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Baseline

Characterization of plastic debris from surface waters of the eastern Arabian Sea–Indian Ocean

S.A. Naidu [a,*], L. Mawii [b], V. Ranga Rao [a], G. Anitha [a], P. Mishra [a], Bhavani E. Narayanaswamy [c], V. Anil Kumar [d], M.V. Ramana Murthy [a], Gupta GVM [d]

[a] National Centre for Coastal Research, Ministry of Earth Sciences, Chennai, India
[b] Centre of Advance study in marine biology, Annamalai University, Parangipettai, India
[c] Scottish Association for Marine Science, Oban, Argyll PA37 1QA, Scotland, UK
[d] Centre for Marine Living Resources and Ecology, Ministry of Earth Sciences, Kochi, India

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ABSTRACT

The quantity of floating plastic debris (FPD) is continuously being increased in the oceans. To assess their size, structure, and composition along the eastern Arabian Sea (EAS), FPD samples were collected by using a surface plankton net. The microplastic size fraction (0.5–5 mm) was the most prevalent accounting for >50% of the total, followed by mesoplastics (5–25 mm; ~40%) and macroplastics (>25 mm; ~10%). The collected FPDs were categorized into five different types and eight colours. Attenuated Total Reflectance-Fourier Transform Infrared Spectrometry (ATR-FTIR) analysis of the plastics revealed that polypropylene, polyethylene, and nylon were the most dominant polymers, and these comprised mostly of fibre/fishing line. The abundance of FPD in the EAS (0.013 ± 0.012 no.s/m^3) was found to be very low compared to elsewhere. The prevalent microplastics presence in the oceans might have occurred mainly by the degradation of larger items. It increases bioavailability, and hence, is a risk to marine ecosystems.

Plastic pollution in the marine environment from the coastal areas to the open oceans is a worldwide problem and has been well-documented in recent years (Barnes et al., 2009; Browne et al., 2011; Eriksen et al., 2014; Law and Thompson, 2014; Galgani et al., 2015; Li et al., 2021). The production rates and pattern of plastic use have seen an exponential increase since the 1950s, with projections of 600 MT by 2025 and exceeding 1 BT by 2050 (Lusher et al., 2017). A significant fraction of this, arising initially from land-based human activities and improper disposal at a later time, gets transported to the ocean by river runoff (UNEP, 2005; Jambeck et al., 2015). In addition, microplastic abundance is an order of magnitude higher during heavy rainfall, confirming the observations of Veerasingam et al. (2016a, 2020b) that huge quantities of fresh microplastics are washed from the land to coastal seas through rivers. High quantities of plastics have been observed floating in surface waters of the Eastern Indian Ocean (EIO) during the monsoon season, and it has been suggested that the EIO might also be a hotspot for microplastics pollution (Li et al., 2021). The production of huge amounts of mismanaged plastic waste and rapid industrialization has led to an increase in plastic wastes, especially along the densely populated coasts throughout the world (Jambeck et al., 2015).

Microplastics are small plastic particles ranging in size from microns to millimetres. They can be manufactured specifically for commercial use and are termed primary microplastics or fragments and are formed by the breakdown of larger plastics such as bags and ropes. Secondary microplastics are derived by different physical, chemical, and biological breakdown processes (Cole et al., 2011; Wright et al., 2013). These plastic particles include both high- and low-density polymers: polyethylene (PE) and polypropylene (PP) are low-density polymers that float at the sea surface and can be transported to long distances by wind and oceanic currents (Eriksen et al., 2014; Law and Thompson, 2014; Veerasingam et al., 2016a; Zhang, 2017), whereas the high-density polymer particles such as polyvinyl chloride (PVC) are more likely to sink and accumulate in the sediment (Browne et al., 2011; Courtene-Jones et al., 2020). Some of these microplastic particles and fibres can eventually end up in the marine fauna: initially through grazing, filter-feeding, and deposit-feeding modes of nutrition (Cole et al., 2011; Lusher et al., 2015; Courtene-Jones et al., 2017; Galloway et al., 2017), later through bioaccumulation (Thompson et al., 2004; Naidu, 2019;

* Corresponding author.
E-mail address: snaidu@nccr.gov.in (S.A. Naidu).

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James et al., 2020), and are eventually consumed by humans (Cox et al., 2020).

