Journal of Hazardous Materials 495 (2025) 139114

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Plastic pollution in brackish waters: Macroalgae as collectors of plastic debris

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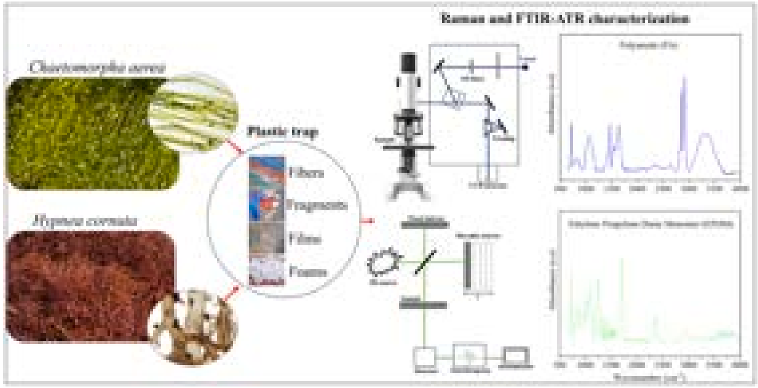
HIGHLIGHTS

- Macroalgae passively trap plastics in transitional waters.
- A mix of plastics and elastomers accumulate on macroalgae.
- Microplastic level on macroalgae are over 100 times higher than in surrounding waters.
- Removing macroalgal biomass helps reduce plastic and restore coastal ecosystems.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Plastic litter
Chaetomorpha aerea
Hypnea cornuta

ABSTRACT

Transitional waters, like the Capo Peloro lagoon, are ecologically and commercially valuable but particularly vulnerable to plastic pollution. This study investigates, for the first time, how two bloom-forming macroalgae, *Chaetomorpha aerea* and *Hypnea cornuta*, trap plastic debris in Ganzirri lake (Capo Peloro lagoon). Both species

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https://doi.org/10.1016/j.jhazmat.2025.139114
Received 10 April 2025; Received in revised form 26 June 2025; Accepted 30 June 2025

Brackish water
Natural reserve
Special protected area
Conservation

acted as natural traps for plastics, ranging from macroplastics (> 25 mm) to microplastics (< 5 mm). *C. aerea* captured more macroplastic (4.91 items/kg) than *H. cornuta* (2.19 items/kg). The average abundance of microplastics on *C. aerea* (0.35 items/g) and *H. cornuta* (0.51 items/g) was more than 100 times higher than surrounding waters (0.003 items/ml). FTIR and Raman analysis identified 16 synthetic polymers, 3 elastomers, and 2 anthropogenic microfibers, revealing a great polymer diversity. A wider spectrum of anthropogenic microparticles was isolated from macroalgae, with 11 different materials identified in *C. aerea* and 14 in *H. cornuta*, compared to 7 found in the water. Wastewater from domestic laundry, dumping activities, mollusc farming, and fisheries were identified as the main sources of plastics. While algae removal may help reduce plastic pollution, it must be managed sustainably to prevent biodiversity loss or secondary pollution. The results highlight the importance of integrat macroalgae management with broader conservation strategies to protect these vulnerable ecosystems.

1. Introduction

The rapid surge in global plastic production, coupled with widespread overuse and insufficient waste management practices, has led to a concerning accumulation of plastic debris [1,2]. Once in the environment, plastic items gradually fragment into smaller particles - macroplastics (> 25 mm), mesoplastics (5–24.9 mm), and microplastics (0.001–4.9 mm) - through a combination of abiotic (e.g., UV radiation, mechanical forces) and biotic (e.g., microbial activity) processes [3,4]. Plastics of all sizes can pose serious threats to marine and freshwater organisms [5–8] and disrupt aquatic coastal ecosystems [9,10]. These impacts have broader consequences for food security, environmental safety, and human health [11]. Additionally, plastic debris can act as a carrier for pollutants, pathogens, and invasive species, further amplifying its ecological risks [12,13].

Transitional waters (TWs), including coastal ponds and lagoons, are distinctive ecosystems defined by shallow depths, significant temperature fluctuations, marked spatial and temporal variations in salinity, high productivity, limited circulation, and low hydro-dynamism [14,15]. These ecosystems are vital for providing key services such as enhancing water quality by filtering pollution from rivers, offering habitat and food for both resident and migratory species, and supporting fish populations. TWs are also some of the most polluted environments, heavily impacted by human activities like agriculture, improper waste disposal, urban and industrial wastewater, and tourism [16,17]. In recent decades, the conservation of TWs has gained increasing importance, as evidenced by initiatives such as the European Water Framework Directive (WFD) 2000/60/EC, the Mediterranean Wetland Initiative (1991), and the Land-Ocean Interactions in the Coastal Zone (LOICZ, 1993).

Algae constitute a highly diverse group of photosynthetic organisms that are fundamental to the functioning of aquatic ecosystems. Based on their pigmentation, cellular structure, and storage compounds, algae are typically classified into three main groups: green algae (Chlorophyta), brown algae (Phaeophyceae), and red algae (Rhodophyta). In recent years, algae have gained considerable interest for their role in pollutant removal, particularly owing to their renewable nature, low cost, abundance, and high adsorption capacity [18,19]. The presence of functional groups such as carboxyl, sulfonate, hydroxyl, and amine on algal cell walls enables effective interaction with contaminants, including microplastics, through mechanisms like biosorption and surface adhesion [20]. Recent studies demonstrated the ability of algal biomass to remove microplastics from aqueous environments via coagulation, flocculation, and electrostatic interactions [19,20].

These interactions are influenced by the physicochemical properties of both algae and microplastic particles, including surface charge and hydrophobicity. Their environmental compatibility further supports their potential as sustainable agents for water and wastewater treatment applications [21].

To date, studies investigating plastic retention in macroalgal species have been limited to marine environments. Macroalgae such as *Pyropia yezoensis*, *Ulva prolifera*, *Sargassum horneri*, *Cladophora* sp., *Undaria pinnatifida*, and *Ulva pertusa* have been found to trap plastic litter in the Yellow Sea [22–26]. Esiukova et al. [27], examining macroalgae from the Baltic Sea, namely *Furcellaria lumbricalis, Coccotylus truncatus, Polysiphonia fucoides, Cladophora rupestris,* and *Cladophora glomerata*, highlighted their role as microplastic traps. More recently, Ben Haddad et al. [28] reported that macroalgal blooms (*Codium decorticatum*) along the Atlantic coast of Morocco acted as collectors of plastic debris.

Capo Peloro is a brackish coastal system located in northeastern Sicily (Italy), comprising two adjacent brackish coastal lakes: Ganzirri and Faro. The Capo Peloro lagoon has been extensively studied from multiple perspectives due to its ecological importance, particularly its rich biodiversity in both fish species [29] and molluscs [30–33], as well as its environmental significance [15] It is also recognized as a sanctuary for migratory birds [34–35]. In addition, the Capo Peloro lagoon holds significant commercial value. Faro Lake is renowned for its shellfish farming [36–38] while Ganzirri Lake is a key site for fishery of endemic bivalve species. The lagoon complex is subjected to considerable anthropogenic pressure, primarily driven by extensive urbanization. The conservation of Capo Peloro lagoon is crucial for preserving the ecological balance of the area and sustaining local biodiversity [15]. Ganzirri Lake is characterized by the presence of macroalgal species such as *Agardhiella subulata* (Rhodophyta) [39], *Hypnea cornuta* (Rhodophyta) [40], *Chaetomorpha aerea* (Chlorophyta), and several species of genus *Gracilaria* (Rhodophyta) [41]. Frequently, the blooms spread over the lake, causing temporary dystrophic events and marked reduction of the dissolved oxygen [15,42,43]. Between the end of spring and the beginning of autumn, macroalgae reproduces rapidly, generating significant amount of biomass that cause several problems, including the reduction in water quality due to decreased in dissolved oxygen levels and interfere with shellfish harvesting boats. We therefore decided to study the 'trap' effect of two macroalgal species, *Chaetomorpha aerea* and *Hypnea cornuta,* present in Ganzirri Lake. In this study, we hypothesized that bloom-forming macroalgae can effectively trap plastics, making them an ideal way for treating plastics in a natural reserve. This study aims to: 1) quantify the ability of the two species to trap plastic waste, from macro to microplastics; 2) evaluate any differences between the two macroalgal species in relation to the substrate and morphology; and 3) evaluate if the removal of algae can be used as a strategy to mitigate the impact of plastics within a natural reserve. It is important to emphasize that the aim of this study is not to assess the microplastics incorporated by the algae, but rather to quantify the plastics adhered to and/or trapped within the macroalgal biomass. The expected results also include the first evaluation of plastic pollution in a transitional environment, providing insight into how the two challenges—MPs and macroalgal blooms—interact with each other simultaneously.

The unique characteristics of the Capo Peloro lagoon, combined with its ecological and biological significance, make it a crucial site for studying plastic pollution in the coastal ecosystem [44], and the Ganzirri Lake is an ideal area to study the interaction between plastics and macroalgal blooms. The relationships between Mediterranean brackish regions, representing unique and rare areas with fluctuating dynamics difficult to understand, are crucial for research in this field. Moreover, enhancing our understanding of the ecological dynamics that support the sustainability of protected areas is essential for sustaining protected areas, as plastic litter threatens ecosystem services, causes economic losses [45,46], and impact aquatic biota and coastal aquatic ecosystems [10,47], with potential consequences for food security, safety, and human health [48,49].

2. Methods and materials

2.1. Study area

Capo Peloro (Messina), located at the northeastern tip of Sicily (Italy) between the Tyrrhenian and Ionian Seas (Mediterranean Sea), is a transitional brackish aquatic system (Fig. 1). Since 2001, it has been part of the "Oriented Natural Reserve of Capo Peloro", which is designated as a Site of Community Importance (SCI) under Council Directive 92/43/EEC on the "Conservation of natural habitats and of wild fauna and flora". Additionally, it serves as an important feeding and nesting site for birds due to its strategic location along migratory routes and supports a rich diversity of avifauna. For this reason, it is included in a Special Protected Area (SPA) for migratory birds under Council Directive 79/409/EEC on the "Conservation of wild birds", commonly known as the Birds Directive. Capo Peloro has been designated as a "Heritage of Ethnic-Anthropological Interest" under the declaratory provision 1342/88, in recognition of its longstanding traditions in aquaculture, particularly the cultivation of mussels, clams, and cockles. Mussels are farmed only in the Faro Lake, while endemic clams, little neck clams, and cockles are harvested in the Ganzirri Lake.

The two lakes vary significantly in their geomorphological, hydrographic, and trophic characteristics, including differences in morphology, depth, and salinity levels [36,50]. In this study, we focused exclusively on Ganzirri Lake. The lake covers an area of 40 ha, with a maximum depth of 8 m. Ganzirri Lake is connected to the Ionian Sea via the "Due Torri" canal and the "Catuso" canal (covered canal equipped with a grid that does not allow the passage of macrolitter). Ganzirri Lake is linked to Faro Lake through the "Margi" canal. This channel network facilitates the inflow of oxygen-rich seawater into the lakes, enhancing water reoxygenation and maintaining conditions favorable for the diverse organisms inhabiting these brackish ecosystem [30,37]. Samplings were conducted in the northeastern sector of Ganzirri Lake. This area was chosen because it is characterized by shallow bottoms (maximum depth of 0.8 m) and was visually identified as a zone of macroalgae accumulation (Fig. 1, Table 1). It was selected due to the high concentration of plastic debris observed there, primarily attributed to prevailing southeasterly winds [44,51]. Furthermore, the north–south current in the Strait of Messina (known as scendente) carries plastic

Table 1

Stations, coordinates, and depths of samplings of *Chaetomorpha aerea* and *Hypnea cornuta* from Ganzirri Lake.

