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Spatial and temporal distribution of marine debris in coastal sediment of South Caspian Sea: effect on coastal nematode communities

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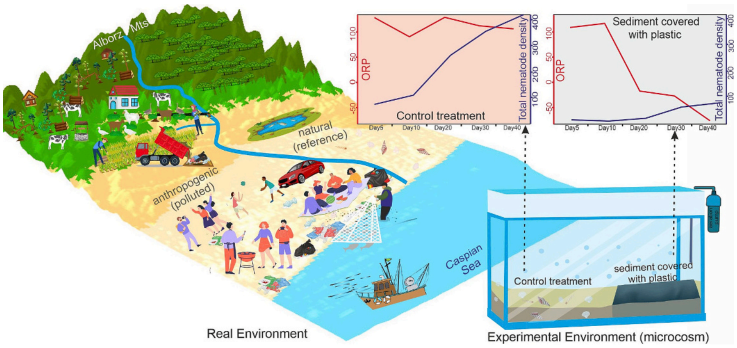
HIGHLIGHTS

- Debris numbers differed significantly between winter and summer at a site.
- Clean Coast Index: 20 % clean, 40 % moderately clean, and 40 % dirty/very dirty.
- Macroplastics on sediment reduced ORP and altered total nematode community.
- Nematode density and diversity declined under macroplastics treatments.

GRAPHICAL ABSTRACT



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ABSTRACT

The present study investigated the spatial and temporal distribution, as well as the composition of coastal debris, with a particular focus on the effects of macroplastics on nematode communities in the sediments of the southern Caspian Sea. Samples were collected on ten sampling site during two season summer and winter of 2023. A total of 7283 and 7766 pieces of coastal debris were collected from the studied areas in summer and winter, respectively. Debris density ranged from 0.18 to 0.84 items/m^2 and 0.17 to 1.04 items/m^2 in summer and winter, respectively. Generally, the results showed the highest concentration at the central stations and the lowest at the eastern stations. Plastic items, especially plastic bags, predominated the debris, constituting 60.35 % and 60.82 % of the total debris collected in summer and winter, respectively. Based on Clean Coast Index (CCI), sampling sites ranged clean to dirty and clean to extremely dirty in summer and winter, respectively.

In the laboratory, the impact of single-use plastic bags on nematode community characteristics was investigated experimentally in a microcosm study over 5, 10, 20, 30, and 40 days in five separate aquariums. The results showed that macroplastics on sediment significantly ($p < 0.05$) reduced sediment oxygen reduction potential (ORP) among the various times and treatments and altered the total nematode community. Additionally, total

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nematode density and diversity indices significantly decreased under macroplastics treatments each time ($p < 0.05$). These findings highlight the detrimental effects of marine debris on ecosystem health.

1. Introduction

The disposal and accumulation of debris in coastal and marine environments pose one of the fastest-growing threats to the health of global coastal and marine ecosystems. Any persistent solid material, produced or processed, discarded, disposed of or abandoned in marine and coastal environments is called marine debris (UNEP, 2009). Marine debris includes items made by people that are directly or indirectly, intentionally or accidentally dumped in seas, rivers or beaches. Marine debris is made up of many different types of materials and can be classified into several distinct categories such as plastics, metals, glass, processed wood, paper, clothing and textiles (Edyvane et al., 2004; Galgani et al., 2010). Marine debris originates from a wide range of sources. The majority of marine debris (approximately 80 %) entering the seas and oceans originates from land-based sources (Allsopp et al., 2006), and a portion of marine debris can be attributed to maritime transport, industrial exploration and offshore oil platforms, fishing and aquaculture (UNEP, 2009). Marine debris is present in all marine habitats, from densely populated areas to remote areas far from human activities. The density of marine debris varies markedly across locations and is shaped by human activity, hydrological and meteorological conditions, geomorphology, entry points, and the physical characteristics of the debris. Studies confirm that litter is transported by ocean currents and tends to accumulate in a limited number of convergence zones or subtropical gyres (UNEP and NOAA, 2011). Although the types of debris in coastal and marine areas vary across the world, plastic materials generally account for the largest amount of debris in coastal and marine ecosystems worldwide. Generally, about 60 to 80 % of coastal and marine debris is plastic (Derraik, 2002; Gregory and Ryan, 1997).

Macroplastics (items >5 mm) pose substantial environmental concerns, with a pronounced impact on coastal regions. This category includes bottles, fishing gear, larger debris, and single-use plastic bags. The primary sources of macroplastics, especially single-use plastics in coastal areas, are industrial discharges, as well as tourism and recreational activities (Sarafraz et al., 2016; Taheri et al., 2018). Single-use plastics contribute substantially to the global plastic waste crisis, as they are often discarded after minimal utility. Approximately 5 % of all plastic produced ultimately makes its way to coastal habitats as debris (Green et al., 2015; Jambeck et al., 2015), and about 70 % of plastic debris eventually settles on the seafloor, contributing to pollution and threatening marine and coastal ecosystems (Thie et al., 2003). Due to their durability and low degradation rate, macroplastic debris can accumulate and concentrate in coastal sediments (Nabizadeh et al., 2019; Hidalgo-Ruz and Thie, 2013) therefore, they can have long-lasting and significant impacts on the fauna that inhabit these sediments. However, over time, sunlight and wave action can break down macroplastics into smaller fragments, leading to microplastics, which can be ingested by marine organisms, entering the food chain (Provencher et al., 2014; Goldstein and Goodwin, 2013; Steer et al., 2017).

The Caspian Sea, the largest inland body of water on earth, is classified as a non-tidal lake. This sea faces serious threats, including physical modification, water and sediment pollution, coastal erosion, water level fluctuations, and climate change (Bastami et al., 2014: Bastami et al., 2018; Lahijani et al., 2023), as well as plastic pollution (Manbohi et al., 2021a and Manbohi et al., 2021b). The Iranian coastline along the Caspian Sea extends approximately 820 km and includes the provinces of Golestan, Mazandaran, and Guilan. The primary economic activities in this region are agriculture, tourism, and fisheries. More than 8 million people reside in these provinces, but during the New Year and summer holidays, the population typically increases by over 40 % (Mehdinia et al., 2020). This surge in visitors contributes to coastal pollution from plastic waste and other materials.

Various studies have investigated the amount and composition of debris in coastal and marine areas and the effects of debris, especially plastic materials, on benthic communities (Raju and Matsushita, 2025, Laglbauer et al., 2014; Green et al., 2015; Veerasingam et al., 2020; Okuku et al., 2021; Clemente et al., 2018; Clemente et al., 2022; Taheri et al., 2024). However, there is limited information on debris accumulation in coastal sediments along the southern Caspian Sea. Understanding the spatial and temporal distribution of debris in the coastal sediments of the south Caspian Sea is critical for assessing its ecological impact, particularly on nematode communities-key bioindicators of sediment health. As macroplastics and other debris accumulate, they alter sediment structure, chemical composition, and trophic interactions, potentially disrupting nematode biodiversity and ecosystem functioning. This study provides essential baseline data on macroplastic pollution trends in a region facing intense anthropogenic pressure, bridging the gap between debris contamination and its cascading effects on benthic organisms. By linking debris dynamics to nematode