Although the per capita plastic consumption rate of India is less than half of the global average (22 kg), the plastic recycling rate is three times higher (60%) than the global average (PlasticEurope, 2018; Seetharaman and Bureau, 2019). The long coastline of India experiences high levels of plastic pollution as a result of numerous industries located near the coasts with a direct outflow of untreated domestic sewage and fishing activities, which has put ever-increasing pressure on the coastal environment. As a result, the coastal waters have been recognized as hotspots for plastic pollution (Sruthy and Ramasamy, 2017; Robin et al., 2020; Veerasingam et al., 2020a, 2020b). However, a substantial number of studies on plastic litter have specifically focused on beaches (Veerasingam et al., 2016a, 2016b; Tiwari et al., 2019) and in biota (Naidu et al., 2018; Naidu, 2019; Daniel et al., 2020; Goswami et al., 2020; James et al., 2020; Selvam et al., 2021) which has raised the suggestion that there needs to be more focused research on microplastics along the Indian coast. Typically, once the plastics reach the coast, they are often transported far from their original source by wind and ocean circulation, both in coastal (Veerasingam et al., 2016a, 2016b; Zhang, 2017) and open oceans (Eriksen et al., 2014; Li et al., 2021). Such transportation pathways of plastic debris are also expected in the EAS which is characterized by a strong seasonal hydrodynamic setting with strong winds, currents, and circulation patterns (Shankar and Shetye, 1997; Shenoi et al., 2004). The present study, therefore, aimed to provide the fundamental data regarding the abundance, distribution, and characteristics (size, shape, and colour) of plastic debris along the EAS.

The eastern Arabian Sea (EAS) is a unique system for various processes such as biogeochemistry, upwelling, winter convective mixing, and formation of oxygen minimum zones (Dileepkumar, 2006; Gupta et al., 2016). The present study area lies between 8–22°N and 66–76°E, which is entirely within India's Exclusive Economic Zone. It experiences a bi-annual reversal of the monsoon wind, being blown from the southwest from June–September (known as the summer monsoon), whereas the winter monsoon occurs from November to February, wind blowing from the northeast (Shankar and Shetye, 1997; Shenoi et al., 2004). The unique monsoon system and seasonal hydrodynamic settings spread the transportation of buoyant plumes in the shelf waters of the Arabian Sea (Veerasingam et al., 2016a; Seena et al., 2019). Furthermore, the long Indian coastline >7500 km, hosts ~14% of the total subcontinent population, distributed through nine states and two union territories (ENCORE, 2019). Despite increasing awareness regarding plastic pollution, the increase in densely populated coastal cities and towns, growth in coastal tourism combined with rising industrial/fishing activities all contribute to debris accumulation observed along the coast (Robin et al., 2020; Selvam et al., 2021).

