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Increasing risk of invasions by organisms on marine debris in the Southeast coast of India

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ABSTRACT

Increasing amount of anthropogenic litter in the marine environment has provided an enormous number of substrates for a wide range of marine organisms, thus serving as a potential vector for the transport of fouling organisms. Here, we examined the fouling organisms on different types of stranded litter (plastic, glass, rubber, foam sponge, cloth, metal and wood) on eight beaches along the southeast coast of India. In total, 17 encrusting species belonging to seven phyla (Arthropoda, Bryozoa, Mollusca, Annelida, Cnidaria, Chlorophyta and Foraminifera) were identified on 367 items, with one invasive species, the mussel *Mytella strigata*, detected. The most common species associated with marine litter were the cosmopolitan bryozoans *Jellyella tuberculata* (%O = 31.64 %) and *J. eburnea* (28.61 %), the barnacle species *Lepas anserifera* (29.97 %), *Amphibalanus amphitrite* (22.34 %) and *Amphibalanus* sp. (14.16 %), and the oyster species *Saccostrea cucullata* (13.62 %) and *Magallana bilineata* (5.44 %). We also reported the first records on stranded litter of four species: the gastropod species *Pirenella cingulata* and *Umbonium vestiarium*, the foraminiferan *Ammonia beccarii*, and the oyster *M. bilineata*. This study is thus the first documentation of marine litter as a vector for species dispersal in India, where the production and consumption of plastic rank among the highest in the world. We also highlight the increasing risk of invasions by non-indigenous organisms attached to debris along the southeast coast of India. Comprehensive monitoring efforts are thus needed to elucidate the type of vectors responsible for the arrival of invasive species in this region. Raising awareness and promoting education are vital components in fostering sustainable solutions to combat plastic pollution in the country and globally.

1. Introduction

Marine debris is currently a major global environmental threat that has gained more attention in the last decades from the scientific community, intergovernmental organizations and agencies due to its severe impacts on fisheries, ecosystems and ultimately human health (Beaumont et al., 2019). Marine debris such as plastic, food cover, glass, rubber, tyre, household material, among others, is disposed, discarded or abandoned in coastal and marine environments (Coe and Rogers, 1997; UNEP/PAM/MEDPOL, 2009; Thompson and Gall, 2014; Bergmann et al., 2015) or brought indirectly to the sea by inland waterways and winds (UNEP, 2009; Lima et al., 2014; Jambeck et al., 2015; Aragaw, 2021).

It has been estimated that 4.8–12.7 million tons of marine litter enter into marine habitats annually (Jambeck et al., 2015). Furthermore, nearly 19 to 23 million tons of marine debris produced worldwide in 2016 entered aquatic habitats (Borrelle et al., 2020). Once debris enters the sea, it either floats or sinks, and can be transported to other areas by currents, washing up onto the shoreline and beaches (Van der Mheen et al., 2020; Mghili et al., 2020; Behera et al., 2021; Bouzekry et al., 2022; Fruergaard et al., 2023), or drifting offshore (Lebreton et al., 2012) and sinking to the deepest ocean trench (Chiba et al., 2018).

Marine litter also causes major threats to marine biota, for instance, through ingestion and entanglement of marine megafauna, such as

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sharks, fish, turtles, dolphins, and seabirds, among others (Derraik, 2002; Kühn et al., 2015; Wilcox et al., 2015; Nelms et al., 2016; Panti et al., 2019; Roman et al., 2019; Kühn and van Franeker, 2020; Naidoo et al., 2020; Salazar-Casals et al., 2022). The role of floating plastics as artificial substrates has also been extensively documented (Aliani and Molcard, 2003; Bravo et al., 2011; Reisser et al., 2014). However, its role as dispersal vector for native and invasive species has received less attention (Barnes and Milner, 2005; Kiessling et al., 2015; Rech et al., 2016; Póvoa et al., 2021; Subías-Baratau et al., 2022; Mghili et al., 2023). Moreover, a few studies have identified the fouling organisms, such as bryozoans, to species level and have characterized the plastics on which these organisms were attached (Subías-Baratau et al., 2022).

To date, approximately 400 marine species of bryozoans, molluscs, barnacles, polychaetes, sponges, hydrozoans and ascidians have been recorded rafting on marine litter, favoring the spread of non-native and even invasive species (Winston, 1982; Kiessling et al., 2015; Li et al., 2016; Rech et al., 2018a; Battaglia et al., 2019; Shabani et al., 2019; Amaral-Zettler et al., 2021; De-la-Torre et al., 2021; Póvoa et al., 2021, 2022; Lacerda et al., 2022; Rizzo et al., 2022; Subías-Baratau et al., 2022). Marine organisms can also use anthropogenic debris, such as plastics, for laying their eggs as recently reported for the first time in cephalopods and catsharks (Gündoğdu et al., 2017; Subías-Baratau et al., 2022).

Some of the main dispersal vectors for marine organisms are fishing ropes, styrofoam and wood (Carlton and Fowler, 2018; Rech et al., 2018b; Battaglia et al., 2019; Shabani et al., 2019; Mantelatto et al., 2020; De-la-Torre et al., 2021; Póvoa et al., 2021, 2022; Lacerda et al., 2022; Rizzo et al., 2022; Subías-Baratau et al., 2022). Some of these substrates, generally of anthropogenic origin (Campbell et al., 2017; Rech et al., 2018a; Póvoa et al., 2021), can float for a long period of time and reach large distances (>1000 km) (Barnes and Fraser, 2003; Goldstein et al., 2014; Rech et al., 2018b; García-Gomez et al., 2021; Póvoa et al., 2021). Recent studies reported various examples of medium and long-distance transport of marine organisms, such as barnacles, bryozoans, bivalves, gastropods, sponges, echinoderms, polychaetes, spirorbids, green algae and anthozoan corals, attached to marine litter (Shabani et al., 2019; Goldstein et al., 2014; Rech et al., 2018b; Battaglia et al., 2019; Al Khayat et al., 2021; De-la-Torre et al., 2021; Póvoa et al., 2021, 2022; Mghili et al., 2022; Subías-Baratau et al., 2022; Brandler and Carlton, 2023). Among marine fouling organisms, invasive species may alter the structure of the endemic community, causing a serious threat to local biodiversity and, sometimes, the decline or extinction of native species, as well as economic loss (Gallardo et al., 2019; Gallardo et al., 2019; Pyšek et al., 2020; Tapkir et al., 2022). Marine litter can also increase the growth of microbes, harmful algae and pathogens (Cyanobacteria, fungi and algae) (Maso et al., 2016; Gayle et al., 2018; Vaksmaa et al., 2021; Pasqualini et al., 2023).

The southeast coast of India is one of the richest marine biodiversity regions in India (Venkataraman and Maelkani, 2007) with >380 fish species (Purusothaman et al., 2015; Mogalekar et al., 2018). It also acts as nursery ground for various fish and shell fish larvae, plankton diversity, macrobenthic communities and meiofauna assemblages (Mahesh and Saravanakumar, 2015; Punniyamoorthy et al., 2021; Saravanakumar et al., 2021). Furthermore, the IUCN endangered species, such as olive ridley (*Lepidochelys olivacea* (Eschscholtz, 1829)) and green turtle (*Chelonia mydas* (Linnaeus, 1758)), are frequently occurring along this coast (Chandrasekar and Srinivasan, 2013). However, its biodiversity richness is threatened by anthropogenic activities (urbanization and economic development), extreme weather events, habitat loss, pollution and invasion of non-native species (Ravi, 2011; Rameshkumar and Rajaram, 2017; Vidyasakar et al., 2020; Gunasekaran et al., 2021; Sanjai Gandhi et al., 2021; Gunasekaran et al., 2022). In the southeast coast of India, the Tamilnadu region receives the largest amount of litter (Patterson Edward et al., 2020; Vidyasakar et al., 2020; Neelavannan et al., 2022; Pattiaratchi et al., 2022). However, its impact on the marine fauna is unknown because no research has been conducted on the potential of marine litter as a dispersal vector of non-indigenous marine organisms, including invasive species. Assessing the nature of biofouling should be a high priority to detect new species introduction and develop effective plans to prevent and mitigate their spread. This study aims to report, for the first time, biofouling communities attached to marine litter found on eight beaches of Tamilnadu in the southeast coast of India. Species-specific substrate preferences are also analyzed.

2. Materials and methods

2.1. Study area

Tamilnadu coast is located in the southern part of India and is connected to the Bay of Bengal. The Tamilnadu coastline is the third largest coastal region of India with 1076 km of coastal length and an Exclusive Economic Zone (EEZ) of 73,359 mile^2, contributing 0.72 million tons of fish production. The major geomorphic features of this coastal line comprise raised beaches, sand dunes, mangroves swamp, estuaries and tidal flats. This coastal region supports an enormous variety of important marine species, including molluscs, sea turtles, coral reef fishes and others (Chinnadurai and Fernando, 2007; Babu et al., 2010; Satheeshkumar and Khan, 2012; Chandrasekar and Srinivasan, 2013).

The study area is densely populated by various major and minor chemical-based industries, involved in mineral and metal processing, oil refinement, pharmaceutical, dye and fertilizer production. It also receives a large amount of debris from recreational, fishing and tourism activities (Dowarah and Devipriya, 2019; Jeyasanta et al., 2020; Sanjai Gandhi et al., 2021; Gunasekaran et al., 2022; Kannan et al., 2023a) and from international shipping from Southeast Asian countries (Dharani et al., 2003). Climate in the area is tropical, with temperatures between 20.5 and 37.8 °C and high rainfall from northeast during the monsoon season (November to February, average precipitation over the period 698 mm). The resulting wind and hydrodynamic may influence the dispersal and transport of marine litter (Al Khayat et al., 2021).

