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Assessing marine litter in a highly polluted area in the Mediterranean: A multi-perspective approach in the Saronikos Gulf, Greece

K. Kouvara[a,*], A. Kosmopoulou[b], E. Fakiris[a], D. Christodoulou[a], A. Filippides[c], S. Katsanevakis[d], C. Ioakeimidis[e], M. Geraga[a], P. Xirotagarou[b], F. Galgani[f], G. Papatheodorou[a]

[a] Laboratory of Marine Geology and Physical Oceanography (Oceanus-Lab), Department of Geology, University of Patras, 26504, Greece
[b] A.C. Laskaridis Charitable Foundation, Zalokosta 4, Athens 10671, Greece
[c] OZON, Non-Governmental Organization, Corinth 20100, Greece
[d] Department of Marine Sciences, University of the Aegean, 81100, Greece
[e] UN Environment Programme/Mediterranean Action Plan (UNEP/MAP), Vas. Konstantinou 48, Athens 11635, Greece
[f] Ifremer Centre Mediterranée, Laboratoire LER/PAC, immeuble Agostini, ZI Furiani, Bastia, Corse 20600, France

A R T I C L E I N F O

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Composition
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Plastic pollution

A B S T R A C T

Marine litter poses a significant environmental challenge in the Saronikos Gulf, Greece. Employing an integrated approach, data from both beach and underwater sites were analyzed. The average litter density on beaches was 2.61 items m^{-2}, with plastic being the most common material, notably small polystyrene fragments and cigarette butts. The western part of the Gulf exhibited higher litter density, mainly due to surface circulation patterns. Most beaches fell short of meeting Good Environmental Status criteria for marine litter. Higher litter densities were observed in autumn. Benthic litter density decreased with depth, being 23 times higher in shallower waters, with plastic being the predominant type. This extensive study offers crucial insights into the pollution status and litter distribution in the Saronikos Gulf, contributing significantly to the global understanding of marine litter distribution on coastal ecosystems. Such information is crucial for raising awareness, informing policy decisions, and driving environmental actions.

1. Introduction

Marine litter represents one of the most pervasive and persistent pollutants in marine ecosystems (Andrady, 2015; Anfuso et al., 2015), transforming it into one of the most crucial environmental issues of our era (Rangel-Buitrago et al., 2022). Dealing with this problem is increasingly urgent for national, international, and local authorities and organizations (González-Fernández et al., 2021; Löhr et al., 2024). The Marine Strategy Framework Directive (MSFD) established the guidelines for European Member States to achieve Good Environmental Status (GES) in their marine waters by 2020. Descriptor 10 of this directive focuses on marine litter (European Commission, 2008). Marine litter originates from various sources, including land-based activities (e.g., improper waste management, littering, stormwater runoff), marine-based activities (e.g., fishing, shipping, offshore oil and gas operations) (Galgani et al., 2015), and even accidental events (e.g., container spills, natural disasters) (Sewwandi et al., 2023).

Litter has detrimental effects on marine ecosystems. It poses entanglement risks to marine animals, such as seals, turtles, and birds, causing injuries, impaired mobility, and even death. Marine animals also ingest plastic litter, leading to internal injuries, malnutrition, and toxicity (Kühn et al., 2015; Li et al., 2016). The presence of marine litter alters habitats, damages coral reefs and other sensitive ecosystems, modifies benthic communities, and affects the overall biodiversity and health of marine life (Akhtar et al., 2022; Gall and Thompson, 2015; Katsanevakis et al., 2007). The problem of marine litter also has economic consequences (Newman et al., 2015). It affects fisheries and aquaculture industries, as lost or abandoned fishing gear continues to trap and kill marine organisms, reducing catches and damaging equipment (Azevedo-Santos et al., 2021; Perroca et al., 2022). Coastal tourism can suffer from marine litter, impacting local economies that rely on these industries. Marine litter also poses risks to human health. Microplastics, resulting from the breakdown of larger plastic items, are found in the oceans and can enter the food chain. When consumed by fish and other marine organisms, microplastics can accumulate and potentially be ingested by humans, leading to health concerns (Cox et al., 2019;

* Corresponding author.
E-mail address: k.kouvara@ac.upatras.gr (K. Kouvara).

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Santillo et al., 2017).

Litter accumulates in all components of the marine environment, including shorelines (beach-stranded) (Federigi et al., 2022), seafloor (benthic) (Spengler and Costa, 2008), and water column/surface (floating) (Campanale et al., 2019; Pogojeva et al., 2021). A multi-perspective approach, where both stranded and benthic litter are studied with the combination of various sampling methods in a specific area, enables the researchers to better grasp the extent of pollution, identify its sources, and evaluate its impacts on ecosystems (Schulz et al., 2015; Thiel et al., 2013; Van Cauwenberghe et al., 2013). As a result, policy-makers, resource managers, and other stakeholders can develop targeted strategies to address this issue.

Studies suggest that marine litter is abundant in the Mediterranean Sea (Canals et al., 2021; Cau et al., 2024; Cózar et al., 2015; Galgani et al., 2000; Pierdomenico et al., 2019), and more recently, the influx of marine litter into the Greek seas has been exacerbated by the COVID-19 pandemic, attributed to improper disposal and management of personal protective equipment (PPE) (Kouvara et al., 2022). The primary aim of this research was to assess the abundance, composition, spatial distribution, and potential sources of marine litter in the Saronikos Gulf, which is recognized as one of the most polluted areas in the Mediterranean (Spedicato et al., 2019). The distribution and quantification of marine litter provide vital information for developing global strategies to address this pervasive issue. To the best of our knowledge, this study is one of the few that analyzes both beach and seafloor data for a specific area, collected through various approaches.

2. Methods

2.1. Study area

The Saronikos Gulf is located in the eastern part of the Mediterranean Sea, off the coast of Greece, and is connected to the Aegean Sea to the south. Its coastline stretches approximately 744 km in length, covering an area of 2866 km^2 (Orfanidis et al., 2001). The Gulf is a complex marine basin characterized by a variety of geomorphic features, including islands, peninsulas, bays, and inlets, which provide sheltered harbors and anchorages for boats and ships, thus enhancing marine traffic. The bottom topography is characterized by an intricate system of submarine canyons, ridges, and basins. The deepest parts of the Gulf are found in the western and central regions, with a maximum depth of 421 m in Epidavros Basin. The northeastern part is characterized by shallow basins and sandy shoals (Foutrakis and Anastasakis, 2020). The water circulation in the Gulf is primarily influenced by the wind, and waves are small due to limited fetch, except in the southeast direction. As a result, either cyclonic or anti-cyclonic circulations are formed, depending on factors such as wind direction, coastline shape, and bottom topography (Fig. 1a) (Coachman et al., 1976; Kontoyiannis, 2010). The coastal zone is important for its *Posidonia oceanica* meadows, which are habitats for many marine organisms (Georgiou et al., 2021). The Gulf is also home to a diverse range of marine species, including crustaceans and mollusks (Katsiaras et al., 2015). In addition to its ecological importance, the study area also has significant cultural and historical value, with many ancient ruins and archaeological sites located along its shores (Baika, 2008; Georgiou et al., 2021; Mourtzas and Kolaiti, 2013; Papatheodorou et al., 2014; Tartaron et al., 2011).

Human activities, such as agriculture, aquaculture, tourism, navigation, fishery, urbanization, and industrialization, exert significant impacts on the environmental condition of the Gulf. Some of the most critical industrial, port, naval, and shipbuilding facilities in Greece are located along the shores of the Gulf (Brodersen et al., 2018; Filippi et al., 2023; Gerakaris et al., 2017; Mazioti et al., 2023; Papantoniou et al., 2023; Parinos et al., 2019; Prifti et al., 2022). The port of Piraeus, for instance, ranks among Europe's largest ports in passenger traffic, serving approximately twenty million passengers annually (olp.gr, n.d.). Regarding fishing activity in the Saronic Gulf, it is one of the most productive and active fishing areas in the Greek seas (Maina et al., 2016). Moreover, the Gulf holds considerable maritime importance (Fig. 1b) due to its role in connecting the Aegean Sea with the Ionian Sea through the artificial Corinth Canal (Filippi et al., 2023). Some of the largest cities nearby include Athens metropolitan center (with over three million inhabitants), Eleusina, and Megara. According to the 2021 census, the municipalities around the Gulf had an estimated combined population of approximately 680,000 people (Hellenic Statistical Authority, 2021). Additionally, the Gulf is a popular tourist destination, drawing visitors who enjoy its beaches and historic sites, and explore the numerous islands within the Gulf. Furthermore, several landfills are in the vicinity, some of which are legal, while others operate illegally (Papachristopoulou et al., 2020). Greece has faced waste management challenges and criticism for its high landfill rates, as reported by the European Environment Agency (Lowen, 2013; European Commission Press Corner, 2015). The rivers flowing into the Gulf are generally relatively small, except for the Cephissus River, which is all boxed and drains the Athens Basin and has been significantly impacted by human activities, including pollution and dam construction (Tsangaris et al., 2014). Furthermore, before the construction of the Wastewater Treatment Plant (WWTP) in Psittalia, sewage was being discharged untreated into the Keratsini - Salamina straits (Gkaragkouni et al., 2021). Various aquaculture facilities can be found in the Gulf, including fish farming, and shellfish cultivation (Papachristopoulou et al., 2020; Pavlidou et al., 2019; Tsangaris et al., 2014). Lastly, Politikos et al. (2017) developed a model to simulate the transport of floating litter particles in the Aegean Sea, revealing the presence of recurrently high concentrations of floating litter particles in Saronikos Gulf. The modeling of transport pathways also suggests that Saronikos Gulf acts as a primary receptor for litter from other areas.