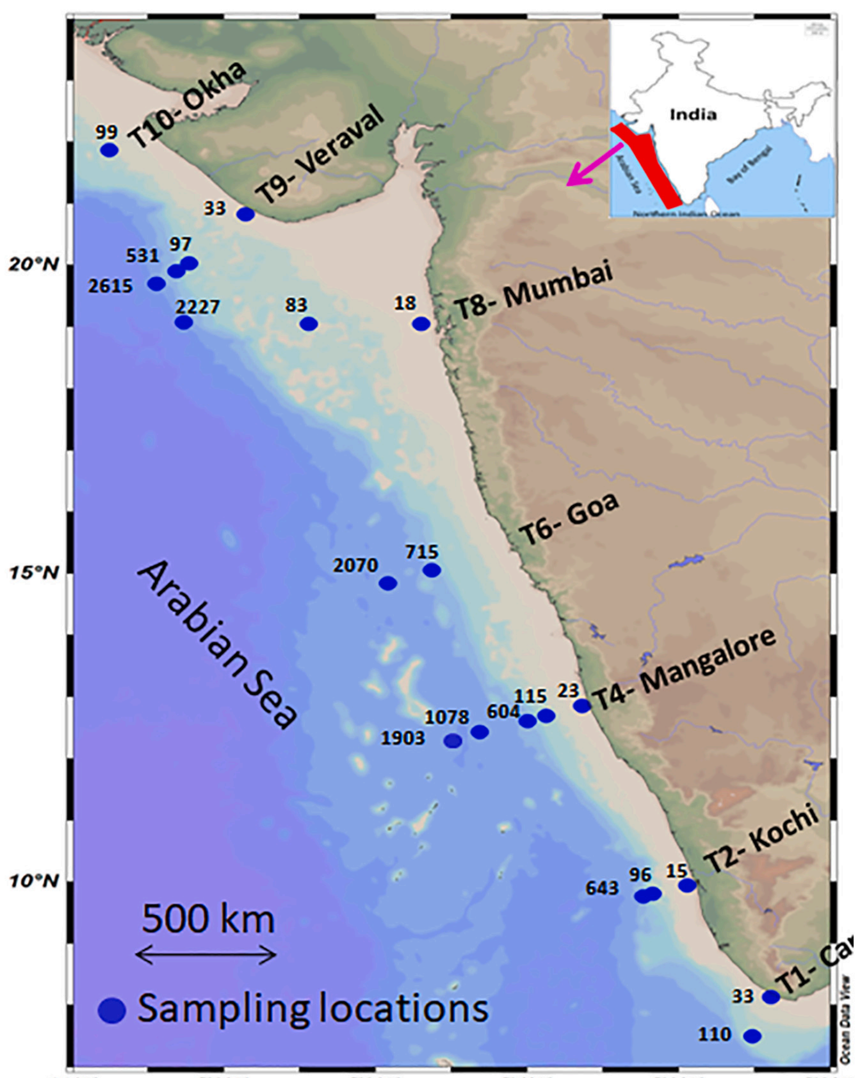

Fig. 1. The study area shows plastic debris collected from surface water sampling of the eastern Arabian Sea (blue dots indicate station locations with initial depth (m)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Twenty samples were collected along seven transects in three regions (Fig. 1): South Eastern Arabian Sea (SEAS): T1 = Cape, T2 = Kochi; Central Eastern Arabian Sea (CEAS): T4 = Mangalore, T6 = Goa; North Eastern Arabian Sea (NEAS): T8 = Mumbai, T9 = Veraval, and T10 = Okha during March 2018 onboard the Fishery Oceanographic Research Vessel-Sagar Sampada (Cr·No-373). The study region was divided into two depth categories: shelf waters (<200 m) and open ocean waters (>200 m), and further separated into three regions i.e., SEAS (T1 and T2), CEAS (T4 and T6), and NEAS (T8, T9, and T10) (Fig. 1). In this study, a bongo net system (0.61 m wide × 0.16 m vertical opening, 0.333 mm mesh, and 3 m long) (Hydrobios, Germany) was used. The net was deployed from the research vessel and towed along the top 30 cm of the water column at an average speed of 2.4–2.5 knots for 20 mins (Table 1) (Doyle et al., 2011; references therein). Sampling details such as time, depth, flow meter reading, wind speed, and ship speed are given in Table 1. A calibrated flow meter (Hydrobios, Germany) was used to calculate the volume of water filtered per tow. On retrieval of the trawl, the cod-end was rinsed carefully, materials in the net were transferred into glass bottles, and fixed with 5% buffered formalin (Lusher et al., 2015; Naidu et al., 2018).

In the laboratory, all the samples were sieved through a set of stacked stainless steel sieves (2 mm and 0.5 mm). This allowed for the separation of organic materials (plankton and other wood/plant materials), both marine and terrestrial, and different sized plastics, making it easier to manually sort the plastic particles. The larger plastic items were removed using forceps and washed gently with distilled water before being placed in glass bottles. For the extraction of microplastics, the material retained on the 0.5 mm mesh sieve was treated with 30% hydrogen peroxide (H_2O_2) (1:5 v/v) solution at 60 °C to remove the organic matter (James et al., 2020). The resulting residue was mixed with sodium chloride solution (NaCl; 1.2 g/cm^3) for density separation to take place and thus allowing easier removal of the microplastics (e.g. Saliu et al., 2018). The resulting supernatant was passed through a 0.5 mm mesh to collect the microplastics. The 0.5 mm mesh sheets were folded, sun-dried, visualized, and photographed by using a stereomicroscope (RSMr-Series). Extreme care was taken to avoid any contamination from airborne particles and sample processing/handling was undertaken in a closed room (Naidu et al., 2018; Robin et al., 2020). To avoid the misidentification of visual plastics and floating plastics, debris was defined based on three criteria (KIMO, 2007; GESAMP, 2019): 1) no cellular or organic structures, 2) should be thick throughout their length, and 3) clear and homogenous colour throughout. Additionally, doubtful particles/fibres were preidentified by using the hot needle method (Hurley et al., 2018). The shapes were defined as fibres which have a long and thin appearance, fragments which once used to be the part of a larger plastic item, films which are a very thin layer of plastic, foam or sponges that are light, and pellet pieces which are either ovoid or disc-shaped. Plastic debris in surface waters was calculated according to the number of items per unit volume (no.s/m^3) (Robin et al., 2020). To understand the characterization of the plastics, plastic items were classified into three size classes: microplastics (0.5–5 mm), mesoplastics (5–25 mm), and macroplastics (>25 mm) following the method described by Jayasiri et al. (2013) and Lee et al. (2013).