To assess biofouling communities on beached marine litter, four urban (Puducherry-S1, Silver beach- S4, Samiyarpettai- S6 and Puthupettai- S7) and four village (Veerampattinam- S2, China Veerampattinam- S3 Periyakuppam- S5 and Parangipettai- S8) beaches were selected (Fig. 1; Supplementary Table S1) along the southeast coast of Tamilnadu to represent most of its shoreline, considering site accessibility, level of exposure and usage/activity. The urban beaches are referred here to frequented beaches with a large amount of activities (e.g. swimming and fishing) and the village beaches to beaches near small populations mainly used during holiday seasons. The Puducherry beach (S1) is a natural urban beach and this site is one of the busiest beaches in the state, attracting 3000 visitors per day and even more during weekends and public holidays. In the Puducherry coast, beaches are generally narrow and suffers from severe erosion along the northern segment, whereas the southern segment is comparatively broader and characterized by a depositional nature. The Silver beach (S4), situated between Parangipetai to the south, Pondicherry to the north, Cuddalore city to the west and the Bay of Bengal to the east, covers an area of 2 km^2. The study area is composed of fluvio-marine quaternary sediments. Fishing and tourism activities are major sources of plastic litter in S4 (Kannan et al., 2023a). On the other hand, Samiyarpettai (S6) and Puthupettai (S7) small urban beaches are located on the Coromadel coast of the Bay of Bengal. The Veeramapttinam, Chinna veerampattinam, Periyakuppam and Parangipettai are village beaches, which have significant lower population density and fishing activities when compare to S1 and S2. Recently these two beaches became some of the most popular holiday locations of the region.

2.2. Litter sampling

The sampling was conducted on the eight sites between March and April 2022 following the methods used on the beaches of Morocco and

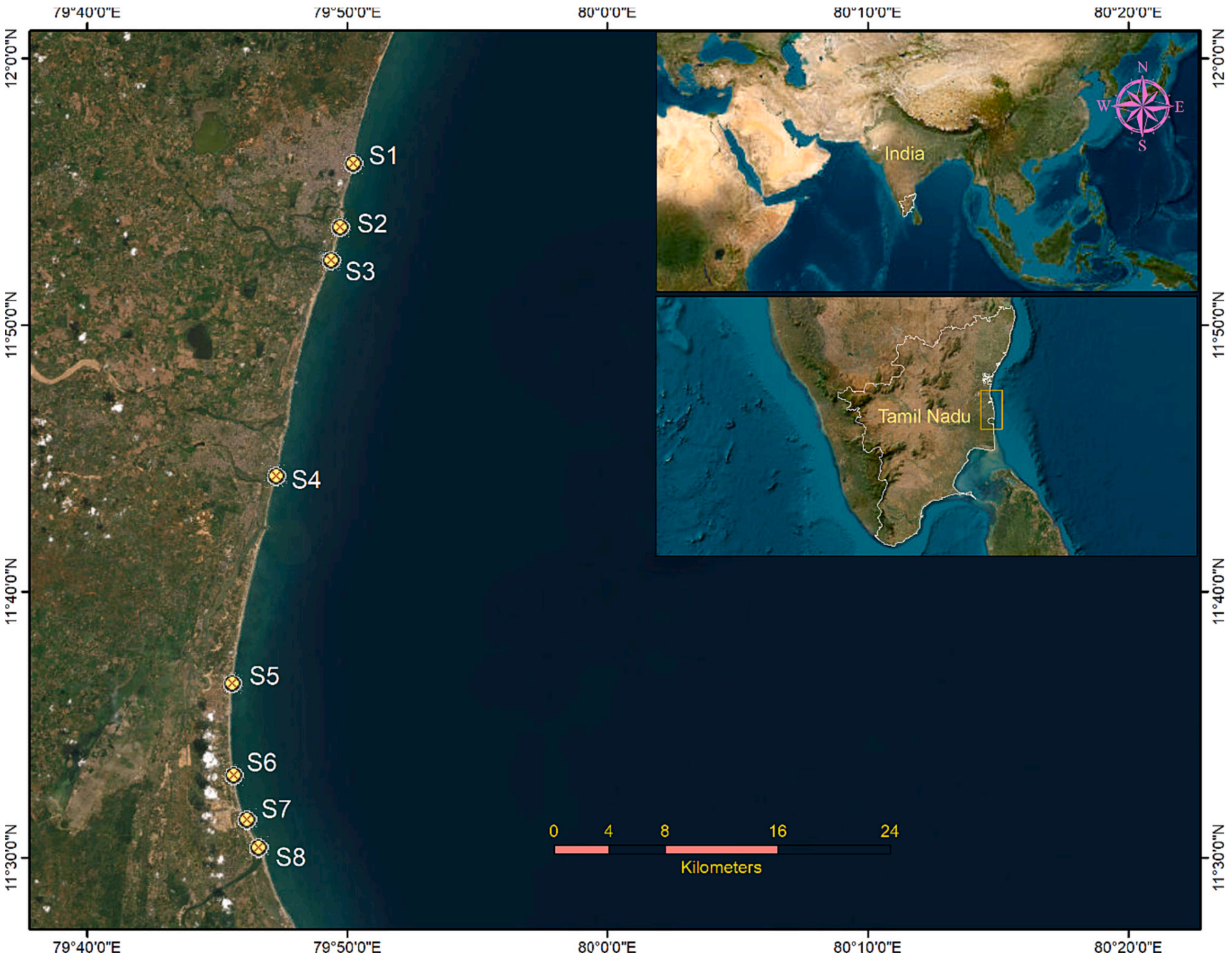

Fig. 1. Sampling sites of stranded marine litter along the southeast coast of India.

Peru described in De-la-Torre et al. (2021) and Mghili et al. (2022). Along the length of each beach, 100 m transects were randomly selected, maintaining at least 30 m distance between them. The Global Positioning System was used to register the geographic coordinates of each transect on each beach. At each beach, sampling was carried out for nearly 60 min in daylight, prior to the beach cleanup. Marine litters were collected in the tidal zone. Only the fouled litter items were considered for this study. The collected fouled litters were stored in aluminum foil bags, transported to the Faculty of Marine Science at Annamalai University, and classified according to the codes and categories developed by the United Nations Environment Programme (Cheshire et al., 2009). The source of collected marine litter were also categorized into two groups: sea based and land-based origin (Veiga et al., 2016). The sea-based origin group includes debris from the fishing industry, commercial and recreational shipping, and offshore platforms (Stelfox et al., 2020; Richardson et al., 2021), while the land-based origin group includes debris from recreation, tourism, shoreline, medical and agricultural activities. It should be acknowledged that, while this classification may help to determine the contribution of various anthropogenic activities, the origin of the litter cannot be determined with absolute certainty.

Each marine litter item collected was scrutinized to carefully record all fouling individuals and photographed following previous studies (Shabani et al., 2019; De-la-Torre et al., 2021; Mghili et al., 2022; Póvoa et al., 2022; Subías-Baratau et al., 2022). Samples were preserved in 70 % ethanol to allow further identification. Fouling species were identified at the lowest taxonomic level using a stereomicroscope and taxonomic guides. As it is standard practice given their fine diagnostic characters, low-vacuum scanning electron microscopy (SEM) was used to identify bryozoan species by means of a Hitachi TM4000plus Tabletop at the Natural History Museum, University of Oslo (Norway). After species identification, the number of individuals/colonies were counted for each taxon. Identified species were classified as invasive and/or cryptogenic based on their distribution and population status on the World Register of Marine Species (WoRMS Editorial Board, 2019) and the Global Invasive Species Database (International Union for Nature Conservation, http://www.iucngisd).

The frequency of occurrence was calculated for each fouled species. Non-parametric tests (Kruskal-Wallis) were employed to check whether the number of individuals/colonies and taxa varied by litter type. Statistical tests were carried out using the SPSS v20 software at the 0.05 level of significance.

A subset of 10 beached litter items were analyzed using a FT-IR spectrometer to identify the polymer composition based on IR absorption bands representing the presence or absence of specific functional groups in the material. The spectra collected were analyzed with Open Specy v0.9.3 software (Cowger et al., 2021) and compared to spectra references in library databases to identify the compounds. The plot in Fig. 2 was constructed using ggplot2 (Wickham, 2016) in R version 4.2.0 (https://www.rproject.org/).

