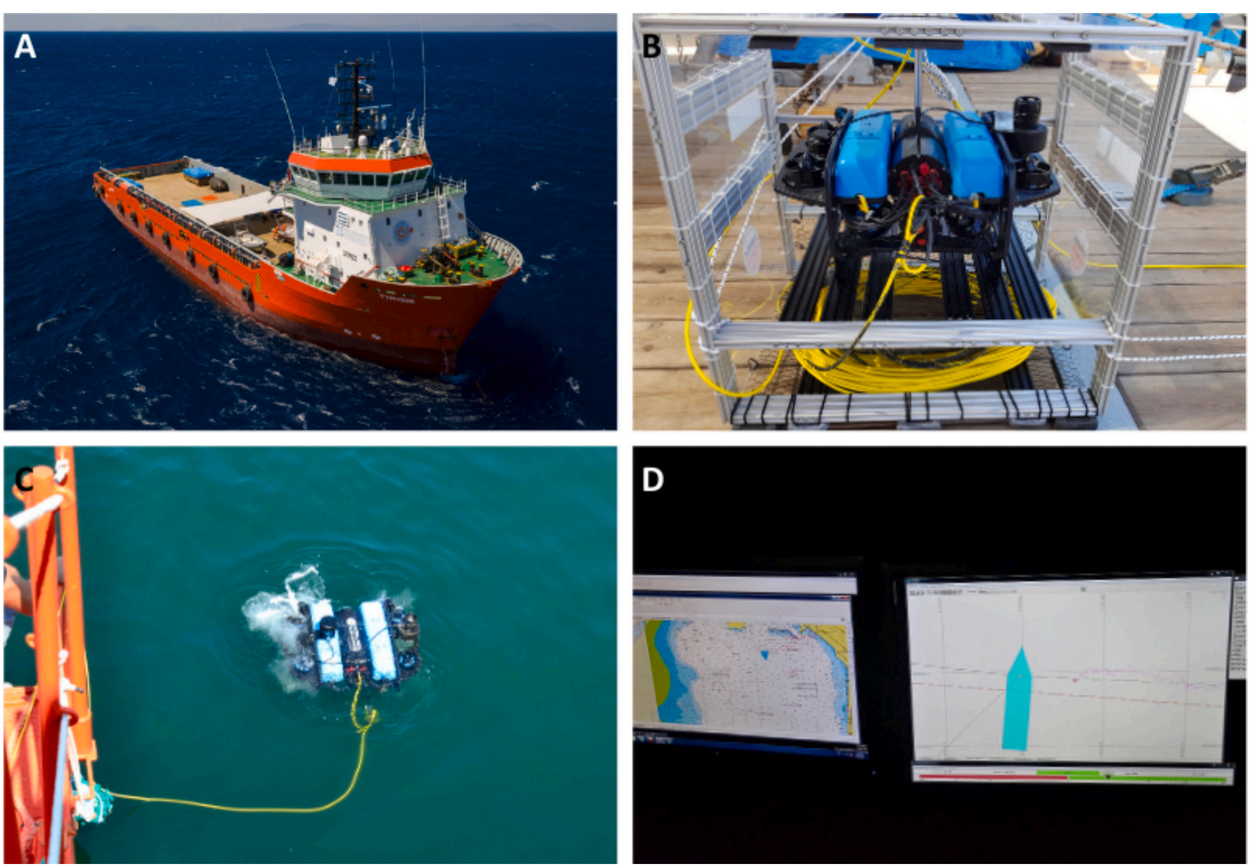

Fig. 2. (A) The "Typhoon" research vessel, of Athanasios C. Laskaridis Charitable Foundation, (B, C) BlueRobotics BlueROV2 and (D) recording of the vessel's dynamic positioning and the ROV track in Hypack software.

two laser beams (providing a 40-cm scale for measurements) and four lights (1500 lm each). During the 2024 expedition, the ROV was further equipped with a Cerulean Sonar Omniscan 450 SS side-scan sonar operating at a frequency of 450 kHz, along with Cerulean Sonar SonarView recording software. A Blueprint Seatrac Ultra-Short Baseline (USBL) underwater acoustic positioning system with an external battery pack and navigation software (Hypack Max) installed on a laptop was used to continuously provide accurate (<1 m) geographic positions of the ROV tracks along the seafloor. *Typhoon* vessel was equipped with a Dynamic Positioning system to support ROV operation by maintaining a constant position and orientation.

Between 2020 and 2024, a total of forty (40) ROV dives were conducted, resulting in 33 h of video footage and covering a total area of 9835 m^2. Of these, thirty-four (34) were carried out in the inner and central Gulf at depths ranging from 13 to 33 m, while six (6) were conducted in the outer Gulf at depths between 35 and 90 m (Fig. 1). The transects ranged in length from 34 to 962 m, with a combined total of approximately 31 km. The number of transects and the recording time depended on the weather and visibility conditions. The characteristics of each transect are reported in Table S1 of supplementary material.

Furthermore, litter between 0 and 5 m depth was recorded by visual census during scuba dives at eleven (11) selected locations in western Gulf of Thermaikos, mainly fishing ports (Fig. 1), with seven (7) dives conducted in 2020 and four (4) in 2021. The length of the transects ranged from 10 to 500 m. The dive surveys primarily focused on cleaning efforts, so the area covered in each case was determined based on the extent of pollution and the prevailing conditions. Several divers worked simultaneously underwater, while volunteers assisted from the dock. The total area covered was estimated to be 73,557 m^2, calculated using Global Positioning System (GPS) and waypoints. All marine litter items larger than approximately 2.5 cm, within the sampling area were collected and removed from the seafloor. More information about the dive sites is available in Table S2 of the supplementary material.

2.3. Video and data analysis

ROV videos underwent quantitative analysis, as described by Angiolillo et al. (2021) and Higueruelo et al. (2023), which involved excluding footage that was off-bottom, poorly focused, obscured by sediment clouds, or had a high particle load from the total transect length and further analysis. While reviewing the video, all potential litter items were recorded in a database, and screenshots were taken. Subsequently, the images were re-checked alongside the video footage multiple times to ensure the validity of the results. The classification of litter times was done following the Joint List of Litter Categories for Macrolitter Monitoring (J-code List) (Fleet et al., 2021), prepared by the MSFD Technical Group on Marine Litter, in collaboration with EU Member States and the Regional Sea Conventions. Litter identification and classification were limited by the overall low visibility in the Thermaikos Gulf, which is attributed to its high eutrophication levels, as well as the difficulty in accurately discerning material types. In most instances, only a limited view of the litter could be obtained because the ROV had to navigate in very close proximity to the seafloor to observe any objects. Additionally, many of the objects found were partially covered by fine sediment and appeared to have remained on the seabed for a long time, having been colonized by organisms, which further complicated identification. Only recognizable litter items were considered for material classification. When possible, the litter material was recorded and classified as either fishing-related or non-fishing-related, with the latter classification used to determine the source.

The investigated area was calculated by multiplying the transect length by a width of 0.6 m (the visual field of the ROV moving 0.3–0.4 m above the sea bottom) obtained by using laser beams as a metric scale. The ROV operated at an average speed of 0.2 m/s. Transect length was estimated using ROV tracks through a GIS (Geographic Information System) software (ESRI ArcMap 10.8), which also allowed the georeferentiation of each litter item across the seafloor. Litter density was determined for each transect, expressed as items per unit area (items/km^2) and items per unit length (items/100 m), enabling comparisons with previously published findings. Results were then expressed using the average density (± standard error) of all transects.