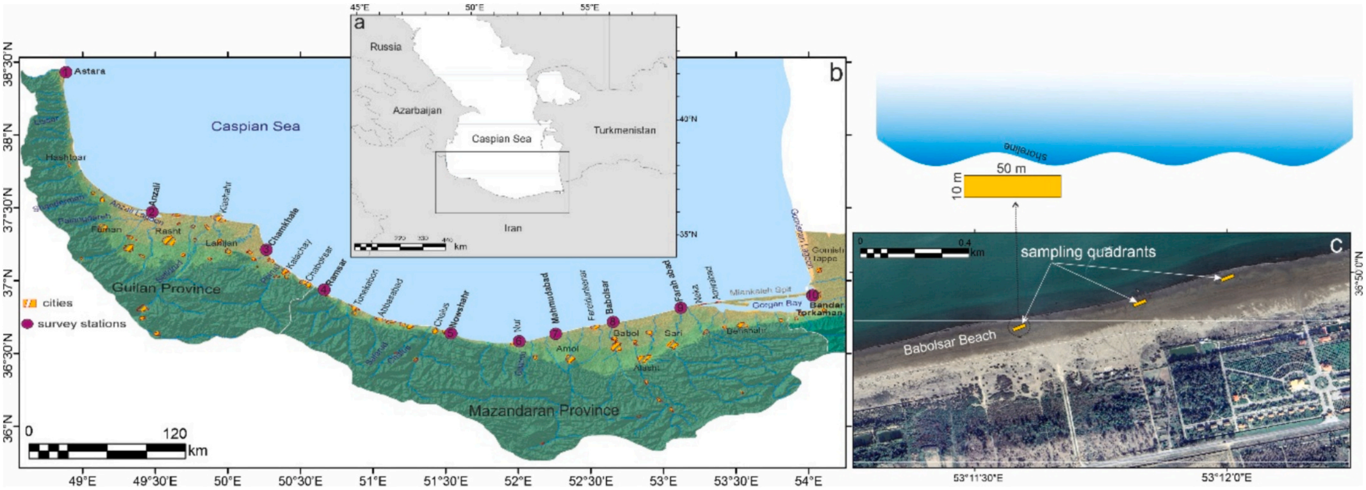

Fig. 1. Map of the study area showing coastal debris sampling sites.

Table 1
The Clean Coast Index (CCI) values were classified according to the methodology of Alkalay et al. (2007).

	C_i (items/m^2)	CCI values	Coast index	Visual assessment
1	0–0.1	0–2	Very clean	No debris is observed in the coastal region
2	0.1–0.25	2.1–5	Clean	No debris is observed in much of the coastal region
3	0.25–0.5	5.1–10	Moderate	Few debris items are observed in the coastal region
4	0.5–1	10.1–20	Dirty	Several debris are observed in the coastal region
5	>1	20+	Extremely dirty	The coastal region is fully covered by debris

community responses, the findings can inform conservation strategies, mitigate long-term ecological risks, and support sustainable management of the Caspian's fragile coastal ecosystems. This paper presents the spatial distribution and composition of coastal debris on coastal sediment along the southern Caspian Sea. Furthermore, we present the results of a microcosm experiment designed with a natural free-living nematode community to evaluate the effects of single-use macroplastic on nematode community characteristics (density, diversity, and community structure) over 5, 10, 20, 30, and 40 days.

2. Materials and methods

2.1. Field investigation

Owing to limited information on coastal debris in the South Caspian Sea, ten beaches spanning about 500 km of coastline were chosen to assess the spatial distribution of debris in summer and winter 2023 (Fig. 1). The selection of coastal cities for this beach litter study was based on several key criteria. Primarily, these cities are prominent tourist destinations, ensuring high human activity and potential waste generation. Additionally, they offer easy access to the shoreline and well-maintained roads, facilitating sample collection and logistical efficiency. From a scientific perspective, the chosen sites represent diverse environmental conditions (e.g., sediment type, and urbanization levels), enabling a comprehensive analysis of anthropogenic impacts. Their geographical distribution also allows for comparative studies across different ecosystems, while their susceptibility to seasonal pollution fluctuations makes them ideal for assessing temporal trends in litter accumulation. At each station, three transects, each 50 m long and parallel to the waterline, were established, extending 10 m from the waterline inland. Along these transects, all non-natural anthropogenic debris was collected by recorders who walked along the width of the surveyed area. The debris was labeled, and upon arrival in the lab, all were cleaned and identified according to the procedure prescribed by OSPAR (OSPAR, 2010) lists.

2.2. Clean Coast Index (CCI)

To assess the cleanness of the beach, a clean coast index (CCI) was applied which classifies the coast based on the number of debris collected. The CCI provides a quantitative metric for categorizing beaches according to the density of litter detected within a given area. CCI was calculated as the following formula:

$$CCI = C_i \times K \quad (1)$$

where K is a constant meaningless value (20) to make the numerical value of the CCI understandable. C_i is the collected number of debris per unit area and is calculated as the following:

$$Ci = N/(W \times L) \quad (2)$$

where N is the number of collected debris, W and L are the width and

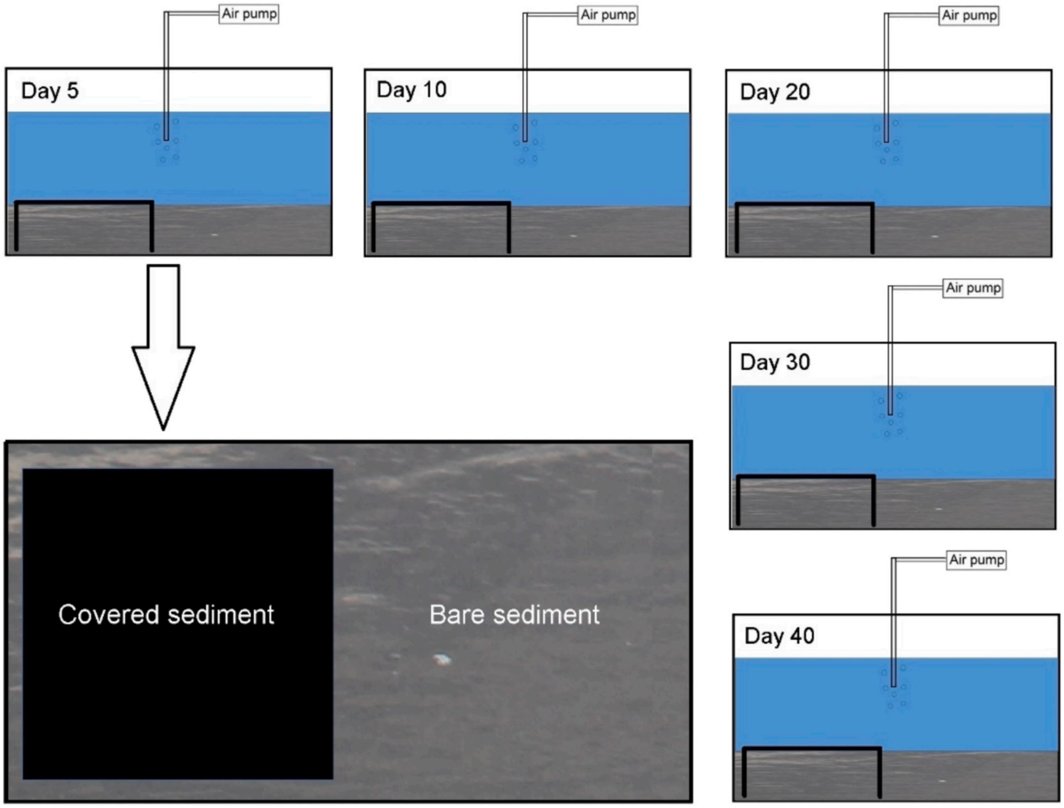

Fig. 2. Schematic drawing of the experimental set up.

length of the sampled area, respectively.

CCI measures clearness of the coast in a five-level classification: very clean ($0 < CCI < 2$), clean ($2.1 < CCI < 5$), moderate ($5.1 < CCI < 10$), dirty ($10.1 < CCI < 20$), and very dirty ($CCI > 20$) (Table 1).

Table 2
Types and abundances of debris collected across sampling sites (mean ± SD, items/500 m^2).