2.2. Data collection for beach litter

In the present study, all available data on marine litter in the Saronikos Gulf were collected through a variety of sources: publicly accessible database (Marine LitterWatch), already published data (Ioakeimidis et al., 2014, 2015; Katsanevakis and Katsarou, 2004; Kouvara et al., 2022; Papachristopoulou et al., 2020) and fieldwork consisting in collection and categorization of stranded material on beaches and visual census of macrolitter on the seafloor, as reported in Table 1.

Data from 108 beaches around the Saronikos Gulf were collected through the above-mentioned sources (Fig. 1). For eighteen of them, multiple samplings were conducted over the years. For these cases, the average of the recordings was used for the analysis. The survey encompassed a 15 km coastline and a total area of 0.25 km^2. The samplings were conducted between 2013 and 2023, with varying frequencies each year. The majority of the samplings (approximately 60 %) were conducted in 2018, and another 20 % were conducted in 2020. Therefore, 80 % of the data used in the current survey comes from these two years. Regarding seasonality, the sampling efforts for each of Summer, Autumn, and Winter are more than ten, and for Spring, less than ten. Furthermore, the beaches were categorized into four separate groups based on the definitions provided by Williams and Micallef (2009): urban, rural, touristic, and remote. Urban beaches are situated within cities, whereas rural beaches are located far from urban areas and typically lack visitor amenities and infrastructure. Touristic beaches are popular destinations for providing a wide range of services and activities for visitors, such as accommodations, restaurants, and entertainment options. Remote beaches are far from urban centers and tourist hubs, often with challenging access. Based on the above, out of the total 108 studied beaches, five were urban, six were rural, twenty-eight were touristic, and sixty-nine were remote. For more information about the sampled locations, please refer to the supplementary material.

The Marine LitterWatch database is an initiative led by the European Environment Agency (EEA) and the European Commission's Joint Research Centre (JRC). It serves as a centralized repository for collecting

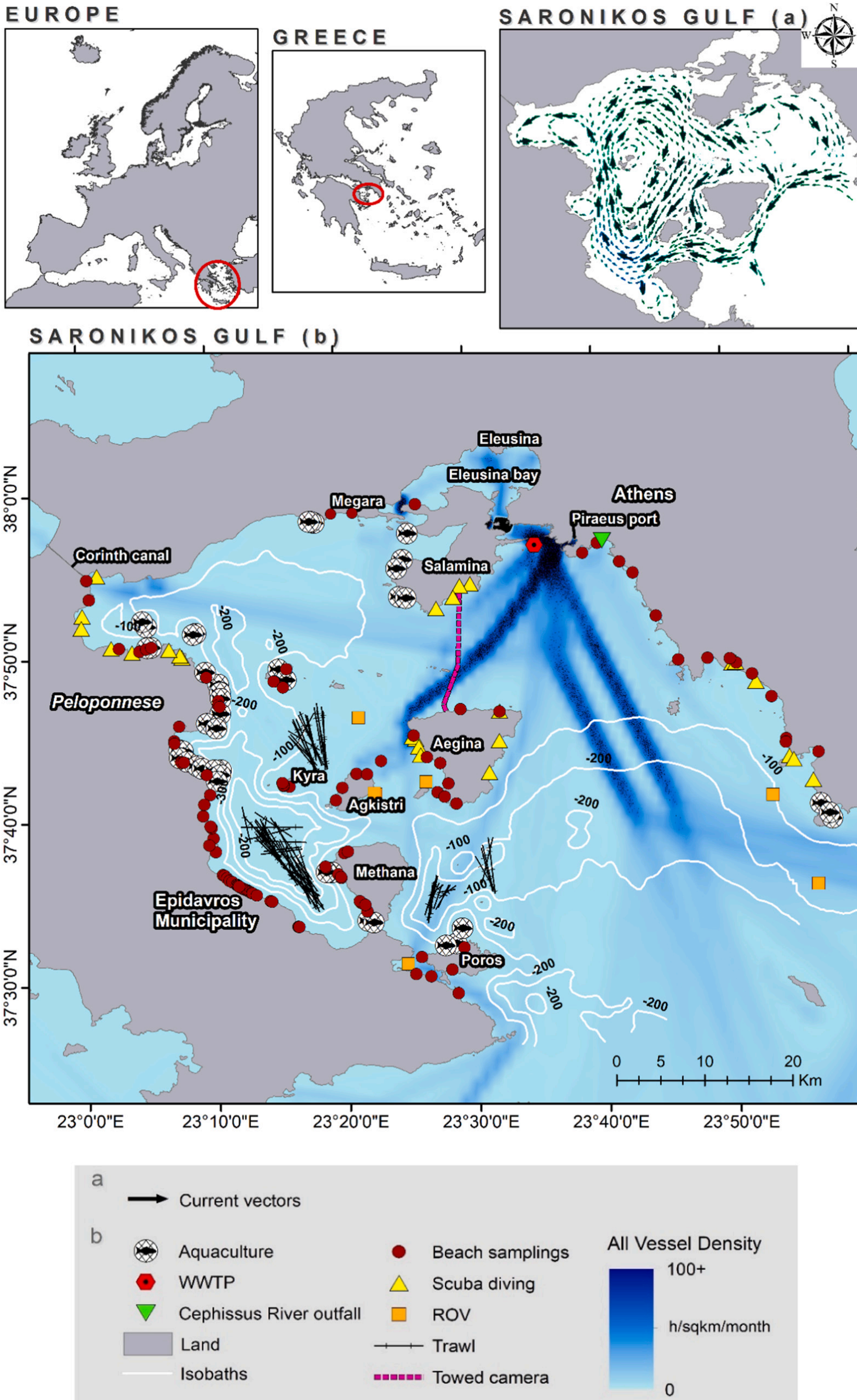

Fig. 1. Map of the study site: (a) General near-surface circulation of the Saronikos Gulf, considering the case of North winds 3-4 Beaufort Wind Force Scale (map modified after Papachristopoulou et al., 2020), (b) human activities in the Saronikos Gulf and sample locations.

Table 1
Data sources for studying marine litter pollution in Saronikos Gulf.

	Beach		Counts	Seafloor		Counts
Public database	Marine LitterWatch		17	–		
Reprocessed published data	Papachristopoulou et al., 2020		62	Katsanevakis and Katsarou, 2004		25
	Kouvara et al., 2022		5	Ioakeimidis et al., 2015, 2014		2, 70
				Kouvara et al., 2022		6
Fieldwork	Beach monitorings		24	Towed Underwater Camera (TUC)		1
				Remotely Operated Vehicle (ROV)		5
		Total	108		Total	109

and organizing marine litter data. The required area was selected using the Data Viewer tool, and the data from seventeen cleanup campaigns conducted in the Gulf was downloaded.

Between August 2017 and August 2018, Papachristopoulou et al. (2020) employed vessel-based photography and in-situ sampling surveys to develop a regression model that accurately quantifies marine litter abundance on remote and inaccessible beaches. This model serves as a cost-effective tool for monitoring such coastlines. The number of litter items assessed by the split regression analysis for each of the fifty-eight remote beaches and the recordings from in situ monitorings in four selected beaches along the western Saronikos Gulf were used for the present study. Moreover, data for five beaches in the Gulf were extracted from the work of Kouvara et al. (2022), who analyzed findings from cleanups around Greece during the COVID-19 pandemic.

Fieldwork was carried out between the years 2017 and 2023 and included samplings on twenty-four beaches, following the 'Guidance on Monitoring of Marine Litter in European Seas' developed by the Technical Subgroup on Marine Litter (TSG-ML) in collaboration with the JRC. The survey process involved documenting and characterizing each beach site, including its geographical and physical features, and proximity to potential litter sources (e.g., substrate, tourist establishments, trash bins, roads, and rivers). The surveyors walked along two or more transects of at least 100 m each. These transects were spaced apart by a minimum distance of 50 m. Beaches smaller than 100 m in length were entirely surveyed. Surveyors moved along 5 m-separated transects parallel to the coastline, covering the area from the strandline to the back of the beach, identified by coastal features like vegetation, dunes, cliffs, roads, fences, or other structures. During the survey, litter removal was performed simultaneously, with all anthropogenic litter items measuring ≥2.5 cm in their longest dimension documented according to the Master List of litter item categories.