To identify the type of polymer, samples were analyzed using a Shimadzu Fourier Transform Infrared Spectrometer (FTIR) coupled with Attenuated Total Reflectance (ATR) diamond crystal attachment. Absorption spectra were recorded as an average of 64 scans in the mid-infrared range 4000–400 cm^{-1}, and polymer type was determined by comparing sample FTIR spectra against known spectra from databases (Shimadzu polymers Library) as described by Veerasingam et al. (2020a). The scanning electron microscope (SEM) images of microplastics were obtained to determine the surface morphology of these particles by following the procedure of Wang et al. (2019). Plastic particles are coated with a thin film of gold coating on both sides and then analyzed using the SEM (JSM-IT500 model, JEOL InTouchScope™) with a voltage of 3 kV. Graphical representation was undertaken by using ODV Software (Version 4.0) with DIVA gridding to show the spatial distribution, and an ANOVA test was performed (Windows 10; Microsoft Excel) to determine the significance between regions.

Plastic items have been found widely distributed in shallow coastal waters (<25 m) of India (Veerasingam et al., 2016b, 2020b; James et al., 2020; Robin et al., 2020; Selvam et al., 2021). In the present study, a total of 276 visible plastic items were recorded within a range of 2–64 (14 ± 16 items; $n = 20$) from the coastal to open ocean surface waters of the EAS (Fig. 2 & Table 1), indicating lower concentrations compared to shallow coastal waters of India (0–125 items: James et al., 2020). The abundance of floating plastic debris varied from 0.002–0.046 no.s/m^3 (0.013 ± 0.012; Table 1) and was found to be almost the same order of magnitude reported from coastal waters of the Northeast Pacific Ocean (0.004–0.19 no.s/m^3, Doyle et al., 2011). Nevertheless, these values were lower than those reported elsewhere from various coastal and open ocean waters (Table 2).

The probable reason for the lower abundance of plastic in this study is because the samples were collected during the inter monsoon season:

Table 1
Surface water sample collection using a bongo net sampler with details of initial and final readings (time, depth, flow meter reading, ship speed, wind, and ship speed). Plastic abundance is per unit volume. ND denotes no data.

Transect	Time		Depth (m)		Flow meter reading		Wind speed (m/s)		Ship speed (m/s)		Plastic items	Plastic abundance (no·s/m^3)
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final		
T1	11.49	12.13	33	32	76,504	83,100	2.1	2.1	ND	ND	64	0.041
T1	11.54	12:18	110	115	87,479	90,343	4.2	6.2	1.8	2.8	6	0.009
T2	11.06	11:27	15	15	65,760	68,842	5.1	8.3	2.2	2.2	12	0.017
T2	8.45	09:05	97	112	18,497	22,158	6.3	ND	1.4	2.9	4	0.005
T2	11.45	12:05	643	849	24,714	27,913	6.2	8.6	2.2	2.8	3	0.004
T4	11.07	11:28	24	26	43,937	48,564	3.2	3.1	3.3	2.9	50	0.046
T4	22.25	22:46	115	120	53,806	59,475	3.1	1.4	2.9	2.7	3	0.002
T4	1.05	01:25	604	702	61,203	61,953	2.5	4.9	2.2	3.1	3	0.017
T4	5.35	05:55	1078	1070	63,933	67,358	4.1	4.4	0.8	0.3	6	0.007
T4	16.06	16:26	1904	1945	68,920	76,592	7.2	ND	2.4	2.5	22	0.012
T6	11.47	12:07	715	789	86,546	91,218	7.4	7.1	2.9	2.8	9	0.008
T6	23.01	23:22	2071	2070	94,432	98,660	5.5	5.5	3	2.6	22	0.022
T8	16.43	17:03	18	21	1179	5995	ND	ND	2.3	2.1	14	0.012
T8	12.56	13:16	83	86	13,457	17,321	5	1.4	3.1	3.7	13	0.014
T8	12.18	12:38	2227	2475	29,589	32,853	3.1	3.7	3	2.1	7	0.009
T9	22.38	22:58	33	34	57,643	61,285	4.3	5.8	1.9	2.5	9	0.010
T9	9.15	09:35	97	93	47,497	51,607	2	5.5	2.6	2.4	2	0.002
T9	5.23	05:43	531	439	42,870	45,543	5.3	4.7	2.3	2.2	2	0.003
T9	22:05	22.29	2616	1600	35,017	38,797	2.2	2.5	2.8	2.2	12	0.013
T10	12.17	12:37	99	98	68,432	74,164	3.3	3.1	2.8	2.6	13	0.010