Station	Date	*Chetomorpha aerea* Weight [g]	*Hypnea cornuta* Weight [g]	Water [L]
G1	23/05/2024	3725	2625	0
G2	23/05/2024	0	3225	0
G1	19/06/2024	2750	3015	3
G2	19/06/2024	0	4780	3
G1	8/07/2024	3675	4894	3
G2	8/07/2024	0	4644	3
G1	17/07/2024	2400	960	3
G2	17/07/2024	0	4150	3
G1	30/09/2024	2740	0	3
G2	30/09/2024	0	0	0
Total		15,290	28,293	21

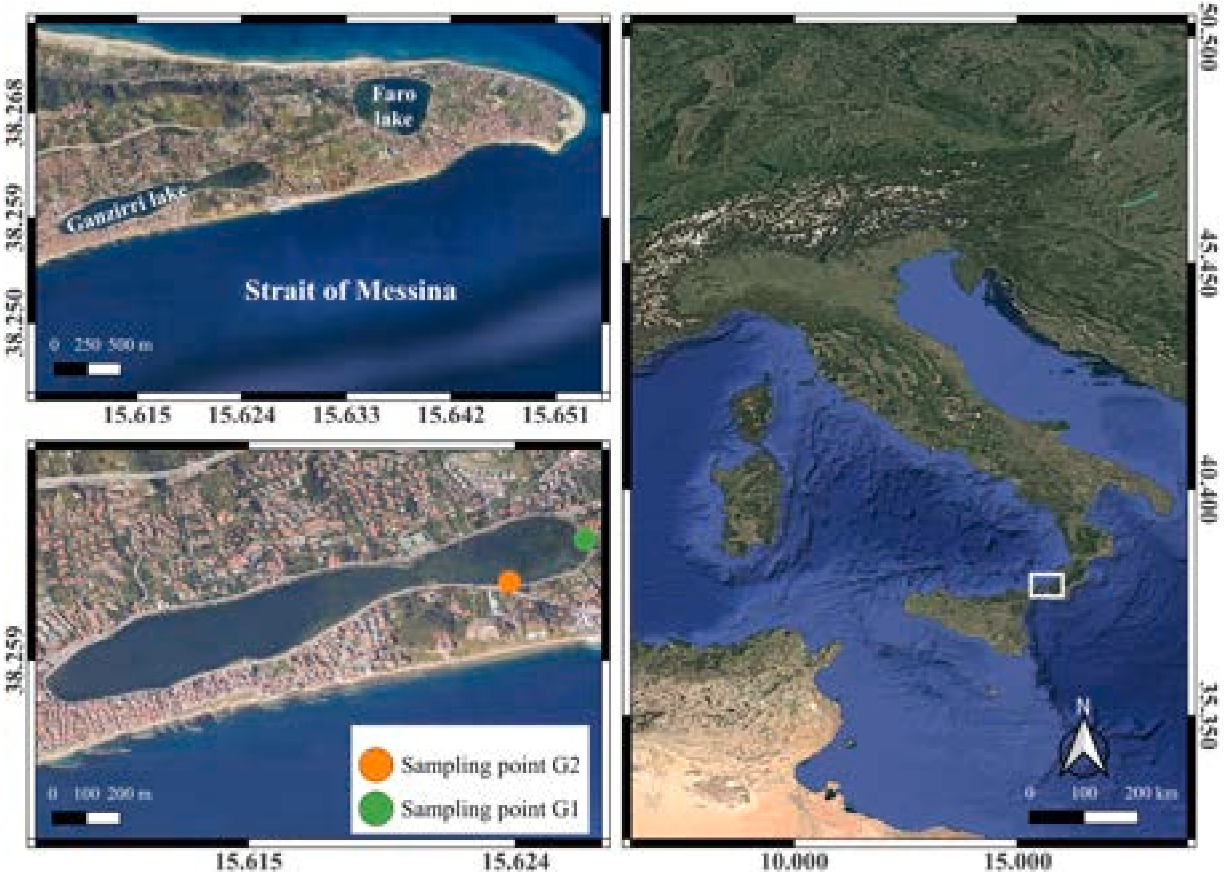

Fig. 1. Geographical location of Ganzirri Lake. Green dot = Sampling Point G1; Orange dot = Sampling Point G2. The map was generated using QGIS software (version 3.42 München).

waste from the Ionian Sea into the lake via the Due Torri canal, where it becomes trapped in the algal mass when the current reverses direction (south–north, known as montante). This area is also completely closed to human activity, as it serves as a key resting area for migratory birds due to the presence of perching structures [44]. Two sampling points were selected, namely G1 and G2 (Table 1). *H. cornuta* was found at both stations, with particularly high abundance at G2, while *Chaetomorpha aerea* was observed exclusively at G1 (Table 1).

2.2. Samplings

Five sampling campaigns were conducted between May and September 2024, strategically planned to coincide with the peak of macroalgal blooms and capture seasonal variations of plastic trapping (Table 1). Collected macroalgae were photographed (Fig. 2) and an aliquot of 50 g of each macroalgae species was immediately stored in individual glass containers for subsequent MPs isolation. All plastic items found trapped in macroalgae were placed in labeled bags and transported to the laboratory. Water samples were taken from areas of dense macroalgae growth or their immediate surroundings. To capture

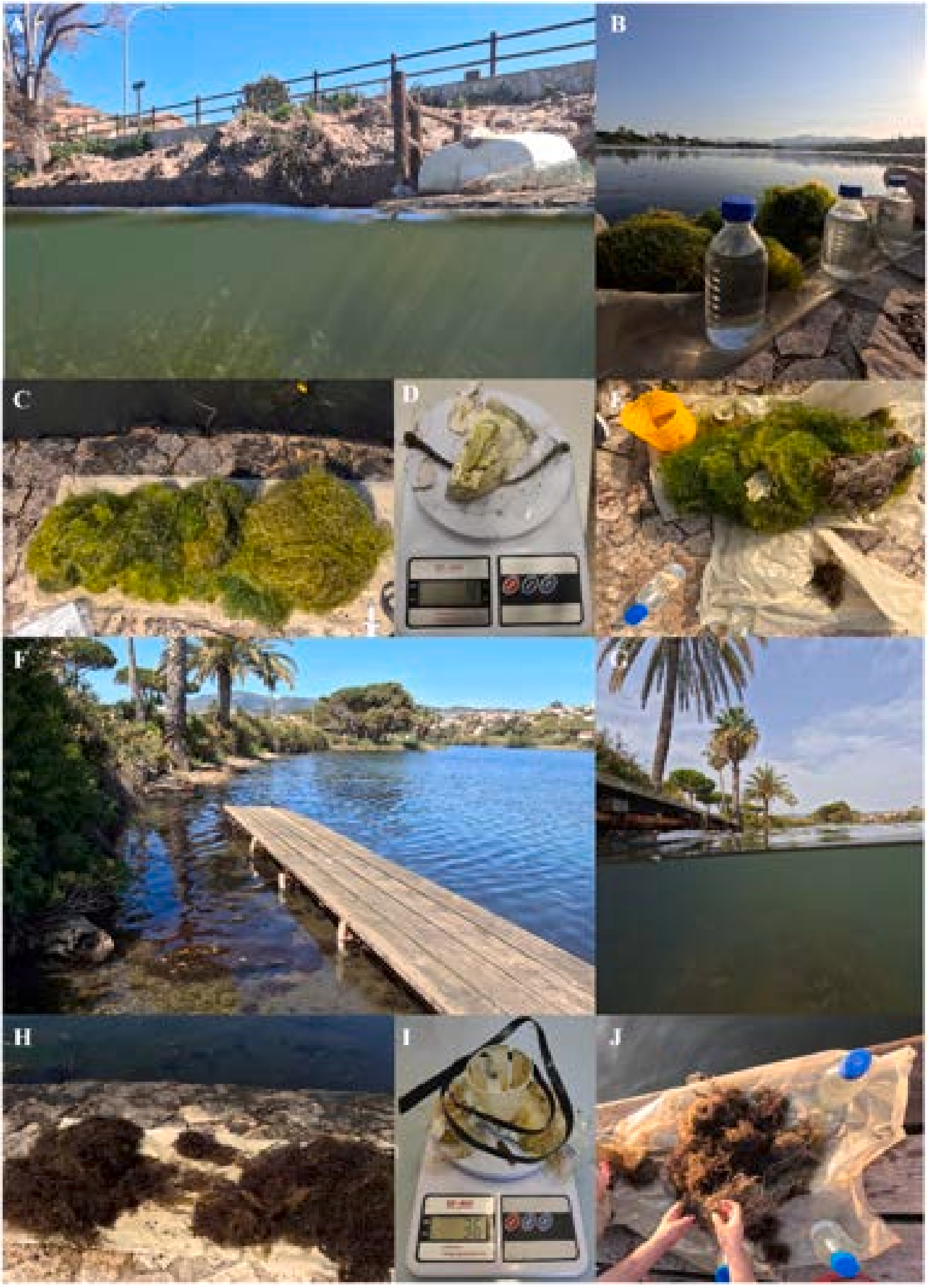

Fig. 2. Sampling sites G1 (A, B) with *Chaetomorpha aerea* (C) and plastic items isolated from the algal biomass (D, E); sampling site G2 (F, G) with *Hypnea cornuta* (H) and related plastic debris (I, J).

only floating MPs, superficial sample waters were taken, using 1 L laboratory glass bottles. At each station, three replicates were collected (in total 3 liters per station, Table 1).

2.3. Plastic isolation

All collected plastics were photographed, weighed, counted, and then categorized. The categories used for the macroplastics were: beverage bottles (< 0.5 l and > 0.5 l), cable ties, cigarette butts and filters, cotton buds, fishing line/monofilament, macrofiber, plastic cup or plastic cup fragments, plastic drink caps/lids, plastic packaging for cigarette boxes, plastic pieces (from 2.5 cm to 50 cm), plastic wire, polystyrene pieces (from 2.5 cm to 50 cm), rope (diameter < 1 cm and > 1 cm), sanitary pads, snack wrap, soft plastic [fragments of envelopes), plastic pieces (5 mm $< x <$ 25 mm), and other type of plastic litter. The density of each macro and mesoplastic category within each sample of macroalgae, was expressed as the number of items per fresh weight kilogram (items/kg) of macroalgae.

The macroalgae were analyzed by visual sorting for MPs isolation, they were placed in an open Petri dish and observed under a stereomicroscope (Leica M205C). The suspected MPs were categorized and isolated on slides for the characterization of polymer. Each water sample was filtered using a vacuum filtration system with 0.45 µm pore-size filter papers (Ø: 47 mm, Millipore). The filters were then examined under a stereomicroscope, and the suspected particles were categorized and isolated for identification assays. MPs were divided into five size categories: < 1 mm, 1–1.9 mm, 2–2.9 mm, 3–3.9 mm, and 4–4.9 mm. All plastic items ranging in size between 5 and 25 mm were classified as mesoplastics.

2.4. Quality control

Lab cotton coats and latex gloves were worn in the laboratory to prevent any contamination. In addition, the access to the laboratory was restricted to minimize the risk of accidental airborne contamination. All the operations were performed under a microbiological hood, with workspaces and tools rigorously cleaned using ethanol and filtered deionized water to eliminate any particle contamination. Additionally, beakers were washed with distilled water and covered with aluminium foil between each step to prevent airborne contamination. Opened Petri dishes with a moist filter, were placed in working spaces (laboratory and microbiological hood) during the whole sampling process to assess the airborne contamination [52]. To avoid airborne contamination, the fibers found on the control filters were recorded, quantified and compared in term of size, shape and colour with those found in the samples. If the fibers in the algae and water samples matched those of the control filters, they were excluded from the results as air contamination.