Summer						
Sampling sites	Plastics	Textile	Glass	Paper	Metal	Others
1	119.67 ± 25.50 ^{c}	8 ± 3.60 ^{ab}	16 ± 6.24 ^{d}	38.66 ± 4.93 ^{abc}	3.33 ± 1.52 ^{a}	32.33 ± 7.50 ^{bcd}
2	282.33 ± 21.12 ^{e}	12.33 ± 7.50 ^{bc}	13.33 ± 5.03 ^{cd}	52.00 ± 8.54 ^{bcd}	4 ± 2 ^{ab}	27.33 ± 8.73 ^{bc}
3	81.6667 ± 7.63 ^{b}	7.33 ± 2.08 ^{ab}	7.66 ± 2.51 ^{abc}	46.66 ± 6.66^{bc}	6.33 ± 2.08 ^{abcd}	31.33 ± 12.34 ^{bc}
4	273.33 ± 25.16 ^{e}	15.33 ± 4.16 ^{c}	19 ± 5.56 ^{d}	63.00 ± 15.52 ^{d}	8.33 ± 1.15 ^{cd}	39.33 ± 7.37 ^{cd}
5	261.67 ± 17.55 ^{e}	18.33 ± 2.51 ^{c}	15.33 ± 2.51 ^{d}	64.33 ± 5.03 ^{d}	9.33 ± 1.52 ^{d}	44.33 ± 8.62 ^{d}
6	114 ± 6 ^{c}	5 ± 3 ^{a}	7 ± 4.35 ^{abc}	30.33 ± 5.50 ^{a}	5.33 ± 1.52 ^{abc}	23 ± 4.58 ^{b}
7	182.33 ± 9.29 ^{d}	12.33 ± 2.08 ^{bc}	12.66 ± 2.08 ^{bcd}	52.66 ± 5.50 ^{cd}	6.33 ± 2.08 ^{abcd}	19.66 ± 1.52 ^{ab}
8	74.33 ± 9.29 ^{b}	3.33 ± 2.08 ^{a}	5.66 ± 1.52 ^{ab}	38.00 ± 7.55 ^{ab}	7.33 ± 3.51 ^{bcd}	23 ± 5.56 ^{b}
9	39.33 ± 5.13^{a}	5.33 ± 3.05 ^{a}	2.66 ± 2.08 ^{a}	29.66 ± 5.03 ^{a}	6.66 ± 2.51 ^{abcd}	9.66 ± 3.78 ^{a}
10	36.33 ± 10.01 ^{a}	7.66 ± 2.51 ^{ab}	7.66 ± 3.21 ^{abc}	26.33 ± 5.50 ^{a}	4 ± 1 ^{ab}	8 ± 1 ^{a}

Different letters indicate significant difference in each column ($p < 0.05$).

Winter						
Sampling sites	Plastics	Textile	Glass	Paper	Metal	Others
1	130.00 ± 39.68 ^{c}	8.00 ± 2.64 ^{ab}	19.66 ± 6.80 ^{cd}	37.33 ± 3.05 ^{abc}	5.00 ± 2.00 ^{a}	25.66 ± 7.09 ^{bc}
2	287.33 ± 2926 ^{e}	16.33 ± 10.40 ^{bc}	11.00 ± 1.73 ^{abc}	56.66 ± 6.65 ^{ef}	5.66 ± 2.51 ^{ab}	28.00 ± 11.35 ^{bc}
3	91.33 ± 8.02 ^{bc}	7.33 ± 3.05 ^{a}	8.66 ± 2.51 ^{ab}	51.66 ± 12.34^{de}	8.33 ± 1.52 ^{abc}	35.66 ± 11.71 ^{cd}
4	367.67 ± 69.81^{g}	17.33 ± 7.76 ^{c}	20.33 ± 10.40 ^{d}	65.33 ± 9.50 ^{f}	8.33 ± 1.52 ^{abc}	42.33 ± 3.05 ^{d}
5	267.00 ± 19.31 ^{e}	20.33 ± 4.16 ^{c}	17.33 ± 1.52 ^{bcd}	66.00 ± 6.08 ^{f}	12.00 ± 3.00 ^{c}	46.66 ± 10.96 ^{d}
6	117.67 ± 7.50 ^{c}	6.33 ± 2.52 ^{a}	8.00 ± 4.22 ^{a}	30.00 ± 6.08 ^{ab}	7.33 ± 2.08 ^{ab}	24.66 ± 6.50 ^{bc}
7	183.00 ± 1587 ^{d}	12.33 ± 2.51 ^{abc}	13.33 ± 3.51 ^{abcd}	50.00 ± 6.08 ^{cde}	6.33 ± 3.51 ^{ab}	20.66 ± 2.08 ^{ab}
8	62.00 ± 3.00 ^{ab}	3.33 ± 0.57 ^{a}	5.33 ± 3.51 ^{a}	40.66 ± 11.37 ^{bcd}	9.66 ± 1.52 ^{bc}	24.33 ± 7.02 ^{bc}
9	35.66 ± 4.04 ^{a}	5.66 ± 3.07 ^{a}	4.33 ± 1.52 ^{a}	30.66 ± 3.51 ^{ab}	7.33 ± 1.52 ^{ab}	10.00 ± 3.00 ^{a}
10	32.66 ± 11.01 ^{a}	6.33 ± 2.51 ^{a}	7.00 ± 5.00 ^{a}	26.33 ± 3.21 ^{a}	5.33 ± 15 ^{a}	8.00 ± 2.64 ^{a}

Different letters indicate significant difference in each column ($p < 0.05$).

2.3. *Experimental setup, sampling, and laboratory treatment*

The experimental setup required sediment containing the natural free-living nematode community excluding abundant macrofauna. Therefore, sediment from a sandy coastal station at Sisangan in Mazandaran province was collected with a shovel up to 25 cm deep. The sediments were sliced into 0–5 cm, 6–15 cm, and 16–25 cm sections, on the field wet sieved to remove macrofauna (> 1 mm) and immediately transported to the laboratory (< half hour). The sediments were reconstructed by stacking subsequent sediment horizons and randomly poured into 5 aquariums (70*40*50 cm) up to 25 cm in height and gently filled with filtered seawater from the sampling site (passed through a 38-μm filter and salinity 12) and the aquariums were left to acclimatize at 20 °C for 7 days and continuously aerated. After acclimation time, each aquarium was divided into two equal parts, sediment on the left part was coated with single-use plastic bags with 40-μm diameter thickness, and all edges 25 cm deep in the surrounding sediments and the other part was assumed as control treatment (bare sediment) (Taheri et al., 2024). In this way, two treatments were established in each aquarium: 1- treatment covered with plastic and 2- without plastic (control treatment) (Fig. 2). During the experiment, temperature was maintained constant (20 °C) in each aquarium with aquarium heater (200 W) and each aquarium was individually aerated with an air pump and the water was homogenized with bubbling air stones placed above the heaters (Gingold et al., 2013; Taheri et al., 2025). Salinity was checked every day. Whenever salinity increased, enough aerated freshwater (same temperature) was added to each aquarium. Every ten days, 10 % of each aquarium water were removed and replace with filtered seawater from the sampling site with the same temperature as the aquarium water (Yazdani Foshtomi et al., 2010; Taheri et al., 2025). Aquariums lasted for 5, 10, 20, 30, and 40 days and aerated continuously. Our selected exposure period (5–40 days) was designed based on the life cycle characteristics of vast majority of free-living nematodes, which typically complete their life cycles within 20–30 days (Platt and Warwick, 1988). The 40-day timeframe allowing us to observe meaningful community-level responses. This experimental design is supported by previous studies in similar systems (Taheri et al., 2015, 2024), where analogous durations (23 days and 60 days, respectively) successfully detected significant changes in nematode density, diversity and community structure. At the end of each time, the overlying water was gently siphoned off, taking care to minimize sediment disturbance. Then, the covered area was opened and sediment oxidation-reduction potential and pH of the sediment (~2 cm) were measured in both regions (covered and control treatments) using a portable multimeter (HACH HQ40d, USA). The surface sediment (~2 cm) in both areas was sampled using a 60 mL syringe (26.7 mm diameter) and stored in clean plastic containers. Total organic matter (TOM) was determined by weight loss on ignition (4 h at 550 °C) after drying (24 h at 90 °C) to a constant weight (Heiri et al., 2001). Finally, in each area, three cores were inserted down to 5 cm depth (i.d 4 cm), fixed in a buffered 4 % formaldehyde solution, and stained with Rose Bengal for nematode studies (Taheri et al., 2015, 2024). Each sample was sieved through a 1000 μm and a 38 μm mesh size sieve and the fraction remaining on the 38 μm sieve was centrifuged three times with Ludox (specific gravity of 1.18) to separate organisms from sediments and then counted under stereomicroscope. From every sample, 120 nematodes (or all nematodes if a lower number was observed) were hand-picked randomly (Taheri et al., 2014, 2015) and were transferred to pure glycerin via a dehydration procedure (Vincx, 1996) and mounted on microscopic slides for identification to species level using the NeMys online identification system (Nemys, 2024). All nematodes were assigned to different feeding