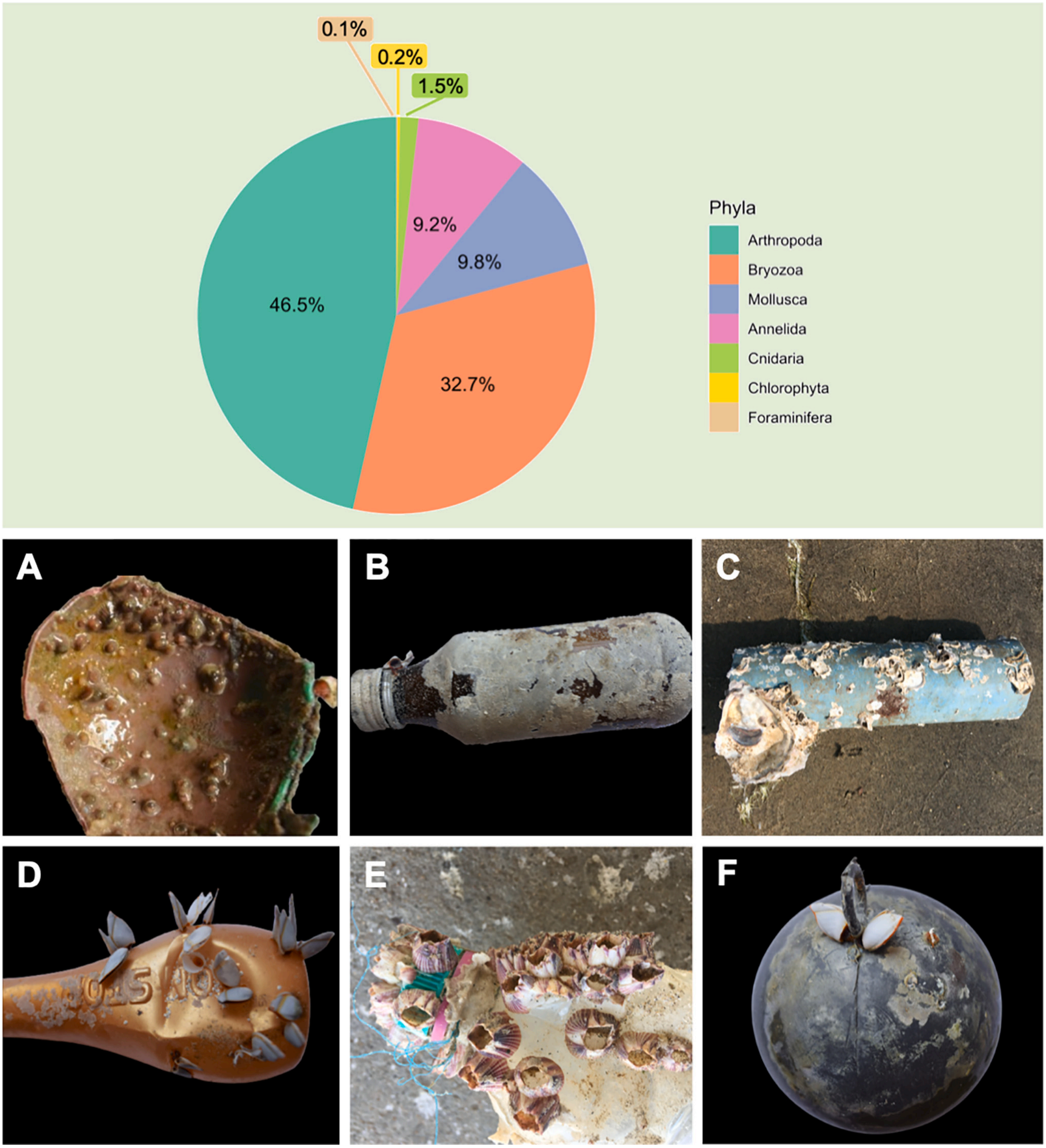

Fig. 2. Percentages of the seven different phyla recorded fouling the marine litter sampled and examples of stranded marine litter with fouling organisms sampled on the beaches studied. A) individuals of the anemone *Anthopleura* sp.; B) encrusting bryozoan colonies of *Jellyella tuberculata*; C) individuals of the oyster *Magallana bilineata*; D) goose barnacles of the species *Lepas anserifera*; E) acorn barnacles of the species *Amphibalanus amphitrite*; F) encrusting bryozoan colonies of *Biflustra savartii.*

3. Results

3.1. Fouling organisms

A total of 3130 specimens/colonies belonging to seven phyla and representing 17 species were recorded on marine debris (Fig. 2 and Table 1). The number of individuals/colonies registered on each litter varied from 1 to 176 (mean = 8.64). Three species of barnacles represented almost half (46.5 %) of all fouling specimens, while three species of bryozoans accounted for the 32.7 % of the recorded specimens (Figs. 2–3; Table 1).

The most common species associated with marine litter were the cosmopolitan bryozoans *Jellyella tuberculata* (Bosc, 1802) (31.6 %) and *J. eburnea* (Hincks, 1891) (28.61 %), the barnacles *Lepas anserifera* Linnaeus, 1767 (30 %), *Amphibalanus amphitrite* (Darwin, 1854) (22.3 %) and *Amphibalanus* sp. (14.2 %), and the oyster *Saccostrea cucullata*

Table 1
List of fouling species and their frequency of occurrence on all stranded litter items. Abbreviations for Status: C = cryptogenic; I = invasive; N = native.

Phylum	Species	Status	Number of specimens/ colonies	Number of litter items	%
Annelida	Polychaete worm	N	289	113	30.00
Arthropoda	*Lepas anserifera*	C	697	110	29.97
Arthropoda	*Amphibalanus amphitrite*	N	475	82	22.34
Arthropoda	*Amphibalanus* sp.	N	282	52	14.16
Mollusca	*Magallana bilineata*	N	95	20	5.44
Mollusca	*Saccostrea cucullata*	N	150	50	13.62
Mollusca	*Isognomon nucleus*	N	15	11	2.99
Mollusca	*Perna viridis*	N	15	3	0.81
Mollusca	*Pirenella cingulata*	N	5	1	0.27
Mollusca	*Umbonium vestiarium*	N	2	1	0.27
Mollusca	*Mytella strigata*	I	26	2	0.54
Foraminifera	*Ammonia beccarri*	N	2	1	0.27
Cnidaria	*Anthopleura* sp.	N	47	2	0.54
Chlorophyta	*Enteromorpha* sp.	N	7	7	1.90
Bryozoa	*Jellyella tuberculata*	N	503	114	31.61
Bryozoa	*J. eburnea*	C	334	105	28.61
Bryozoa	*Biflustra savartii*	N	186	41	11.17

(Born, 1778) (13.6 %). We also found 26 individuals of a non-indigenous mussel, *Mytella strigata* (Hanley, 1843), attached to fishing nets.

3.2. Plastic type

A total of 367 fouled litter items were collected and analyzed along the eight sampled beaches. They fall into seven main groups (Fig. 2; Supplementary Table S2): plastic (277 items, 75.5 %), glass (52 items, 14.2 %), rubber (13 items, 3.5 %), foam sponge (12 items, 3.3 %), cloth (10 items, 2.7 %), metal (2 items, 0.5 %) and wood (1 item, 0.3 %). Urban beaches (Puducherry, Silver, Samiyarpettai and Puthupettai) had the highest abundance and percentage of fouled litter compared to village beaches (Table S1).

Fouling organisms were observed on 20 types of marine litter according to the UNEP code (Supplementary Table S2). The most frequent types were PL24 (plastic fragments) followed by PL01 (bottle caps & lids), PL02 (bottles <2 L), GC02 (bottles & jars), PL07 (plastic bags), PL14 (plastic buoys) and PL06 (food containers). Other items were also reported in lower numbers (ropes, clothing, fishing net, cigarette lighters, bottles >2 L, shoes, tyres, metal body spray, gloves, inner-tubes, cutlery and paint brush). Land-based activities were the major source accounting for the 88.5 % of total litter collected, followed by sea-based activities with 11.5 % (e.g. buoys, fishing net and ropes; Supplementary Table S2). Regarding polymer composition of the plastic items, most of the litter items were composed of polyethylene (40 %) and polyamide (40 %), while polyethylene terephthalate (PET) represented the 20 %.

Diversity was higher on plastic litter compared to other materials, and varied among litter categories. The highest number of species was found on PL02 (12 species), PL24 (11 spp.), PL14 (9 spp.) and PL01 (9 spp.). The lowest diversity was recorded on CL01 (clothing, shoes), PL20 (fishing net) and ME10 (metal body spray). The density of marine organisms was not significantly different between types of marine litter (Kruskal-Wallis test, H (19) = 19, $p = 0.45$) with the highest mean number of individuals/colonies on PL03 (bottles >2 L, mean = 29) and PL02 (mean = 18.5) and the lowest on PL11 (cigarette lighters, mean = 1.8).

The three barnacle species were present on all types of litter but they were dominant on plastic and glass bottles, buoys, fishing ropes, bottle caps/corks and foam sponges (Table 2). Foraminifera, Cnidaria and Chlorophyta were exclusively observed on plastic items.

4. Discussion

Marine debris carries fouling organisms including invasive species that potentially have ecological impact on the marine environment and may threaten biodiversity. In this study, a total of 3130 specimens/ colonies belonging to seven phyla and 17 species has been found on marine debris, identifying for the first time its role as a dispersal vector of marine organisms along the Indian coast. The most abundant taxa found on marine debris were arthropods, bryozoans and molluscs consistent with previous studies in different regions worldwide (Gündoğdu et al., 2017; Rumbold et al., 2020; Póvoa et al., 2021; Rech et al., 2021; Mghili et al., 2022; Póvoa et al., 2022; Subías-Baratau et al., 2022; Brandler and Carlton, 2023). The number of taxa recorded in this study

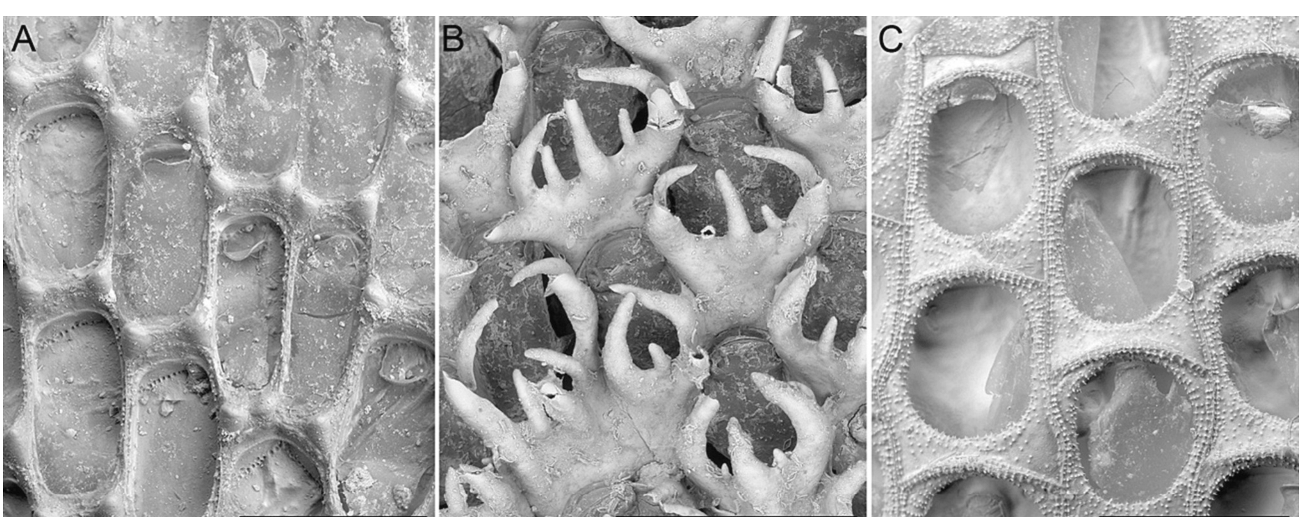

Fig. 3. Scanning electron micrographs of the bryozoan species found encrusting the marine debris. A, *Jelliella tuberculata*; B. *Jelliella eburnea*; C. *Biflustra savartii*. All scale bars are 500 μm.