2.5. Polymer characterization by Raman and FTIR-ATR spectroscopy

The identification of the polymeric composition of the suspected microparticles extracted from macroalgae and water was carried out by Raman spectroscopy and Fourier Transform Infrared Attenuated Total Reflection Spectroscopy (FTIR-ATR). The Raman characterization was primarily used for microfibers and micro fragments with minimal thickness, while the FTIR-ATR spectroscopy was applied to MPs which had a high thickness [53]. For the microparticles analyzed with Raman characterization, an Lab-RAM **HR Evolution** micro-Raman spectrometer (Horiba Scientific) equipped with a 532 nm laser diode was employed. Depending on the sample properties and the level of fluorescence generated, either a 20 × or 50 × objective lens was selected. The system's aperture was adjusted between 50 and 500 µm, and gratings of either 600 or 1800 grooves/mm were employed as appropriate. A CCD detector cooled to 77 K was used to collect Raman signals over the range of 200–4000 cm^{-1} with an integration time varying between 5 and 10 s and a number of accumulations ranging from 2 and 100, depending on the Raman activity of the sample measured and the fluorescence generated by it. The laser power was maintained below 5 mW to avoid sample degradation, and several measurements were taken for each sample to establish the reproducibility of spectra. Furthermore, different parts of the same MP were tested to eliminate the influence of local impurities on the MPs Raman spectra. Spectral data were initially processed using the Labspec 6 software to remove fluorescence background, apply baseline subtraction, and filter noise. For the microparticles analyzed with FTIR-ATR spectroscopy, spectra were recorded by using a single reflection horizontal ATR accessory equipped with a diamond crystal fixed at a 45° incidence angle (Platinum ATR, Bruker). The crystal was mounted on a Vertex 80 V FTIR spectrometer (Bruker). The spectral range investigated was 400–4000 cm^{-1} and, for each spectrum, an average of over 64 scans with a resolution of 4 cm^{-1} was used. A background scan was recorded prior to the measurement and subtracted from the sample spectra. Measurements were conducted in an evacuated optics bench configuration to eliminate atmospheric moisture effects and the ATR correction to each spectrum was applied using the OPUS software [Bruker optics). For sample identification, the Bruker OPUS commercial spectral search software was employed.

All the spectra (Raman and IR) were analyzed with the Bio-Rad KnowItAll informatics system, utilizing the SLoPP and SLoPP-E libraries [54] to determine the polymeric composition of the samples. The Hit Quality Index (HQI) was used to describe the correlation between the spectra of unknown samples and reference compounds. Spectra, or portions of spectra, with a Hit Quality Index (HQI) of 80 % or higher were included in the analysis.

2.6. Statistical analysis

The abundance of the data was tested for homoscedasticity and normality using the Levene and Shapiro–Wilk tests. Since the data did not meet the assumptions required for conducting a parametric analysis of variance (ANOVA), even after log transformation, the Mann-Whitney test, a nonparametric test, was used to assess if there were plastic density differences between the two macroalgae. Statistical analyses were conducted using GraphPad Prism 8.4.2.3. All results were considered significant when $p < 0.05$. To compare microlitter composition between algal species in term of size, shape, colour, and polymer, data were also analysed using multivariate analysis with the package Primer 7 [55] Abundance data (microplastic items/g), following log transformation, was used to compute a Euclidean distance resemblance matrix. Analysis of Similarities (ANOSIM) was performed to assess the significance of differences in micro-litter composition between algal species. Multi-Dimensional Scaling (MDS) ordination was then applied to visualize the degree of similarity among the algal species.

3. Results

3.1. Macro and mesoplastic abundance

In the *Chaetomorpha aerea*, 75 macroplastics items were isolated with a total density of 4.91 items/kg of fresh algae weight (w.w.) (Table 2). Whereas, in *Hypnea cornuta,* 62 macroplastics items were identified with a total density of 2.26 items/kg (Table 2). No significant differences were detected between algal species in terms of abundance (Mann-Whitney U: 184, $p > 0.05$). The main category found in *C. aerea* was soft plastic (52 %) followed by plastic pieces (2.5 cm $< x <$ 50 cm, 14.67 %), fishing line or monofilaments (12 %), plastic cup or plastic cup fragments (4 %), plastic pieces ($>$ 50 cm, 2.67 %), polystyrene pieces (2.5 cm $< x <$ 50 cm, 2.67 %), snack wraps (2.67 %), beverage bottles $<$ 0.5 l, cable ties, cigarette butts and filters, cotton buds, plastic wires, and ropes with diameter $>$ 1 cm (1.33 %) and other items (1.33 %) (Figs. 3 and 4).

In *H. cornuta,* the most abundant type of entrapped plastic waste was soft plastic accounting for 40.32 %, followed by fishing lines (11.29 %),

Table 2
Macroplastic items entrapped in *Chaetomorpha aerea* and in *Hypnea cornuta*.

Litter type	*Chaetomorpha aerea*		*Hypnea cornuta*	
	N	items/kg	N	items/kg
Beverage bottles < 0.5 l	1	0.07	0	0
Beverage bottles > 0.5 l	0	0	1	0.04
Cable ties	1	0.07	0	0
Cigarette butts and filters	1	0.07	0	0
Cotton buds	1	0.07	0	0
Fishing line/Monofilament	9	0.59	9	0.33
Plastic cup or plastic cup fragments	3	0.2	3	0.11
Plastic drink caps/lids	0	0	1	0.04
Plastic packaging for cigarette boxes	0	0	4	0.15
Plastic pieces > 50 cm	2	0.13	0	0
Plastic pieces 2.5 cm > < 50 cm	11	0.72	5	0.18
Plastic wire	1	0.07	0	0
Polystyrene pieces 2.5 cm > < 50 cm	2	0.13	5	0.18
Rope [diameter > 1 cm)	1	0.07	3	0.11
Rope [diameter < 1 cm)	0	0	1	0.04
Sanitary pads	0	0	1	0.04
Snack wrap	2	0.13	0	0
Soft plastic [fragments of envelopes)	39	2.55	25	0.91
Other items	1	0.07	4	0.15
Total	75	4.91	62	2.26

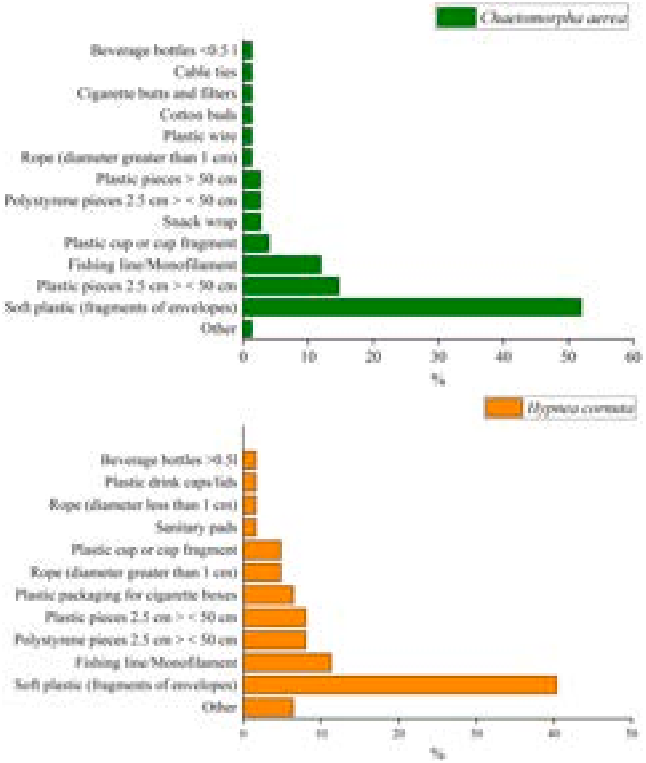

Fig. 3. Percentage of macroplastics found in *Chaetomorpha aerea* (upper panel) and in *Hypnea cornuta* (bottom panel).

plastic pieces (2.5 cm < x < 50 cm, 8.06 %), polystyrene pieces (2.5 cm < x < 50 cm, 8.06 %), cigarette plastic packaging (6.45 %), plastic cups or plastic cup fragments (4.84 %), ropes with diameter (> 1 cm, 4.84 %), macrofibers (3.23 %), beverage bottles (> 0.5 l), plastic drink caps/lids, ropes with diameter < 1 cm, sanitary pads (1.61 %), and other plastics item (6.45 %) (Figs. 3 and 4).

Mesoplastic items included fragments of both hard and soft plastics as well as fibers. In *C. aerea*, the mesoplastic density was 136 items per kilogram. In *H. cornuta*, the mesoplastic density was 72 items per kilogram. Additionally, two mesoplastic items were isolated from water, corresponding to a density of 0.09 items per liter.

3.2. Anthropogenic microparticles abundance

A total of 215 suspected microparticles were found entrapped in macroalgae samples, in particular, 88 of these were entrapped in *C. aerea* samples. The average abundance of MPs on *C. aerea* was 0.352 items/g (SD: 0.22) fresh algae weight. The types of anthropogenic microparticles identified in the study, along with their concentrations and frequency of occurrence are reported in Table 3 and Fig. 5. The most common size range was 1–1.9 mm (35.90 %), followed by 2–2.9 mm (23.08 %), < 1 mm (20.51 %), 3–3.9 mm (12.82 %), and 4–4.9 mm (7.69 %) (Fig. 5 A.1). The debris types consisted mainly of fibers (76.92 %), followed by fragments (21.79 %), and spheres (1.328 %) (Fig. 5 A.2). Regarding colour, blue was the most common (32 %), followed by black (30 %), white/transparent (19 %), grey (7 %), light blue (5 %), red (5 %), brown (2 %), and green (1 %) (Fig. 5 A.3).

For what concerns *H. cornuta,* a total of 127 suspected MPs were isolated. The average abundance of MPs on *H. cornuta* was 0.313 items/g (SD: 0.31) fresh algae weight (Table 3). The most common size category was 2–2.9 mm (27.73 %), followed by 1–1.9 mm (26.89 %), < 1 mm (21.01 %), 3–3.9 mm (15.97 %), and 4–4.9 mm (8.40 %) (Fig. 5 B.1). Fibers were the predominant type, accounting for 85.71 %, followed by fragments (7.57 %), foams (3.36 %), and films (3.36 %) (Fig. 5 B.2).

Regarding the colour, the items entrapped in *H. cornuta* were mostly black (34 %), followed by white/transparent (28 %), blue (28 %), light blue (4 %), brown (3 %), and grey (3 %) (Fig. 5 B.3).

As regards MPs abundance from water samples, a total of 69 suspected microparticles were isolated. The mean abundance was 3.3 items/L (SD: 0.04) (Table 3). The most common size category was 1–1.9 mm (45.45 %), followed by particles smaller than 1 mm (34.85 %), 2–2.9 mm (13.63 %), 3–3.9 mm (4.55 %), and 4–4.9 mm (1.52 %) (Fig. 5 C.1). The debris types consisted mainly of fibers [94.2 %), followed by fragments [5.8 %) [Fig. 5 C.2). In terms of colour, black microparticles were the most common [41 %), followed by white/transparent [21 %), blue [18 %), light blue [14 %), brown [5 %), and red [1 %) [Fig. 5 C.3).

3.3. Polymer characterization

A subsample of macro- and mesoplastics, represented by plastic fragments and macrofibers were analysed using FTIR-ATR spectroscopy. In *C. aerea*, the main polymers identified were polyamide (PA), polyethylene (PE), and polypropylene (PP), (17 %), followed by cellulose acetate (CA, 13 %), styrene ethylene/butylene styrene (SEBS, 9 %), ethylene propylene diene monomer (EPDM, 9 %) polyacrylamide (PAM, 5 %) (Fig. 6A). In *H. cornuta*, the dominant polymer identified was PA, accounting for 50 %, followed by acrylic fiber (AC, 12 %), polyacrylamide (PAM, 12 %), polyacrylate (PAC, 13 %), and polytetrafluoroethylene (PTFE, 13 %) (Fig. 6B).

Among the 189 microparticles analysed, 69 exhibited spectra of insufficient quality due to intense fluorescence interference, significant peak overlap, and pronounced line broadening, rendering identification impossible. The remaining 120 microparticles were successfully identified by comparison with established spectral libraries. These included 40 items from *C. aerea*, 36 from *H. cornuta*, and 44 from water samples.

The polymeric analysis of particles isolated from *C. aerea* showed a mix of 11 different kind of anthropogenic microparticles. PU was most represented polymers (20 %), followed by ethylene propylene diene monomer (EPDM, 16 %), olefin fiber (OF, 8 %), polyethylene (PE, 8 %), polypropylene (PP, 8 %), poly-1-butene (PB, 4 %), polyacrylonitrile (PAN, 4 %), synthetic resin (4 %), polyethylene terephthalate (PET, 4 %), and polyethylene vinyl acetate (PEVA, 4 %) (Fig. 7 A.1). Cotton fibers represented the 20 % of total items (Supplementary Fig. 1).