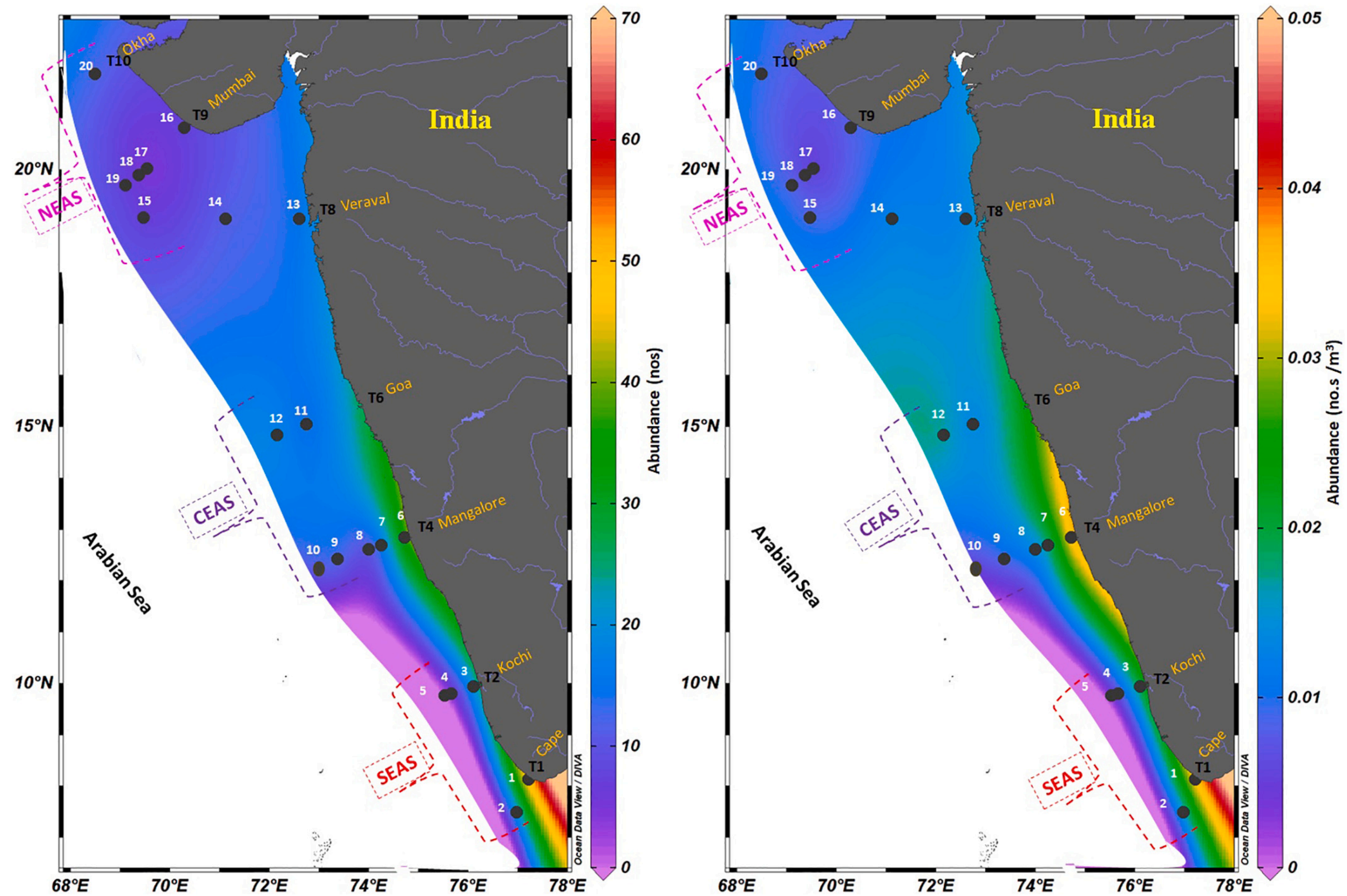

Fig. 2. Spatial distribution of floating plastic debris a) particle concentration (nos) and b) per unit volume (no.s/m^3) in the eastern Arabian Sea in the spring inter monsoon.