The bottom type and epifaunal organisms associated with the bottom were also recorded. The epifaunal organisms on the bottom were identified up to the lowest possible taxonomic level. However, identification at species level for some organisms from video footage was restricted due to poor video quality, high particle content in the water column and/or limited resolution for detecting morphological characteristics distinguishing similar species. Fish abundance was assessed by counting individual specimens up to a maximum of 10, with larger groups categorized into abundance classes (11–30, 31–50, 51–100, 100+) (Andaloro et al., 2013; Consoli et al., 2016). The same method was applied to estimate the abundance of all other benthic organisms (other than fish). The results were presented as individuals (or colonies for colonial invertebrates) per 100 m and per km^2. Pearson's correlation coefficient was used to assess the relationship between fish abundance and litter density.

In addition, the litter items removed from the seafloor during the 11 scuba dives were then categorized according to the J-code List. Items were classified into eight major material categories (plastic, metal, paper, rubber, glass/ceramics, processed/worked wood, cloth/textile, and other) on an aggregated basis. When assessing litter density during the dives, the measurement unit used was items per hectare (items/ha). This unit was chosen because it best suited the conditions of the sampling points, which were mainly located in ports. A hectare is a practical way to quantify litter over a relatively large but defined area. Cases of litter-fauna interactions were recorded both during the dives and upon closer examination of litter items afterward.

3. Results

The survey area was predominantly characterized by soft substrate (muddy sediments with shell fragments) (Zarkanellas and Kattoulas, 1982). In the five transects conducted at greater depths in the outer gulf (55–90 m), trawl marks were observed, indicating intense fishing activity in the Thermaikos Gulf. Fig. 3 shows images of trawl marks captured by the ROV and the mini side-scan sonar integrated into the ROV.

A total of 157 litter items were observed in 27.5 h of usable bottom imagery obtained by the ROV. Litter was present in 32 out of 40 transects (80 %). Examples of the observed litter are shown in Fig. 4. Approximately 20 % ($n = 31$) of the items classified as litter could not be identified. Among the identifiable items ($n = 126$), plastics were the most prevalent material type, comprising about 80 % of the identifiable litter in the ROV samplings, followed by metal at up to 12.5 %. 65 % of the identifiable litter was attributed to fishing sources, primarily consisting of lost nets, lines, and ropes. The remaining litter could not be attributed to a specific source with certainty. One event of ghost fishing was identified (Fig. 4H).

Litter density based on ROV data, depicted in Fig. 5A, ranged from 0 to 83,817 items/km^2 with an average (±standard error) density of 14,951 (±2611) and from 0 to 5.03 items/100 m with an average of 0.90 (±0.16) items/100 m. Litter is not evenly distributed across the area, as locations with high litter density were found adjacent to areas with low density. High densities were recorded in the innermost part of the gulf near Thessaloniki city and in the northern central gulf between the fishing port of Nea Michaniona and the northwestern delta of the Axios River. High density was also observed along a NNE-SSW corridor in the eastern part of the inner gulf. Low densities were primarily observed in the outer gulf but were also scattered within the inner gulf.

In Fig. 6, the average litter density across different depth ranges is presented. The highest density was recorded in the 15–25 m depth range (17,491 items/km^2), which is 1.8 times higher than the 25–35 m range

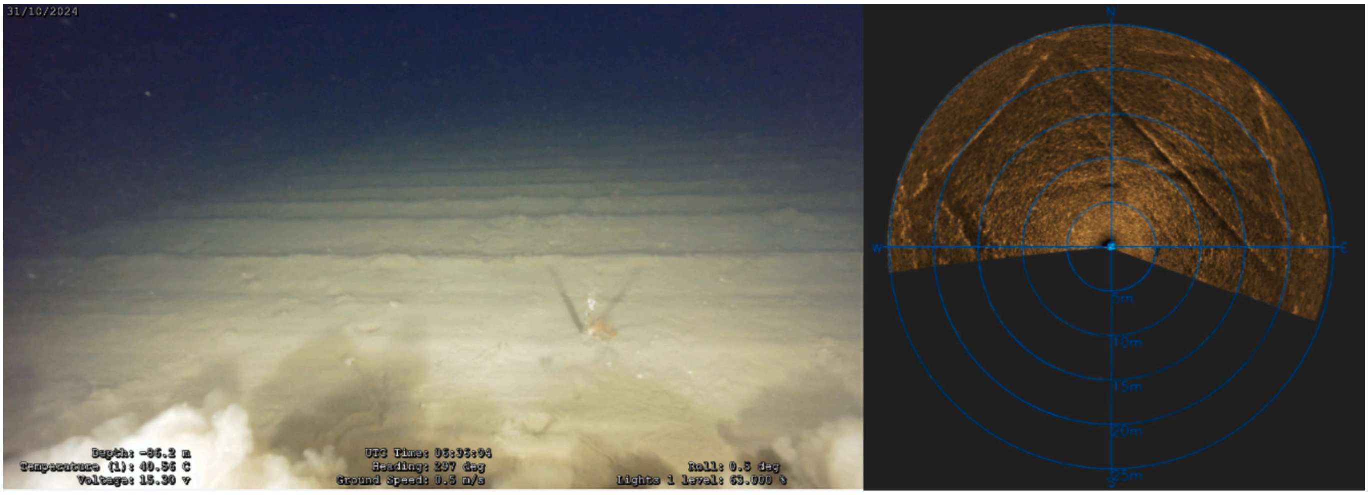

Fig. 3. Trawl marks in the study area as depicted by the ROV (left) and the side-scan sonar (right).

(9642 items/km^2) and 2.3 times higher than the densities observed at depths between 35 and 90 m (7,456 items/km^2). Therefore, a decrease in density is observed as the depth increases.

A total of 25 animal taxa were recorded in the videos (3 Porifera, 5 Cnidaria, 1 Mollusca, 1 Crustacea, 1 Annelida, 1 Bryozoa, 2 Echinodermata, 1 Ascidiacea, 9 Osteichthyes and 1 Chondrichthyes) (Table 1). The main structuring sessile invertebrates were massive-erect sponges (*Aplysina aerophoba*, *Axinella* sp. and *Ulosa digitata*), the sea-pen *Veretillum cynomorium* and the tube-forming polychaete *Sabella spallanzani*. The most frequently observed fishes were *Diplodus annularis*, gobiids and *Pagellus acarne*. In addition, in the outer Thermaikos Gulf, at depths of 50–90 m, a multitude of small unidentified decapods were found hiding in holes on the seabed.

The main benthic biocoenoses in the surveyed area were those of muddy detritic bottoms, circalittoral coastal terrigenous muds and – to a smaller extent – coastal detritic bottoms with rhodoliths.

A total of 2021 fish individuals were counted during this survey, corresponding to an abundance of 12.62(±1.62) fish/100 m (ranging from 0 to 45.41 fish/100 m) and 210,296(±26,977) fish/km^2 (ranging from 0 to 756,869 fish/km^2). A total of 1170 individuals or colonies from the remaining organism categories, mostly sessile species belonging to the invertebrate taxa (Table 1), were recorded in the videos, corresponding to an abundance of 7.72(±1.72) animals/100 m (ranging from 0 to 42.33 animals/100 m) and 128,620(±28,652) animals/km^2 (ranging from 0 to 705,426 animals/km^2). The highest fish densities were found in the southeastern part of the inner Thermaikos. There was no statistically significant correlation observed between the distributions of fish and litter ($r = 0.38$). However, the videos revealed that most of the litter items were likely colonized by encrusting algae and sessile invertebrates. Approximately 13 % of the litter was associated with fauna interactions. In certain cases, epibenthic, solitary and sedentary fishes were found near litter, possibly using it as shelter (Fig. 7). Additionally, there were instances where litter items, such as fishing lines, sacks, or nylon sheets, appeared to be entangled in sponges, *Sabella spallanzani* polychaete tubes, and other benthic sessile organisms. However, the extent of any physical damage, if present, was not measured. No cases of entanglement of motile organisms were recorded, except for one instance of a ghost fishing net.