In *H. cornuta*, the compositional analysis revealed 14 different anthropogenic microparticles. The predominant polymer was polyurethane (PU) [21 %), followed by polyacrylate (PAcr) (8 %), polyester (PES) [8 %), polyethylene-co-polypropylene (PE-co-PP) (8 %),

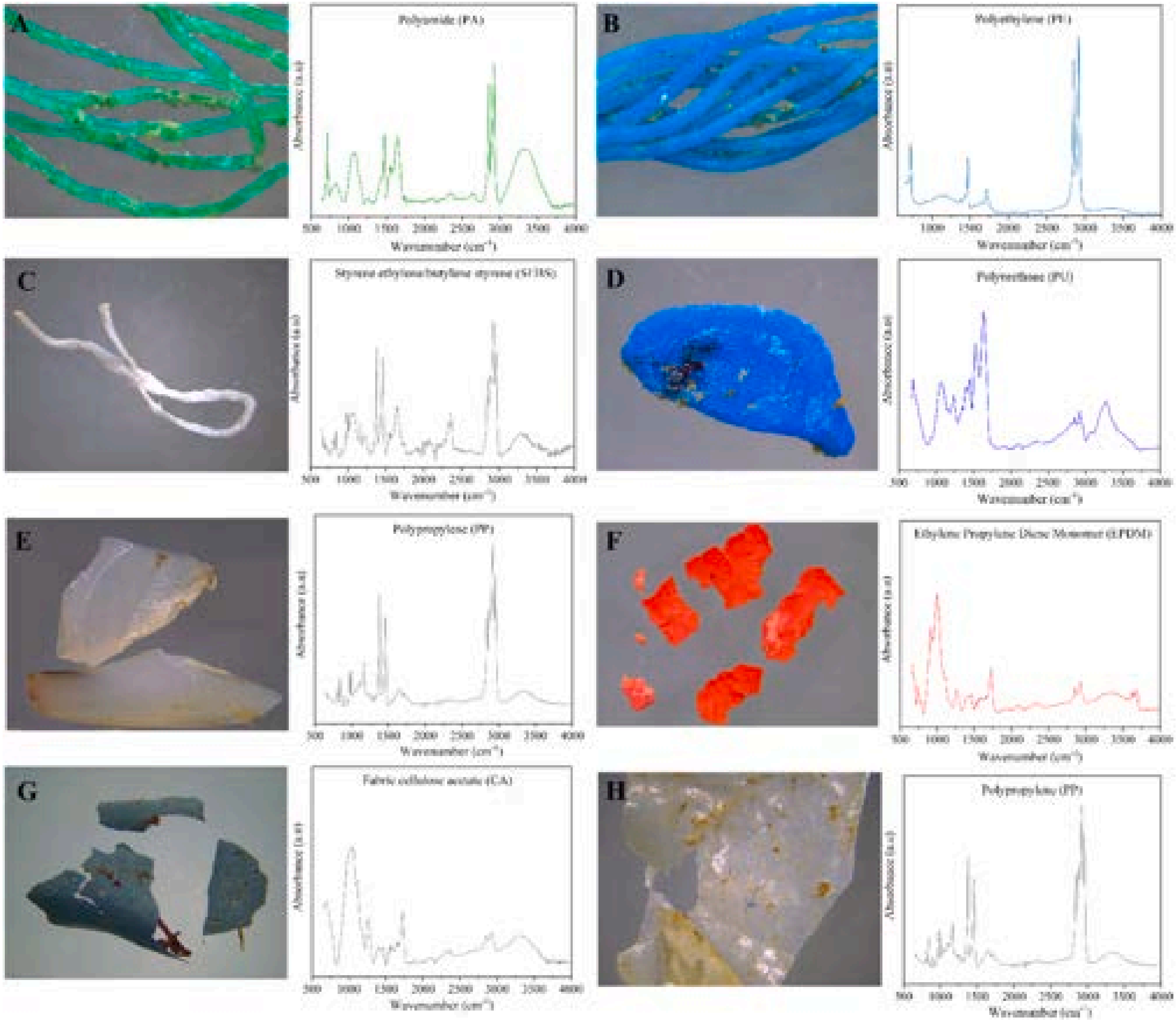

Fig. 4. Images of various mesoplastic samples entrapped in *Chaetomorpha aerea* and *Hypnea cornuta*, analysed using Fourier-transform infrared (FTIR) spectroscopy. From the top left, there is a green fiber made of polyamide (PA; A), a blue fiber of polyethylene (PE; B), a white fiber of styrene-ethylene/butylene-styrene (SEBS; C), a blue fragment of polyurethane (PU; D), a white/transparent fragment of polypropylene (PP; E), a red fragment of ethylene-propylene-diene monomer (EPDM; F), a grey fragment of fabric cellulose acetate (CA; G), and a transparent film of polypropylene (PP; H).

polytetrafluoroethylene (PTFE) (8 %), polyurethane rubber (PU Rubber) (7 %), poly(Styrene-co-Divinylbenzene) (PS-co-DVB) (4 %), polyamine (PAM) [4 %), polyethylene (PE) [3 %), polyolefin (PO) [3 %), and polypropylene (PP) (3 %). Cotton (15 %), cellulose acetate (CA) (4 %), and dyed cellulose [4 %) were also isolated Fig. 7 B.1 and Supplementary Fig. 1).

Regarding to the results of the statistical analysis, ANOSIM was applied to test the potential differences in microlitter composition. The global R was equal to 0.007 [$p > 0.05$), indicating that there are no statistically significant differences between the two species in terms of microlitter composition(items/g). The relative nMDS is shown in Fig. 8.

For water samples, the main category of microparticles identified included cotton (41 %), polyethylene vinyl acetate (PEVA) (19 %), polyethylene (PE) (13 %), dyed cellulose (11 %), polyurethane (PU) (8 %), polyacrylonitrile (PAN) (5 %), and cellulose acetate (CA) (3 %) (Fig. 7 C.1).

4. Discussion

This study assesses the presence of plastic litter trapped in two macroalgae species, *Chaetomorpha aerea* and *Hypnea cornuta,* in the brackish waters of a protected area. The samplings were restricted to the spring, summer, and autumn seasons. While these periods capture peak macroalgal growth, no data were collected during the winter season, when macroalgae are less abundant due to lower temperatures. This seasonal gap limits the understanding of year-round plastic entrapment dynamics. The reduced biomass in colder months likely diminishes the capacity of macroalgae to retain macroplastic debris. Additionally, further research across longer temporal scales would help generalize these findings and assess interannual variability

4.1. Trapping capacity of macroalgae

In this study, we found that algae act as a trap for plastic litter ranging from macro (> 25 mm) to micro (< 5 mm). Like other

Table 3
Abundance of anthropogenic microparticles on macroalgae and in the water of Ganzirri Lake [Cap-o Peloro Natural Reserve).

Categorization		*Chaetomorpha aerea* items/g	*Hypnea cornuta* items/g	Water items/ml
Size	< 1 mm	0.076	0.112	0.0010
	1–1.9 mm	0.148	0.152	0.0014
	2–2.9 mm	0.080	0.132	0.0004
	3–3.9 mm	0.036	0.072	0.0001
	4–4.9 mm	0.012	0.040	0.0001
Shape	Fibers	0.280	0.436	0.0030
	Fragments	0.068	0.036	0.0002
	Films	0.000	0.020	0.0000
	Foams	0.000	0.016	0.0000
	Spheres	0.004	0.000	0.0000
Colour	Blue	0.112	0.132	0.0006
	Black	0.100	0.168	0.0012
	White/ Transparent	0.068	0.144	0.0007
	Grey	0.012	0.016	0.0000
	Light blue	0.020	0.028	0.0005
	Red	0.016	0.000	0.0000
	Brown	0.020	0.020	0.0002
	Green	0.004	0.000	0.0000

macrophytes, including dune plants [56–57], mangroves [58–59], and seagrass [27,60–63], macroalgae entangle a significant amount of plastic litter [64] (Supplementary Table 1). In this study, *C. aerea* trapped more macroplastic items (4.91 items/kg) than *H. cornuta* (2.19 items/kg). While the statistical analysis did not reveal significant differences in plastic trapping between algae, these differences could become relevant over longer time scales or under changing environmental conditions (e.g., global warming). Long-term studies are necessary to clarify such potential differences.

The average abundance of microplastics on *C. aerea* (0.35 items/g) was 113 times higher than surrounding waters (0.0031 items/ml). This difference was higher in *H. cornuta* for which the average abundance (0.51 items/g) was 162 times higher than surrounding waters. In marine environment, Feng et al. [23] reported that the abundance of microplastics [MPs) in drifting *Ulva prolifera* was 595–3917 times higher than in seawater. Similarly, Gao et al. [24] found that in China, *U. prolifera* could retain MPs at concentrations up to 10,000 times greater than those in the surrounding water. In contrast, Feng et al. [22], analyzing *Pyropia yezoensis, Ulva prolifera, Sargassum horneri, Cladophora* sp.*, Undaria pinnatifida,* and *Ulva pertusa*, observed only a slight increase in MP retention by macroalgae,about 1.57 times higher than in the surrounding water. These differences in retention may be attributed to variations in algal species, sampling conditions, or analytical methods, as suggested by Li et al. [26].

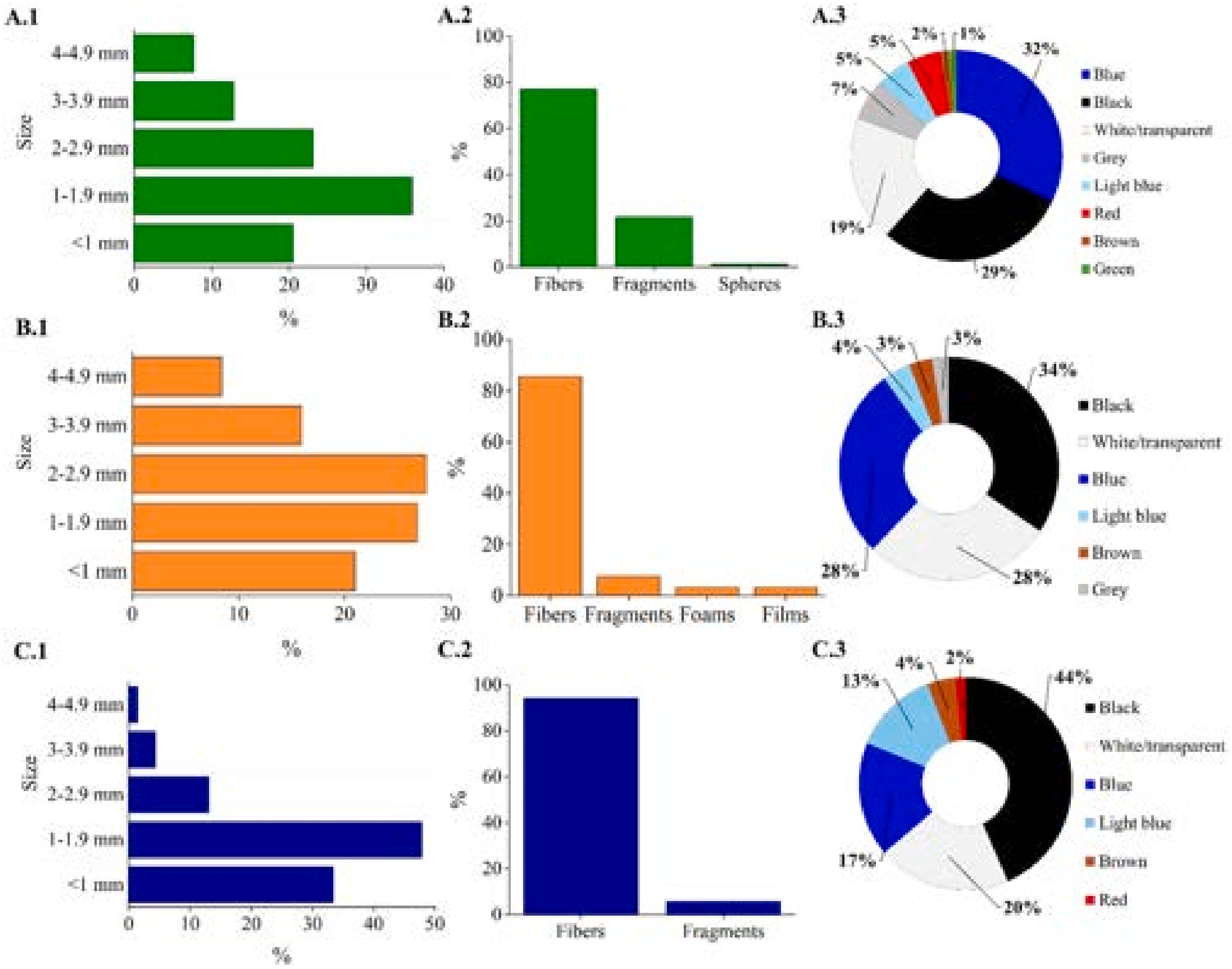

Fig. 5. Size (A.1, B.1, C.1), shape (A.2, B.2, C.2), and colour (A.3, B.3, C.3) of anthropic microparticles found in *Chaetomorpha aerea* (A), *Hypnea cornuta* (B), and water (C) samples from Ganzirri Lake.