2.3. Data collection on seafloor

Information from 109 underwater samplings conducted in the Gulf was accessible. The data were collected mainly from three temporal periods over the last twenty years, specifically in 2003, 2013–2014, and 2019–2020. These samplings employed various methodologies and covered different depths, ranging from 0 to 350 m, enabling the assessment of litter distribution and abundance across a wide range of underwater habitats. The composition of litter items has been documented for 100 sampling locations, including twenty-five dives, five ROV transects, and seventy hauls. Overall, the study covered an area of around 6 km^2, providing a comprehensive overview of the extent of litter pollution on the seafloor of the Saronikos Gulf.

In their study, Katsanevakis and Katsarou (2004) conducted a visual census during scuba dives in 2003 at depths ranging from 0 to 25 m to examine the abundance and composition of marine litter in the shallow coastal regions of Greece. Twenty-five of these samplings were in Saronikos Gulf and included in the current analysis. Ioakeimidis et al. (2014) presented benthic marine litter data collected as bycatch by professional otter trawlers in the eastern Mediterranean and Black Seas. Between 2013 and 2014, seventy hauls were located in the area of interest, distributed over the depth range of 50–350 m. In 2014, Ioakeimidis et al. (2015) conducted two ROV transects in the eastern part of Saronikos Gulf. The first transect was carried out at a depth of 111–115 m, and the second was conducted at 94–98 m depth. In the selected locations, assessment of benthic marine litter was not possible through commercial trawl fisheries or scuba diving. Additionally, data from six scuba dives carried out in 2020 at depths ranging from 0 to 10 m were retrieved from Kouvara et al. (2022).

In the winter of 2018, the specially designed vessel Milady Milord III NP 488 conducted a transect approximately 14.2 km long in the northern central part of the Gulf, in the maritime area between the islands of Aegina and Salamina (Fig. 2), carrying a SeaViewer underwater towed camera (TUC), covering depths from 0 to 95.5 m. This camera is designed for rapid image capture and it is equipped with LED lights that can capture images even in areas with very low visibility. The visual data recorded by the camera were linked with the high-precision positioning data provided by the Leica Viva GS14 GNSS receiver for generating georeferenced snapshots of the images.

In the summer of 2019, five ROV transects were performed at the center and west of the Gulf, between the islands of Aegina and Agkistri, and the passage of Methana-Poros (Fig. 2), spanning a depth range of 20–54 m. A Blue Robotics ROV2 was used for one transect and a SubSea Tech Guardian Mini-ROV was used for the four rest transects. The ROV was armed with a high definition (4 k) underwater camera facing down to acquire high definition planimetric seafloor images, protected via a 150 m depth rated casing, a manipulator to be able to collect any interesting litter items, and a Blueprint Seatrac Ultra-Short Baseline (USBL) underwater acoustic positioning system with external battery pack and a navigation software installed on a laptop (Hypach 2013). Equipped with a Dynamic Positioning system, M.V. TYPHOON of Athanasios C. Laskaridis Charitable Foundation efficiently served as the surface support vessel for the study.

2.4. Data processing

Initially, the heterogeneous data (different years/seasons/sampling methods) from the 108 beaches collected for this survey were aggregated into one database (see Supplementary material) to facilitate the analyses. Similarly, for the 109 underwater sites. The main features of

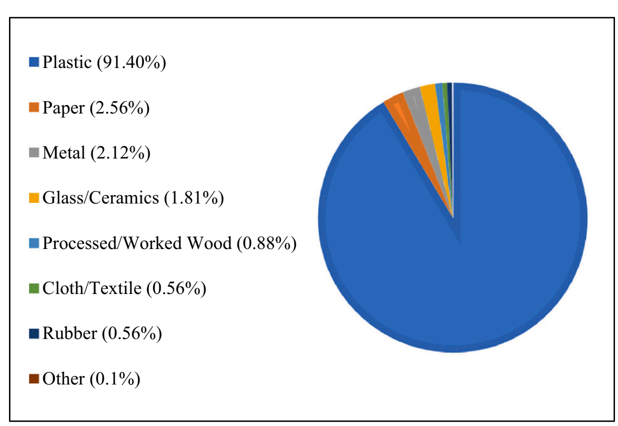

Fig. 2. Percentage composition of marine litter, sorted by material.

the dataset were summarized and described using descriptive statistics. Litter density per unit area (items m^{-2} for beaches and items km^{-2} for seafloor) was determined at each sample location, facilitating comparisons with previously published findings. Results were then expressed using the average density and standard error. For illustrative purposes, sample locations were assigned to cells of a 2.5 × 2.5 km square grid, and the mean density was computed for each grid cell. The marine litter items recorded were classified into eight major material categories (plastic, metal, paper, rubber, glass/ceramics, processed/worked wood, cloth/textile and other) on an aggregated basis. Additional data processing involved merging relevant litter types into the "SUPs" (single-use plastics) category, in accordance with EU Directive 2019/904 (European Commission, 2019). Specifically, the following plastic items were included in this group: Cotton bud sticks; Cutlery, plates, straws, and stirrers; Food containers; Cups for beverages and their lids; Drink bottles and their lids; Cigarette butts and filters; Plastic bags; Packets and wrappers; Wet wipes and sanitary items (incl. single-use masks and gloves). In addition, indexes clustering the beaches based on their environmental status were calculated: the General Index (Marin et al., 2019) was used for all litter types and the Clean-Coast Index (Alkalay et al., 2007) was utilized exclusively for plastic litter pollution. Regarding density variations across seasons, the 108 beaches were grouped together based on the season during which the sampling occurred, and subsequently, the average density and standard error per season was computed.

Due to the absence of an underwater positioning system, typically a USBL, the TUC's underwater images were georeferenced with an accuracy of 2 m with the method developed by Fakiris et al. (2022). The ROV videos were georeferenced with high precision (<1 m) using the USBL system. The analysis of the video files included the detection and classification of any visible benthic litter items, following the dedicated TGML/JRC guidance document on monitoring marine litter in European seas (Hanke et al., 2013). The covered area was calculated by multiplying the linear distance of the ROV transects on the seafloor by the average field of view of the ROV's camera, which is 1.5 m for the Blue Robotics ROV2 and 1.25 m for the SubSea Tech Guardian Mini-ROV. Recordings of marine litter from beaches, dives, TUC, ROV, and bottom trawls were used for mapping in the ArcMap 10.8 GIS application, with bathymetric data sourced from GEBCO and maritime traffic data from EMODnet.

3. Results

3.1. Beaches

In total, 139,000 items were counted from the 108 beaches around the Gulf. Litter was found at 99.1 % of the surveyed locations. Plastic was the most recurrent category, accounting for 91.4 % of the total (Fig. 2). In Fig. 4, the top 10 most encountered plastic litter categories are presented. The most abundant plastic items were polystyrene pieces 2.5–50 cm making up 27.6 % of plastics, followed by cigarette butts and filters at 18.7 %, and fragments of non-foamed plastic 2.5–50 cm at 11.3 % (Fig. 3). SUPs accounted for 41.7 % of the total.

Litter density ranged from 0 to 23.6 items m^{-2} with a mean of 2.61 (±0.41) items m^{-2} and from 0 to 13,643 items/100 m with a mean of 1502 (±208) items/100 m. The mean density of beach litter (items m^{-2}) in grid cell size of 2.5 km × 2.5 km is presented in Fig. 4. Higher litter densities were observed on the west side of the Gulf, particularly along the shores of the Peloponnese and on the islands of Kyra and Agkistri.

According to General Index, 16.7 % were classified as "very clean", 14.8 % as "clean", 11.1 % as "moderate", 11.1 % as "low cleanliness" and 46.3 % as "very low cleanliness". The spatial distribution of studied beaches based on cleanliness is depicted in Fig. 4. Similar results were obtained from the Clean-Coast Index, with 19.6 % classified as "very clean", 16.1 % as "clean", 12.5 % as "moderate", 8.9 % as "low cleanliness" and 42.9 % as "very low cleanliness".