Table 2
Abundance of individuals/colonies of each phylum on the different types of marine litter.

	Annelida	Arthropoda	Mollusca	Foraminifera	Cnidaria	Chlorophyta	Bryozoa	Total
Plastic	246	1080	249	2	47	7	781	2412
Nylon	17	245	52	–	–	–	–	314
Glass	–	50	2	–	–	–	242	294
Synthetic fiber	26	79	5	–	–	–	–	110
Total	289	1454	308	2	47	7	1023	3130

was lower compared to previous studies in which benthic litter or floating debris were also surveyed (e.g. 22 species: Aliani and Molcard, 2003; 116: Astudillo et al., 2009; 95: Goldstein et al., 2014; 17: Gündoğdu et al., 2017; 38: Battaglia et al., 2019; 21: Shabani et al., 2019; 91: Crocetta et al., 2020; 13: Pinheiro et al., 2021; 26: Subías-Baratau et al., 2022; 33: Brandler and Carlton, 2023).

All the fouling species found in this study were sessile, except for the gastropods *Pirinella cingulata* and *Umbonium vestiarium* (Table 1). This is because mobile species are often lost during or after stranding (Goldstein et al., 2014; Póvoa et al., 2022). The density of mobile species may thus be higher than that of sessile species (Astudillo et al., 2009; Kiessling et al., 2015). Among taxonomic groups, bryozoans and barnacles were the most species-rich and the most abundant as previously reported in several studies (e.g. Rech et al., 2018a, 2021; Shabani et al., 2019; Al Khayat et al., 2021; Cesarini et al., 2022; Mghili et al., 2022; Póvoa et al., 2022; Subías-Baratau et al., 2022; Brandler and Carlton, 2023). Indeed, bryozoans are known to be diverse, ubiquitous and common on a wide range of natural and artificial substrates at all latitudes and depths (Ramalho et al., 2011; Bock and Gordon, 2013; Souto et al., 2016; Almeida et al., 2017; Figuerola et al., 2017, 2018, 2019; Rosso et al., 2018).

The most common bryozoan species found on anthropogenic marine litter here have also been found in several regions around the world (Gündoğdu et al., 2017; Miralles et al., 2018; Rech et al., 2018b, 2021; Battaglia et al., 2019; Rumbold et al., 2020; Shabani et al., 2019; Al Khayat et al., 2021; Póvoa et al., 2022; Subías-Baratau et al., 2022). For instance, *Jellyella tuberculata* and *J. eburnea* are common rafters on anthropogenic marine litter (Goldstein et al., 2014; Kiessling et al., 2015; Carlton and Fowler, 2018; McCuller and Carlton, 2018; Rech et al., 2021), with the latter species having reached a cosmopolitan distribution (Carlton and Fowler, 2018; McCuller and Carlton, 2018; Miralles et al., 2018; Rech et al., 2021). The presence of cosmopolitan species provides evidence that transoceanic dispersion occurs, as these species have an unknown or uncertain biogeographic origin.

The common occurrence of the barnacles *Lepas anserifera* and *Amphibalanus amphitrite* confirms that both species have a well-developed ability to attach to artificial materials of different compositions (Katsanevakis and Crocetta, 2014; Shabani et al., 2019; Al Khayat et al., 2021). We also present the first records on stranded litter for the species *P. cingulata*, *U. vestiarium*, the foraminiferan *Ammonia beccarii* and the oyster *Magallana bilineata* (Table 1).

Remarkably, we found the non-indigenous mussel *Mytella strigata* attached in high density groups to fishing nets. This species, previously documented in India in 2019 on floating plastic bottles, wooden pilings, hulls of boats and walls of fish cages, is considered invasive (Jayachandran et al., 2019). Marine litter may thus have facilitated its spread in Indian waters. Our findings indicate that the growing presence of plastic litter may increase the probability of introducing non-indigenous and invasive species into Indian waters, potentially generating a negative impact on the ecological characteristics of the invaded habitat as already happened (Rech et al., 2016; Miralles et al., 2018; Lins and Rocha, 2022). The phyla recorded here include several invasive species previously documented on marine litter (Garcia-Vazquez et al., 2018; Miralles et al., 2018; Rech et al., 2018b; Lins and Rocha, 2022).

The stranded litter collected was composed mostly of plastic material, which is also in line with previous results from other Indian beaches (Kaviarasan et al., 2022; Mishra et al., 2023). The dominance of plastic litter is due to the combination of its low decomposition rate and high persistence (Derraik, 2002) with the dramatically increased input from land- and sea-based activities since the mid-XX century (Jambeck et al., 2015; Lau et al., 2020). Furthermore, the low density of most plastics facilitates its spreading throughout different oceans and ecosystems by winds and ocean currents. In particular, the main sources of plastic debris were land-based (88.6 %), while recreational activities followed by fishing activities were the major sources of marine litter, both results consistent with previous studies on other Indian beaches (Sulochanan et al., 2019; Gunasekaran et al., 2022; Kaviarasan et al., 2022; Mishra et al., 2023).

Species diversity was higher on plastic litter compared to other materials, with variations observed across different categories, likely due to their higher abundance, prolonged presence and persistence in the marine environment. Several past studies reported the preference of arthropods, molluscs and annelids for plastic material (Rech et al., 2021; Mghili et al., 2022; Póvoa et al., 2022). Nevertheless, three barnacle species were found on all types of litter as these species are capable to attach to a diverse range of litter, regardless of the litter type. While bryozoans preferentially colonized plastic surfaces and glass bottles, other studies found that they also frequently colonize hard plastic and nylon (Rech et al., 2021; Póvoa et al., 2022). Consistent with our findings, litter with simple, smooth surfaces, such as plastic and glass, are usually highly covered by sessile organisms including bryozoans, polychaetes and hydrozoans (Kiessling et al., 2015; Rech et al., 2018a; Póvoa et al., 2022). Other phyla, such as Foraminifera, Cnidaria and Chlorophyta, were exclusively observed on plastic, confirming previous knowledge regarding cnidarians (Crocetta et al., 2020; Rech et al., 2021; Mghili et al., 2022).

Litter items with high buoyancy, such as bottles, buoys and plastic bags (mostly made of polyethylene or expanded polystyrene), supported abundant macroinvertebrate assemblages. These materials can be more suitable for macroinvertebrate colonization and transportation, as they can persist on the sea surface for longer periods of time (Goldstein et al., 2014; Rech et al., 2021). However, their capacity to transport fouling organisms is also influenced by other factors, such as size, texture, persistence, polymer type, material color and roughness (Rech et al., 2018a, 2021; Shabani et al., 2019; Póvoa et al., 2021; Mghili et al., 2022; Póvoa et al., 2022). In particular, biofouling of floating debris may also decrease its buoyancy causing it to sink (Kaiser et al., 2017; Kooi et al., 2017). A recent study provided evidence of this phenomenon as the most abundant fouled benthic plastics had lower densities than seawater, and all bryozoan species were characteristic of shallower depths than those sampled (Subías-Baratau et al., 2022). Benthic plastic debris substrates may thus change biodiversity of benthic communities. Furthermore, litter with low buoyancy, such as fishing nets and ropes made of polyamide, may have been deposited in the seafloor before being colonized.

Litter distribution was uneven among the studied beaches, with urban beaches displaying the highest abundances of fouled litter. This finding is consistent with previous studies conducted along the Indian coast, which also identified urban areas as the main contributors to marine litter accumulation (Sulochanan et al., 2019; Gunasekaran et al., 2022; Kaviarasan et al., 2022; Mishra et al., 2023). The greater quantity of marine litter is probably the result of higher population density and significant coastal tourism in urban beaches. In contrast, village beaches showed lower litter abundances, probably because they are less frequented by human activity. Once litter reaches the beaches, it can eventually enter the coastal waters. The introduction of large quantities of litter makes it more probable for marine organisms to settle on these substrates in urban areas compared to villages. Furthermore, factors like winds, currents and waves may also contribute to the variation in fouled litter abundance on the studied beaches (e.g. Rech et al., 2018a).

In comparison to open sea areas, urban coastal environments are also more prone to the introduction of invasive species, through different pathways, including marine litter (González-Ortegón and Moreno-Andrés, 2021; Wang et al., 2021). Alien species can probably benefit more from, or can at least be less affected by, urbanization compared to indigenous species owing to their adaptive behavioral traits and strategies that allow them to cope better with changing conditions (González-Ortegón and Moreno-Andrés, 2021; Wang et al., 2021). Therefore, the monitoring of biological invasions should prioritize coastal waters near urban areas due to the high number of pressures they experience, including intense vessel traffic and abundant marine litter introduction. Implementing monitoring programs becomes crucial to understand the extent of the interaction between marine litter and fouling organisms, as well as to assess the role of marine litter in introducing non-indigenous and invasive species.

Based on the inscriptions present on the fouled litter, we found that four items might potentially come from Indonesia (PL06, with bryozoans and polychaetes, approximate distance from our sampling station 5607 km), six from Myanmar (PL02, with *L. anserifera*, 2252 km), and two from Sri Lanka (PL02, with bryozoans, 274 Km). In line with this observation, these specific items were plastic bottles with high buoyancy, suggesting the potential for long distance transport. However, further in-depth studies in this region are necessary to substantiate this hypothesis. Marine debris has been previously considered a primary vector for carrying marine species to remote areas (García-Gomez et al., 2021).