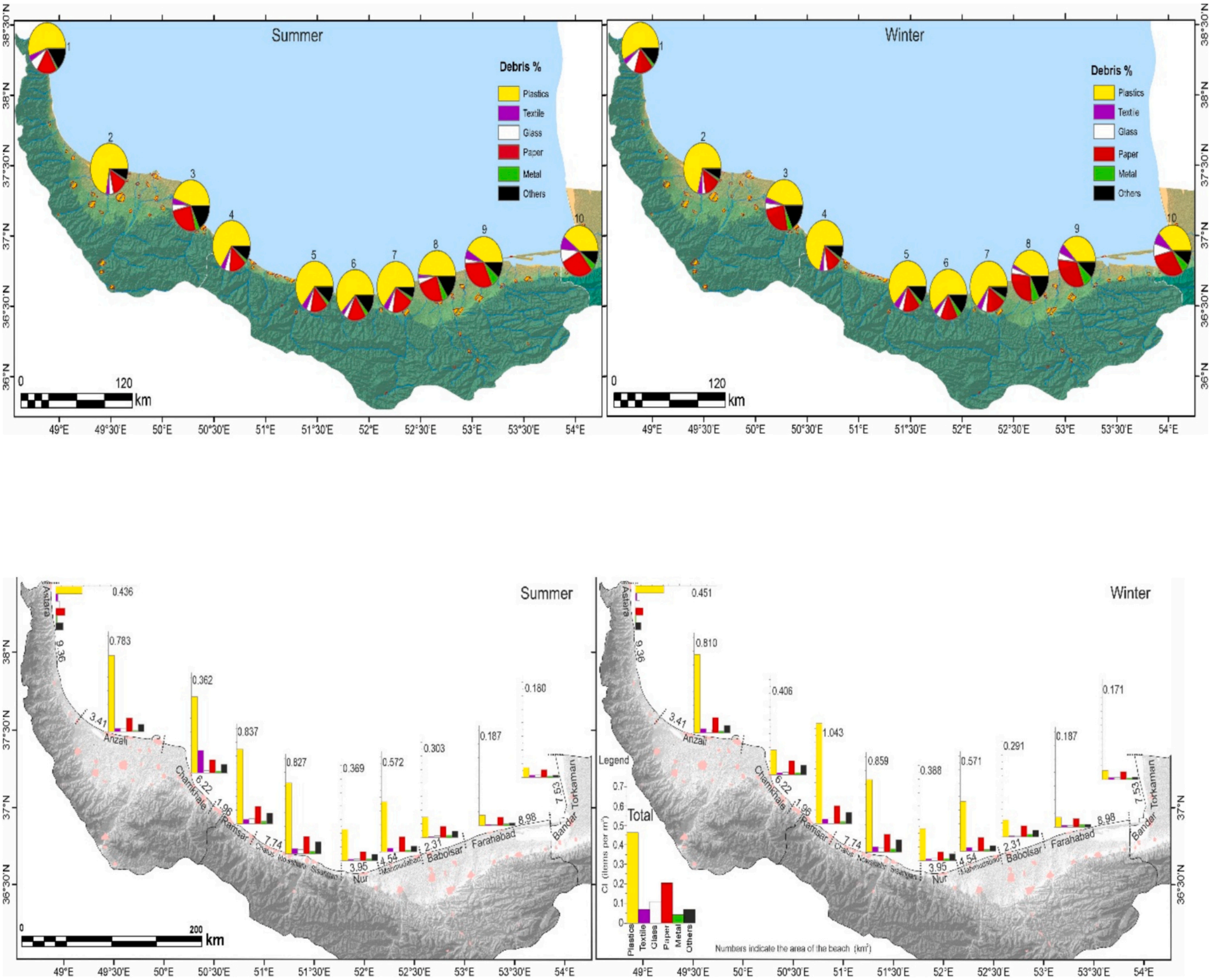

Fig. 3. Composition of debris collected across sampling sites.

types based on the morphology of the buccal cavity: (1A) selective deposit feeders; (1B) non-selective deposit feeders; (2A) epistrate (diatom) feeders; (2B) predators/omnivores (Wieser, 1953).

2.4. Statistical analysis

For every exposure time, the number of species (S), Shannon diversity (H', log e), Margalef's index (d), and evenness (Pielou's, J) were calculated (Anderson et al., 2008). Possible differences in the spatial distribution of coastal litters, total nematode density, species number, Shannon diversity, evenness, and all environmental conditions (univariate) and community structure (multivariate) between covered and control treatments in each time tested via one-way permutational ANOVA (PERMANOVA, $n = 3$). Euclidean distance and Bray–Curtis-based resemblance matrices were used for univariate and multivariate data. Whenever a significant difference was observed, a pairwise test was performed. Owing to the restricted number of possible permutations of pairwise tests, p values were obtained from the Monte Carlo (9999) permutation test. Homogeneity of multivariate dispersion was tested with PERMDISP for any of the significant terms in Permanova analyses. Non-significant PERMDISP results indicate a significant PERMANOVA to be a difference due to location. A nonmetrical multidimensional scaling (MDS) plot based on Bray–Curtis similarity was used to visualize the community structure. Furthermore, one-way SIMPER analysis based on nematode abundance of the full sediment column was used to identify the nematode species having important contributions within-group similarity. The cut-off level for a low contribution was 100 %. The above analyses were performed in PRIMER v6 with PERMANOVA+ add-on (Anderson et al., 2008).

3. Results

3.1. Debris accumulation and composition

During the summer and winter seasons, 7283 and 7766 pieces of marine debris were collected in the studied area, respectively. In general, most debris was collected at central sites (4 and 5), while the eastern sites exhibited less buried debris. For both seasons, the collected pieces of debris in the studied sites were in descending order (Table 2):

Sampling sites: site 4 > site 5 > site 2 > site 7 > site 1 > site 8 > site 9 > site 10.

In the summer, the plastic group consisted of 60.35 % (0.29 items/m^2) of the total collected number of debris, and the paper group was in second place (18.19 %, 0.09 items/m^2) (Fig. 3). The metal group with the lowest incidence comprised 2.51 % (0.01 items/m^2) of the total debris number. In summer, the highest percent of plastic pieces was seen