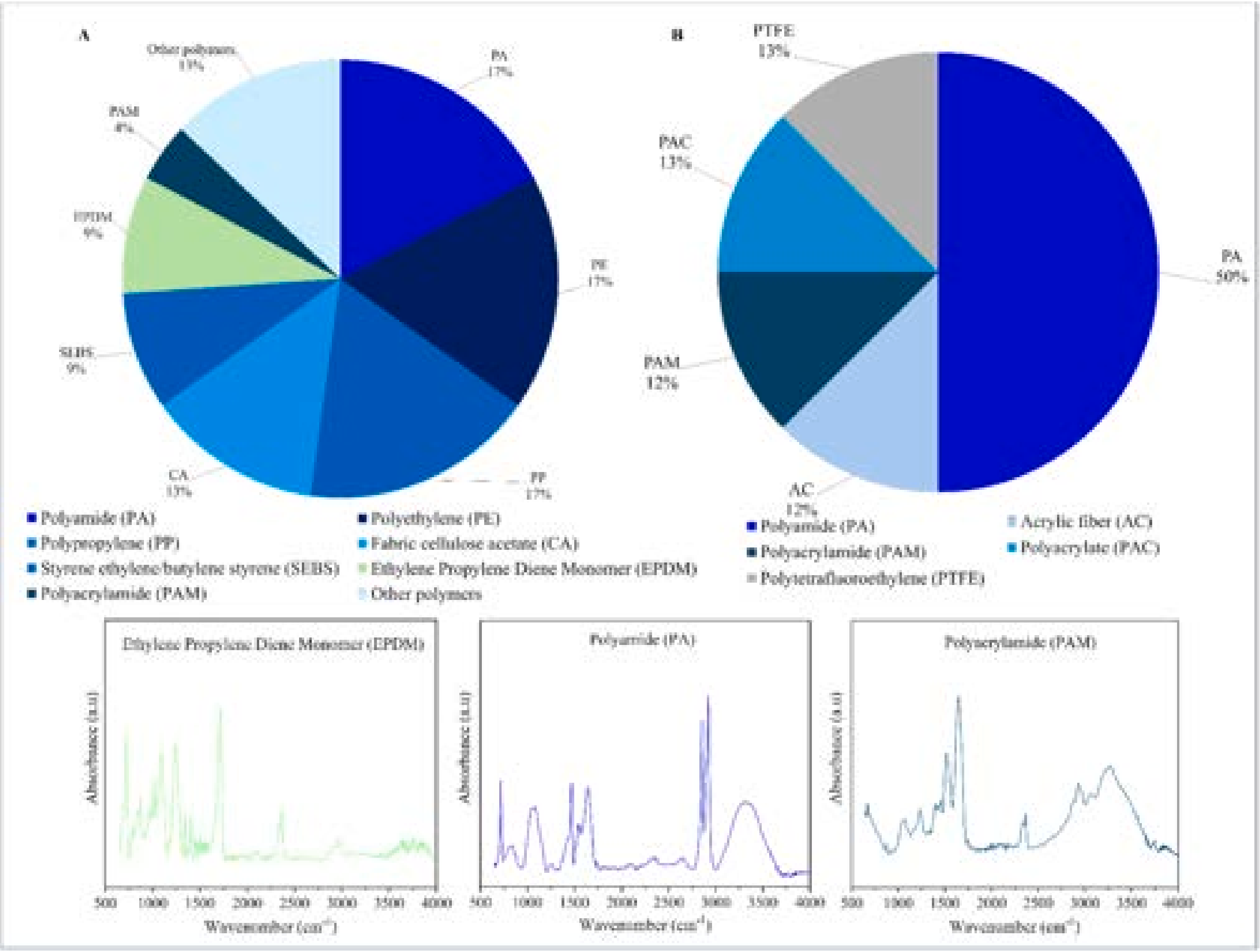

Fig. 6. Percentages of polymers (macro- and mesoplastics) found in *Chaetomorpha aerea* (A) and *Hypnea cornuta* (B) samples. FTIR spectra of ethylene propylene diene monomer (left), polyamide (middle), and polyacrylamide (right).

C. aerea, with its unbranched thallus, grows throughout the water column and features thick-walled ulvans and calcium carbonate deposits in its cell walls [65]. These structural and biochemical characteristics make the algal surface relatively rigid and smooth, which may limit the physical entrapment and electrostatic adhesion of microplastics. The presence of calcium carbonate may further hinder the attachment of MPs by reducing surface charge interactions. In contrast, *H. cornuta* attaches to substrates with its erect thallus, characterized by uniaxial apices and cross-sections, which may be more efficient in trapping MPs. Moreover, the cell wall of *H. cornuta* contains various types of carrageenans most likely kappa-carrageenan [66], which could facilitate the adhesion of MPs through electrostatic interactions and/or electric charges [67,68]. Carrageenans, being highly sulphated polysaccharides, confer a negative charge to the cell wall surface, enhancing the binding potential for positively charged or polar microplastic particles. This could explain the higher density of MPs observed in *H. cornuta*, especially when compared to the seawater background levels. Additionally, the morphological complexity of *H. cornuta* may promote the formation and retention of microbial biofilms on its surface. These biofilms produce extracellular polymeric substances (EPS) that can increase the adhesion of MPs through sticky, gel-like matrices. The interaction between MPs and biofilms on algal surfaces has been shown to be influenced by seasonal and spatial variability, further contributing to species-specific retention patterns [69,70]. Another possible explanation lies in the ecological positioning of the species: *H. cornuta* tends to form dense mats on substrates, which may passively accumulate MPs through sedimentation and water movement, while *C. aerea* growth is exposes it to more hydrodynamic forces, potentially reducing long-term particle retention.

In general, the presence of MPs on the surface of macroalgae can be explained by several mechanisms, as suggested by Goss et al. [60]. Macroalgae may trap MPs particles by producing chemicals or by using electrostatic interaction [71]. MPs can adhere to macrophytes through biofilms, which vary based on location and season, leading to differences in adhesive properties among biofilm communities [69,70].

As regards the changes that plastics and macroalgae can undergo, we must examine two types of problems. The macrophytes that cover the plastics determine biofouling, which involves a significant change in the surface of the plastic. This becomes rougher and more porous, exposed to the attack of other organisms and, increasing its weight, will tend to settle on the seabed, altering other habitats. This factor exponentially increases the ecological implications that plastics have in the environment. This important problem is also accompanied by a purely biological one, which focuses attention on the consequences that plant organisms suffer from interactions with plastics. From the literature data, it emerges that macrophytes can undergo significant morphological alterations. For example, Tuuri & Leterme [72] showed that *Elodea* sp., exposed to plastics, shows slowed growth and a significant decrease in the number of shoots. These data lead us to suspect that morphological alterations may also occur in macroalgae exposed to plastics [73]

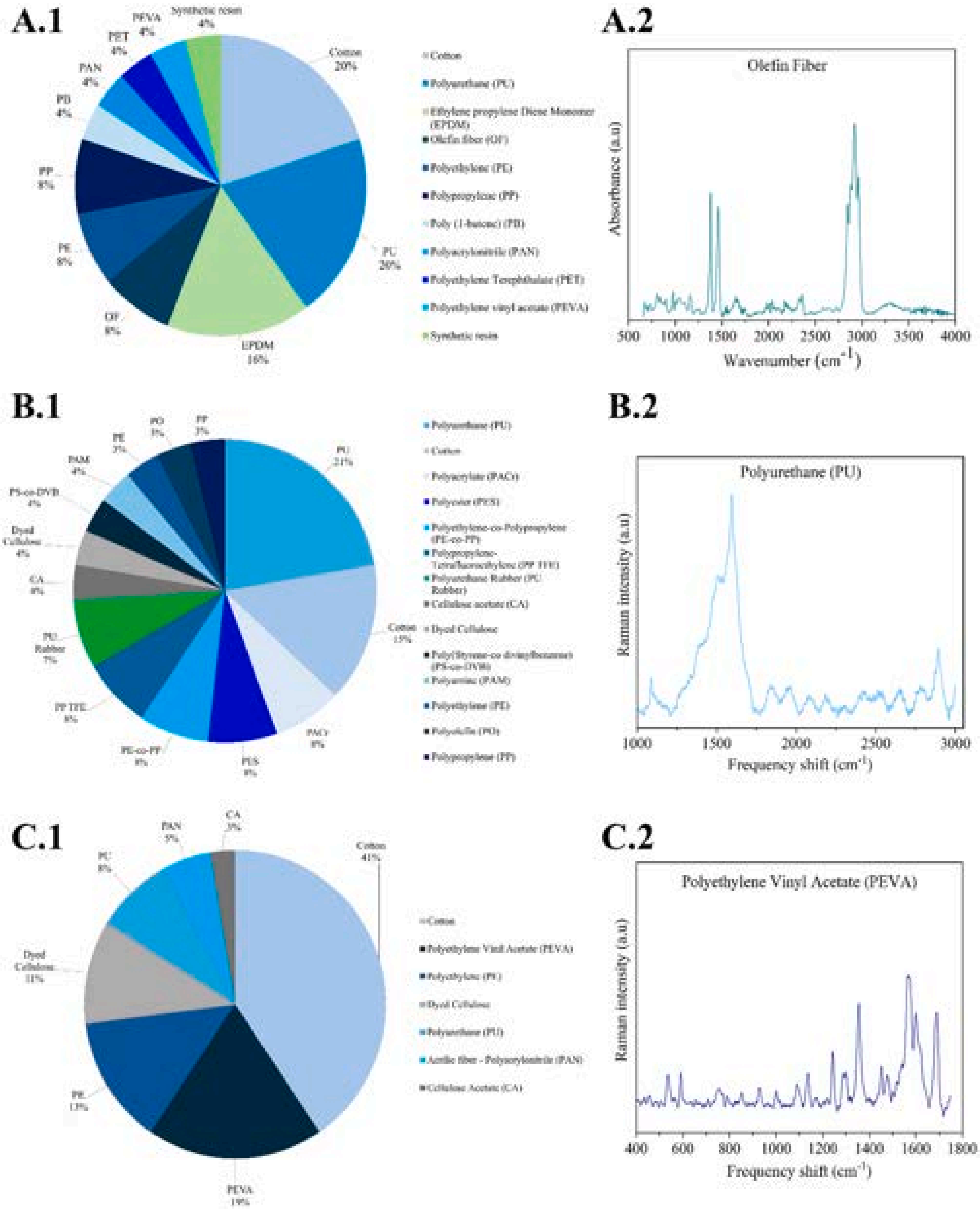

Fig. 7. Composition percentages of anthropogenic microparticles isolated from *Chaetomorpha aerea* (A.1), along with the FTIR-ATR spectra of olefin fiber (A.2). Anthropogenic microparticle percentages from *Hypnea cornuta* (B.1), with Raman spectra of polyurethane (B.2). Composition percentage of anthropogenic microparticles found in water samples (C.1), along with the Raman spectra of the polyethylene vinyl acetate (C.2).

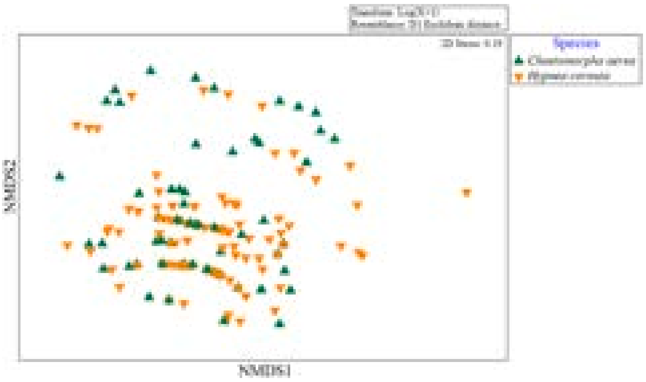

Fig. 8. Non-metric multi- dimensional scaling (nMDS) ordination of the algae according to micro-litter composition.

by the potential impact that these could have on the photosynthetic process, on the supply of nutrients or on other physiological processes. Knowledge in this field is still very limited; therefore, it would be desirable to investigate these issues in the future.