A total of 3713 items were collected and categorized from the scuba divers in shallow waters of Thermaikos Gulf, corresponding to an average litter density of 7379 (±4295) items/ha (range of 12.5 to 48,100 items/ha) and 429 (±166) items/100 m (range of 5 to 1924 items/100 m). The highest densities are observed near the most densely populated area of Thessaloniki and in the suburb of Nea Michaniona (Fig. 5B). In the 0–5 m depth range, the density was nearly 49 times higher than at the 15–90 m depths examined using the ROV. Plastic was the most abundant litter material (76.41 %), followed by metal (14.11 %) and rubber (3.39 %) (Fig. 8). The most numerous category of litter was single-use plastic cups and their lids, accounting for 13.45 %, followed by plastic drink bottles at 11.98 % and metal drink cans at 11.08 % (Fig. 9). Approximately half of the litter (46.16 %) collected from shallow water cleanups falls into the category of single-use plastics. Additionally, 22.41 % was related to fishing. Many items were also found that indicate the living conditions and time spent by fishers on their boats, such as blankets, kitchen utensils, and clothing items (Fig. 9).

In seven (7) out of eleven (11) scuba dives, a total of 170 animals were observed either entangled in or interacting with litter. A lot of these records involved animals that had entered through an opening in debris, such as metal cans, and became trapped. Additionally, the use of litter as shelter or for attachment was frequently observed. Some examples are presented in Fig. 10.

4. Discussion and conclusions

The Thermaikos Gulf is a heavily urbanized and exploited area, significant for the Eastern Mediterranean for both economic and ecological reasons. Several previous studies have addressed the environmental condition of the gulf (Androulidakis et al., 2021; Christophoridis et al., 2009; Kalaitzidou et al., 2022; Kapsimalis et al., 2010; Karageorgis et al., 2006; Karageorgis et al., 2005; Mpimpas et al., 2001; Petala et al., 2018; Symeonidis et al., 2016), but this research is the first to present data on pollution from anthropogenic litter. This research establishes benchmark levels and could inspire similar future studies in the region. Additionally, the obtained monitoring data could assist authorities in selecting measures to reduce litter inputs and evaluating the effectiveness of existing measures, as suggested by Galgani et al. (2024) for monitoring efforts within the framework of the MSFD. The ROV-optical survey conducted in the Thermaikos Gulf, combined with scuba diving samplings, provided extensive data on litter accumulation, benthic fauna, and their interactions. We identified potential pollution sources, generated density distribution maps, determined the dominant litter category, and highlighted ports as key accumulation zones for marine litter. The persistent problem of single-use plastics and the lack of proper litter management were also emphasized once again.

Research in the Thermaikos Gulf proved to be quite challenging due to the prevailing conditions. Visibility was low during most dives, requiring the ROV to operate in close proximity to the seafloor in order to discern any details. As a result, the field of view was reduced, limiting the overall study area. Additionally, interruptions frequently occurred in

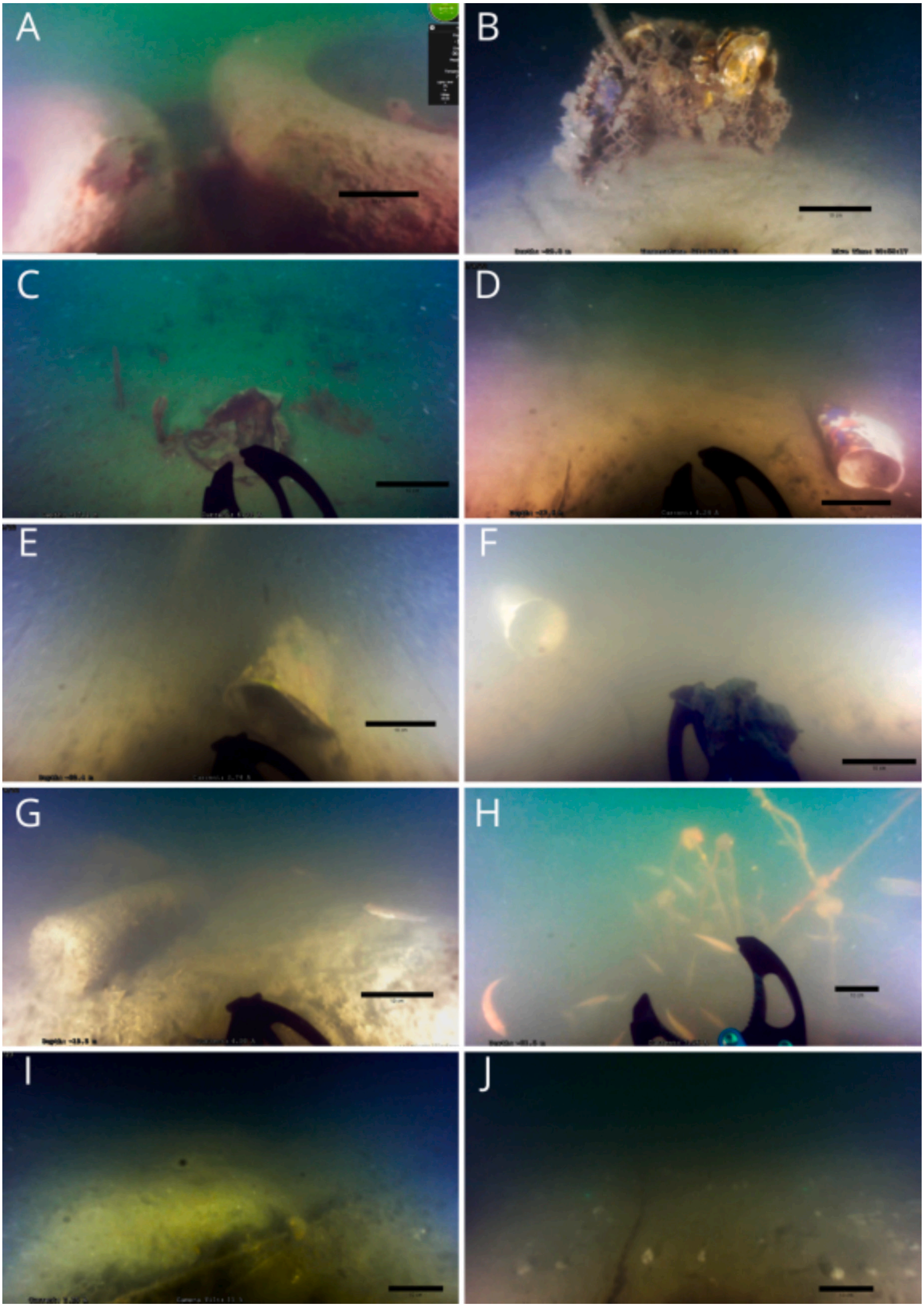

Fig. 4. Examples of litter objects detected during ROV dives on the seafloor of Thermaikos Gulf. (A) two tires; (B) part of fishing equipment; (C) a metallic item; (D) a plastic toy bucket; (E) a food wrapper; (F) a plastic cup; (G) a plastic drink bottle; (H) a "ghost" fishing net; (I) a rope with a cork; and (J) a rope. Scale bar: 10 cm.