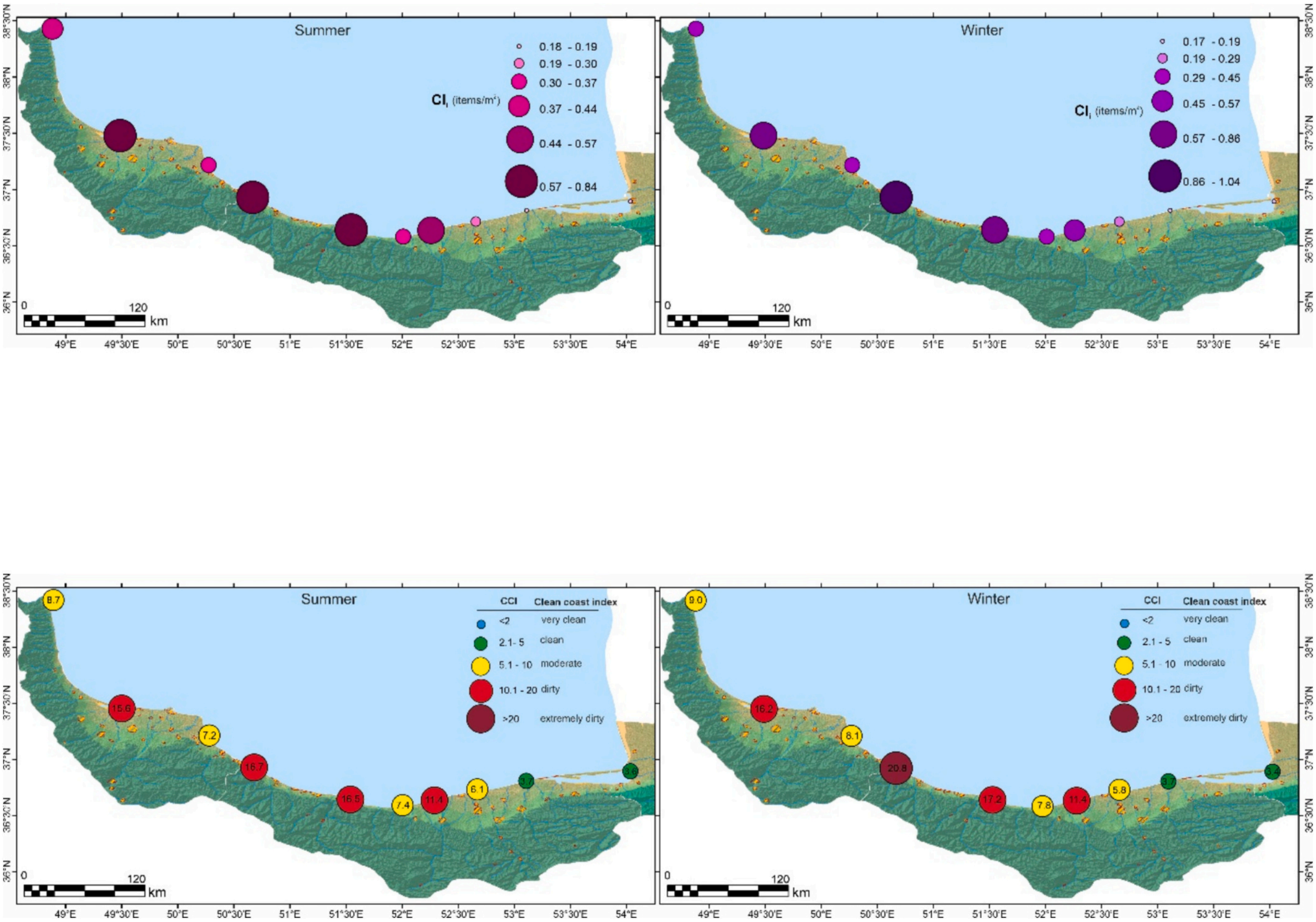

Fig. 4. Contamination Index (Ci) and Clean Coast Index (CCI) values across sampling sites.

at site 2 (72.16 %, 0.56 items/m^2), site 4 (65.29 %, 0.55 items/m^2), and site 5 (63.27 %, 0.52 items/m^2) whereas the lowest percent of plastic incidents was observed at site 10 (39.97 %, 0.07 items/m^2). The most and the lowest percent of paper debris were recorded at site 9 (31.65 %, 0.05 items/m^2) and site 2 (13.30 %, 0.10 items/m^2), respectively. The metal occurrence was least at site 2 (1.01 %, 0.01 items/m^2) and highest at site 9 (7.12 %, 0.01 items/m^2) (Fig. 3).

In winter, plastic composed 60.82 % (0.31 items/m^2) of the total number of debris, and the paper was in the second order (17.56 %, 0.09 items/m^2) (Fig. 3). Metal debris represented the least share of the total debris collected (2.91 %, 0.02 items/m^2). In addition, the highest percent of plastic was observed at Site 2 (70.93 %, 0.57 items/m^2), site 4 (70.41 %, 0.74 items/m^2), and Site 5 (62.16 %, 0.53 items/m^2) but the lowest percent of debris pieces was found at Site 10 (37.33 %, 0.07 items/m^2) (Fig. 3).

The percent of metal pieces was highest at site 9 (7.91 %, 0.02 items/

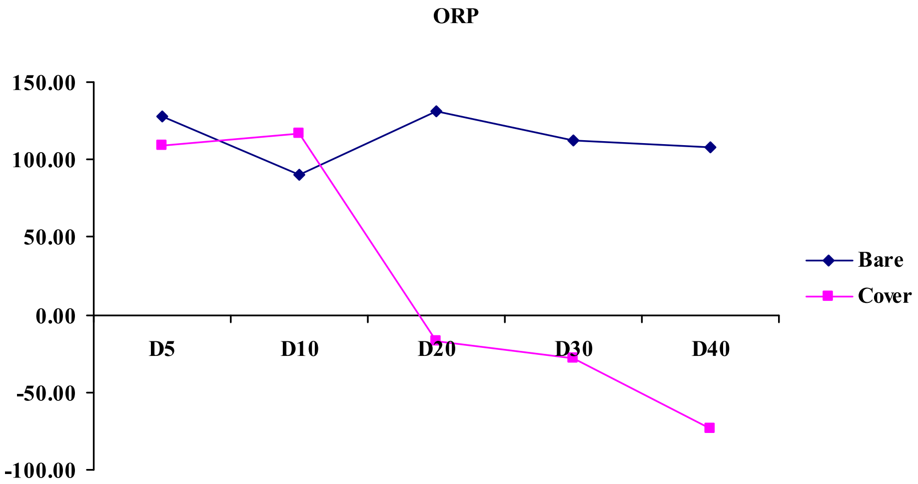

Fig. 5. Fluctuations in oxidation-reduction potential (ORP) values for both treatments (B = control, C = covered sediment).

Table 3
Physicochemical parameters during the experimental treatments (B = control, C = covered sediment).

	pH	ORP	TOM
T5B	7.57 ± 0.25^{a}	128.33 ± 7.64 ^{a}	2.41 ± 0.09 ^{a}
T5C	7.57 ± 0.28 ^{a}	109.00 ± 12.29 ^{a}	2.33 ± 0.09 ^{a}
T10B	7.73 ± 0.02 ^{a}	90.30 ± 11.85 ^{a}	2.31 ± 0.06 ^{a}
T10C	7.54 ± 0.14 ^{a}	116.60 ± 9.63 ^{b}	2.29 ± 0.07 ^{a}
T20B	7.24 ± 0.22 ^{a}	131.67 ± 9.61 ^{a}	2.40 ± 0.18 ^{a}
T20C	7.35 ± 0.19 ^{a}	−17.33 ± 89.03 ^{b}	2.44 ± 0.18 ^{a}
T30B	7.45 ± 0.12 ^{a}	112.67 ± 17.50 ^{a}	2.52 ± 0.07 ^{a}
T30C	7.32 ± 0.09 ^{a}	−27.67 ± 7.51 ^{b}	2.50 ± 0.05 ^{a}
T40B	7.24 ± 0.14 ^{a}	108.33 ± 35.47 ^{a}	2.44 ± 0.12 ^{a}
T40C	7.11 ± 0.06 ^{a}	−74.00 ± 5.29 ^{b}	2.48 ± 0.08 ^{a}

Different letters indicate significant difference in each column ($p < 0.05$).

m^2) and the lowest at site 2 (1.37 %, 0.01 items/m^2). The highest and the lowest percent of paper incidents were detected at site 9 (32.68 %, 0.05 items/m^2) and site 4 (12.58 %, 0.13 items/m^2), respectively.

In both seasons, plastic comprised the largest portion, followed by paper, other materials, glass, textile, and metal.

Moreover, the number of debris showed a significant difference between winter and summer ($p < 0.05$) in a specific site. However, the total number of debris had no significant difference between summer and winter ($p > 0.05$) (Table 2).