4.2. Polymer composition and sources

The predominance of fibers observed in this study strongly indicates textile-based pollution, likely originating from domestic wastewater discharges and urban runoff. This finding aligns with previous research highlighting microfibers as a major component of microplastic pollution in aquatic environments [74]. The occasional presence of fragments, foams, and films suggests the occurrence of secondary microplastic pollution, most likely resulting from the environmental degradation of larger plastic debris, such as packaging materials that enter the lake system. Colour analysis further supports these source attributions. Black fibers were the most dominant and are likely linked to tubular mussel farming nets, which are typically black in colour. The presence of blue fibers can be associated with polyester ropes used in mussel farming, indicating degradation of aquaculture equipment. These associations suggest that aquaculture and fishing activities are notable contributors to the microplastic pollution observed, in addition to terrestrial sources.

The FTIR and Raman analysis identified 16 synthetic polymers (e.g., PA, PE, PP, PU, PES, PET, PAcr, PEVA, PAN, PTFE, CA, SEBS, PAM, PO, PS-co-DVB, and synthetic resin), three elastomers (EPR, EPDM, and PU rubber) and two anthropogenic microfibers (cotton and dyed cellulose). A wider spectrum of anthropogenic microparticles was isolated in macroalgae, with 11 items in *C. aerea* and 14 in *H. cornuta*, compared to 7 items found in the water. Notably, we also detected elastomers such as EPR and EPDM, which have not been previously reported in similar marine macroalgal contexts. Our results revealed a greater diversity and complexity of polymer types compared to previous studies conducted in marine environment the Baltic Sea [27], the Yellow Sea, see Supplementary Table 1 [22–26].

This result is closely linked to the characteristics of the Ganzirri lake. In fact, as previously reported by Bottari et al. [44], this is a highly urbanised coastal area strongly affected by several anthropic activities [e.g. tourism, fishing, and mariculture activities). In addition, pollutants may also be introduced through runoff processes from human activities and illegal wastewater discharges [75]. These factors, together with low water circulation levels, make it a highly vulnerable site.

The most common anthropogenic microparticles found in the analysed samples (*C. aerea, H. cornuta*, and water) were cotton. The significant presence of cotton, along with smaller amounts of PES, PAcr, and dyed cellulose suggests an additional source of pollution, likely associated with domestic wastewater discharges. Their occurrence could be related to illegal wastewater discharges that have been observed around the lake perimeter in a recent past. Moreover, microfibers released from textiles through urban runoff represent another source of MPs contamination in coastal environments [76–78].

PE and PP are commonly associated with packaging and single-use products due to their relatively short lifespans. These polymers are among the most abundant in Mediterranean waters [79], in beach sediments [35,80], and they have been already documented in various marine species [78,81].

Moreover, the occurrence of PE, PP, and PA may be linked to the degradation of abandoned fishing gear and the release of waste from intensive mussel farming and fishing activities in the area. PU is a material widely used in marine coatings to protect vessels from corrosion and biofouling [82]. The presence of PU in this study could be likely linked to fishing vessels operating in the lake.

However, this study also identified other synthetic polymers from the elastomer class, such as EPR, EPDM, PU rubber, and synthetic resin. Notably, EPR is commonly used in the automotive industry for tyres and automotive parts, as well as in the production of tubes, O-rings, gaskets, accumulator bladders, and wire and cable connectors [83]. The presence of these elastomers is primarily associated with tyre wear on roads, with these materials entering the marine environment through runoff processes. This aligns with the fact that the Capo Peloro area experiences significant traffic along its coast and urban runoff [84].

All these plastic materials degrade over time due to mechanical stress, UV radiation, and biofouling, resulting in an ongoing influx of progressively smaller plastics into the aquatic ecosystem. Once released, these fibers not only contaminate the water column but also become entangled in macroalgae, increasing the risk of plastic bioaccumulation within the local food web, as has been previously observed in marine environment studies [22]. This raises concerns for macro-herbivorous organisms that consume these algae, as it may facilitate the entry of MPs into marine food webs [85] similar to what has been observed in seagrass-associated fishes [86] and detritivores invertebrates [87].

4.3. Algae removal

During late spring and early summer, *C. aerea* (and to a lesser extent *H. cornuta*) reproduces rapidly, accumulating significant biomass within Ganzirri lake. Mollusks farming cooperatives in the lake, in partnership with the management authority, routinely oversee its removal. In the past, both macroalgae were routinely collected and discarded; however, in recent years, the disposal process has not been completed, resulting in large amounts of these algae accumulating along the lake's shores. Consequently, plastic adhered to and/or trapped in macroalgae is simply moved by the water to the edges of the lake. It is important to emphasize that this practice is inappropriate, as it not only damages the area's aesthetics, but it could also interfere with the development of riparian vegetation. In contrast, proper disposal would provide multiple environmental recovery benefits. The collection of invasive algal species from Ganzirri Lake could offer a triple opportunity: 1) mitigating their negative impacts associated with excessive biomass, 2) removing plastic from the environment, and 3) transforming macroalgae into valuable resources, such as new bioactive compounds with biotechnological potential in different fields, including food and feed industries, cosmetic and pharmaceutical applications [68,88–93].

5. Conclusion

This study demonstrates the role of *Chaetomorpha aerea* and *Hypnea cornuta* as effective collectors of plastic debris in transitional environments, highlighting their potential use as bioindicators and as tools for monitoring and mitigating plastic pollution. Furthermore, this research emphasizes the urgent need to include macroalgae management into broader conservation frameworks to ensure the protection of biodiversity and the maintenance of critical ecosystem services.

Proper removal of macroalgae can significantly contribute to environmental sustainability by reducing the plastic pollution. To achieve this, regular cleaning programs, community engagement, and increased public awareness are essential. Furthermore, addressing the root causes of plastic pollution—such as overproduction and excessive consumption—requires well-structured policies and targeted initiatives. Local and regional administrations should be encouraged to establish dedicated working groups to assess specific situations and implement effective solutions.

This study lays the groundwork for future research on the role of macroalgae in plastic pollution management and supports the development of more sustainable strategies for for environmental conservation.

Environmental Implications

This study provides the evidence that *Chaetomorpha aerea* and *Hypnea cornuta* effectively collect plastic debris in transitional waters. Our findings highlight the potential of macroalgae as bioindicators for plastic pollution. These species offer a promising approach for monitoring and reducing plastic pollution in transitional waters. We emphasize the need to integrate macroalgae management into conservation strategies to protect transitional waters, particularly in areas like Capo Peloro Lagoon, which face threats from urbanization and low water circulation.

CRediT authorship contribution statement

Valeria Conti Nibali: Writing – review & editing, Validation, Formal analysis. **Giuseppa Genovese:** Writing – review & editing, Formal analysis. **Elisa Punzo:** Writing – review & editing, Formal analysis. **Mikołaj Mazurkiewicz:** Writing – review & editing, Validation, Formal analysis. **Teresa Bottari:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Giovanna D'Angelo:** Writing – review & editing, Supervision, Formal analysis, Data curation. **Monique Mancuso:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Data curation. **Bilal Mghili:** Writing – review & editing, Supervision, Formal analysis, Data curation. **Caterina Branca:** Writing – review & editing, Validation, Formal analysis. **Francesca Fabrizi:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Damiano Spagnuolo:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Funding

This study was funded by the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4 - Call for tender No. 3138 of 16 December 2021, rectified by Decree n.3175 of 18 December 2021 of the Italian Ministry of University and Research funded by the European Union – Next Generation EU. Award Number: Project code CN_00000033, Concession Decree No. 1034 of 17 June 2022 adopted by the Italian Ministry of University and Research, Project title "National Biodiversity Future Center - NBFC".

Declaration of Competing Interest

All authors must disclose any financial and personal relationships with other people or organizations that could inappropriately influence or bias their work.

Acknowledgements

Special thanks to Massimiliano Pinat, Fabrizio Lanzafame, Giulia Celeste, and Maria Timenkova for their administrative support. Additionally, the authors would like to thank Maria Letizia Molino, the manager of the Cape Peloro Natural Reserve, for facilitating the collection of samples. Thank you to Giovanni Ficarra for his valuable advice and to the four anonymous reviewers for their constructive feedback.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2025.139114.

Data availability

Data will be made available on request.

References

[1] Barnes, D.K., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos Trans R Soc Lond B Biol Sci 364 (1526), 1985–1998. https://doi.org/10.1098/rstb.2008.0205.

[2] Chen, Z., Si, W., Johnson, V.C., Oke, S.A., Wang, S., Lv, X., Tan, M.L., Zhang, F., Ma, X., 2025. Remote sensing research on plastics in marine and inland water: Development, opportunities and challenge. J Environ Manag 373, 123815. https://doi.org/10.1016/j.jenvman.2024.123815.

[3] Zheng, H., Huang, S., Huang, J., Zeng, H., Xu, M., Cai, A., Zhou, S., Ma, X., Deng, J., 2024. Unveiling the optical and molecular characteristics of aging microplastics derived dissolved organic matter transformed by UV/chlor[am]ine oxidation and its potential for disinfection byproducts formation. J Hazard Mater 480, 136440. https://doi.org/10.1016/j.jhazmat.2024.136440.

[4] Lin, J., Cheng, Q., Kumar, A., Zhang, W., Yu, Z., Hui, D., Zhanga, C., Shana, S., 2025. Effect of degradable microplastics, biochar and their coexistence on soil organic matter decomposition: a critical review. TrAC 183, 118082. https://doi.org/10.1016/j.trac.2024.118082.

[5] Porcino, N., Bottari, T., Mancuso, M., 2023. Is wild marine biota affected by microplastics. Animals 13, 147. https://doi.org/10.3390/ani13010147.

[6] Contino, M., Ferruggia, G., Indelicato, S., Pecoraro, R., Scalisi, E.M., Salvaggio, A., Brundo, M.V., 2023. Polystyrene nanoplastics in aquatic microenvironments affect sperm metabolism and fertilization of *Mytilus galloprovincialis* [Lamark, 1819). Toxics 11, 924. https://doi.org/10.3390/toxics11110924.

[7] Contino, M., Ferruggia, G., Pecoraro, R., Scalisi, E.M., Cavallaro, G., Bonaccorso, C., et al., 2023. Uptake routes and biodistribution of polystyrene nanoplastics on zebrafish larvae and toxic effects on development. Fishes 8 (3) https://doi.org/10.3390/ fishes8030168.

[8] Gündoğdu, S., Yeşilyurt, I.N., Abbas, Z., Baylan, M., 2024. Effects of microplastics on aquatic organisms: a comprehensive review. Article 2 Turk J Zool 48, 5. https://doi.org/10.3390/ani13010147.

[9] Jepsen, E.M., de Bruyn, P.J.N., 2019. Pinniped entanglement in oceanic plastic pollution: a global review. Mar Pollut Bull 145, 295–305. https://doi.org/10.1016/j.marpolbul.2019.05.042.

[10] Gunasekaran, K., Mghili, B., Bottari, T., Mancuso, M., Machendiranathan, M., 2024. Ghost fishing gear threatening aquatic biodiversity in India. Biol Conserv 291 (2), 110514. https://doi.org/10.1016/j.biocon.2024.110514.

[11] Nihart, A.J., Garcia, M.A., El Hayek, E., et al., 2025. Bioaccumulation of microplastics in decedent human brains. Nat Med 31, 1114–1119. https://doi.org/10.1038/s41591-024-03453-1.

[12] Amelia, T.S.M., Khalik, W.M.A.W.M., Ong, M.C., et al., 2021. Marine microplastics as vectors of major ocean pollutants and its hazards to the marine ecosystem and humans. Prog Earth Planet Sci 8, 1–26. https://doi.org/10.1186/s40645-020-00405-4.