March to May. Negligible runoff from the land carries lower quantities of plastic compared to the monsoon period (James et al., 2020; Robin et al., 2020; Li et al., 2021). The spatial abundance of floating plastic debris in shelf waters was found to be statistically and significantly higher (i.e., depth < 200 m; 17 ± 20 items) (F-test; F = 6.922; $p < 0.005$; Fig. 2 and Table 1) compared to that of the open ocean (i.e., depth > 200 m; 10 ± 18 items). The relatively high abundance of plastic debris found in the shallow coastal waters (<30 m contour; Fig. 2) was expected as there would be direct input from domestic sources, industrial complexes, fishing, recreational activities, and other local sources (Seena et al., 2019; Robin et al., 2020). The plastic abundance between the regions did not vary significantly (SEAS vs CEAS and SEAS vs NEAS; F = 0.204; $p < 0.110$ and F = 0.699; $p < 0.414$, respectively), whereas a statically slight significant difference was found between CEAS vs NEAS (F = 3.433; $p < 0.083$; Fig. 2). This might indicate a homogeneous (SEAS vs CEAS and SEAS vs NEAS) and heterogeneous (CEAS vs NEAS) distribution of plastic debris in surface waters between the regions. Generally, the hydrodynamic settings (flow rates, wind directions, currents, circulation pattern, and residence time) are the most likely reasons behind the homogeneous (Isobe et al., 2014) or heterogeneous distribution of the plastic debris (Lusher et al., 2015; Veerasingam et al., 2016a) in coastal waters.

Globally, plastic waste is characterized into different sizes, shapes/types, and colours, and is often used to identify its source and fate in the marine environment (Browne et al., 2011; Li et al., 2021). The size fractionation analysis revealed that microplastics were the most dominant (51%), followed by mesoplastics (38%) and macroplastics (11%) (Fig. 3). The higher abundance of micro- and meso-plastics (present study: 89%) are similar to those reported from different coastal waters (South Korea: ~90%: Lee et al., 2013; Japan: ~80%: Isobe et al., 2014). The origin and input of the plastic wastes are from surface runoff through urban areas, atmospheric deposition, spillages from ships, fishing activities, and coastal and offshore activities (UNEP, 2005; GESAMP, 2019). The fragmentation and cracks on the surfaces of particles indicate that breakdown processes reduce particle sizes even further and would increase their bioavailability to the pelagic–benthic biota (Wright et al., 2013; Courtene-Jones et al., 2017; Wang et al., 2019). The SEM analysis results of the microplastic particles showed many breakages on fibre/fishing line (×1000 magnification; Fig. 5b), multilayer composition on the films (×3000 magnification; 5e), and rough surfaces on the fragments (×300 magnification; 5 h). The breakdown of large-sized plastics may account for the high percentage contribution of microplastics, as observed in this study (Figs. 4 and 5).

The shape of the extracted plastic items was categorized into five types: fibre/fishing line, fragment, film, foam, and pellet (Figs. 3 and 4). Fibre/fishing line accounted for 47% of the total plastic types followed by fragments (27%), films (18%), and foams (7%), whereas pellets accounted for less than 1% (Fig. 3c–d). The predominance of fibres and fragments in this study are about (~75%), which is similar to the results reported along the southern Sri Lankan coast (Koongolla et al., 2018) and the southwest coast of India (Robin et al., 2020). In addition, fibre/fishing lines also accounted for 99% of microplastics reported in Arctic polar waters (Lusher et al., 2015). The sources and occurrences of fibre/fishing lines and fragments in coastal waters are linked to aquaculture, domestic activities, and textile industries (UNEP, 2005). Further, the presence of fibre/fishing lines from fishing grounds along the Mumbai coast, are mostly derived from discarded rope materials and fishing activities (Selvam et al., 2021). The microplastic fibres of textile and

Table 2
Characterization and abundance of plastic observed in surface waters of eastern Arabian Sea, in comparison with other studies around the world. The abbreviations shown in table are Polyester (PES), polystyrene (PS), polyvinyl chloride (PVC), polypropylene (PP), polyethylene (PE), low density polyethylene (LDPE), polyamide (PA), nylon (NY).