3.2. Clean Coast Index (CCI)

During both the summer and winter seasons, the maximum C_i value was recorded at station 4, while the minimum was at station 10 (Fig. 4). The C_i value in summer and winter ranged between 0.18 and 0.84 items/m^2 and 0.17–1.04 items/m^2, respectively (Fig. 4).

The range of CCI was from 3.60 to 16.73 in summer and from 3.43 to 20.85 in winter (Fig. 4). In both seasons, CCI showed its highest and lowest values at site 4 and site 10, respectively. Based on CCI, sites 9 and 10 were classified as clean, and sites 8, 6, 3 and 1 as moderate clean in summer and winter. Sites 2, 4, 5 and 7 in summer and sites 2, 5 and 7 in winter were classified as dirty. Site 4 was very dirty in winter. In both seasons, 20 % of the sampling sites were clean, 40 % were moderately clean, and the remaining sites were dirty or very dirty (Fig. 4).

3.3. Physical and chemical parameters of laboratory treatment

The results of the statistical tests revealed a significant difference in the pH values of both treatments (control and covered) at different times. The PERMDISP test for pH was not significant (F = 0.286, p (perm) = 0.594). The pH fluctuated in both treatments and gradually decreased in general. ORP significantly differed among the various times and treatments ($p < 0.05$). The PERMDISP test for ORP was significant (F = 109.04, p (perm) = 0.001). The lowest value of ORP was detected in the control treatment group on day 10, and no significant difference was detected in the ORP values on the other days. The ORP value of the Cover treatment sharply decreased after day 10 and reached its minimum on day 40 (Fig. 5). The organic matter content (TOM) in the control treatment group did not significantly differ with increasing experimental days ($p > 0.05$), but its highest and lowest contents in the Cover treatment were recorded on days 30 and 10 of the experimental period, respectively ($p < 0.05$) (Table 3).

3.4. Biodiversity indices

Twelve species belonging to 10 genera were identified in both treatments (control and covered) during the experimental period. The genus *Daptonema*, with 3 species, was the most diverse. The number of species at different times and in different treatments significantly differed. The PERMDISP test for the number of species was significant (F = 3.99, p (perm) = 0.04). The species number (S) gradually decreased in both treatments with increasing experimental days (Fig. 6). The species richness (d) significantly differed at various times and gradually decreased over time. The evenness index (J) significantly differed among the testing times and treatments ($p < 0.05$). The PERMDISP test was not significant (F = 8.85, p (perm) = 0.77). In general, the evenness index gradually decreased in both treatments as the number of

Fig. 6. Variations in biodiversity indices (species richness, diversity, evenness) and density values for both treatments (B = control, C = covered sediment).

Table 4
Comparison of the species number (S), species richness (d), Shannon diversity (H) and evenness (J) during the experiment. B = control treatment, C = covered sediment.

	S	d	J	H	density
T5B	7.67 ± 0.58 ^{a}	1.90 ± 0.15 ^{a}	0.92 ± 0.03 ^{a}	1.86 ± 0.05 ^{a}	77.67 ± 19.73 ^{a}
T5C	6.67 ± 0.58 ^{a}	2.12 ± 0.14 ^{a}	0.88 ± 0.03 ^{a}	1.67 ± 0.09^{b}	18.00 ± 9.85 ^{b}
T10B	9.00 ± 0.00 ^{a}	2.04 ± 0.04 ^{a}	0.86 ± 0.01 ^{a}	1.88 ± 0.02 ^{a}	110.33 ± 16.04 ^{a}
T10C	7.33 ± 1.15 ^{a}	2.36 ± 0.24 ^{a}	0.96 ± 0.03 ^{b}	1.90 ± 0.12 ^{a}	10.67 ± 4.04 ^{b}
T20B	7.00 ± 1.73 ^{a}	1.40 ± 0.40 ^{a}	0.65 ± 0.04 ^{a}	1.26 ± 0.25 ^{a}	262.67 ± 53.45 ^{a}
T20C	5.67 ± 0.58 ^{a}	1.20 ± 0.15 ^{a}	0.71 ± 0.03 ^{a}	1.24 ± 0.09 ^{a}	21.67 ± 11.93 ^{b}
T30B	6.33 ± 0.58 ^{a}	1.28 ± 0.14 ^{a}	0.51 ± 0.05 ^{a}	0.93 ± 0.13 ^{a}	358.67 ± 20.53 ^{a}
T30C	7.00 ± 0.00 ^{a}	1.50 ± 0.08 ^{a}	0.67 ± 0.06 ^{b}	1.31 ± 0.11 ^{b}	67.67 ± 16.29 ^{b}
T40B	6.00 ± 2.65 ^{a}	1.26 ± 0.66 ^{a}	0.75 ± 0.04 ^{a}	1.30 ± 0.31 ^{a}	418.67 ± 23.25 ^{a}
T40C	5.00 ± 0.00 ^{a}	1.00 ± 0.01 ^{a}	0.58 ± 0.01 ^{b}	0.93 ± 0.02 ^{a}	83.67 ± 17.62 ^{b}

Different letters indicate significant difference in each column ($p < 0.05$).

experimental days increased (Fig. 6). The Shannon index (H) significantly differed among various times and treatments ($p < 0.05$) and slowly decreased in both treatments during the experimental period. The PERMDISP test was not significant (F = 1.05, p (perm) = 0.31). There were significant differences in nematode density among the different times and treatments ($p < 0.05$). Nematode density significantly increased in the control treatment group after 10 days of the experiment ($p < 0.05$), as the highest density was achieved on day 40 (Fig. 6). In the Cover treatment, the nematode density did not significantly differ on days 5, 10, and 20 ($p > 0.05$) but increased on days 30 and 40 of the experimental period (Table 4).

3.5. Community structure

The community structure changed with time and treatment during the experimental period primarily due to the presence or absence of specific nematode species. In general, the community structure differed between the Cover and control treatment groups according to the nMDS plot (stress: 0.13, $p < 0.05$) (Fig. 7).

Results of SIMPER analysis revealed that the relative abundance of observed species and their feeding type contribution also changed between nematode communities in covered and control treatments (Table 5). However, there were no noticeable changes in the percentage of non-selective deposit feeders (1B) and epistrate (diatom) feeders (2A) in different treatments though the contribution of specific nematode species was changed in both treatments.

4. Discussion

4.1. Quantity and composition of debris

Coastal debris accumulation is a global environmental challenge requiring targeted management strategies. Effective mitigation depends on understanding key factors influencing debris quantity and composition, including: (1) human behavior (e.g., littering attitudes, tourism activities), (2) waste management efficacy (e.g., cleanup frequency, trash bin availability), (3) coastal urbanization levels, and (4) hydrogeomorphic dynamics (e.g., tides, winds, proximity to urban centers) (Nachite et al., 2019; Rangel-Buitrago et al., 2019; Asensio-Montesinos et al., 2020). Among these, visitor behavior is a critical determinant. Persistent debris items—plastics (bags, bottles), metals, cigarette butts, and paper waste—often result from improper disposal rather than inadequate cleanup (Rangel-Buitrago et al., 2019; Jonidi Jafari et al., 2021). This issue is exacerbated in high-traffic tourist areas, as observed in Sites 4 and 5 of our study, where dense populations correlated with elevated debris loads. To reduce debris accumulation, integrated approaches combining public education, behavioral interventions, and improved waste infrastructure are essential, particularly in urbanized coastal zones.