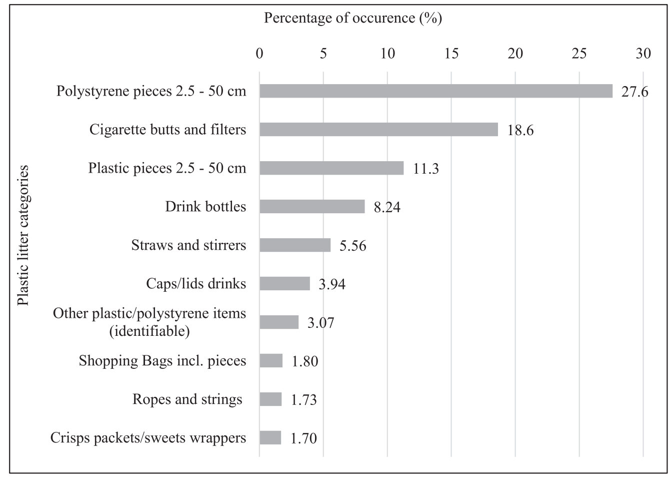

Fig. 3. Percentage of occurrence of the top 10 most abundant plastic litter categories on beaches.

Remote shores in Saronikos Gulf tended to accumulate more litter, with a mean density of 3.13 (±0.52) items m^{-2}, followed by touristic beaches with 1.92 (±0.85) items m^{-2}. Beaches located within urban areas exhibited the lowest levels of pollution (Fig. 5). The distribution of various beach types across different cleanliness classes is illustrated in Fig. 5. More than half of the remote beaches were found to be of very low cleanliness. Touristic beaches were more evenly distributed across different cleanliness classes: 32 % of them had very low cleanliness, while 25 % were classified as very clean. Moreover, 33 % of rural beaches were identified as having very low cleanliness, and an additional 33 % were found to be moderately clean. The vast majority (80 %) of urban beaches were found to be clean, with the remaining 20 % categorized as having very low cleanliness.

The top ten most common items for each beach type are presented in Fig. 6. Small polystyrene pieces constituted an astonishing 43.5 % on remote shores, followed by plastic bottles at 14.8 % and small plastic pieces at 7.91 %. On touristic beaches, cigarette butts and filters claimed the top spot, accounting for 35.2 %—a notable difference from other litter categories—followed by small polystyrene pieces at 15.2 % and plastic pieces at 13.3 %. The presence of paper fragments (2.12 %) and glass/ceramic fragments (1.45 %) was noteworthy. Rural beaches were primarily contaminated by small plastic pieces at 13.3 %, followed by cigarette butts and filters at 8.79 % and straws and stirrers at 7.83 %. In general, rural areas exhibited a greater variety of litter categories. Finally, urban shores featured a wide range of litter categories, primarily dominated by cigarette butts and filters at 14.4 %, followed by straws and stirrers at 11.5 % and plastic caps/lids drinks at 10.7 %.

SUPs constituted 26.7 % of the total litter on remote shores, 49.3 % on touristic beaches, 44.7 % on rural beaches, and 56.7 % on urban beaches.

The observed density on beaches varied across seasons (Fig. 7). It should be noted that the following seasonal variations mainly represent the years 2018 and 2020, during which we had the majority of the measurements. The litter density in autumn seemed to be relatively higher than in other seasons, whereas it decreased during winter. In spring, the litter density further decreased, indicating a continued decline in litter accumulation compared to autumn and winter. During summer, a slight increase in litter density was observed, although it remained lower than the observed litter density in autumn. In Fig. 7, the seasonal variations in litter density across the four studied beach types are also depicted. In remote beaches, a higher mean density was observed during the rainy seasons of autumn and winter, slightly decreasing in spring and dropping by half in summer. Touristic beaches exhibited elevated mean densities throughout the summer, reaching their peak in autumn, followed by a decrease in winter and the lowest

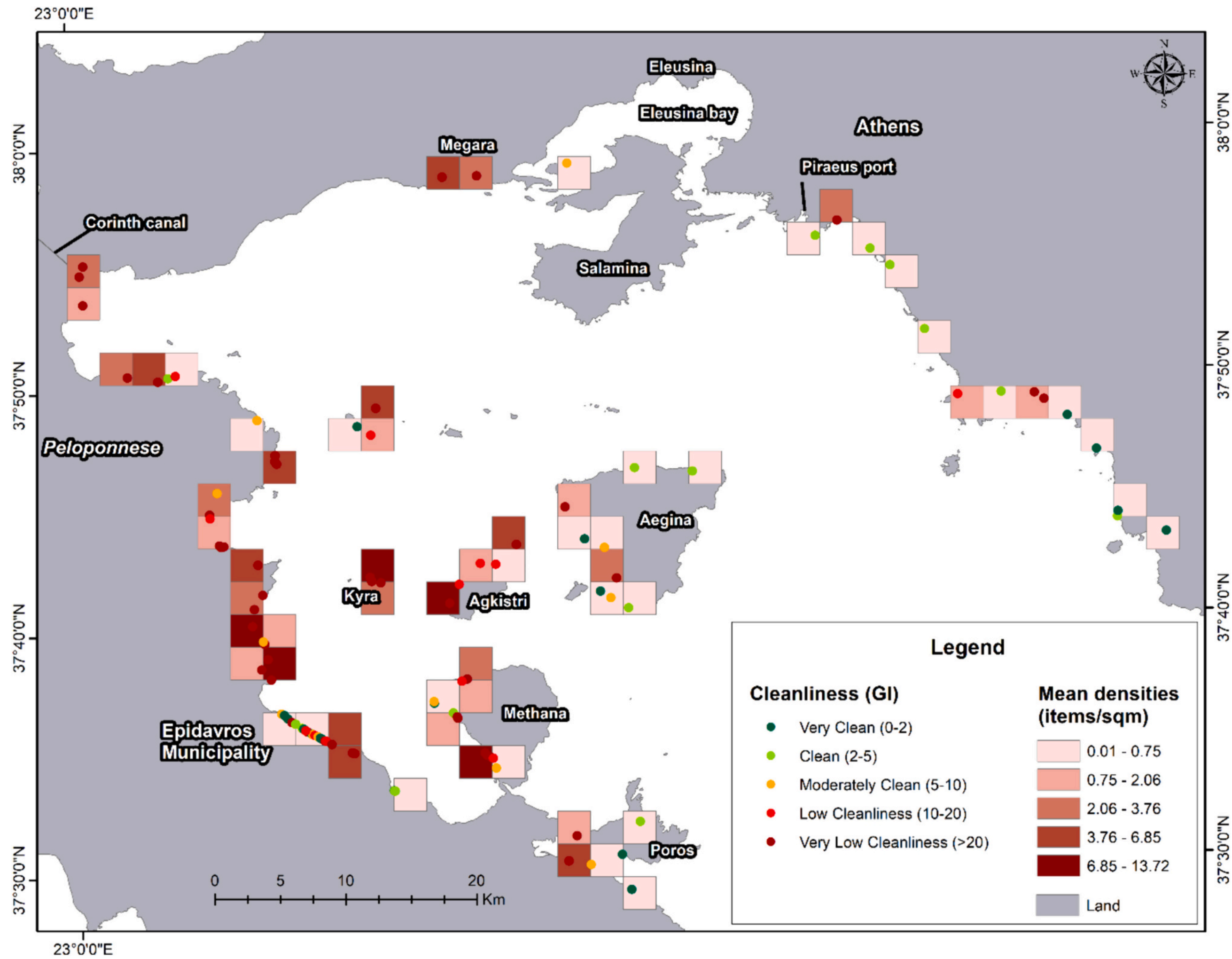

Fig. 4. Mean litter densities (items m^{-2}) per grid cell size of 2.5 km × 2.5 km and distribution of beaches based on cleanliness (GI).

mean value in spring. The higher density for rural beaches occurred in summer. In contrast, the peak density for urban beaches was observed in autumn, surpassing that of summer. However, data for winter and spring are lacking.

3.2. Seafloor

A total of 8529 items were counted from the 109 samplings on the seafloor of Saronikos Gulf (Fig. 8), corresponding to a mean litter density of 12,145 items km^{-2} (range of 117–251,250 items km^{-2}). For comparison, the mean density at depths of 0–25 m and 25–350 m was calculated and found to be 36,956 and 1634 items km^{-2}, respectively. Litter was found in all sampling efforts. Plastics were the most abundant marine litter type (87 %), followed by metal (7.81 %) (Fig. 9).

The mean density (items km^{-2}) of seafloor samplings per grid cell size of 2.5 km × 2.5 km is depicted in Fig. 10, highlighting areas of higher litter density in shallow waters.

If depth is considered, the highest average litter density (36,956 items km^{-2}) was recorded in shallow waters (0–25 m depth). Within the depth range of 25 to 45, the density decreased by half. Moving on to the following depth range (45–115 m), data collected by TUC, ROVs, and trawlers revealed a significant decrease in average density, approximately ten times lower. While progressing towards greater depths (200–250 m and 300–350 m), a slight decrease in litter density was observed. Litter density shows an exponential trend with depth, as depicted in Fig. 11.