This study demonstrates that Indian beaches are littered by recreational, fishing and tourism activities as well as domestic use, and this littering may facilitate biological invasions. A reduction of marine littering would help reducing the risk of introduction of non-indigenous species. To control its input, it is important to focus on its sources (Lau et al., 2020). Efforts should also be made to mitigate the leakage of debris from fishing activities. Education has to be focused on changing the human behavior regarding the use of plastics (Bouzekry et al., 2022), encouraging the reuse, recycling (e.g. the program Container Deposit Legislation (CDL) that encourages public participation in recycling plastic waste bottles by offering small cash incentives to individuals who return beverage containers; Al Khayat et al., 2021; Schuyler et al., 2018) and recovery of new and innovative resources. This could be supported by the establishment of innovative solutions in the context of the circular economy. While beach clean-ups may also help reduce the risk of introducing non-indigenous species via plastic litter, it is essential to acknowledge that they do not provide a comprehensive solution to the plastic problem. Conversely, awareness campaigns serve as one of the potential tools to mitigate the amount of litter arising from recreational beach use (Grelaud and Ziveri, 2020). Given that plastic pollution is a global issue, international cooperation is required to coordinate efforts and make informed decisions that can effectively reduce the amount of floating plastics, thus mitigating the risk of invasive species transportation between oceans. At the local scale, there is a need for more extensive research on floating litter in Indian waters to comprehensively understand and address this issue. We also highlight the need for further collaborative research involving taxonomists with expertise on different groups and molecular biologists to monitor the occurrence of non-native species on marine debris.

5. Conclusions

India ranks among the top producers and consumers of plastic globally (Shahab and Anjum, 2022). Like many other countries, India suffers the challenge of managing the escalating amounts of plastic waste (Kannan et al., 2023b). Sadly, inadequately managed plastic litter finds its way into the marine environment, exacerbating the situation. The Covid-19 pandemic has further contributed to this issue with increased demand for single-use plastic (e.g. face masks and gloves) (Gunasekaran et al., 2022; Kannan et al., 2023b). It is clear that inadequately managed litter in the region has significant adverse effects on coastal biodiversity. While many previous studies have quantified the impact of plastic litter on marine wildlife in Indian waters mainly associated with ingestion and entanglement (e.g., Nisanth and Kumar, 2019; Harikrishnan et al., 2023; Kannan et al., 2023b), this is the first documentation of marine litter acting as a vector for species dispersal in Indian waters. Our results indicate that floating plastic litter represents a habitat for a diverse array of marine biota, including invasive species. Moreover, our study shows the potential of marine litter to transport marine organisms by over significant distances. As the volume of plastic litter entering the Pacific Ocean grows, it will increasingly become a substrate for marine species, heightening the risk of introducing non-native species into Indian waters. These non-native marine species can turn invasive and profoundly impact habitats and diminish the essential services they provide. More extensive research and monitoring surveys targeting fouling litter thus play a crucial role in detecting alien species in Indian waters. However, it is raising awareness and promoting education that are vital components in fostering sustainable solutions to combat plastic pollution in the country and globally.

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CRediT authorship contribution statement

Gunasekaran Kannan: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Roles/Writing - original draft

Bilal Mghili: Roles/Writing - original draft

Emanuela DiMartino: Data curation; Investigation; Methodology; Writing - review & editing

Anna Sanchez Vidal: Data curation; Investigation; Methodology; Supervision; Writing - review & editing

Blanca Figuerola Balañá: Conceptualization; Data curation; Investigation; Methodology; Supervision; Roles/Writing - original draft; Writing - review & editing

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.115469.

References

Al Khayat, J.A., Veerasingam, S., Aboobacker, V.M., Vethamony, P., 2021. Hitchhinking of encrusting organisms on floating marine debris along the west coast of Qatar. Arabian/Persian Gulf. Sci. Total Environ. 776, 145985 https://doi.org/10.1016/j.scitotenv.2021.145985.
Aliani, S., Molcard, A., 2003. Hitch-hiking on floating marine debris: microbenthic species in the Western Mediterranean Sea. Migrations and dispersal of marine organisms. Dev. Hydrobiol. 174, 59–67. https://doi.org/10.1007/978-94-017-2276-6_8.
Almeida, A.C.S., Souza, F.B.C., Menegola, C.M.S., Vieira, L.M., 2017. Diversity of marine bryozoans inhabiting demosponges in northeastern Brazil. Zootaxa 4290, 281–323. https://doi.org/10.11646/zootaxa.4290.2.3.
Amaral-Zettler, L.A., Ballerini, T., Zettler, E.R., Asbun, A.A., Adame, A., Casotti, R., Dumontet, B., Donnarumma, V., Engelmann, J.C., Frere, L., Mansui, J., Philippon, M., Pietrelli, L., Sighicelli, M., 2021. Diversity and predicted inter- and intra-domain interactions in the Mediterranean Plastisphere. Environ. Pollut. 286, 117439. https://doi.org/10.1016/j.envpol.2021.117439.
Aragaw, T.A., 2021. The macro-debris pollution in the shorelines of Lake Tana: first report on abundance, assessment, constituents, and potential sources. Sci. Total Environ. 797, 149235 https://doi.org/10.1016/j.scitotenv.2021.149235.
Astudillo, J.C., Bravo, M., Dumont, C.P., Thiel, M., 2009. Detached aquaculture buoys in the SE Pacific: potential dispersal vehicles for associated organisms. Aquat. Biol. 5, 219–231. https://doi.org/10.3354/ab00151.
Babu, A., Kesavan, K., Annadurai, D., Rajagopal, S., 2010. Abundance and diversity of by-catch molluscs from Cuddalore coast. Mar. Biodivers. Rec. 3, 1–5. https://doi.org/10.1017/S1755267210000503.
Barnes, D.K.A., Fraser, K.P.P., 2003. Rafting by five phyla on man-made flotsam in the Southern Ocean. Mar. Ecol. Prog. Ser. 262, 289e291. https://doi.org/10.3354/meps262289.
Barnes, D.K.A., Milner, P., 2005. Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean. Mar. Biol. 146, 815–825. https://doi.org/10.1007/s00227-004-1474-8.
Battaglia, P., Consoli, P., Ammendolia, G., D'Alessandro, M., Bo, M., Vicchio, T.M., Pedà, C., Cavallaro, M., Andaloro, F., Romeo, T., 2019. Colonization of floats from submerged derelict fishing gears by four protected species of deep-sea corals and barnacles in the Strait of Messina (central Mediterranean Sea). Mar. Pollut. Bull. 148, 61–65. https://doi.org/10.1016/j.marpolbul.2019.07.073.
Beaumont, N.J., Aanesen, M., Austen, M.C., Borger, T., Clark, J.R., Cole, M., Hooper, T., Lindeque, P.K., Pascoe, C., Wyles, K.J., 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.
Behera, D.P., Prabhu, K., Sivaraj, S., Lakshmi, P.D., Yusof, S.I., 2021. A preliminary investigation of marine litter pollution along Mandvi beach, Kachchh, Gujarat. Mar. Pollut. Bull. 165, 112100 https://doi.org/10.1016/j.marpolbul.2021.112100.
Bergmann, M., Gutow, L., Klages, M., 2015. Marine Anthropogenic Litter, first ed. Springer International Publishing, New York.
Bock, P.E., Gordon, D.P., 2013. Phylum Bryozoa Ehrenberg, 1831. Zootaxa 3703, 67–74. https://doi.org/10.11646/zootaxa.3703.1.14.
Borrelle, S.B., Ringma, J., Law, K.L., Monnahan, C.C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G.H., Hilleary, M.A., Eriksen, M., Possingham, H.P., Frond, H.D., Gerber, L.R., Polidoro, B., Tahir, A., Bernard, M., Mallos, N., Barnes, M., Rochman, C.M., 2020. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science 369, 1515–1518. https://doi.org/10.1126/science.aba3656.
Bouzekry, A., Mghili, B., Aksissou, M., 2022. Addressing the challenge of marine plastic litter in the Moroccan Mediterranean: a citizen science project with schoolchildren. Mar. Pollut. Bull. 184, 114167 https://doi.org/10.1016/j.marpolbul.2022.114167.
Brandler, K.G., Carlton, J.T., 2023. First report of marine debris as a species dispersal vector in the temperate Northwest Atlantic Ocean. Mar. Pollut. Bull. 188, 114631 https://doi.org/10.1016/j.marpolbul.2023.114631.
Bravo, M., Astudillo, J.C., Lancellotti, D., Luna-Jorquera, G., Valdivia, N., Thiel, M., 2011. Rafting on abiotic substrata: properties of floating items and their influence on community succession. Mar. Ecol. Prog. Ser. 439, 1–17. https://doi.org/10.3354/meps09344.
Campbell, E., Alfaro-Shigueto, J., Mangel, J.C., 2017. Whale entanglements in Peru: frequency and cost. In: 22nd Biennial Conference on the Biology of Marine Mammals (Halifax).
Carlton, J.T., Fowler, A.E., 2018. Ocean rafting and marine debris: a broader vector menu requires a greater appetite for invasion biology research support. Aquat. Invasions 13, 11–15. https://doi.org/10.3391/ai.2018.13.1.02.
Cesarini, G., Secco, S., Battisti, C., Questino, B., Marcello, L., Scalici, M., 2022. Temporal changes of plastic litter and associated encrusting biota: evidence from Central Italy (Mediterranean Sea). Mar. Pollut. Bull. 181, 113890 https://doi.org/10.1016/j.marpolbul.2022.113890.
Chandrasekar, K., Srinivasan, M., 2013. Sea turtle exploitation from Tamil Nadu, Southeast coast of India. J. Entomol. Zool. Stud. 1, 11–14.
Cheshire, A., Adler, E., Barbière, J., Cohen, Y., Evans, S., Jarayabhand, S., Jeftic, L., Jung, R.T., Kinsey, S., Kusui, E.T., 2009. UNEP/IOC Guidelines on Survey and Monitoring of Marine Litter. United Nations Environment Programme and Intergovernmental Oceanographic Commission.
Chiba, S., Saito, H., Fletcher, R., Yogi, T., Kayo, M., Miyagi, S., Ogido, M., Fujikura, K., 2018. Human footprint in the abyss: 30 year records of deep-sea plastic debris. Mar. Policy 96, 204–212. https://doi.org/10.1016/j.marpol.2018.03.022.
Chinnadurai, G., Fernando, O.J., 2007. Meiofauna of mangrove of the southeast coast of India with special reference to the free-living marine nematode assemblage. Estuar. Coast. Shelf Sci. 72, 329–336. https://doi.org/10.1016/j.ecss.2006.11.004.
Coe, J.M., Rogers, D., 1997. Marine Debris: Sources, Impacts, and Solutions, first. ed. Springer International Publishing, New York.
Cowger, W., Steinmetz, Z., Gray, A., Munno, K., Lynch, J., Hapich, H., Primpke, S., De Frond, H., Rochman, C., Herodotou, O., 2021. Microplastic spectral classification needs an open source community: open specy to the rescue! Anal. Chem. 93, 7543–7548. https://doi.org/10.1021/acs.analchem.1c00123.
Crocetta, F., Riginella, E., Lezzi, M., Tanduo, V., Balestrieri, L., Rizzo, L., 2020. Bottom trawl catch composition in a highly polluted coastal area reveals multifaceted native biodiversity and complex communities of fouling organisms on litter discharge. Mar. Environ. Res. 155, 104875 https://doi.org/10.1016/j.marenvres.2020.104875.
De-la-Torre, G., Dioses-Salinas, D.C., Pérez-Baca, B.L., Cumpa, L.A.M., Pizarro-Ortega, C.V.I., Torres, F.G., Gonzalez, K.N., Santillàn, L., 2021. Marine macroinvertebrates inhabiting plastic litter in Peru. Mar. Pollut. Bull. 167, 1–10. https://doi.org/10.1016/j.marpolbul.2021.112296.
Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44, 842e852. https://doi.org/10.1016/s0025-326x(02)00220-5.
Dharani, G., Nazar, Abdul, Venkatesan, R., Ravindran, M., 2003. Marine debris in Great Nicobar. Curr. Sci. 85, 574–575.
Dowarah, K., Devipriya, S.P., 2019. Microplastic prevalence in the beaches of Puducherry, India and its correlation with fishing and tourism/recreational activities. Mar. Pollut. Bull. 148, 123–133. https://doi.org/10.1016/j.marpolbul.2019.07.066.
Figuerola, B., Barnes, D.K.A., Brickle, P., Brewin, P.D., 2017. Bryozoan diversity around the Falkland and South Georgia Islands: overcoming Antarctic barriers. Mar. Environ. Res. 126, 81–94. https://doi.org/10.1016/j.marenvres.2017.02.005.
Figuerola, B., Gordon, D.P., Cristobo, J., 2018. New deep Cheilostomata (Bryozoa) species from the Southwestern Atlantic: shedding light in the dark. Zootaxa 4375 (2), 211–249. https://doi.org/10.11646/zootaxa.4375.2.3.
Figuerola, B., Gore, D.B., Johnstone, G., Stark, J.S., 2019. Spatio-temporal variation of skeletal Mg-calcite in Antarctic marine calcifiers. PLoS One 14 (5), e02120231. https://doi.org/10.1371/journal.pone.0210231.
Fruergaard, M., Simon, N.L., Marianne, N.L., Nicole, R.P., Kasper, B.N., Abline Bentzon, T., Sidsel, K.S., Laura, I.A.N., Bao-Son, T., Phuong Thao, T.T., Hai, D.N., Lam, N.N., Thorbjorn, J.A., 2023. Abundance and sources of plastic debris on beaches in a plastic hotspot, Nha Trang, Viet Nam. Mar. Pollut. Bull. 186, 114394 https://doi.org/10.1016/j.marpolbul.2022.114394.
Gallardo, B., Bacher, S., Bradley, B., Fransico, A.C., Gallien, Laure, Jonathan, M.J., Cascade, J.B.S., Vila, M, 2019. InvasiBES: understanding and managing the impacts of invasive alien species on biodiversity and ecosystem services. NeoBiota 50, 109–122. https://doi.org/10.3897/neobiota.50.35466.
García-Gomez, J.C., Garrigos, M., Garrigos, J., 2021. Plastic as a vector of dispersion for marine species with invasive potential. A review. Front. Ecol. Evol. 9, 629756 https://doi.org/10.3389/fevo.2021.629756.
Garcia-Vazquez, E., Cani, A., Diem, A., Ferreira, C., Geldhof, R., Marquez, L., Molloy, E., Perché, S., 2018. Leave no traces – beached marine litter shelters both invasive and native species. Mar. Pollut. Bull. 131, 314–322. https://doi.org/10.1016/j.marpolbul.2018.04.037.
Gayle, I.H., Takeaki, H., Hiroshi, K., 2018. Invasion threat of benthic marine algae arriving on Japanese tsunami marine debris in Oregon and Washington, USA. Phycologia 57 (6), 641–658. https://doi.org/10.2216/18-58.1.
Goldstein, M.C., Carson, H.S., Eriksen, M., 2014. Relationship of diversity and habitat area in North Pacific plastic-associated rafting communities. Mar. Biol. 161, 1441–1453. https://doi.org/10.1007/s00227-014-2432-8.
González-Ortegón, E., Moreno-Andrés, J., 2021. Anthropogenic modifications to estuaries facilitate the invasion of non-native species. Processes 9, 740. https://doi.org/10.3390/pr9050740.
Grelaud, M., Ziveri, P., 2020. The generation of marine litter in Mediterranean island beaches as an effect of tourism and its mitigation. Sci. Rep. 10, 20326. https://doi.org/10.1038/s41598-020-77225-5.
Gunasekaran, K., Karthikeyan, P., Yosuva, M., Manigandan, V., Subagunasekar, M., 2021. Nivar cyclonic impacts on mollusk habitat destruction in Parangipettai, southeast coast of Tamil Nadu, India: a case study. Mar. Pollut. Bull. 173, 113022 https://doi.org/10.1016/j.marpolbul.2021.113022.
Gunasekaran, K., Mghili, B., Saravanakumar, A., 2022. Personal protective equipment (PPE) pollution driven by the COVID-19 pandemic in coastal environment, Southeast coast of India. Mar. Pollut. Bull. 180, 113769 https://doi.org/10.1016/j.marpolbul.2022.113769.
Gündoğdu, S., Çevik, C., Karaca, S., 2017. Fouling assemblage of benthic plastic debris collected from Mersin Bay, NE Levantine coast of Turkey. Mar. Pollut. Bull. 124, 147–154. https://doi.org/10.1016/j.marpolbul.2017.07.023.
Harikrishnan, T., Madhuvandhi, J., Priya, S., Rekha, S., Krishnamurthy, R., Thiagarajan, R., Muthukumar, T., Govarthanan, M., Gopalakrishnan, S., 2023. Microplastic contamination in commercial fish species in southern coastal region of India. Chemosphere 313, 137486. https://doi.org/10.1016/j.chemosphere.2022.137486.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347, 768–771. https://doi.org/10.1126/science.1260352.