Location specification	Depth contour	Categories			Polymer type	Plastic abundance (no·s/m^3)	Reference
		Size	Shape	Colour			
Arctic polar waters	Coastal and open ocean	0.25 mm–4.75 mm	Fibre, fragments and films	Black, blue	PES, PS, PVC, PP, PE	0–1.3	Lusher et al., 2015
Coastal waters of Kochi, India	Coastal waters	1 mm–5 mm	Fragment, fibre, pellet, filament, film	Blue, green, white, black, pink, orange, yellow, red, brown	PE, PP,	10–140	James et al., 2020
Indonesian coast	Coastal waters	2.5 mm–5 mm	Fragments, films	White, blue, green, purple, yellow	PP, PS, LDPE, others	0.27–0.54	Syakti et al., 2017
Kenyan coastline	Coastal and open ocean	0.25 mm–2.4 mm	Fibre, pellet, fragment, foam, film	Black, blue, green, brown, orange, pink, red, transparent, white	PP, LDPE	33.3–275	Kosore et al., 2018
Kuala Nerus, Kuantan marine waters	Port area	<5 mm	Filament, fragment, others	Black, blue, brown, gray, red, orange, yellow and transparent	PES, PS, PA, PVC,PP, PE	0.13–0.69	Khalik et al., 2018
Northeast pacific ocean	Coastal and open ocean	<1 mm –7.71 mm	Product fragments, fishing net and line fibres	NA	PP, others	0.004–0.19	Doyle et al., 2011
Northeastern Qatar EEZ	Coastal waters	125 μm-15.98 mm	Granular, fibres	Blue and opaque white	PP, LDPE, PES, PS, PVC, PA	0–3	Castillo et al., 2016
Northwestern Mediterranean Sea	Coastal and open ocean	0.33 mm–5 mm	Fragment, film	NA	PE	0.116	Collignon et al., 2012
Southern California coast	Coastal waters	0.35 mm–4.7 mm	Fragments, pellet, films, foams, resin	NA	PS	7.25	Moore et al., 2002
Southern coastline of Sri Lanka	Coastal waters	1.5 mm–2.5 mm	Pellet, fragment, film, monofilament, foam	Blue, green, white, yellow, gray, red, translucent	PE, PP, PS	0–29	Koongolla et al., 2018
Southwest coast of India	Coastal waters	0.3 mm–4.75 mm	Fragment, fibre/fishing line, foams, film, pellet,	Red, blue, black, white, yellow, green, violet	PE, PP, RY, PS, CE, ALKYD	0.22–3.58	Robin et al., 2020
Eastern Arabian Sea, Indian Ocean	Coastal and open ocean	0.5 mm–25 mm	Fibre, fragment, film, foam, pellet	White, blue, yellow, green, black, green, transparent, brown, others	PP, LDPE, NY	0.002–0.046	Present study

fishing lines have been frequently reported from coastal marine fauna (Courtene-Jones et al., 2017; Naidu et al., 2018; Daniel et al., 2020; James et al., 2020; Robin et al., 2020). The observed films in this study were mostly mono- and/or multi-layered films (Fig. 5d & e). In effect, different colour materials are used by the plastic industry for different applications such as packing, clothing, shipping, agriculture, food, and pharmaceutical industries. Additionally, the leaching of additives/colourants and chemicals from the surface areas of microplastics (films/sheets) may result in greater bioavailability of these particles to water column biota. A recent study by Naidu (2019) detected the presence of colourants in filter-feeding bivalves found in harbours around the Chennai coast, implying that the use of a wide array of colourants/additives in plastics can eventually end up in the biota.

Based on the colour, different studies postulated ideas regarding the origin of plastic material, for example, it was suggested that black, blue, and white colours tended to be the most prominent in fishery-related activities (Lusher et al., 2015; James et al., 2020; Robin et al., 2020). The present study categorized eight major types of FPDs (blue, brown, green, orange, transparent, white, yellow, and others (violet, pink, and black)) in the surface waters of EAS (Fig. 3e & f). These colours are most commonly used in packing, clothing, fishing, and other applications (James et al., 2020). Generally, factors like colour, size, and type of plastic may influence microplastic ingestion by organisms as they are mistaken as food particles (Wright et al., 2013). Hence, there is a higher risk and associated growing concern that plastics may act as a vector for the transportation of chemical additives and hydrophobic compounds that pose a threat to marine life (GESAMP, 2019).

Plastic debris observed in surface waters of the EAS was mainly polyethylene (PE) and polypropylene (PP) (Fig. 5a–c). The observed macroplastics such as polyethylene terephthalate (PET), low-density polyethylene (LDPE), and (PE) are presented in Fig. S1. The high quantity of these polymers and nylon, found in the aquatic environment is thought to be because of their wide range of applications; particularly in packaging and their overarching compound stability (Lusher et al., 2015; Kosore et al., 2018). In addition, earlier studies have also found that PE and PP are the dominant polymers found on beaches, coastal waters, and in biota from Indian waters (Veerasingam et al., 2016a, 2016b; James et al., 2020; Robin et al., 2020). Moreover, these low-density buoyant plastic polymers (PE and PP) can be transported in the realms of 1000 s of kms in the oceans by wind and currents from one region to another region, ingested by surface pelagic feeding biota (Lusher et al., 2015) and can potentially act as a mechanism for the transport of chemicals and associated chemicals. However, the abundance and transportation of floating plastic debris in coastal waters are mainly governed by prevalent hydrographical conditions; and the Arabian Sea is no different with its unique surface current direction, which differentiates the abundance and distribution of plastic debris along the coastal open ocean or vice versa. Considering the importance of the increase in plastic pollution, the dynamic pathways and its fate in the marine environment of EAS need further attention. Therefore, future studies should address a responsible oceanographic process that spread and transport plastic debris across the EAS and its possible impact on living resources.