4. Discussion

4.1. Beaches

Published data on the amount, distribution, and composition of beach-stranded litter along the coastline of Greece are rather limited. The densities reported within this study for the beaches in Saronikos Gulf ranged from 0 to 23.6 items m^{-2} with an average of 2.61 (±0.41) items m^{-2} and are nearly eleven times higher than the values reported by Vlachogianni et al. (2018), who studied ten Greek beaches and found a mean density of 0.24 items m^{-2}. Additionally, the mean density of the current study is approximately 1.5 times higher than the mean density of 1.69 items m^{-2} found in four Greek coastal protected areas (Vlachogianni, 2019). It is also higher than the densities reported in other coastal Mediterranean areas (Aydin et al., 2016; Ciufegni et al., 2024; Munari et al., 2016; Nachite et al., 2019; Orthodoxou et al., 2022). Based on the available data, it is evident that the level of litter on the beaches in the Saronikos Gulf greatly surpasses the threshold required to achieve the GES, legally defined for MSFD at 22 items/100 m coastline in Europe (Van Loon et al., 2020) or in a lesser extent above the proposed Threshold Value of 130 items/100 m for UNEP/MAP IMAP Common Indicator 22 (beach marine litter) in the Mediterranean Sea (UNEP MAP, 2021). This situation underscores the current state of pollution and degradation within this coastal ecosystem, attributed to the presence of litter.

Most litter items were made of plastic, accounting for 91.4 % of all

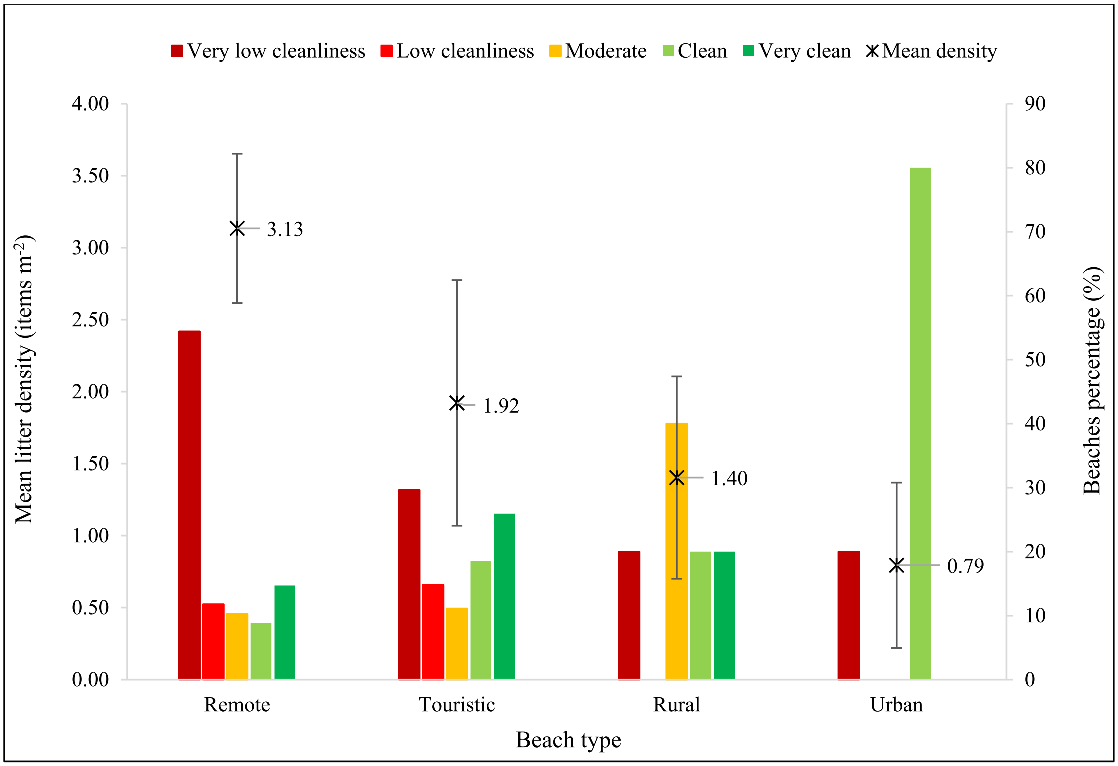

Fig. 5. Mean litter density (items m^{-2}) for each beach type and percentage composition of the different beach types based on cleanliness (GI).

the litter collected. Similar results (>90 %) were obtained by Vlachogianni et al. (2018) and the MELTEMI (2020) EU project. Kordella et al. (2013) conducted beach litter surveys on eighty beaches across Greece and also found that plastic was the prevailing material, although with a much lower contribution to the total (43–51 %). The rise in the plastic percentage along the shores of the Saronic Gulf in the current study could be attributed to an increase in its usage. However, the most likely scenario is that it is due to differences in methodology between the studies, either during the sampling process, or in the categorization of litter, or a combination of both. As the authors report, volunteers who conducted the samplings in 2006–2007 likely recorded cigarette butts as paper. Similar, and slightly lower percentages (80–90 %) have been reported in other coastal Mediterranean areas (Asensio-Montesinos et al., 2019a; Munari et al., 2016; Nachite et al., 2019; Šilc et al., 2018; Vlachogianni, 2019). The prevalence of plastic over other materials is primarily due to the widespread use and improper disposal of plastic products, their durability, their ability to be transported by wind and water currents, and their eventual breakdown into smaller pieces.

The most encountered plastic items on beaches included small polystyrene pieces, constituting 27.6 % of all plastic items, followed by cigarette butts and filters at 18.7 % and small plastic pieces at 11.3 %. These findings align with prior studies conducted by Vlachogianni et al. (2018) and MELTEMI (2020) in Greece. Small plastic and polystyrene fragments predominantly stem from the degradation of larger plastic objects, a process accelerated by prolonged exposure to sunlight, wave action, and physical abrasion. In particular, polystyrene pieces are frequently associated with fishing activities, stemming from the fragmentation of larger Styrofoam cooler boxes commonly used to store caught fish. Plastic fragments are transported to beaches and stranded there due to the influence of wave action. Cigarette butts and filters, on the other hand, tend to accumulate on beaches due to improper disposal by beachgoers. It's a common misconception that cigarette butts, made of what appears w to be paper, will naturally break down or be washed away by the waves. In reality, cigarette filters are composed of cellulose acetate, a type of plastic that does not readily biodegrade (Wu and Yang, 2023). Given their small size, both small artificial polymer pieces and cigarette butts are less susceptible to being washed back into the sea by winds and waves and are often missed by regular clean-up operations (Fernández García et al., 2024; Loizidou et al., 2018). Consequently, they are considered persistent forms of litter accumulating over time (Loizidou et al., 2018).

We can make certain assumptions concerning the correlation between litter categories and beach types. Firstly, the findings on remote shores suggest that these are primarily related to marine activities and are transferred by currents. More specifically, the vast majority of the recorded litter consisted of polystyrene pieces ranging from 2.5 cm to 50 cm, possibly originating from aquaculture units primarily operating on the west side of the bay (Fig. 1b), where the remote shores are located, however fisheries cannot be excluded. Additionally, the prevalence of unidentifiable plastic/polystyrene items and fragments suggests that these items entered the marine environment long ago and have been subjected to environmental factors, such as wave action and UV radiation (Ríos et al., 2018). As anticipated, due to the challenging accessibility of remote shores, SUPs are found in low frequencies, with the sole exception being plastic bottles, which, being lightweight, could easily be transported via currents (Schwarz et al., 2019). Touristic beaches demonstrate higher pollution levels with small items, which tend to be overlooked during clean-up efforts (Zhao et al., 2015). As expected, the most common litter category on touristic beaches is cigarette butts (Orthodoxou et al., 2022). Moreover, the presence of paper fragments, known for their limited durability when exposed to the environment, serves as an indicator of recent littering (Prevenios et al., 2018). The high percentage of SUPs is attributed to beach visitors, and the presence of glass/ceramic fragments suggests local littering, as these materials are not easily transported by water or wind. Similar conclusions can be drawn from the most frequently encountered litter on urban beaches. Seven out of ten categories are SUPs, with cigarette butts and filters being the most common litter type. In their work, Asensio-Montesinos et al. (2021) state that among other beach types, urban beaches are the most polluted with cigarette butts. Lastly, rural beaches are mostly