Jayachandran, P.R., Aneesh, B.P., Oliver, P.G., Philomina, J., Jima, M., Harikrishnan, K., Bijoy Nandan, S., 2019. First record of the alien invasive biofouling mussel *Mytella strigata* (Hanley, 1843) (Mollusca: Mytilidae) from Indian waters. BioInvasions Rec. 8, 828–837. https://doi.org/10.3391/bir.2019.8.4.11.

Jeyasanta, K.I., Sathish, N., Patterson, J., Edward, J.K.P., 2020. Macro-, meso- and microplastic debris in the beaches of Tuticorin district, southeast coast of India. Mar. Pollut. Bull. 154, 111055 https://doi.org/10.1016/j.marpolbul.2020.111055.

Kaiser, D., Kowalski, N., Waniek, J.J., 2017. Effects of biofouling on the sinking behavior of microplastics. Environ. Res. Lett. 12, 12. https://doi.org/10.1088/1748-9326/aa8e8b.

Kannan, G., Kolandhasamy, P., Anbukkarasu, S., Sigamani, S., Ayyappan, S., Rajendran, R., 2023a. Marine plastics on the beaches of Cuddalore coast, Southeast coast of India: a assessment of their abundance during Covid lockdown and post lockdown. Reg. Stud. Mar. Sci., 103051 https://doi.org/10.1016/j.rsma.2023.103051.

Kannan, G., Mghili, B., De-la-Torre, G.E., Prabhu, K., Machendiranathan, M., Rajeswari, M.V., Saravanakumar, A., 2023b. Personal protective equipment (PPE) pollution driven by COVID-19 pandemic in Marina Beach, the longest urban beach in Asia: abundance, distribution, and analytical characterization. Mar. Pollut. Bull. 186, 114476 https://doi.org/10.1016/j.marpolbul.2022.114476.

Katsanevakis, S., Crocetta, F., 2014. Pathways of introduction of marine alien species in European waters and the Mediterranean – a possible undermined role of marine litter. In: Marine Litter in the Mediterranean and Black Seas, pp. 61–68.

Kaviarasan, T., Dhineka, K., Sambandam, M., Sivadas, S.K., Sivyer, D., Hoehn, D., Pradhan, U., Mishra, P., Murthy, M.R., 2022. Impact of multiple beach activities on litter and microplastic composition, distribution, and characterization along the southeast coast of India Ocean Coast. Manag. 223, 106177 https://doi.org/10.1016/j.ocecoaman.2022.106177.

Kiessling, T., Gutow, L., Thiel, M., 2015. Marine litter as habitat and dispersal vector. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham, pp. 141–181. https://doi.org/10.1007/978-3-319-16510-3 (298).

Kooi, M., Van Nes, E., Scheffer, M., Koelmans, A., 2017. Ups and downs in the ocean: effects of biofouling on vertical transport of microplastics. Environ. Sci. Technol. 51, 7963–7971. https://doi.org/10.1021/acs.est.6b04702.

Kühn, S., van Franeker, J.A., 2020. Quantitative overview of marine debris ingested by marine megafauna. Mar. Pollut. Bull. 51, 110858 https://doi.org/10.1016/j.marpolbul.2019.110858.

Kühn, S., Bravo Rebolledo, E.L., Van Franeker, J.A., 2015. Deleterious effects of litter on marine life. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer, Berlin.

Lacerda, A.L.D.F., Taylor, J.D., Rodrigues, L.D.S., Kessler, F., Secchi, E.R., Proietti, M.C., 2022. Floating plastics and their associated biota in the Western South Atlantic. Sci. Total Environ. 805, 1–14. https://doi.org/10.1016/j.scitotenv.2021.150186.