[13] Tumwesigye, E., Nnadozie, C.F., Akamagwuna, F.C., Noundou, X.S., Nyakairu, G. W., Odume, O.N., 2023. Microplastics as vectors of chemical contaminants and biological agents in freshwater ecosystems: current knowledge status and future perspectives. Environ Pollut 330, 121829. https://doi.org/10.1016/j.envpol.2023.121829.

[14] McLusky, D.S., Elliott, M., 2007. Transitional waters: a new approach, semantics or just muddying the waters. Estuar Coast Shelf Sci 71 (3-4), 359–363. https://doi.org/10.1016/j.ecss.2006.08.025.

[15] Leonardi, M., Azzaro, F., Azzaro, M., Caruso, G., Mancuso, M., Monticelli, et al., 2009. Multidisciplinary study of the Cape Peloro brackish area [Messina, Italy): characterization of trophic conditions, microbial abundance and activities. Mar Ecol 30, 33–42. https://doi.org/10.1111/j.1439-0485.2009.00320.x.

[16] Lotze, H.K., Lenihan, H.S., Bourque, B.J., Bradbury, R.H., Cooke, R.G., Kay, M.C., et al., 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 312 (5781), 1806–1809. https://doi.org/10.1126/science.1128035.

[17] Lechthaler, S., Waldschläger, K., Stauch, G., Schüttrumpf, H., 2020. The way of macroplastic through the environment. Environments 7 (10), 73. https://doi.org/10.3390/environments7100073.

[18] Nasrabadi, A.E., Eydi, M., Bonyadi, Z., 2023. Utilizing *Chlorella vulgaris* algae as an eco-friendly coagulant for efficient removal of polyethylene microplastics from aquatic environments. Heliyon 9 (11), e22338. https://doi.org/10.1016/j.heliyon.2023.e22338.

[19] Lotfigolsefidi, F., Davoudi, M., Sarkhosh, M., et al., 2025. Removal of microplastics by algal biomass from aqueous solutions: performance, optimization, and modeling. Sci Rep 15, 501. https://doi.org/10.1038/s41598-024-84114-8.

[20] Nasoudari, E., Ameri, M., Shams, M., Ghavami, V., Bonyadi, Z., 2021. The biosorption of Alizarin Red S by *Spirulina platensis*; process modelling, optimisation, kinetic and isotherm studies. Int J Environ Anal Chem 103 (3), 633–647. https://doi.org/10.1080/03067319.2020.1862814.

[21] Abdallah, Y.K., Estevez, A.T., 2023. Biomaterials for water purification: integrating *Chlorella vulgaris* and *Monoraphidium conortum* in architectural systems for the biodegradation of sulfamethoxazole from wastewater. In: Nourishing Tomorrow: Clean Engineering and Nature-Friendly Living, World Scientific, pp. 213–243. https://doi.org/10.1142/9789811264375_0006.

[22] Feng, Z., Zhang, T., Wang, J., Huang, W., Wang, R., Xu, J., et al., 2020. Spatio-temporal features of microplastics pollution in macroalgae growing in an important mariculture area, China. Sci Total Environ 719, 137490. https://doi.org/10.1016/j.scitotenv.2020.137490.

[23] Feng, Z., Zhang, T., Shi, H., Gao, K., Huang, W., Xu, J., et al., 2020. Microplastics in bloom-forming macroalgae: distribution, characteristics and impacts. J Hazard Mater 397, 122752. https://doi.org/10.1016/j.jhazmat.2020.122752.

[24] Gao, F., Li, J., Hu, J., Li, X., Sun, C., 2020. Occurrence of microplastics carried on *Ulva prolifera* from the Yellow Sea. China CSCEE 2, 100054. https://doi.org/10.1016/j.cscee.2020.100054.

[25] Huang, Y., Xiao, X., Xu, C., Devi, Perianen, Y., Hu, J., Holmer, M., 2020. Seagrass beds acting as a trap of microplastics - emerging hotspot in the coastal region? Environ Pollut 257, 113450. https://doi.org/10.1016/j.envpol.2019.113450.

[26] Li, Q., Su, L., Ma, C., Feng, Z., Shi, H., 2022. Plastic debris in coastal macroalgae. Environ Res 205, 112464. https://doi.org/10.1016/j.envres.2021.112464.

[27] Esiukova, E.E., Lobchuk, O.I., Volodina, A.A., Chubarenko, I.P., 2021. Marine macrophytes retain microplastics. Mar Pollut Bull 171, 112738. https://doi.org/10.1016/j.marpolbul.2021.112738.

[28] Ben-Haddad, M., Rida Abelouah, M., Hajji, S., Abou Oualid, J., Rangel-Buitrago, N., Alla, A.A., 2024. Macroalgal blooms on Moroccan coasts: plastic trapping and tourism challenges. Reg Stud Mar Sci 70, 103390. https://doi.org/10.1016/j.rsma.2024.103390.

[29] Potoschi, A., Manganaro, A., Battaglia, P., 2002. Censimento della fauna ittica nei pantani di Capo Peloro (Sicilia Nord-orientale). Biol Mar Medit 9, 785–788.

[30] Giacobbe, S., 2012. Biodiversity loss in Sicilian transitional waters: the molluscs of Faro Lake. Biodivers J 3 (4), 501–510.

[31] Vitale, D., Giacobbe, S., Spinelli, A., De Matteo, S., Cervea, J.L., 2016. Opistobranch mollusks inventory of the Faro Lake, a Sicilian biodiversity hot spot. Italian. J Zool 83 (4), 524–530. https://doi.org/10.1080/11250003.2016.1236843.

[32] Bottari, T., Spinelli, A., Busalacchi, B., Rinelli, P., Giacobbe, S., 2017. Transplant trials of the fan mussel *Pinna nobilis* inside the coastal lagoon of Capo Peloro [Central Mediterranean, Italy). J Shellfish Res 36 (1), 3–8 https://doi.org/10.2983/ 035.036.0102.

[33] Iaria, C., Piro, M.G., Natale, S., Capparucci, F., Villari, G., Vico, G., Carella, F., 2025. Cytopathology and phylogeny of *Pinna nobilis* Picornavirus [PnPV) infecting haemocytes of the noble pen shell population from Lake Faro [Southern Italy). J Invertebr Pathol 14 (212), 108381. https://doi.org/10.1016/j.jip.2025.108381.

[34] Panuccio, M., 2011. Wind effects on visible raptor migration in spring at the Strait of Messina, Southern Italy. J Raptor Res 45 (1), 88–92.

[35] Branca, C., Fabrizi, F., Mghili, B., Conti-Nibali, V., Gunasekaran, K., Bottari, T., et al., 2025. Plastic pollution in a special protected area for migratory birds. Sci Total Environ 958, 177918. https://doi.org/10.1016/j.scitotenv.2024.177918.

[36] Mazzola, A., Bergamasco, A., Calvo, S., Caruso, G., Chemello, R., Colombo, F., et al., 2010. Sicilian transitional waters: current status and future development. Chem Ecol 26, 267–283. 〈〉https://hdl.handle.net/10447/65411.

[37] Parrino, V., Costa, G., Giannetto, A., De Marco, G., Cammilleri, G., Acar, Ü., et al., 2021. Trace elements [Al, Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn) in *Mytilus galloprovincialis* and *Tapes decussatus* from Faro and Ganzirri Lakes [Sicily, Italy): Flow cytometry applied for hemocytes analysis. J Trace Elem Biol 68, 126870. https://doi.org/10.1016/j.jtemb.2021.126870.

[38] Bruno, F., Nava, F., Fazio, F., Sansotta, C., Bruschetta, G., Licata, P., et al., 2024. Heavy Metals Bioaccumulation in *Mytilus galloprovincialis* and *Tapes decussatus* from Faro Lake [Messina), Italy. Biol Trace Elem Res 202, 5762–5770. https://doi.org/10.1007/s12011-024-04128-1.

[39] Manghisi, A., Morabito, M., Bertuccio, C., Le Gall, L., Couloux, A., Cruaud, C., et al., 2010. Is routine DNA barcoding an efficient tool to reveal introductions of alien macroalgae? A case study of *Agardhiella subulata* [Solieriaceae, Rhodophyta) in Cape Peloro lagoon [Sicily, Italy). Cryptogam Algol 31 (4), 423.

[40] de Jesus, P.B., Costa, A.L., Nunes, J.M.D.C., Manghisi, A., Genovese, G., Morabito, M., et al., 2019. Species delimitation methods reveal cryptic diversity in the *Hypnea cornuta* complex [Cystocloniaceae, Rhodophyta). Eur J Phycol 54 (2), 135–153. https://doi.org/10.1080/09670262.2018.1522454.

[41] Bertuccio, C., Genovese, G., Manghisi, A., Morabito, M., 2014. Changes in the benthic algal flora of lake Ganzirri, north-eastern Sicily [Italy). Nat Rerum 3 (2013/2014), 79–91.

[42] Bertuccio, C., 2013. Macroalgae. A guide to the observation of macroalgal flora in Ganzirri brackish pond, Cape Peloro Lagoon [Messina, Sicily), unicum of biodiversity and culture. Aracne Eds 236.

[43] Zhuo, T., He, L., Chai, B., Zhou, S., Wan, Q., Lei, X., Zhou, Z., Chen, B., 2023. Micro-pressure promotes endogenous phosphorus release in a deep reservoir by favouring microbial phosphate mineralisation and solubilisation coupled with sulphate reduction. Water Res 245, 120647. https://doi.org/10.1016/j.watres.2023.120647.

[44] Bottari, T., Houssa, R., Brundo, M.V., Mghili, B., Maaghloud, H., Mancuso, M., 2024. Plastic litter colonization in a brackish water environment. Sci Total Environ 912, 169177. https://doi.org/10.1016/j.scitotenv.2023.169177.

[45] Krelling, A.P., Williams, A.T., Turra, A., 2017. Differences in perception and reaction of tourist groups to beach marine debris that can influence a loss of tourism revenue in coastal areas. Mar Policy 85, 87–99. https://doi.org/10.1016/J. Marpol.2017.08.021.

[46] Beaumont, N.J., Aanesen, M., Austen, M.C., Börger, T., Clark, J.R., Cole, M., et al., 2019. Global ecological social and economic impacts of marine plastic. Mar Pollut Bull 142, 189–195 https://doi. org/10.1016/j.marpolbul.2019.03.022.

[47] Bottari, T., Mghili, B., Gunasekaran, K., Mancuso, M., 2024. Impact of plastic pollution on marine biodiversity in Italy. Water 16, 519. https://doi.org/10.3390/w16040519.

[48] Dong, C.D., Chen, C.W., Chen, Y.C., Chen, H.H., Lee, J.S., Lin, C.H., 2020. Polystyrene microplastic particles: in vitro pulmonary toxicity assessment. J Hazard Mater 385, 121575. https://doi.org/10.1016/j.jhazmat.2019.121575.

[49] Anifowoshe, A.T., Akhtar, M.N.M., Abisola, S., Asem, S.I., Toyyibah, F., Nongthomba, U., 2025. Microplastics: a threat to Fetoplacental unit and Reproductive systems. Toxicol Rep 14, 101938. https://doi.org/10.1016/j.toxrep.2025.101938.

[50] Bergamasco, A., 2008. Caratterizzazione della qualita` degli ambienti acquatici di transizione della Regione Sicilia. Final Rep Act 2005–2006.

[51] Ferrarin, C., Bergamasco, A., Umgiesser, G., Cucco, A., 2013. Hydrodynamics and spatial zonation of the capo Peloro coastal system [Sicily) through 3-D numerical modelling. J Mar Syst 117-118, 96–107.

[52] Micalizzi, G., Chiaia, V., Mancuso, M., Bottari, T., Mghili, B., D'Angelo, G., et al., 2024. Investigating the effects of microplastics on the metabolism of *Trematomus bernacchii* from the Ross Sea [Antarctica). Sci Total Environ 955, 176766. https://doi.org/10.1016/j.scitotenv.2024.176766.

[53] Savoca, S., Capillo, G., Mancuso, M., Bottari, T., Crupi, R., Branca, C., et al., 2019. Microplastics occurrence in the Tyrrhenian waters and in the gastrointestinal tract of two congener species of seabreams. Environ Toxicol Pharm 67, 35–41. https://doi.org/10.1016/j.etap.2019.01.011.