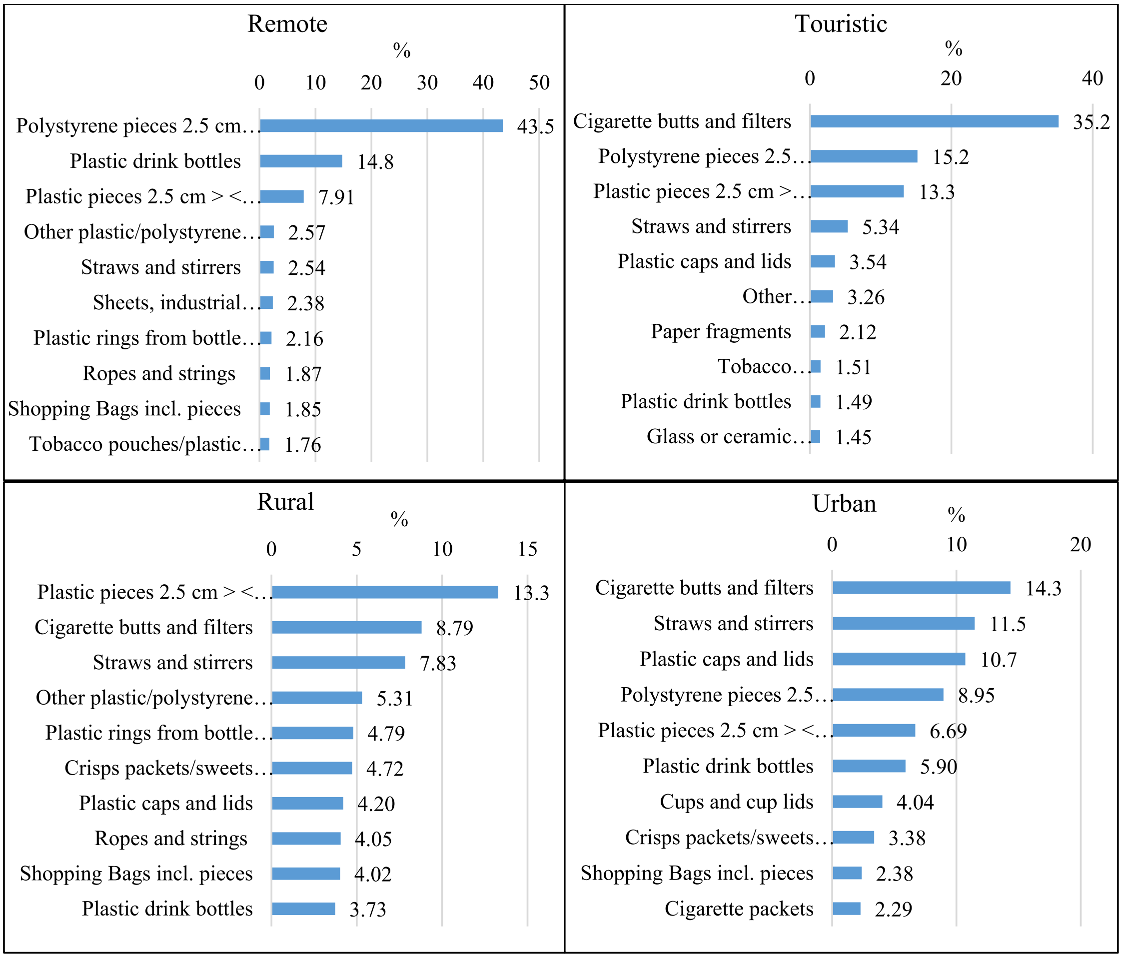

Fig. 6. Percentage of occurrence of the ten most abundant litter categories on each beach type.

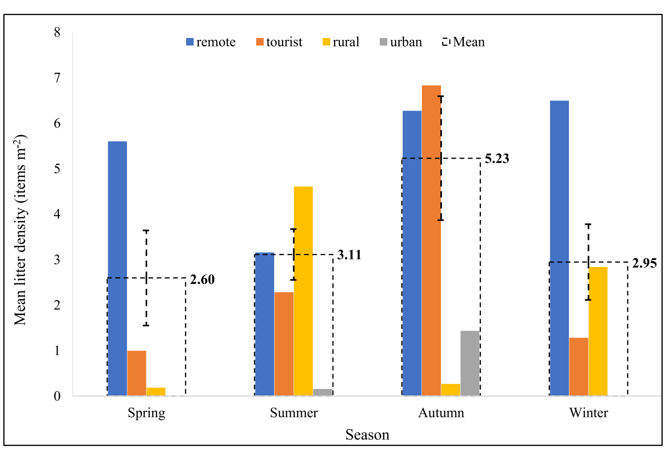

Fig. 7. Seasonal litter density (items m^{-2}) variations (mean and for each beach type).

contaminated by small plastic pieces, suggesting the accumulation of litter over time, cigarette butts and filters indicating the presence of visitors, other SUPs, which could come from landfills or other land-based sources of pollution or be transferred from long distances through currents and ropes and strings, which are related to fishing activities.

In the western part of the Gulf, particularly in the broader Epidavros Bay area, there has been a notable increase in litter density. Ioakeimidis et al. (2014) suggested that increased litter densities in the western region of the Saronikos Gulf can be attributed to specific transport mechanisms. These mechanisms are influenced by the anti-cyclonic surface water circulation pattern described by Kontoyiannis (2010), which prevails for most of the year. Papachristopoulou et al. (2020) also concurred with this perspective, noting that the near-surface circulation patterns in the Saronikos Gulf tend to carry litter from the islands Aegina and Agkistri as well as from the northeast shores, depositing it in the western region. The westward distribution currents in the Aegina, Methana, and Agkistri straits also serve as significant pathways for floating litter within Epidavros Bay (Fig. 1a). Moreover, the coastal morphology in the western region, characterized by narrower beaches, restricts litter dispersion, leading to higher density. Other plausible contributors to litter accumulation include the presence of fishing farms in the area (Fig. 1b).

Regarding cleanliness across different beach types, remote shores were the most polluted, and there are two possible reasons for this. One is their spatial location, mainly concentrated on the west side of the Gulf, resulting in the accumulation of litter brought in by water circulation. The other factor includes the lack of regular cleaning operations. In their survey in coastal areas along the Province of Alicante, Spain, Asensio-Montesinos et al. (2019b) also found that natural areas were the most polluted. For all the other beach types, we cannot definitively establish a clear correlation between beach type and pollution level in our study since the different beach types are not evenly distributed across the Gulf, and the sampling period differs. While further data acquisition is necessary to delve deeper into this topic, our study asserts that litter deposition is influenced by a complex interplay of environmental and

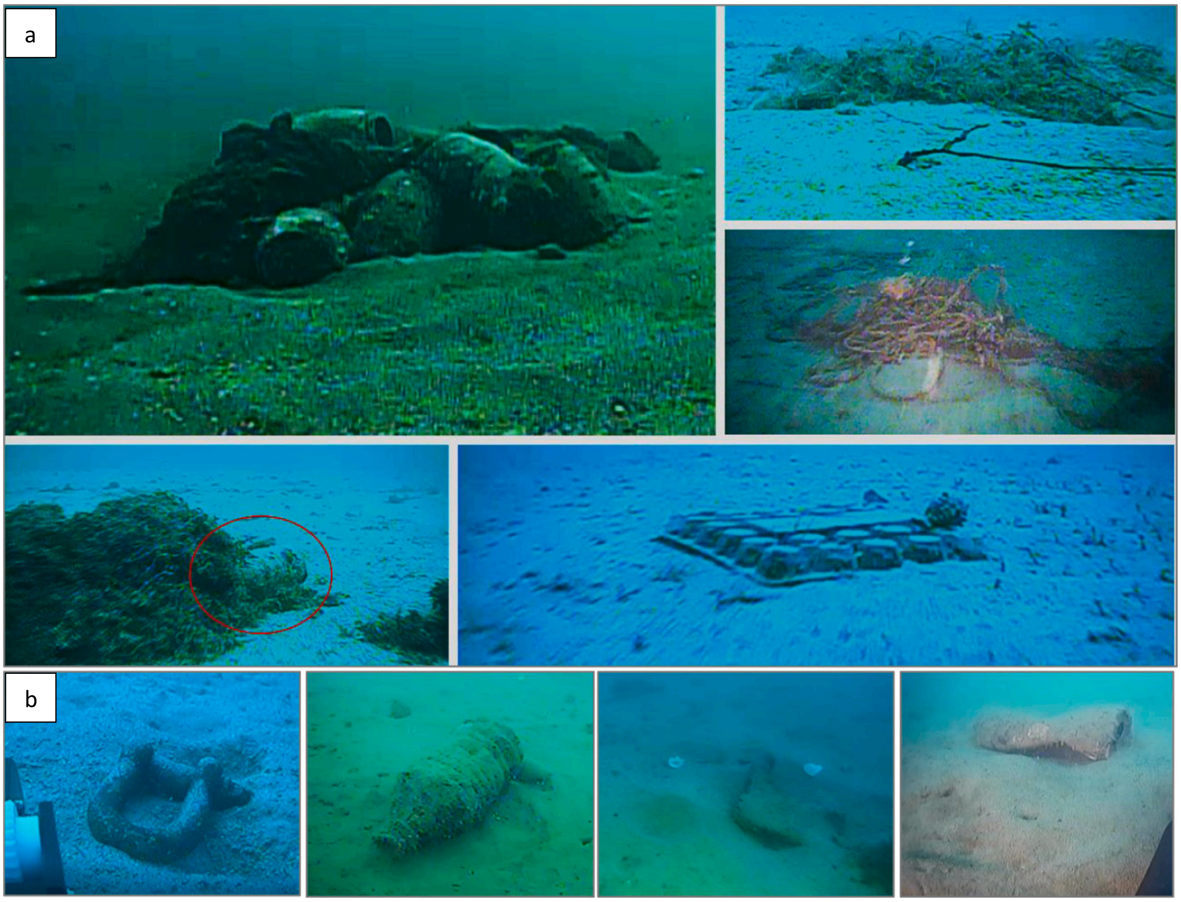

Fig. 8. Selected marine litter items detected in the (a) TUC and (b) ROV videos.