Lau, W.W.Y., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., Koskella, J., Velis, C.A., Godfrey, L., Boucher, J., Murphy, M.B., Thompson, R.C., Jankowska, E., Castillo Castillo, A., Pilditch, T.D., Dixon, B., Koerselman, L., Kosior, E., Favoino, E., Gutberlet, J., Baulch, S., Atreya, M., Fishcer, D., He, K.H, Petit, M.M., Sumaila, R., Neil, E., Bernhofen, M.V., Lawrence, K., Palardy, J.E., 2020. Evaluating scenarios toward zero plastic pollution. Science 369 (6510), 1455–1461. https://doi.org/10.1126/science.aba9475.

Lebreton, L.C., Greer, S.D., Borrero, J.C., 2012. Numerical modelling of floating debris in the world's oceans. Mar. Pollut. Bull. 64, 653–661. https://doi.org/10.1016/j.marpolbul.2011.10.027.

Li, H.X., Orihuela, B., Zhu, M., Rittschof, D., 2016. Recyclable plastics as substrata for settlement and growth of bryozoans *Bugula neritina* and barnacles *Amphibalanus amphitrite*. Environ. Pollut. 218, 973–980. https://doi.org/10.1016/j.envpol.2016.08.047.

Lima, A.R.A., Costa, M.F., Barletta, M., 2014. Distribution patterns of microplastics within the plankton of a tropical estuary. Environ. Res. 132, 146–155. https://doi.org/10.1016/j.envres.2014.03.031.

Lins, D.M., Rocha, R.M., 2022. Invasive species fouling *Perna perna* (Bivalvia: Mytilidae) mussel farms. Mar. Pollut. Bull. 181, 113829 https://doi.org/10.1016/j.marpolbul.2022.113829.

Mahesh, R., Saravanakumar, A., 2015. Temporal and spatial variability of fin fish assemblage structure in relation to their environment parameters in Pichavaram mangrove ecosystem, India. Indian J. Geo-Mar. Sci. 44, 910–923.

Mantelatto, M.C., Póvoa, A.A., Skinner, L.F., Araujo, F.V., de Creed, J.C., 2020. Marine litter and wood debris as habitat and vector for the range expansion of invasive corals (*Tubastraea* spp.). Mar. Pollut. Bull. 160, 111659 https://doi.org/10.1016/j.marpolbul.2020.111659.

Maso, M., Fortuno, J.M., Juan, S.D., Demestre, M., 2016. Microfouling communities from pelagic and benthic marine plastic debris sampled across Mediterranean coastal waters. Sci. Mar. 60, 117–127. https://doi.org/10.3989/scimar.04281.10A.

McCuller, M., Carlton, J., 2018. Transoceanic rafting of Bryozoa (Cyclostomata, Cheilostomata, and Ctenostomata) across the North Pacific Ocean on Japanese tsunami marine debris. Aquat. Invasions 13, 137–162. https://doi.org/10.3391/ai.2018.13.1.11.

Mghili, B., Analla, M., Aksissou, M., Aissa, C., 2020. Marine debris in Moroccan Mediterranean beaches: an assessment of their abundance, composition and sources. Mar. Pollut. Bull. 160, 111692 https://doi.org/10.1016/j.marpolbul.2020.111692.

Mghili, B., De-la-Torre, G., Analla, M., Aksissou, M., 2022. Marine macroinvertebrates fouled in marine anthropogenic litter in the Moroccan Mediterranean. Mar. Pollut. Bull. 185, 114266 https://doi.org/10.1016/j.marpolbul.2022.114266.

Mghili, B., De-la-Torre, G.E., Aksissou, M., 2023. Assessing the potential for the introduction and spread of alien species with marine litter. Mar. Pollut. Bull. 191, 114913 https://doi.org/10.1016/j.marpolbul.2023.114913.

Miralles, L., Gomez-Agenjo, M., Rayon-Vina, F., Gyraite, G., Garcia-Vazquez, E., 2018. Alert calling in port areas: marine litter as possible secondary dispersal vector for hitchhiking invasive species. J. Nat. Conserv. 42, 12–18. https://doi.org/10.1016/j.jnc.2018.01.005.

Mishra, P., Kaviarasan, T., Sambandam, M., Dhineka, K., Ramana Murthy, M.V., Iyengar, G., Singh, J., Ravichandran, M., 2023. Assessment of national beach litter composition, sources and management along the Indian coast- a citizen science approach. Mar. Pollut. Bull. 186, 114405 https://doi.org/10.1016/j.marpolbul.2022.114405.

Mogalekar, H., Canciyal, J., Dhaval, S.P., Sudhan, C., 2018. Marine and estuarine fish fauna of Tamil Nadu, India. Proc. Int. Acad. Ecol. Environ. Sci. 8, 231–271.

Naidoo, T., Rajkaran, A., Sershen, 2020. Impacts of plastic debris on biota and implications for human health: a South African perspective. S. Afr. J. Mar. Sci. 116, 1–8. https://doi.org/10.17159/sajs.2020/7693.

Neelavannan, K., Achyuthan, H., Sen, I.S., Krishnakumar, S., Gopinath, K., Dhanalakshmi, R., Rajalakshmi, P.R., Sajeev, R., 2022. Distribution and characterization of plastic debris pollution along the Poompuhar Beach, Tamil Nadu, Southern India. Mar. Pollut. Bull. 175, 113337 https://doi.org/10.1016/j.marpolbul.2022.113337.

Nelms, S.E., Duncan, E.M., Broderick, A.C., Galloway, T.S., Godfrey, M.H., Hamann, M., et al., 2016. Plastic and marine turtles: a review and call for research. ICES J. Mar. Sci. 73, 165–181. https://doi.org/10.1093/icesjms/fsv165.

Nisanth, H.P., Kumar, B., 2019. Observations on the entanglement of plastic debris in seabirds of the family Laridae along Kerala Coast, India. Kerala J. Aquat. Biol. Fish. 7, 115–119.

Panti, C., Baini, M., Lusher, A., Hernandez-Milan, G., Bravo Rebolledo, E.L., Unger, B., Syberg, K., Simmonds, M.P., Fossi, M.C., 2019. Marine litter: one of the major threats for marine mammals. Outcomes from the European cetacean society workshop. Environ. Pollut. 247, 72–79. https://doi.org/10.1016/j.envpol.2019.01.029.

Pasqualini, V., Garrido, M., Cecchi, P., Connes, C., Coute, A., El Rakwe, M., Henry, M., Hervio-Heath, D., Quilichini, Y., Simonnet, J., Rinnert, E., Vitre, T., Galgani, F., 2023. Harmful algae and pathogens on plastics in three Mediterranean coastal lagoons. Heliyon 9. https://doi.org/10.1016/j.heliyon.2023.e13654.

Patterson Edward, J.K., Mathews, G., Raj, K.D., Laju, R.L., Bharath, M.S., Kumar, P.D., Arasamuthu, A., Grimsditch, G., 2020. Marine debris — an emerging threat to the reef areas of Gulf of Mannar, India. Mar. Pollut. Bull. 151, 110793 https://doi.org/10.1016/j.marpolbul.2019.110793.

Pattiaratchi, C., Mirjam, V.D.M., Cathleen, S., Bhavani, E.N., Appalanaidu, S., Sara, H., Rachel, W., Nimit, K., Michelle, F., Sarath, W., 2022. Plastics in the Indian Ocean - sources, transport, distribution, and impacts. Ocean Sci. 18, 1–28. https://doi.org/10.5194/os-18-1-2022.

Pinheiro, L.M., Carvalho, I.V., Agostini, V.O., Martinez-Souza, G., Galloway, T.S., Pinho, G.L.L., 2021. Litter contamination at a salt marsh: an ecological niche for biofouling in South Brazil. Environ. Pollut. 285, 117647 https://doi.org/10.1016/j.envpol.2021.117647.

Póvoa, A.A., Skinner, L.F., Vieira de Araújo, F., 2021. Fouling organisms in marine litter (rafting on abiogenic substrates): a global review of literature. Mar. Pollut. Bull. 166, 112189 https://doi.org/10.1016/j.marpolbul.2021.112189.

Póvoa, A.A., Vieira de Araújo, F.V., Skinner, L.F., 2022. Macroorganisms fouled in marine anthropogenic litter (rafting) arround a tropical bay in the Southwest Atlantic. Mar. Pollut. Bull. 175, 113347 https://doi.org/10.1016/j.marpolbul.2022.113347.

Punniyamoorthy, R., Murugesan, P., Mahadevan, G., Sanchez, A., 2021. Benthic meiofaunal diversity in four zones of Pichavaram Mangrove Forest, India. J. Foraminifer. Res. 51, 294–307. https://doi.org/10.2113/gsjfr.51.4.294.

Purusothaman, R., Jayaprabha, N., Sliambarasan, A., Murugesan, P., 2015. Diversity and trophic level of ichthyofauna associated with the trawl bycatches of Cuddalore and Parangipettai, south-east coast of India. Mar. Biodivers. Rec. 8, 1–8. https://doi.org/10.1017/S1755267215000159.

Pyšek, P., Hulme, P.E., Simberloff, D., Bacher, S., Blackburn, T.M., Carlton, J.T., Richardson, D.M., 2020. Scientists' warning on invasive alien species. In: Biological Reviews of the Cambridge Philos. Soc, vol. 95, pp. 1511–1534. https://doi.org/10.1111/brv.12627.

Ramalho, L.V., Muricy, G., Taylor, P.D., 2011. Taxonomic revision of some lepraliomorph cheilostome bryozoans (Bryozoa: Lepraliomorpha) from Rio de Janeiro State, Brazil. J. Nat. Hist. 45, 767–798. https://doi.org/10.1080/00222933.2010.535917.

Rameshkumar, S., Rajaram, R., 2017. Experimental cultivation of invasive seaweed Kappaphycus alvarezii (Doty) Doty with assessment of macro and meiobenthos diversity from Tuticorin coast, Southeast coast of India. Reg. Stud. Mar. Sci. 9, 117–125. https://doi.org/10.1016/j.rsma.2016.12.002.