This study presents the first comprehensive assessment of beach debris distribution and composition along the southern Caspian Sea coastline, spanning over 500 km across ten sampling stations in three provinces. Our systematic investigation provides baseline data on anthropogenic pollution in this understudied region, employing

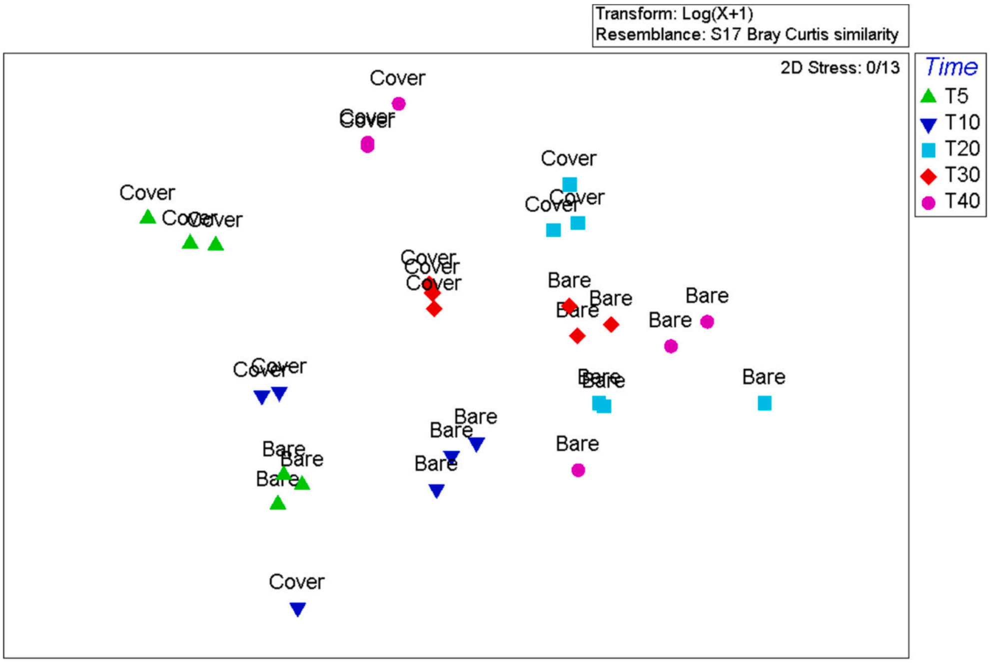

Fig. 7. Non-metric multidimensional scaling (nMDS) plot illustrating differences in benthic community structure between treatments over time.

Table 5
Results of one-way SIMPER analysis comparing the two treatments (B = control, C = covered sediment).

Day 5 Control treatment	FT	Con	Day 5 Covered	FT	Con
Neochromadora poecilosoma	2A	20/89	*Neochromadora poecilosoma*	2A	24/31
Chromadorella parapoecilosoma	2A	15/07	*Daptonema karabugasensis*	1B	20/08
Daptonema karabugasensis	1B	15/07	*Oncholaimus hyrcanus*	2B	18/97
Chromadorita tenuis	2A	14/21	*Daptonema curticauda*	1B	11/07
Daptonema curticauda	1B	11/21	*Daptonema intermedia*	1B	11/07
Axonolaimus spinosus	1B	11/16	*Microlaimus naidinae*	2A	11/07
Oncholaimus hyrcanus	2B	10/29	*Chromadorella parapoecilosoma*	2A	3/44
Adoncholaimus araelensis	2B	2/10			
Day 10 Control treatment	**FT**	**Con**	**Day 10 Covered**	**FT**	**Con**
Daptonema karabugasensis	1B	20/36	*Chromadorella parapoecilosoma*	2A	18/20
Neochromadora poecilosoma	2A	13/58	*Chromadorita tenuis*	2A	18/20
Axonolaimus spinosus	1B	13/26	*Daptonema curticauda*	1B	16/87
Chromadorita tenuis	2A	12/97	*Daptonema karabugasensis*	1B	16/87
Daptonema curticauda	1B	12/38	*Adoncholaimus araelensis*	2B	12/82
Adoncholaimus araelensis	2B	7/91	*Oncholaimus hyrcanus*	2B	10/64
Chromadorina germanica	2A	7/91	*Daptonema intermedia*	1B	3/21
Chromadorella parapoecilosoma	2A	6/65	*Neochromadora poecilosoma*	2A	3/21
Oncholaimus hyrcanus	2B	4/99			
Day 20 Control treatment	**FT**	**Con**	**Day 20 Covered**	**FT**	**Con**
Daptonema karabugasensis	1B	33/01	*Daptonema karabugasensis*	1B	32/97
Daptonema curticauda	1B	27/06	*Daptonema intermedia*	1B	24/37
Chromadorina germanica	2A	16/80	*Daptonema curticauda*	1B	24/26
Axonolaimus spinosus	1B	6/34	*Neochromadora poecilosoma*	2A	7/34
Diplolaimella ocellata	1B	6/34	*Oncholaimus hyrcanus*	2B	7/34
Neochromadora poecilosoma	2A	4/42	*Adoncholaimus araelensis*	2B	3/73
Adoncholaimus araelensis	2B	3/02			
Oncholaimus hyrcanus	2B	3/02			
Day 30 Control treatment	**FT**	**Con**	**Day 30 Covered**	**FT**	**Con**
Daptonema karabugasensis	1B	39/29	*Daptonema karabugasensis*	1B	30/74
Daptonema curticauda	1B	21/94	*Chromadorita tenuis*	2A	16/58
Chromadorina germanica	2A	14/91	*Daptonema curticauda*	1B	14/10
Adoncholaimus araelensis	2B	8/39	*Adoncholaimus araelensis*	2B	11/38
Oncholaimus hyrcanus	2B	8/39	*Daptonema intermedia*	1B	9/89
Neochromadora poecilosoma	2A	7/07	*Neochromadora poecilosoma*	2A	9/89
			Oncholaimus hyrcanus	2B	7/41
Day 40 Control treatment	**FT**	**Con**	**Day 40 Covered**	**FT**	**Con**
Daptonema karabugasensis	1B	32/18	*Daptonema karabugasensis*	1B	39/93
Daptonema curticauda	1B	29/58	*Chromadorita tenuis*	2A	23/95
Chromadorina germanica	2A	26/49	*Oncholaimus hyrcanus*	2B	19/53
Oncholaimus hyrcanus	2B	7/97	*Neochromadora poecilosoma*	2A	9/03
Adoncholaimus araelensis	2B	3/78	*Daptonema intermedia*	1B	7/56

methodologies to enable future comparative analyses. According to UNEP (2009), Iran and Kazakhstan represent critical hotspots for marine debris in the Caspian Sea basin, with population distribution being a key contributing factor. In the present investigation, sites 4 and 5, which are located on the tourist coasts with high levels of population density, had a greater number of debris collected. The report particularly identified Bandar Anzali in Guilan Province as a primary accumulation zone, consistent with our current findings.

In the present work, the number of collected debris during summer and winter was less than that reported for Slovenia (1.51 items/m^2, Fernandino et al., 2016), Brazil (6.06 items /m^2, Silva et al., 2018), Cyprus (9.3 items/m^2, Loizia et al., 2021), and Qatar (1.98 items/m^2, Veerasingam et al., 2020) while it was more than that of Mkomani beach, Kenya (0.042 items/m^2, Okuku et al., 2021) and North-western Adriatic beaches (0.2 litter items/m^2, Munari et al., 2016) (Table 6), implicating the impacts of coastal users, behavior, population density in the coast, rules and legislation on the observed difference in the measured debris amount in various regions of the world (Table 6).

Most coastal cities along the southern Caspian Sea lack effective solid waste management policies, resulting in significant land-based waste leakage into the marine environment. While all Caspian littoral states have established comprehensive legal frameworks for marine protection (e.g., the Tehran Convention), implementation and enforcement remain inadequate (UNEP, 2009). This policy-execution gap underscores the urgent need for stronger regulatory measures and cross-border cooperation to mitigate marine pollution in the region.

4.2. *Free-living nematodes diversity*

The Caspian Sea is a remnant of ancient oceans and has been isolated for millions of years, which has limited species dispersal and resulted in distinct but often low numbers of endemic species, contributing to lower biodiversity compared to more interconnected aquatic systems (Dumont, 1998). Specifically, its biodiversity is 2.5 times lower than that of the Black Sea and five times lower than that of the Barents Sea (Zenkevich, 1963). To date, 50 species of free-living nematodes have been documented across the Caspian Sea's freshwater and brackish waters (Tchesunov, 1981; Mokievsky and Miljutina, 2011). In the current study, 12 species representing 10 genera were identified, with the genus *Daptonema*, comprising three species, accounting for the largest proportion. This finding is consistent with previous research (Taheri et al., 2014; Bastami et al., 2017; Taheri et al., 2017; Taheri et al., 2025).