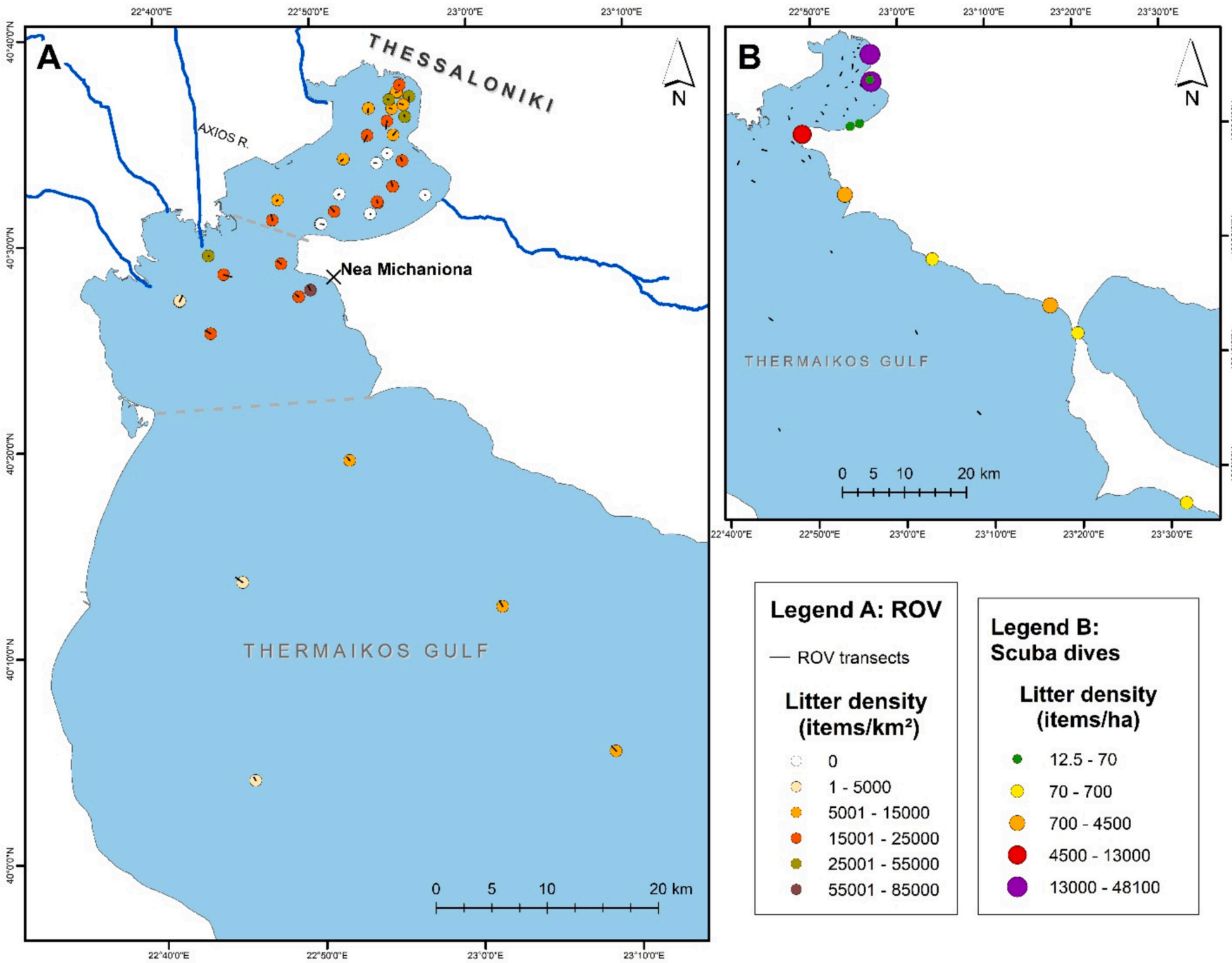

Fig. 5. Spatial distribution map of seafloor average litter densities from A) ROV transects (items/km^2) and B) scuba dives (items/ha) in the Thermaikos Gulf (the dots representing litter concentrations from the scuba dives coincide with fishing ports).

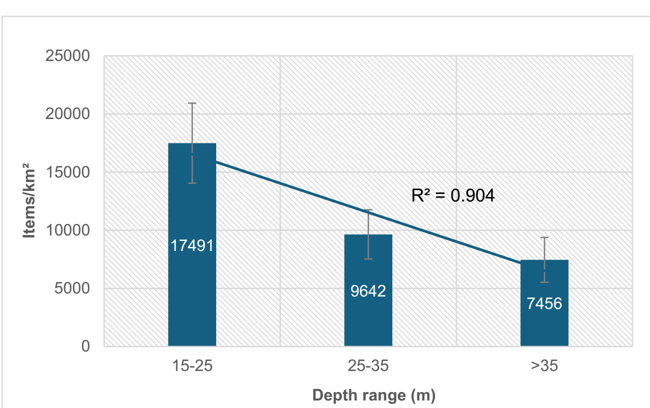

Fig. 6. Average litter densities (items/km^2) by depth range (m). The regression line represents the overall trend in litter density with depth.

the videos when the ROV made contact with the seafloor, disturbing the bottom sediments and placing them in suspension. For the same reason, only a few snapshots could be captured while identifying litter items before the loose sediment resuspended, resulting in 20 % of the litter

Table 1
Animal taxa recorded in ROV videos from the Thermaikos Gulf.

Porifera	**Echinodermata**
Aplysina aerophoba (Nardo, 1833)	*Antedon mediterranea* (Lamarck, 1816)
Axinella sp.	*Ova canalifera* (Lamarck, 1816)
Ulosa digitata (Schmidt, 1866)	
	Ascidiacea
Cnidaria	*Phallusia mammillata* (Cuvier, 1815)
Alcyonium palmatum Pallas, 1766	
Cerianthus membranaceus (Gmelin, 1791)	**Osteichthyes**
Hydrozoa sp.	*Diplodus annularis* (Linnaeus, 1758)
Pachycerianthus solitarius (Rapp, 1829)	Gobiidae spp.
Veretillum cynomorium (Pallas, 1766)	*Mullus surmuletus* Linnaeus, 1758
	Pagellus acarne (Risso, 1827)
Mollusca	*Scorpaena* sp.
Sepia officinalis Linnaeus, 1758	*Serranus cabrilla* (Linnaeus, 1758)
	Serranus hepatus (Linnaeus, 1758)
Crustacea	Soleidae sp.
Squilla mantis (Linnaeus, 1758)	*Spondyliosoma cantharus* (Linnaeus, 1758)
Annelida	**Chondrichthyes**
Sabella spallanzani (Gmelin, 1791)	*Raja* sp.
Bryozoa	
Erect Bryozoa	