[54] Munno, K., De Frond, H., O'Donnell, B., Rochman, C.M., 2020. Increasing the accessibility for characterizing microplastics: introducing new application-based and spectral libraries of plastic particles [SLoPP and SLoPP-E. Anal Chem 92 (3), 2443–2451. https://doi.org/10.1021/acs.analchem.9b03626.

[55] Anderson, M.J., 2024. A Quick Guide to PRIMER. PRIMER-e Learning Hub. PRIMER-e, Auckland, New Zealand. 〈https://learninghub.primer-e.com/books/a-quick-guide-to-primer〉.

[56] Ben-Haddad, M., Abelouah, M.R., Hajji, S., Rangel-Buitrago, N., Alla, A.A., 2023. The halophyte *Cakile maritima* Scop. 1772 as a trap of plastic litter on the Moroccan coast. Mar Pollut Bull 187, 114574. https://doi.org/10.1016/j.marpolbul.2023.114574.

[57] Mancuso, M., Genovese, G., Porcino, N., Natale, S., Crisafulli, A., Spagnuolo, D., et al., 2023. Psammophytes as traps for beach litter in the Strait of Messina [Mediterranean Sea). Reg Stud Mar Sci 65, 103057. https://doi.org/10.1016/j.rsma.2023.103057.

[58] Martin, B., Huveneers, C., Reeves, S., Baring, R., 2025. Mangrove-associated Pacific oysters [*Magallana gigas*) influence estuarine biodiversity. Neobiota 98, 1–26. https://doi.org/10.3897/neobiota.98.131103.

[59] Luo, Y.Y., Christelle Not, C., Cannicci, S., 2021. Mangroves as unique but understudied traps for anthropogenic marine debris: a review of present information and the way forward. Environ Pollut 271, 116291. https://doi.org/10.1016/j.rsma.2023.103057.

[60] Goss, H., Jaskiel, J., Rotjan, R., 2018. *Thalassia testudinum* as a potential vector for incorporating microplastics into benthic marine food webs. Mar Pollut Bull 135, 1085–1089. https://doi.org/10.1016/j.marpolbul.2018.08.024.

[61] Jones, K.L., Hartl, M.G.J., Bell, M.C., Capper, A., 2020. Microplastic accumulation in a *Zostera marina* L. bed at Deerness Sound, Orkney, Scotland. Mar Pollut Bull 152, 110883. https://doi.org/10.1016/j.marpolbul.2020.110883.

[62] Porcino, N., Bottari, T., Falco, F., Natale, S., Mancuso, M., 2023. Posidonia spheroids intercepting plastic litter: implications for beach clean-ups. Sustainability 15, 15740 https://doi.org/10.3390/ su152215740.

[63] Rigatou, D., Gerakaris, V., Digka, N., Adamopoulou, A., Patsiou, D., Hatzonikolakis, Y., et al., 2025. The role of seagrass meadows [*Posidonia oceanica*) as microplastics sink and vector to benthic food webs. Mar Pollut Bull 211, 117420. https://doi.org/10.1016/j.marpolbul.2024.117420.

[64] Li, Q., Su, L., Ma, C., Feng, Z., Shi, H., 2022. Plastic debris in coastal macroalgae. 2022. Environ Res 205, 112464. https://doi.org/10.1016/j.envres.2021.112464.

[65] Aluta, U.P., Aderolu, A.Z., Ishola, I.O., Alyassin, M., Morris, G.A., Olajide, O.A., 2022. Polysaccharides from tropical green seaweed *Chaetomorpha antennina* induces non-specific immune responses and improves antioxidative activities in common carp [*Cyprinus carpio*) leukocyte culture cell line. Algal Res 67, 102872. https://doi.org/10.1016/j.algal.2022.102872.

[66] Souza, R.B., Frota, A.F., Silva, J., Alves, C., Neugebauer, A.Z., Pinteus, S., et al., 2018. In vitro activities of kappa-carrageenan isolated from red marine alga *Hypnea musciformis*: antimicrobial, anticancer and neuroprotective potential. Int J Biol Macromol 112, 1248–1256. https://doi.org/10.1016/j.ijbiomac.2018.02.029.

[67] De Alcântara, M.G., De Freitas Ortega, N., Souza, C.J.F., Garcia-Rojas, E.E., 2020. Electrostatic hydrogels formed by gelatin and carrageenan induced by acidification: rheological and structural characterization. Food Struct 24, 100137. https://doi.org/10.1016/j.foostr.2020.100137.

[68] Zammuto, V., Rizzo, M.G., Spanò, A., Genovese, G., Morabito, M., Spagnuolo, D., et al., 2022. In vitro evaluation of antibiofilm activity of crude extracts from macroalgae against pathogens relevant in aquaculture. Aquac 549, 737729. https://doi.org/10.1016/j.aquaculture.2021.737729.

[69] Oberbeckmann, S., Loeder, M.G.J., Gerdts, G., Osborn, M., 2014. Spatial and seasonal variation in diversity and structure of microbial biofilms on marine

plastics in Northern European waters. FEMS Microbiol Ecol 90 (2), 478–492. https://doi.org/10.1111/1574 6941.12409.

[70] Rummel, C.D., Jahnke, A., Gorokhova, E., Kühnel, D., Schmitt-Jansen, M., 2017. Impacts of biofilm formation on the fate and potential effects of microplastic in the aquatic environment. Environ Sci Technol Lett 4 (7). https://doi.org/10.1021/acs.estlett, 7b00164.

[71] Li, J., Shan, E., Zhao, J., Teng, J., Wang, Q., 2023. The factors influencing the vertical transport of microplastics in marine environment: a review. Sci Total Environ 870, 161893. https://doi.org/10.1016/j.scitotenv.2023.161893.

[72] Tuuri, E.M., Leterme, S.C., 2023. How plastic debris and associated chemicals impact the marine food web: a review. Environ Pollut 321, 121156. https://doi.org/10.1016/j.envpol.2023.121156.

[73] Bhuyan, M.S., Senapathi, V., Karthikeyan, S., Tarikul, Islam Md, Iheanacho, S., Choudhury, A.K., 2025. Microplastics contamination in seaweed: impacts on human health and mitigation approaches. Discov Oceans 2, 2. https://doi.org/10.1007/s44289-025-00041-0.

[74] Liu, J., Liu, Q., An, L., et al., 2022. Microfiber pollution in the earth system. Rev Environ Contam [Former Residue Rev) 260, 13. https://doi.org/10.1007/s44169-022-00015-9.

[75] Kim, S., Tanaka, Y., Nakamura, H., 2023. Fukushima contaminated water risk factor: global implications. J Environ Manag 343, 118259. https://doi.org/10.1016/j.jenvman.2023.118259.

[76] Almroth, B.M.C., Åström, L., Roslund, S., Petersson, H., Johansson, M., Persson, N. K., 2018. Quantifying shedding of synthetic fibers from textiles; a source of microplastics released into the environment. Environ Sci Pollut Res 25, 1191–1199. https://doi.org/10.1007/s11356-017-0528-7.

[77] Galafassi, S., Nizzetto, L., Volta, P., 2019. Plastic sources: a survey across scientific and grey literature for their inventory and relative contribution to microplastics pollution in natural environments, with an emphasis on surface water. Sci Total Environ 693, 133499. https://doi.org/10.1016/j.scitotenv.2019.07.305.

[78] Bouzekry, A., Mghili, B., Bouadil, O., Mancuso, M., Ben-Haddad, M., Bottari, T., et al., 2023. First report of microplastic ingestion in edible fish along Moroccan Mediterranean Coasts. Sustainability 15 (23), 16313. https://doi.org/10.3390/su152316313.

[79] Suaria, G., Avio, C.G., Mineo, A., Lattin, G.L., Magaldi, M.G., Belmonte, G., et al., 2016. The Mediterranean Plastic Soup: synthetic polymers in Mediterranean surface waters. Sci Rep 6 (1), 37551. https://doi.org/10.1038/srep37551.

[80] Bouzekry, A., Mghili, B., Mancuso, M., Bouadil, O., Bottari, T., Aksissou, M., 2024. Anthropogenic microparticles abundance in sandy beach sediments along the Tetouan coast [Morocco Mediterranean]. Environments 11, 83. https://doi.org/10.3390/environments11040083.

[81] Markic, A., Gaertner, J.C., Gaertner-Mazouni, N., Koelmans, A.A., 2020. Plastic ingestion by marine fish in the wild. Crit Rev Environ Sci Technol 50 (7), 657–697. https://doi.org/10.1080/10643389.2019.1631990.

[82] Pistone, A., Scolaro, C., Visco, A., 2021. Mechanical properties of protective coatings against marine fouling: a review. Polym J 13 (2), 173. https://doi.org/10.3390/polym13020173.

[83] Qi, L., 2015. The application of ethylene propylene rubber production technology research. International Conference on Mechatronics, Electronic. Ind Control Eng [MEIC15) 1610–1613. https://doi.org/10.2991/meic-15.2015.368.

[84] Somma, R., Spoto, S.E., Giacobbe, S., 2024. Geological and structural framework, inventory, and quantitative assessment of geodiversity: the case study of the Lake Faro and Lake Ganzirri Global Geosites (Italy). Geosciences 14, 236 https://doi.org/10.3390/ geosciences14090236.

[85] Yang, X., Wang, H., Zhang, L., Kong, L., Chen, Y., He, Q., et al., 2021. Marine algae facilitate transfer of microplastics and associated pollutants into food webs. Sci Total Environ 787, 147535. https://doi.org/10.1016/j.scitotenv.2021.147535.

[86] Baalkhuyur, F.M., Bin Dohaish, E.J.A., Elhalwagy, M.E.A., Alikunhi, N.M., AlSuwailem, A.M., Røstad, A., et al., 2018. Microplastic in the gastrointestinal tract of fishes along the Saudi Arabian Red Sea coast. Mar Pollut Bull 131, 407–415 https://doi.org/10. 1016/j.marpolbul.2018.04.040.

[87] Andrade, C., Sepúlveda, T., Pinto, B., et al., 2025. The feeding mode effect: influence on particle ingestion by four invertebrates from Sub-Antarctic and Antarctic waters. Environ Sci Pollut Res 32, 8318–8339. https://doi.org/10.1007/s11356-025-36144-6.

[88] Marino, F., Di Caro, G., Gugliandolo, C., Spano, A., Faggio, C., Genovese, G., et al., 2016. Preliminary study on the in vitro and in vivo effects of *Asparagopsis taxiformis* bioactive phycoderivates on teleosts. Front Physiol 7, 459. https://doi.org/10.3389/fphys.2016.00459.

[89] Arori, M.K., Muthumbi, M.K., Mutia, A.W.N., Nyonje, B, G.M., 2019. Potential of seaweeds [*Hypnea cornuta* and *Hypnea musciformis*) in Nile tilapia [*Oreochromis niloticus*) fingerlings diets. Int J Fish Aquat Stud 7, 103–107. https://doi.org/10.1007/s10811-021-02676-w.

[90] Zammuto, V., Rizzo, M.G., Spanò, A., Spagnuolo, D., Di Martino, A., Morabito, M., et al., 2022. Effects of crude polysaccharides from marine macroalgae on the adhesion and biofilm formation of *Pseudomonas aeruginosa* and *Staphylococcus aureus*. Algal Res 63, 102646. https://doi.org/10.1016/j.algal.2022.102646.

[91] Saragih, H.T., Fauziah, I.N., Saputri, D.A., Chasani, A.R., 2024. Dietary macroalgae *Chaetomorpha linum* supplementation improves morphology of small intestine and pectoral muscle, growth performance, and meat quality of broilers. Vet World 17 (2), 470. https://doi.org/10.14202/vetworld.2024.470-479.

[92] Sirikwa, L.N., Manguramas, Y.J., Anh, N.T.N., Giang, H.T., 2024. A review of biology and applications of *Chaetomorpha linum* [Müller) Kützing in global aquaculture. J Appl Phycol 1–22. https://doi.org/10.1007/s10811-024-03253-7.

[93] Ficarra, G., Lauro, R., De Maria, L., Irrera, N., Cicero, N., Bitto, A., 2024. *Ulva lactuca* a natural occurring source of minerals to promote bone health and sustain athlete performance. Ital Sci J 1 (4). ⟨https://www.doi.org/10.62684/TPMV8987⟩.