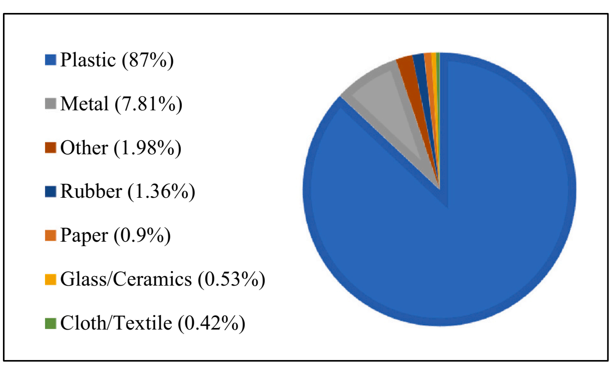

Fig. 9. Percentage composition of marine litter collected in 100 underwater locations, sorted by material.

anthropogenic factors.

Finally, mean litter density in the overall area of Saronic Gulf tends to be higher during autumn, while it decreases during winter and spring. Even though data are not evenly distributed across the years - as primarily two years are represented (2018 and 2020) - the seasonal trends observed seem to agree with the findings from other studies, as there are also reports of higher litter densities in autumn (Burlat and Thorsteinsson, 2022; Terzi and Seyhan, 2017; Topçu et al., 2013) and the rainy season (Fadare et al., 2022). Summer shows a slight increase but remains lower than autumn. Spring exhibited the lowest density also in similar research (Terzi and Seyhan, 2017; Topçu et al., 2013). Several factors could contribute to this seasonal variation in litter density, such as seasonal tourism activities, weather patterns, and beach cleaning efforts during different times of the year. When we consider the aspect of beach type, the seasonal pattern becomes more apparent. Particularly, remote beaches exhibit higher densities during autumn and winter, corresponding to the rainy and windy season. The reason why touristic beaches exhibit the highest density in autumn seems to be related to the accumulation of debris during the summer months, combined with the cessation of beach maintenance by the businesses operating in these areas. Rural beaches exhibit higher litter densities in summer, a trend that can also be explained by the increase in tourist activities during warmer months. However, the notable difference from touristic beaches is that rural beaches typically lack businesses operating within them to facilitate regular cleaning.

4.2. Seafloor

When it comes to the seafloor and from the management perspective, the densities found in the Gulf (with a mean value of 12,145 items km^{-2}) were far above the only existing recommended threshold value calculated for the Mediterranean Sea by UNEP MAP (38 items km^{-2}, UNEP MAP, 2023). Similar to beach litter, this indicates that the good environmental status has not been reached and remains at the worst possible level in the Saronikos Gulf (>5 × Threshold Value).

Moreover, our data showed that the density can vary depending on the depth at which the sampling occurred. For this reason, we presented a mean benthic litter density for the entire Saronic Gulf and the mean densities for depths of 0–25 m, hereafter referred to as shallow waters, and for depths of 25–350 m, referred to as deeper waters. The density in shallow waters was approximately 23 times higher than in deeper waters. Shallow waters are expected to have higher litter densities because of their proximity to human population centers (Katsanevakis and

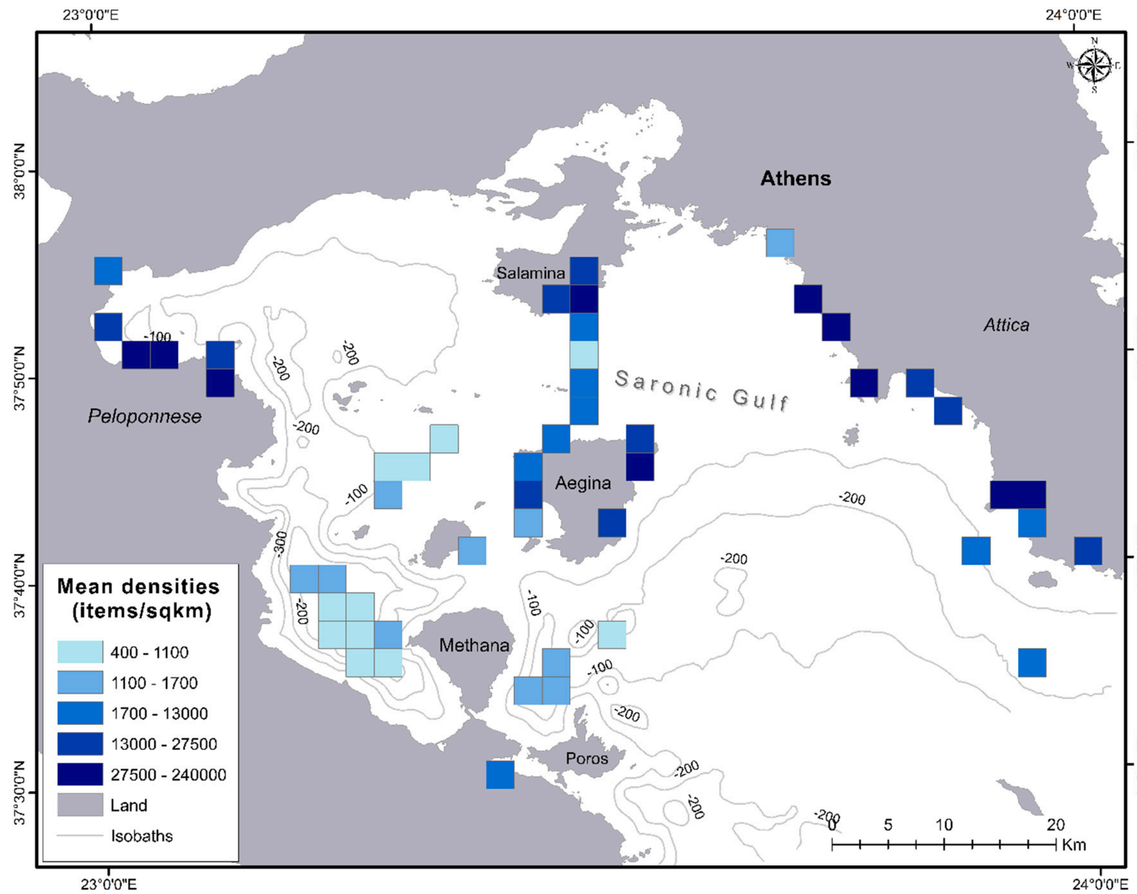

Fig. 10. Mean litter densities (items km^{-2}) per grid cell size of 2.5 km × 2.5 km on seafloor.

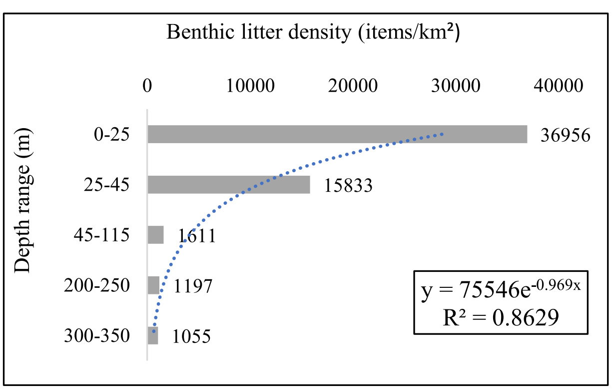

Fig. 11. Mean litter densities (items km^{-2}) by depth range (m).

Katsarou, 2004). Higher litter densities near the coast in the Mediterranean have also been reported by Strafella et al. (2015, 2019). However, deeper waters are not exempt from the issue, as marine litter can still be found in various quantities at all depths (Canals et al., 2021; Galgani et al., 2015; Pham et al., 2014).

Other studies in the Greek region also presented remarkably high litter densities in shallow waters, but lower than those found in the current survey. Specifically, the study by Katsanevakis and Katsarou (2004) in South Peloponnese, Western Crete, and Santorini reported a density 2.5 times lower, while Fakiris et al. (2022) in Ermoupoli Bay, Syros reported a density 1.8 times lower than in Saronikos Gulf. The calculated densities of deeper waters vary widely among different Greek areas (Table 2). The Saronikos Gulf ranks second after the Eastern Ionian coast, where Sánchez et al. (2013) recorded a density of 2300 items km^{-2}.