Ravi, V., 2011. Habitat loss and population reduction of mudskippers (family: Gobiidae) from Tamil Nadu, Southeast Coast of India. In: Marine Biodiversity: Present Status and Prospects, pp. 37–49.

Rech, S., Borrell, Y., García-Vazquez, E., 2016. Marine litter as a vector for non-native species: what we need to know. Mar. Pollut. Bull. 113, 40–43. https://doi.org/10.1016/j.marpolbul.2016.08.032.

Rech, S., Borrel, Y., García-Vazquez, E., 2018a. Anthropogenic marine litter composition in coastal areas may be a predictor of potentially invasive rafting fauna. PLoS One 13, 1–22. https://doi.org/10.1371/journal.pone.0191859.

Rech, S., Salmina, S., Pichs, Y.J.B., García-Vazquez, E., 2018b. Dispersal of alien invasive species on anthropogenic litter from European mariculture areas. Mar. Pollut. Bull. 131, 10–16. https://doi.org/10.1016/j.marpolbul.2018.03.038.

Rech, S., Gusmao, J.B., Kiessling, T., Hidalgo-Ruz, V., Meerhoff, E., Gatta-Rosemary, M., Moore, C., de Vinne, R., Thiel, M., 2021. A desert in the ocean – depauperate fouling communities on marine litter in the hyper-oligotrophic South Pacific substropical gyre. Sci. Total Environ. 759, 143545 https://doi.org/10.1016/j.scitotenv.2020.143545.

Reisser, J., Shaw, J., Hallegraeff, G., Proietti, M., Barnes, D.K.A., Thums, M., Wilcox, C., Hardesty, B.D., Pattiaratchi, C., 2014. Millimeter- sized marine plastics: a new pelagic habitat for microorganisms and invertebrates. PLoS One 9, e100289. https://doi.org/10.1371/journal.pone.0100289.

Richardson, K., Hardesty, B.D., Vince, J.Z., Wilcox, C., 2021. Global causes, drivers, and prevention measures for lost fishing gear. Front. Mar. Sci. 8, 690447 https://doi.org/10.3389/fmars.2021.690447.

Rizzo, L., Minichino, R., Virgili, R., Tanduo, V., Osca, D., Manfredonia, A., Consoli, P., Colloca, F., Crocetta, F., 2022. Benthic litter in the continental slope of the Gulf of Naples (central-Western Mediterranean Sea) hosts limited fouling communities but facilitates molluscan spawning. Mar. Pollut. Bull. 181, 113915 https://doi.org/10.1016/j.marpolbul.2022.113915.

Roman, L., Hardesty, B.D., Hindel, M.A., Wilcox, C., 2019. A quantitative analysis linking seabird mortality and marine debris ingestion. Sci. Rep. 9, 3202. https://doi.org/10.1038/s41598-018-36585-9.

Rosso, A., Di Martino, E., Pica, D., Galanti, L., Cerrano, C., Novosel, M., 2018. Non-indigenous bryozoan species from natural and artificial substrata of Mediterranean submarine caves. Mar. Biodivers. 48, 1345–1355. https://doi.org/10.1007/s12526-016-0602-2.

Rumbold, C.E., García, G.O., Seco Pon, J.P., 2020. Fouling assemblage of marine debris collected in a temperate South-western Atlantic coastal lagoon: a first report. Mar. Pollut. Bull. 154, 111103 https://doi.org/10.1016/j.marpolbul.2020.111103.

Salazar-Casals, A., de Reus, K., Greskewitz, N., Havermans, J., Geut, M., Villanueva, S., Rubio-Garcia, A., 2022. Increased incidence of entanglements and ingested marine debris in Dutch seals from 2010 to 2020. Oceans. 3 (3), 389–400. https://doi.org/10.3390/oceans3030026.

Sanjai Gandhi, K., Pradhap, D., Prabaharan, G., Sing, S.H., Krishnakumar, S., 2021. Distribution of plastic litter in beach sediments of Silver beach, Cuddalore, during Nivar Cyclone- a first report. Mar. Pollut. Bull. 172, 112904 https://doi.org/10.1016/j.marpolbul.2021.112904.

Saravanakumar, M., Murugesan, P., Damotharan, P., Punniyamoorthy, R., 2021. Seasonal composition and diversity of zooplankton in Pichavaram Mangrove Forest, Southeast Coast of India. Int. J. Mod. Trends Sci. Technol. 7, 60–70. https://doi.org/10.46501/IJMTST0709011.

Satheeshkumar, P., Khan, A.B., 2012. Influence of environmental parameters on the distribution and diversity of molluscan composition in pondicherry mangroves, southeast coast of India. Ocean Sci. J. 47, 61–71. https://doi.org/10.1007/s12601-012-0006-6.

Shabani, F., Nasrolahi, A., Thiel, M., 2019. Assemblage of encrusting organisms on floating anthropogenic debris along the northern coast of the Persian Gulf. Environ. Pollut. 254, 1–9. https://doi.org/10.1016/j.envpol.2019.112979.

Shahab, S., Anjum, M., 2022. Solid waste management scenario in India and illegal dump detection using deep learning: an AI approach towards the sustainable waste management. Sustainability 14, 1–28.

Souto, J., Berning, B., Ostrovsky, A.N., 2016. Systematics and diversity of deep-water Cheilostomata (Bryozoa) from Galicia Bank (NE Atlantic). Zootaxa 4067, 401–459. https://doi.org/10.11646/zootaxa.4067.4.1.

Stelfox, M., Lett, C., Reid, G., Souch, G., Sweet, M., 2020. Minimum drift times infer trajectories of ghost nets found in the Maldives. Mar. Pollut. Bull. 154, 111037 https://doi.org/10.1016/j.marpolbul.2020.111037.

Subías-Baratau, A., Sanchez-Vidal, A., Di Martino, E., Figuerola, B., 2022. Marine biofouling organisms on beached, buoyant and benthic plastic debris in the catalan sea. Mar. Pollut. Bull. 175, 113405 https://doi.org/10.1016/j.marpolbul.2022.113405.

Sulochanan, B., Veena, S., Ratheesh, L., Padua, S., Rohit, P., Kaladharan, P., Kripa, V., 2019. Temporal and spatial variability of beach litter in Mangaluru, India. Mar. Pollut. Bull. 149, 110541 https://doi.org/10.1016/j.marpolbul.2019.110541.

Tapkir, S., Boukal, D., Kalous, L., Bartoň, D., Souza, A.T., Kolar, V., Soukalova, K., Duchet, C., Gottwald, M., Smejkal, M., 2022. Invasive gibel carp (*Carassius gibelio*) outperforms threatened native crucian carp (*Carassius carassius*) in growth rate and effectiveness of resource use: field and experimental evidence. Aquat. Conserv. Mar. Freshwat. Ecosyst. 32, 1901–1912. https://doi.org/10.1002/aqc.3894.

Thompson, R.C., Gall, S.C., 2014. Impacts of marine debris on biodiversity: current status and potential solutions. https://www.cbd.int/doc/publications/cbd-ts-67-en.pdf. (Accessed 27 September 2019) (WWW Document).

UNEP, 2009. Marine Litter: A Global Challenge. Nairobi, UNEP, p. 232.

UNEP/PAM/MEDPOL, 2009. Results of the assessment of the status of marine litter in the Mediterranean. In: Meeting of MED POL Focal Points No. 334, p. 91.

Vaksmaa, A., Knittel, K., Abdala Asbun, A., Goudriaan, M., Ellrott, A., Witte, H.J., Vollmer, I., Meirer, F., Lott, C., Weber, M., Engelmann, J.C., Niemann, H., 2021. Microbial communities on plastic polymers in the Mediterranean Sea. Front. Microbiol. 12, 1021. https://doi.org/10.3389/fmicb.2021.673553.

Van der Mheen, M., Van Sebille, E., Pattiaratchi, C., 2020. Beaching patterns of plastic debris along the Indian Ocean rim. Ocean Sci. 16, 1317–1336. https://doi.org/10.5194/os-16-1317-2020.

Veiga, J.M., Fleet, D., Kinsey, S., Nilsson, P., Vlachogianni, T., Werner, S., Galgani, F., Thompson, R.C., Dagevos, J., Gago, J., Sobral, P., Cronin, R., 2016. Identification of Sources of Marine Litter. MSFD GES TG Marine Litter Thematic Report, JRC Technical Report.

Venkataraman, K., Maelkani, V.K., 2007. Marine biodiversity conservation in Tamil Nadu. In: GOMBRT Publication. 7, pp. 13–28.

Vidyasakar, A., Krishnakumar, S., Kasilingam, K., Neelavannan, K., Bharathi, V.A., Godson, P.S., Prabha, K., Magesh, N.S., 2020. Characterization and distribution of microplastics and plastic debris along Silver Beach, Southern India. Mar. Pollut. Bull. 158, 111421 https://doi.org/10.1016/j.marpolbul.2020.111421.

Wang, Y., Tan, W., Li, B., Wen, L., Lei, G., 2021. Habitat alteration facilitates the dominance of invasive species through disrupting niche partitioning in floodplain wetlands. Divers. Distrib. 27, 1861–1871. https://doi.org/10.1111/ddi.13376.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York (ISBN 978-3-319-24277-4, http://ggplot2.org).

Wilcox, C., Sebille, E.V., Hardesty, B.D., 2015. Threat of plastic pollution to seabirds is global, pervasive and increasing. Proc. Natl. Acad. Sci. U. S. A. 112, 11899–11904. https://doi.org/10.1073/pnas.1502108112.

Winston, J.E., 1982. Drift plastic – an expanding niche for a marine invertebrate? Mar. Pollut. Bull. 13, 348–351. https://doi.org/10.1016/0025-326X(82)90038-8.

WoRMS Editorial Board, 2019. World Register of Marine Species. Available From: http://www.marinespecies.org.at.VLIZ. https://doi.org/10.14284/170.