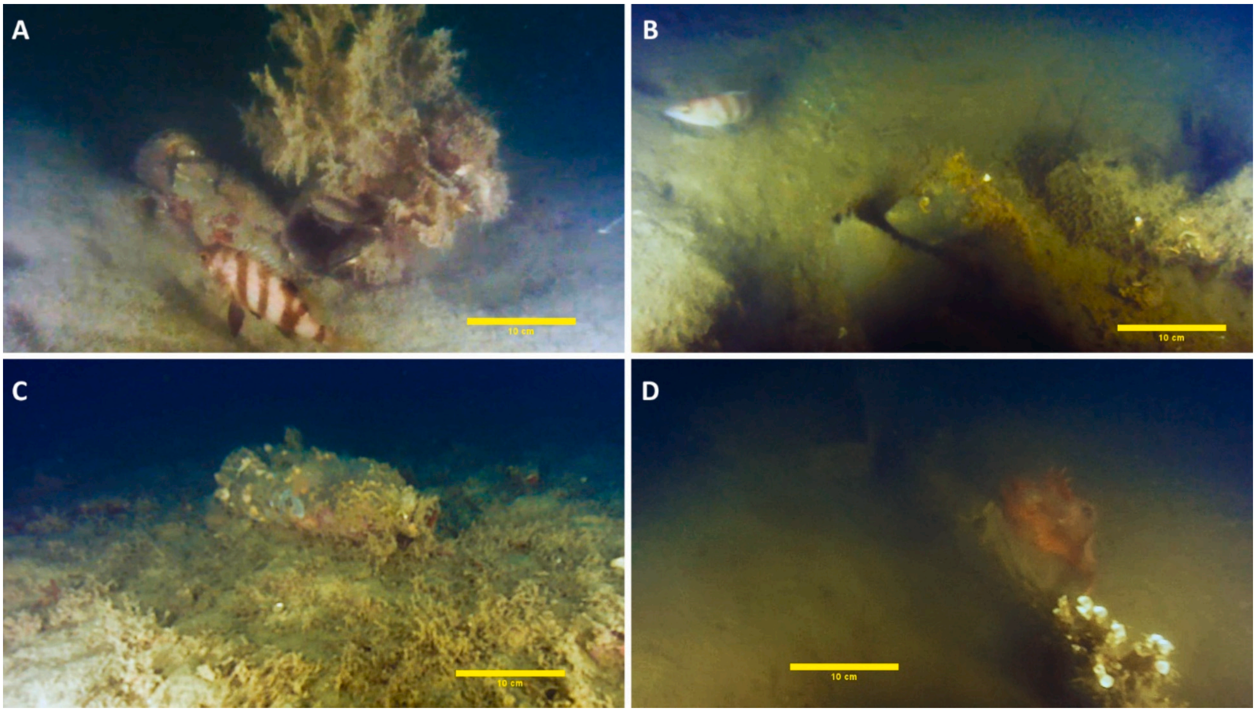

Fig. 7. Examples of litter-fauna interactions documented during the ROV survey. (A) a glass bottle that appears next to a hard substrate with a hydrozoan, bivalve mollusks and a *Serranus hepatus* in close proximity; (B) fish near to a litter item; (C) a plastic bottle encrusted with organisms and (D) *Scorpaena* sp. hiding near litter encrusted with organisms. Scale bar: 10 cm.

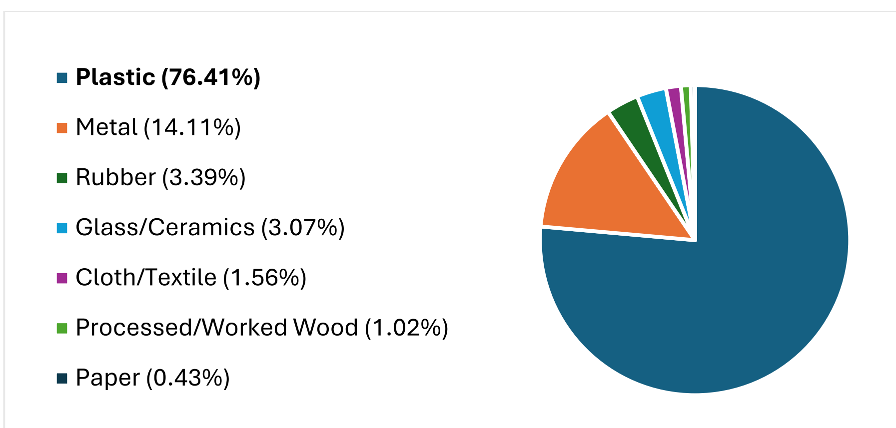

Fig. 8. Percentage composition of marine litter, collected by scuba divers, sorted by material.

items remaining unidentified. The relatively shallow depths, combined with increased marine traffic, prevented the research vessel from approaching certain areas, such as the river mouths, the central shipping channel of the gulf, depths of <10 m, and the western front of the city of Thessaloniki.

In general, the distribution of litter on the seafloor shows significant spatial variability (Galgani et al., 2015). Relatively low densities are often recorded on the continental shelf, as litter disperses over large, flat areas, except in hotspots like rocks, depressions, or channels (Canals et al., 2021; Galgani et al., 2015). The bottom of the Thermaikos Gulf has a gentle slope, characterized by a soft, muddy-sandy substrate interspersed with sporadic mollusk shells, as observed by the ROV. No seafloor structures capable of trapping litter were observed during the transects. Rivers are considered a major pathway for land-based litter to enter the marine environment (Schmidt et al., 2017; Van Calcar and Van Emmerik, 2019). For this reason, the litter observed on the seafloor of the gulf could potentially have originated from the several rivers that flow into it. However, our samplings could not approach the river estuaries to directly assess their contribution to the pollution in the gulf. Additionally, no litter was found that could be definitively identified as originating from the rivers. Higher litter densities were noted in the eastern part of the gulf, likely influenced by the cyclonic circulation pattern in the inner gulf (Androulidakis et al., 2024), and the densely populated eastern coastline, which features numerous marinas and fishing ports. Notably, the highest litter densities were recorded near Thessaloniki, where all transects revealed litter presence, suggesting a strong correlation between high concentrations and urban proximity. Similarly, high concentrations near the fishing hub of Nea Michaniona highlight the substantial role of fishing activities in contributing to pollution. Litter density also varies with depth, decreasing as depth increases - a trend consistent with observations in other parts of Greece, such as the Saronikos Gulf (Kouvara et al., 2024). Another possible

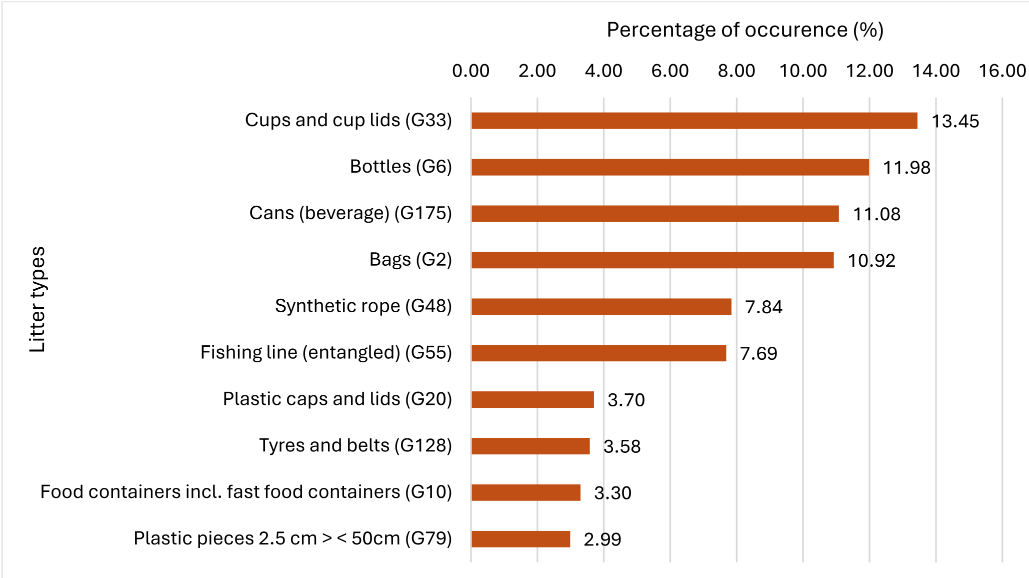

Fig. 9. Percentage of occurrence of the top 10 most abundant litter types in shallow waters collected by scuba divers.