4.3. *Effect of macroplastics on coastal nematode communities*

This study experimentally examined the effects of macroplastics on nematode community characteristics using a microcosm approach over periods of 5, 10, 20, 30, and 40 days in five distinct aquariums. The findings indicated that macroplastics on the sediment significantly decreased ($p < 0.05$) sediment oxygen reduction potential (ORP) across the different time points and treatments, and altered the overall nematode community composition. Furthermore, total nematode density and diversity indices showed significant declines under macroplastic treatments at each time interval ($p < 0.05$).

The results revealed that in both treatments at different times, the sediment organic matter percentage and pH values did not significantly change during the experimental period ($p > 0.05$). Taheri et al. (2014) reported similar results in coastal coarse-grained sediments. However, some studies have demonstrated that buried plastic bags affect the sediment organic matter (Clemente et al., 2022) and pH (Balestri et al., 2017) in the sediment. These variations across different studies may be related to the varied physicochemical conditions of the studied environments (Barrett et al., 2024). Plastics deposited on or buried within sediments can act as a physical barrier and hamper the oxygen exchanges across the air-sediment surface, leading to hypoxic or anoxic conditions in the sediment. Our results indicated that the pore water

Table 6
Spatial distribution of the Clean Coast Index (CCI) in the study region.

Region	Abundances	Marine debris	CCI	Reference
Iran (Caspian Sea)	Summer: 0.18–0.84 Winter: 0.17–1.04	Plastics, Textile, Glass, Paper, Wood, Metal and Others	Summer: Clean–dirty Winter: Clean–Extremely dirty	Present study
Slovenia (Adriatic region)	1.51 items/m^2	Caps and lids, lolly sticks, cutlery, cups, drink bottles, drink bottles, fishing ropes, string, cosmetics packaging, fishing net floats, and foam	Extremely dirty	Laglbauer et al. (2014)
Italy (North-western Adriatic Beaches)	0.2 litter items/m^2	Cigarette butts, unrecognizable plastic pieces, bottle caps	Clean–dirty	Munari et al. (2016)
Brazil (Beaches of Arraial do Cabo)	6.06 unites/m^2	Food packaging, straw, bottle cap, disposable cup, swab rod, light stick, and bottle	Clean–dirty	Silva et al. (2018)
Kenya (Mkomani beach)	0.042 items/m^2	Food products packaging, PC, HP, PET, SL, HDPE, PP, and PVC	Extremely dirty	Okuku et al. (2021)
Cyprus (Eastern region)	9.3 items/m^2	PP and PE	Clean	Loizia et al. (2021)
Qatar (west coast)	1.98 items/m^2	Plastics, metal, glass, paper, fabric, rubber, processed wood	Dirty to extremely dirty	Veerasingam et al. (2020)
Italy (coast of the Strait of Messina	1.2 items /m^2	Plastic litter	Dirty to very dirty	Branca et al. (2025)
Morocco Mediterranean (Tetouan coast)	483.12 Microparticles/kg	Microparticles	Extreme level of impact	Bouzekry et al. (2024)

oxidation-reduction potential (ORP) in the covered treatment decreased throughout the experiment, signifying the development of hypoxic or anoxic conditions in the sediment. This finding is consistent with previous studies (Van Colen et al., 2009; Green et al., 2015; Balestri et al., 2017; Taheri et al., 2024). Direct measurements in previous studies confirm that macroplastics induce hypoxia in underlying sediments. For example, microsensor profiles revealed oxygen depletion to <1 mg/L beneath plastic debris (Nava et al., 2024), while microbial shifts toward anaerobic taxa further corroborate anoxia (Krohn et al., 2025). Such hypoxia directly stresses nematodes, as low-oxygen tolerance thresholds (e.g., <2 mg/L for most genera) align with our observed diversity declines. Though we lacked direct oxygen measurements, the significant ORP reduction in our study mirrors these established mechanisms.

Most free-living nematodes uptake oxygen by diffusion from the environment. Generally, coastal nematode communities prefer oxic environments (Steyaert et al., 2007). While oxygen penetration depth in marine sediment is limited to the upper centimeters (Rasmussen and Jorgensen, 1992) or even millimeters (Wenzhöfer and Glud, 2002; Taheri et al., 2014, 2017), oxygen stress can affect the nematode density, diversity and alter community structure (Gambi et al., 2009; Van Colen et al., 2009; Taheri et al., 2015). Oxygen is crucial for the aerobic respiration of nematodes, enabling them to generate energy (Ott and Schiemer, 1973; Braeckman et al., 2013). The presence of buried plastic bags in sediment can lead to a lack of oxygen, which may reduce feeding activity in nematodes (Steyaert et al., 2007) and can adversely impact their reproduction and juvenile development (Jensen, 1995; Giere, 2009), along with decreasing their survival rates (Austen and Wibdom, 1991). This decline in survival can consequently result in a reduction of both nematode density and diversity (Steyaert et al., 2007; Taheri et al., 2015, 2024), as noted in the current study.

Our results showed a sharp decrease in the density was observed between the two treatments at various time points which emphasizes the importance of oxygen for marine nematodes and is in agreement with the other studies (e.g. Modig and Olafsson, 1998; Wetzel et al., 2001; Van Colen et al., 2009; Taheri et al., 2015, 2024). This difference began on the 5th day, indicating the negative impact of plastic on sediment surfaces. In the cover treatment, density decreased drastically by the 10th day and increased until the 40th day. The initial decrease in density until the 10th day is likely due to stress from reduced oxygen levels (lower ORP) and pH in the cover treatment, leading to a decline in overall species density. However, from day 10 onward, the removal of sensitive species allowed resistant species to persist and adapt to the new conditions. Consequently, the higher reproduction rate of these resistant species led to an increase in nematode density in the cover treatment. By contrast, the density in the control treatment increased over the entire period, presumably due to environmental conditions that better supported reproduction.

5. Conclusions

The results of the present study provide useful information about debris pollution along the coastlines of the southern part of the Caspian Sea. In conclusion, plastic items, particularly plastic bags, constituted the largest proportion of beach debris observed along the coastline in the southern part of the Caspian Sea. In our study area, the majority of land-based debris originates from tourism-related activities along the shoreline (Manbohi et al., 2023). Furthermore, the Caspian Sea's non-tidal nature eliminates tidal currents as a significant factor in debris dispersion. However, this study does not address possible seasonal hydrodynamic differences (currents, storms) that may influence debris accumulation.

Our results showed a species-specific response of the nematode community to the presence of single-use plastic bags buried in the sediment. The presence of single-use plastic bags on sediment sharply decreases total nematode densities, diversity indices, and sediment oxygen redox potential, finally altered total nematode communities. Our results suggest that anthropogenic drivers of hypoxia or anoxia influence community structure and ecosystem functioning, ultimately impacting the food chain. While this study highlights the impact of debris on nematode communities, instrumental limitations prevented the assessment of indirect factors like microbial activity and nutrient fluxes. Future work should explore these mechanisms to fully understand their role in shaping nematode responses. The results can be used to manage marine debris and provide a recommendation for the importance of waste management on public beaches.

CRediT authorship contribution statement

Kazem Darvish Bastami: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Mehrshad Taheri:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hadi Raisi:** Writing – original draft, Validation, Investigation. **Stepan Podolyako:** Writing – original draft, Visualization, Investigation, Data curation. **Maria Biryukova:** Writing – original draft, Formal analysis. **Ali Mehdinia:** Supervision, Resources, Project administration, Funding acquisition. **Ahmad Radmanesh (Manbohi):** Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Investigation, Conceptualization.

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Declaration of competing interest

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

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Data availability

The datasets used during the current study are available from the corresponding author upon request.

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