The sampling methodology may impact the calculated density. Scuba divers can carefully examine the benthic environment and more accurately identify small or buried litter items in the seabed sediment. Additionally, divers can target rocky reefs, *P. oceanica* meadows, and coral formations, where litter can accumulate. However, this method has limitations regarding the extent of the area sampled, safety, and cost. Trawlers primarily focus on harvesting marine organisms for commercial purposes, and their gear is not designed specifically for litter collection. Furthermore, they continuously collect litter from the same areas where they harvest, following specific trawling lanes (hauls) with specific seafloor characteristics (featureless, sandy texture) (Galgani et al., 2015; Canals et al., 2021). Meanwhile, ROVs and cameras are costly to deploy and they could potentially underestimate marine litter densities, as it is challenging to identify buried items and visibility is low in certain marine environments (Ioakeimidis et al., 2015).

Plastic was found to be the most abundant litter category, as stressed in previous studies in Greek (Katsanevakis and Katsarou, 2004; Koutsodendris et al., 2008; Lefkaditou et al., 2013; Stefatos et al., 1999) and Mediterranean waters (Alomar et al., 2020; Fortibuoni et al., 2019; Pasanisi et al., 2023; Pasquini et al., 2016; Spedicato et al., 2019; Strafella et al., 2019). The current study provides additional evidence that the relatively low cost, widespread use, and durability of plastic contribute to its accumulation on the seabed over time.

In an attempt to identify the sources of litter on the seafloor, we compared the most abundant litter categories in shallow waters and in deeper waters in Saronikos Gulf, as reported by Katsanevakis and Katsarou (2004) (25 dives) and Ioakeimidis et al. (2014) (70 hauls), respectively (Table 3). The most common litter categories in shallow waters are plastic bottles, metal cans for beverages and plastic cups for

Table 2
Summary of benthic litter surveys in Greece.

Reference	Region	Year	Method	Sampling effort	Area covered (km^2)	Depth (m)	Mean density (items km^{-2})	Plastic %
Katsanevakis and Katsarou, 2004	South Peloponnese, Western Crete, Santorini	2003	Scuba dives	34	0.076	0–25	14,607	51 %
Fakiris et al., 2022	Ermoupoli's bay (Syros Island)	2016–2019	TUC	–	4.05	3–30	20,000	–
Stefatos et al., 1999	Patras Gulf	1997	Fishing trawlers	3	1.16	80–120	240	83 %
	Echinadhes Gulf	1998		2	1.18	247–360	89	79 %
Koutsodendris et al., 2008	Patras Gulf Western Gulf of Corinth Echinades Gulf Northern Lakonikos Gulf	2000–2003	Fishing trawlers	54	20	15–320	188–437 116 72 85	42–83 %
Sánchez et al., 2013	Eastern Ionian coast	2009	Beam trawlers	6	0.015	40–80	2300	51–95 %
Ioakeimidis et al., 2014	Patras Gulf	2013	Fishing trawlers	18	2.7	–	641 ± 579	60 %
	Echinades Gulf			10	1.89		416 ± 379	67 %
Papadopoulou et al., 2015a	Cyclades	2014	Experimental trawl nets	21	–	–	146	85 %
	N. Evoikos			18			43	67 %
	S. Evoikos			25			112	91 %
	Saronikos Gulf			18			222	91 %
Papadopoulou et al., 2015b	Gournes	2014	Experimental trawl nets	5	0.053	70–80	453	96 %
	Dia			5	0.071	200–210	352	76 %
Fortibuoni et al., 2019	Kerkiraikos Gulf	2014–2015	Bottom trawlers	18	0.66 0.30	43–69	829	86 %
	North Corfu			8		63–267	910	
Spedicato et al., 2019	Aegean Sea (especially the Argo-Saronikos region) including Crete	2013–2015	Bottom trawlers	–	–	10–800	136	70–90 %
Current survey	Saronikos Gulf	2003–2020	Scuba dives, TUC, ROVs	34	0.084	0–25	36,956	83 %
			TUC, ROVs, trawlers	79	4.3	25–350	1634	

Table 3
Top 10 litter categories in shallow waters (Katsanevakis and Katsarou, 2004) and deeper waters (Ioakeimidis et al., 2014).

	Litter categories	Percentage of occurrence (%)
0–25 m	Bottles	22.9
	Cans (beverage)	18.3
	Cups	13.9
	Bags	7.21
	Tires	5.92
	Other plastic	3.35
	Anchorages	2.38
	Other metal	2.25
	Rope	2.12
	Small plastic bags	1.93
50–350 m	Bags	37.5
	Sheets	25
	Fishing line (entangled)	9.91
	Bottles	9.14
	Synthetic rope	5.77
	Fishing net	4.42
	Other plastic	3.00
	Cans (beverage)	2.55
	Clothing/rags	1.38
	Wood (processed)	0.36

drinks, all related to recreational coastal activities. Moreover, passenger vessels generate solid waste daily, which may end up as marine litter. Given the dense marine traffic along the northeastern coastline of the Gulf, the contribution of passenger vessels to the littering of the shallow water seafloor cannot be excluded. On the other hand, the most common litter categories in depths 50–350 m are plastic bags, sheets, and fishing lines. Bags possibly come from the land and are easily drifted by water currents, plastic sheets could be related to a certain type of industrial or agricultural activities on land, and fishing lines come from fishing activities.

It should be mentioned that the diversity in data sources introduces potential biases. Firstly, the reliability and accuracy of data collected through citizen science initiatives, such as Marine LitterWatch, may vary due to the expertise of participants, although the non-governmental organizations that guided the certain clean-up campaigns have long experience in such projects and use standard and straight-forward protocols. Similarly, the published studies used differ in methodology, temporal and spatial coverage. However, the level of uncertainty arising from different protocols and the potential for human error in citizen science is not particularly high based on our experience. There are several examples of published research that confirm that volunteers can collect valid data in environmental sciences and ecology (Aceves-Bueno et al., 2017; Evans et al., 2000; McKinley et al., 2017; Newman et al., 2003; van der Velde et al., 2017). The incorporation of previously published data, along with new samplings, allowed us to gather all the available marine litter data for Saronikos Gulf for the last twenty years, resulting in a comprehensive dataset and covering various water compartments, including both coastal areas and seafloor locations. Despite the different methodologies and the unbalanced temporal data, a deep insight of marine litter in the Saronikos Gulf is provided.

5. Conclusions

In conclusion, this study aims to address current knowledge gaps concerning the environmental status of the Saronikos Gulf, the most important Gulf in Greece, East Mediterranean, with respect to marine litter. In this work, the necessary information is provided for the development of an effective litter pollution management plan by stakeholders. It also seeks to inspire similar research efforts in other regions and to identify possible trends and mechanisms regarding litter distribution and accumulation in a populated and partially enclosed marine area, such as a gulf.

The presence of marine litter was pervasive across the surveyed locations, with certain areas experiencing higher concentrations, likely influenced by currents, coastal morphology, and human activities. Identifying areas failing to meet GES criteria is crucial for policymakers. Plastic was the dominant litter material in all cases, with SUPs, as defined by the EU Directive, accounting for a significant percentage of the total litter. Small polystyrene pieces from fish boxes constituted a pervasive and persistent form of litter. The water surface circulation pattern seemed to mainly determine the spatial distribution of litter, resulting in a more contaminated western side. Shores defined as remote were the most polluted, accumulating litter coming from the sea, while touristic beaches, subject to frequent cleaning operations, were mainly polluted by cigarette butts from visitors. Beach samplings conducted in autumn revealed higher litter densities. The seafloor of the Gulf was also heavily affected by litter, with our samplings indicating an exponential trend with depth, with shallow waters being the most polluted. Building upon these findings, future research efforts could explore long-term impacts for assessing the effectiveness of implemented interventions and understand how litter patterns evolve over time. Additionally, research can focus on engaging industries to adopt eco-friendly packaging, fishing practices, and waste disposal methods.

CRediT authorship contribution statement

K. Kouvara: Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **A. Kosmopoulou:** Investigation. **E. Fakiris:** Investigation, Validation, Visualization, Writing – review & editing. **D. Christodoulou:** Investigation. **A. Filippides:** Investigation. **S. Katsanevakis:** Investigation, Writing – review & editing. **C. Ioakeimidis:** Investigation. **M. Geraga:** Investigation, Writing – review & editing. **P. Xirotagarou:** Investigation. **F. Galgani:** Writing – review & editing. **G. Papatheodorou:** Conceptualization, Investigation, Supervision, Validation, Visualization, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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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.2024.116497.

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