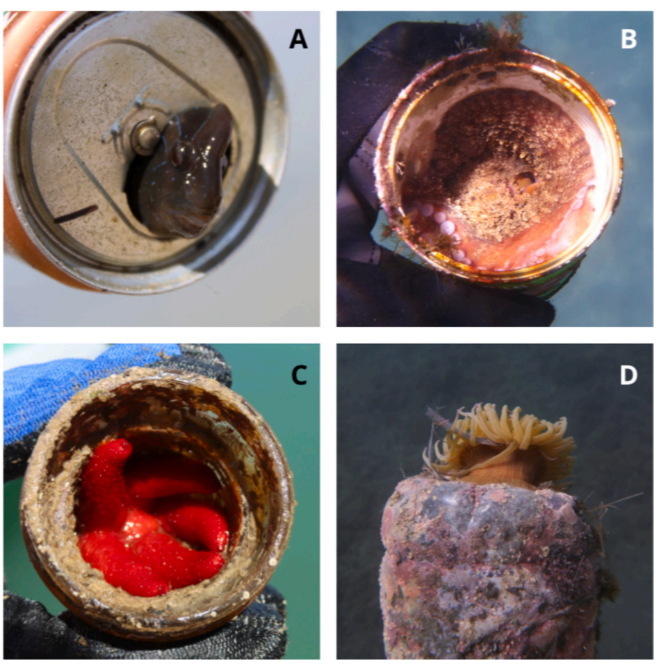

Fig. 10. Examples of litter-fauna interactions observed during the dives: (A) the fish *Salaria* sp. trapped in a metal drink can, (B) *Octopus vulgaris* finding refuge in a metal can, (C) the echinoderm *Echinaster sepositus* found in a glass item, and (D) the anthozoan *Anemonia viridis* attached to a plastic bottle.

explanation for the lower litter densities observed in the outer gulf could be the extensive bottom trawling activity in the area, which may remove or redistribute litter, as noted by Lopez-Lopez et al. (2017). Expanding the research area in future studies could provide a more detailed understanding of the spatial distribution patterns of litter in the Thermaikos Gulf.

Due to the low visibility conditions, the ROV could only detect litter when it came very close to it. Despite this challenge, litter was found in 79 % of the transects. The discovery of 157 items under these conditions allows us to infer that the gulf is likely more polluted than the data could show in the present study. Converting densities to square kilometers highlights the scale of the pollution problem. The densities calculated far exceed the established limit set by UNEP MAP (38 items/km^2, UNEP MAP, 2023) for the Mediterranean Sea seafloor, which should raise concerns among local stakeholders and prompt them to take meaningful action to reduce litter in the gulf.

The surveys carried out by the divers allowed the recording of a litter density almost 50 times greater at depths of 0–5 m, compared to the depths of 15–90 m explored by the ROV. This considerable difference in densities can be explained in several ways. Various studies suggest that nearshore shallow water environments are more polluted (Alomar et al., 2020; Buhl-Mortensen et al., 2022; Haarr et al., 2022; Kouvara et al., 2024). In particular, dives were primarily conducted in small fishing ports along the eastern shore of the Thermaikos Gulf, revealing the significant burden of litter in such locations. This accumulation is attributed to the high maritime traffic and activity, including professional and amateur fishers, as well as other visitors and tourists. This is further confirmed by the main types of litter removed from the seafloor, which were single-use food and drink packaging (i.e., cups, bottles, cans, bags, lids) and fishing-related items (i.e., ropes, fishing lines, tires, nets). Several items were also found that indicate the time fishers spend in the harbor areas and on their boats, such as blankets, clothing, kitchen utensils, plastic chairs, tools, and more. The EU directive obliges all ports to provide reception facilities; however, many ports do not always meet the requirements for the proper management of the waste they are supposed to receive (GESAMP, 2021; Mouat et al., 2010). The accumulation of litter in port areas and marinas, beyond posing ecological risks, also entails economic and safety risks, as it often becomes tangled in vessels (GESAMP, 2021). Furthermore, ports are located in sheltered areas with limited water exchange, which favors the accumulation of litter in these areas. The issue of macro- and microplastic pollution near or within ports has been well-documented in previous studies (Enrichetti et al., 2020; Masiá et al., 2021; Salinas et al., 2024; Schernewski et al., 2023). For example, research has shown that pollution levels in Barcelona's port are 20 times higher than the average recorded for the Mediterranean as a whole (GESAMP, 2021).

Another complementary reason is the differences between the two sampling methods (divers vs. ROV). Divers have a broader field of view than ROVs, which can influence litter detection and, consequently, abundance estimates. Additionally, they can carefully examine the study area, identifying objects from all angles, including small pieces of litter (Consoli et al., 2020b). They also have the advantage of collecting and carefully examining or partially cleaning the items for identification purposes. In contrast, the ROV, depending on the prevailing conditions, captures an image of an object sometimes from only one perspective, which may also be partially buried in sediment or colonized by organisms. Consequently, identification is considerably limited. However, ROVs are particularly useful because they are not restricted by dive time, allowing them to cover greater distances and depths, nor are they limited in the types of environments and depths in which they can operate (Consoli et al., 2016; Etnoyer et al., 2010; Goldstein et al., 2016; Šiljeg et al., 2023; Torquato et al., 2017).

Comparisons between studies on benthic litter are quite challenging, as a variety of factors can vary, including objectives, methodologies, sampling methods, depths, geological structures of the seabed, and/or the units in which results are reported (some provide weight data per unit area, number of items per transect, or number of items per number of video captures) (Angiolillo and Fortibuoni, 2020; Pham et al., 2014; Strafella et al., 2015). Therefore, caution is required when making comparisons, which is why an effort was made to select relatively similar studies (Table 2). Litter density in the Thermaikos Gulf at depths of 0–5 m (7,379 items/ha) was extremely higher than the densities reported by divers in other Greek areas at depths of 0–25 m. Specifically, it was about 20 times higher than that in the Saronikos Gulf (~370 items/ha) (Kouvara et al., 2024) and 51 times higher than in South Peloponnese, Western Crete, and Santorini (~146 items/ha) (Katsanevakis and Katsarou, 2004). The first case is particularly noteworthy, as the Saronikos Gulf is regarded as the most polluted marine area in Greece and the Eastern Mediterranean due to the wide range of human activities it supports, including heavy industry, tourism, and urbanization (Gkaragkouni et al., 2021; Kouvara et al., 2024). It must be noted that (a) most of the samples included in the Saronikos study were collected 20 years ago, and (b) the heavily polluted coastline of the Saronikos Gulf, extending from Eleusina to Piraeus Harbor, was not surveyed. However, the newly selected data indicate that the Thermaikos Gulf is significantly more burdened with litter, making it for now, the most polluted coastal marine area in the shallow waters of Greece.

The average density in the Thermaikos Gulf was higher than in other Mediterranean areas where shallow waters were studied using diving methods. Specifically, it was 12, 16, and 109 times greater than in Bosnia and Herzegovina (10–15 m depth), Montenegro (9–24 m), and Slovenia (3–17 m), respectively, as assessed by the DeFishGear team in the Adriatic Sea (Vlachogianni et al., 2017). Additionally, at depths of 0–40 m in the Southeast Adriatic Sea, the average density was 25 items/ha, which is 295 times lower than in the current study area (Macic et al., 2017). In their work, Consoli et al. (2020b) provided an average density for the Mediterranean at depths of 0–30 m, covered by the Dive Against Debris® program, which equaled to 4355 items/ha. Moreover, the Thermaikos Gulf had a litter density 3.7 times higher than that of two eastern Adriatic Natura 2000 sites, Vis Island and Pakleni Islands, where the average density at depths of 5–12 m was found to be 2000 items/ha (Stagličić et al., 2021). Lastly, Compa et al. (2022) studied marine litter at depths of 1–10 m in Cabrera Marine Protected Area (MPA), Balearic Islands, and found a density ranging from 20 to 6190 items/ha in 2019 and from 0 to 1060 items/ha in 2020. The higher density observed in Thermaikos at 0–5 m could possibly be explained by the sampling locations, which were primarily fishing ports near populated areas, in contrast to the protected areas mentioned above. However, the characteristics of the sampling sites vary significantly, and each case should be studied individually to make more reliable comparisons.

Many of the studies on litter conducted with ROVs in the Mediterranean and off the coast of Europe in the Atlantic Ocean were aggregated and are presented in Table 3. Firstly, it is examined how the Thermaikos Gulf is ranked in comparison to other studies conducted in Greece. The average litter density (14,951 items/km^2) of the Thermaikos Gulf (depths 13–90 m) was found to be approximately 1.3 times lower than that of Ermoupoli's Bay on Syros Island (South Aegean), where Fakiris et al. (2022) explored depths of 3–30 m for benthic litter using a towed underwater camera (TUC), but 1.5 times higher than that of the depths of 0–100 m in the Saronikos Gulf, which were also studied with a TUC (Kouvara et al., 2024). Moreover, the Thermaikos Gulf is found to be more polluted than the Saronikos Gulf at depths of 20–54 m (Kouvara et al., 2024) and 94–115 m (Ioakeimidis et al., 2015), as investigated through ROV operations.

Very high benthic litter density was recorded by Enrichetti et al. (2020) in the Ligurian Sea at depths of 30–220 m, which is one of the most urbanized coasts of the Mediterranean Sea. Moreover, high concentrations, surpassing those found in Thermaikos, have been identified in various regions of Italy from studies conducted in rocky banks and coralligenous outcrops at depths of <300 m. Structures such as rocky and coralligenous outcrops can act as traps for litter, especially fishing gear, which may explain the high densities observed in these studies, in combination with the intense human activity in some of these areas (Angiolillo et al., 2023; Angiolillo et al., 2015; Consoli et al., 2018b; Melli et al., 2017). An exception is the study by Consoli et al. (2018a) at depths of 5–30 m, which reported an average density of 1100 items/km^2. Several canyons were also studied using ROVs, which are considered major litter sinks on the seabed due to their geomorphological characteristics (Galgani et al., 1996). Extremely high litter densities were recorded by Pierdomenico et al. (2019) at the Channels of the Messina Strait (Central Mediterranean), with a range of 121,000–1.3 million items/km^2, up to 14 times higher than Thermaikos Gulf. These litter quantities are likely observed due to flash floods caused by the physiographic setting of this area, combined with high urbanization. La Fonera canyon, in Catalonia, exhibited a relatively similar density to the study area, when comparing items/km^2 (Tubau et al., 2015). Other canyons showed lower densities (Dominguez-Carrió et al., 2020; Mordecai et al., 2011; Tubau et al., 2015; van den Beld et al., 2017). Lastly, significantly lower densities were found in the Faial-Pico Passage at depths of 43–249 m (Rodríguez and Pham, 2017) and at the Condor seamount (Pham et al., 2013) in the Azores, which is relatively distant from populated areas. Some studies reported density only in items per length, so when compared to Thermaikos, several canyons, such as the ones studied in Portugal (Oliveira et al., 2015) and in Catalonia (Tubau et al., 2015), showed higher densities than the present study. On the

Table 2
Seafloor litter densities (items/ha) recorded via scuba diving in very shallow waters (<40 m) across various Mediterranean areas.

Reference	Region	Sampling Year	Depth (m)	Covered Area (km^2)	Average Items/ha
Current study	Thermaikos Gulf (Greece)	2020–2021	0–5	74×10^{-3}	7379
Kouvara et al., 2024	Saronikos Gulf (Greece)	2003–2020	0–25	79×10^{-3}	394
Katsanevakis and Katsarou, 2004	South Peloponnisos, Western Crete and Santorini (Greece)	2003	0–25	76×10^{-3}	146
Vlachogianni et al., 2017	Bosnia and Herzegovina	2014–2015	10–15	–	613
	Montenegro		9–24	–	461
	Slovenia		3–17	–	68
Macic et al., 2017	Montenegro	2012–2014	0–40	–	25
Consoli et al., 2020b	Mediterranean Sea	2011–2018	0–30	119×10^{-3}	4355
Stagličić et al., 2021	Vis Island and Pakleni Islands (Croatia)	2018	5–12	6.4×10^{-3}	2000
Compa et al., 2022	Cabrera MPA, Balearic Islands (Spain)	2019	1–10	10×10^{-3}	20–6190
		2020		7.8×10^{-3}	0–1060

Table 3
ROV and TUC surveys for marine litter in the Mediterranean Sea and Atlantic Ocean.

Reference	Region	Substrate	Sampling Year	Depth (m)	Covered Area (km^2)	Items/km^2		Items/100 m	
						Range	Average	Range	Average
Current study	Thermaikos Gulf, Greece	Mobile bottoms in continental shelf	2020–2024	13–90	9.8×10^{-3}	0–83,817	14,951	0–5.03	0.9
Kouvara et al., 2024	Saronikos Gulf, Greece	Mobile bottoms with sporadic rocky outcrops and *P. oceanica* meadows in continental shelf	2018	0–100	14×10^{-3}	–	9789[*]	–	0.98[*]
			2019	20–54	21×10^{-3}	671–4077	1896	0.1–0.51	0.24
Fakiris et al., 2022	Ermoupoli's bay, Syros Island, Greece	i. Sandy or muddy featureless seabed ii. Rocks, boulders or concrete blocks iii. Small scale depressions caused by anthropogenic seabed mechanical disturbance	2016–2019	3–30[b]	4050×10^{-3}	–	20,000[*]	–	–
Ioakeimidis et al., 2015	Saronikos Gulf, Greece	Mobile bottoms in continental shelf	2014	94–115	7×10^{-3}	4100-4800	4500	1.24–1.44	1.34
Angiolillo et al., 2023	Italy	Coralligenous outcrops	2015–2019	14–199	–	0–1,200,000	54,800	–	–
Consoli et al., 2018a	Straits of Sicily, Italy	Mobile bottoms with sporadic rocky outcrops and scattered *P. oceanica* meadows	2012	5–30	60×10^{-3}	0–6400	1100	–	–
Consoli et al., 2018b	Straits of Sicily, Italy	Rocky banks	2014–2015	20–220	34×10^{-3}	0–140,200	21,300	–	–
Melli et al., 2017	North-western Adriatic Sea, Italy	Rocky outcrops	2014–2015	21–23	39×10^{-3}	12,300-82,900	33,000	–	–
Angiolillo et al., 2015	Campania, Italy	Rocky banks	2010	30–300	6030×10^{-3}	20,000–160,000	120,000	–	–
	Sicily, Italy		2011			0–300,000	90,000	–	–
	Sardinia, Italy		2011			10,000-90,000	30,000	–	–
Tubau et al., 2015	La Fonera canyon, Catalonia	Submarine canyon	2011	140–1731	30×10^{-3}	0–167,540	15,057	0–50.2	4.5
	Cap de Creus canyon, Catalonia			156–1570	50×10^{-3}	2317-28,847	8090	0.7–8.6	2.5
	Blanes canyon, Catalonia			165–1492	20×10^{-3}	666–5347	1559	0.2–1.6	0.4
Dominguez-Carrió et al., 2020	Cap de Creus, Catalonia	Continental shelf and submarine canyon	2007–2013	80–1600	75×10^{-3}	–	11,000	–	–
Fabri et al., 2014	Gulf of Lion and French Riviera (Ligurian Sea)	Submarine canyon	1995, 2009, 2010, 2011	180–700	–	–	–	0–1.2	0.3
Enrichetti et al., 2020	Ligurian Sea	Continental shelf and shelf break	2012–2016, 2018	30–220	–	3200-798,200	152,400	–	–
Mordecai et al., 2011	West coast Portugal	Submarine canyon	2007	741–4574	120×10^{-3}	0–6600	1100	–	–
Pham et al., 2013	Condor seamount, Azores Archipelago, Portugal	Seamount	2010–2011	185–1092	56×10^{-3}	397–1439	975	0.1–0.3	0.3
Oliveira et al., 2015	Atlantic Ocean, Portugal	Submarine canyon	2011	93–553	–	–	–	0.58–3.30	1.67
Rodríguez and Pham, 2017	Faial-Pico Passage, Azores	Shelf break and upper slope	2009–2011	40-525[a]	–	–	–	0-30[a]	0.26[a]
				43-249[b]	50×10^{-3}[b]	–	1490[b]	–	–
van den Beld et al., 2017	Bay of Biscay	Submarine canyon and edge of the continental shelf/canyon	2009–2011	223–2359	0.007×10^{-3}	0–9626	4813	–	–
Pierdomenico et al., 2019	Messina Strait	submarine channels	2016	243–581	–	121,000-1,300,000	–	12–132	–

[*] TUC
[a] total studied area
[b] only ROV-sp

other hand, the canyons in the Gulf of Lion and French Riviera (Ligurian Sea) (Fabri et al., 2014) and the depths of 40–525 m in the Faial-Pico Passage, Azores (Rodríguez and Pham, 2017) exhibited litter densities approximately 3 times lower than those recorded in the Thermaikos Gulf.

Plastic is the dominant material in the case of Thermaikos, as well as in all contemporary studies on marine litter (Diego et al., 2022). Specifically, single-use plastics constitute a significant portion of the total litter in the 0–5 m water depth range. Policy changes have been made in Greece, aligned with the EU Directive 2019/904, which aim to reduce plastic pollution by banning the use of specific single-use plastic items, such as cutlery, plates, straws, and polystyrene food containers.

Effective as of July 2021, the law also promotes the adoption of sustainable alternatives and implements measures like extended producer responsibility and public awareness campaigns to encourage reduced plastic consumption and improved recycling practices (Ministry of Environment and Energy, 2021). The findings of the present study may suggest that the existing legal and management frameworks are either not being effectively implemented or that their impacts have yet to be observed in the aquatic environment. However, this statement should be interpreted with caution, as we cannot determine the percentage of new litter since these areas have likely never been cleaned before, and the litter on the seafloor may have been present for many years. This research is not the first to address the problem of single-use plastics in Greek harbors. Consoli et al. (2020b) also reported significant percentages of single-use plastics in Greek and Mediterranean harbors.

Additionally, a considerable amount of fishing gear was found during the ROV dives (65 % of identifiable litter), likely stemming from the extensive fishing activities taking place in the gulf or possibly originating from the mussel farms located on the western shore. In recent years, local authorities and NGOs have worked together to reduce waste generated by these activities, focusing on recycling materials in specialized facilities designed for managing fishing gear. As part of the "Fishing for Litter" program, bottom trawlers collect and record marine litter in Greek seas (iSea.com.gr). In 2023, the program estimated that approximately 11.5 % of all recorded litter in the Thermaikos Gulf and other areas of the northern Aegean Sea consisted of derelict fishing gear. High percentages of fishing gear have also been reported in several previous studies (Angiolillo et al., 2023; Angiolillo et al., 2015; Bauer et al., 2008; Dominguez-Carrió et al., 2020; Enrichetti et al., 2020; Melli et al., 2017; Oliveira et al., 2015; Pham et al., 2013; Watters et al., 2010).

The findings regarding benthic biocoenoses align with the observations reported in previous studies (Androulidakis et al., 2024; Voultsiadou et al., 2011). The study of zoobenthos plays a vital role in evaluating the environmental health of marine ecosystems, however, as noted by Androulidakis et al. (2024), research in this area remains limited. For this reason, an effort was made to identify the benthic organisms encountered during the ROV transects. This task was not a primary objective of the research but was incorporated, as it was deemed feasible based on the collected videos. Identifying and classifying organisms at the species level is particularly challenging, especially when the only available data consists of imagery. Consequently, some organisms were identified only at higher taxonomic levels (i.e. genus, family, class or even phylum), while others could not be classified at all due to poor visibility conditions. Nevertheless, data on abundance and distribution of benthic biota, especially from soft trawlable bottoms, are essential for both ecological research and management purposes (Gerovasileiou et al., 2019; Rybakova et al., 2020; Stamouli et al., 2022), and as such, the results are presented here, as they may be valuable for future research.

The ROV video analysis revealed that the litter items found exhibited some level of organism colonization, possibly by encrusting algae and sessile invertebrates. This suggests that the items were likely lost or abandoned long ago and have since been utilized by organisms as a substrate. There were also instances where litter had become lodged in sessile fauna, with the extent of physical damage unclear, as well as cases where fish were hiding near the litter. The majority of the analyzed cases did not show clear evidence of harmful interactions between marine litter and organisms. A noteworthy exception is the incident of ghost fishing, which was surrounded by numerous fish likely attempting to feed on the trapped organisms. However, scuba dives in shallow waters revealed a higher level of litter-fauna interactions, with documentation of 170 animals engaging with litter in various ways, from entanglement to using it as a substrate, in just 11 dives. Entanglement in litter disrupts essential ecosystem services (Rangel-Buitrago et al., 2024). Litter-fauna interactions, even if limited to mere encounters with no evident negative impacts, increase the likelihood of entrapment, ingestion, or smothering (Bruemmer et al., 2023) and may also expose organisms to trace elements, persistent organic pollutants, and polycyclic aromatic hydrocarbons (Costa et al., 2022). Angiolillo and Fortibuoni (2020) argue that even sessile species are at risk from entanglement with litter, as it can cause tissue abrasion and branch breakage. In a recent study, 10 out of 16 terrestrial hermit crab species used litter instead of natural shells for their needs, with 84.5 % of the litter items being plastic (Jagiello et al., 2024). Organisms using litter as shelter or attachment sites suggests that litter affects the natural environment in ways we cannot fully predict. It is well known that it can lead to changes in the local community by providing a hard substrate for attachment in areas where such conditions would not naturally exist (UNEP, 2009). The results of the present study provide compelling evidence of the risks that litter poses to marine life. While further research is needed to quantify its impacts on fauna, immediate action is recommended to prevent further damage (Bruemmer et al., 2023).

Through the thorough and relevant analysis of marine litter and its ecological impacts in the Thermaikos Gulf, it is evident that waste management facilities at ports require significant improvements and that stricter enforcement of litter disposal laws is essential. Equally important is the need for public education through awareness campaigns aimed at reducing littering. Future research in the area should focus on long-term monitoring to better understand litter trends. More targeted studies are needed to assess the impacts of litter on the fauna of the gulf, potentially through detailed sampling and evaluations of the extent of the damage caused. Research on microplastics, which is currently nonexistent, would also be particularly valuable for understanding the potential dangers this type of pollution poses to biota and human health. Furthermore, investigating litter in other marine compartments, such as floating or beach-stranded debris, along with their transport mechanisms, could provide valuable insights for developing effective mitigation strategies. Expanding these efforts to include the socioeconomic impacts of marine litter on local communities and industries, such as fisheries and tourism, would further enhance our understanding and inform policy development.

CRediT authorship contribution statement

Konstantina Kouvara: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Evi Lazou-Laskaridis:** Investigation. **Peggy Xirotagarou:** Investigation. **Dimitris Christodoulou:** Writing – review & editing, Methodology, Investigation. **Xenophon Dimas:** Methodology, Investigation. **Maria Geraga:** Writing – review & editing, Methodology, Investigation. **Ioannis Giovos:** Investigation. **Anastasia Charitou:** Investigation. **Vasilis Gerovasileiou:** Writing – review & editing, Writing – original draft. **Francois Galgani:** Writing – review & editing. **George Papatheodorou:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.118109.

Data availability

Data will be made available on request.

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