In conclusion, the presence of floating plastic debris and their characterizations such as size, colour, and shapes in the EAS were examined, and it can be concluded that plastic contamination can be detrimental to the sustainability of the coastal ecosystem services. The relative concentration of plastic abundance was found to be high in coastal waters rather than in open ocean. The overall low plastic abundance and uniform distribution in the surface waters of EAS as compared with other studies could be because of the lack of riverine input and stable hydrodynamic conditions during the spring inter monsoon. The characterization of plastic items based on size has revealed that microplastics are the most dominant followed by

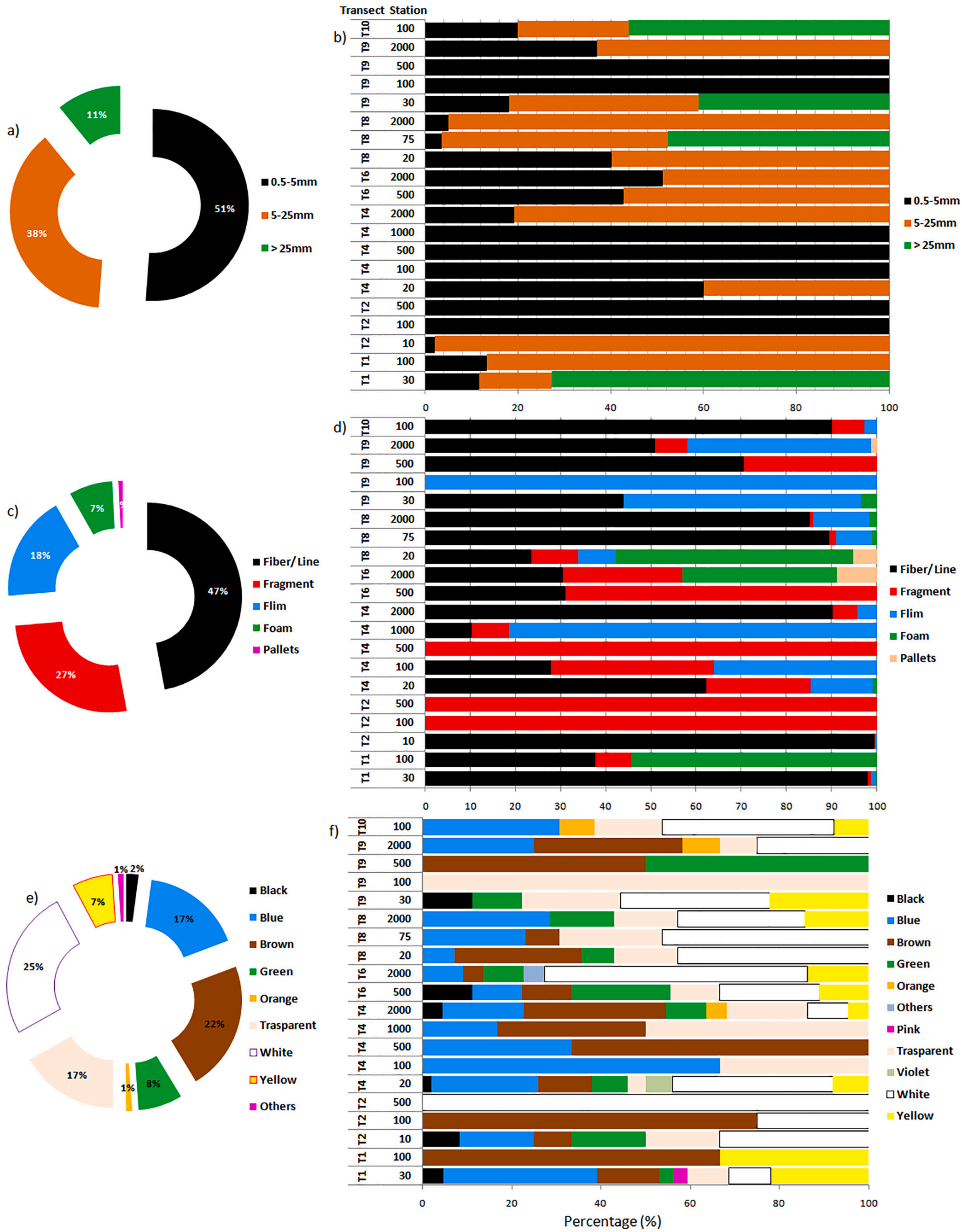

Fig. 3. Percentage of characteristic of plastic debris from surface waters of the eastern Arabian Sea. a & b by size; c & d by shape and e & f colour.

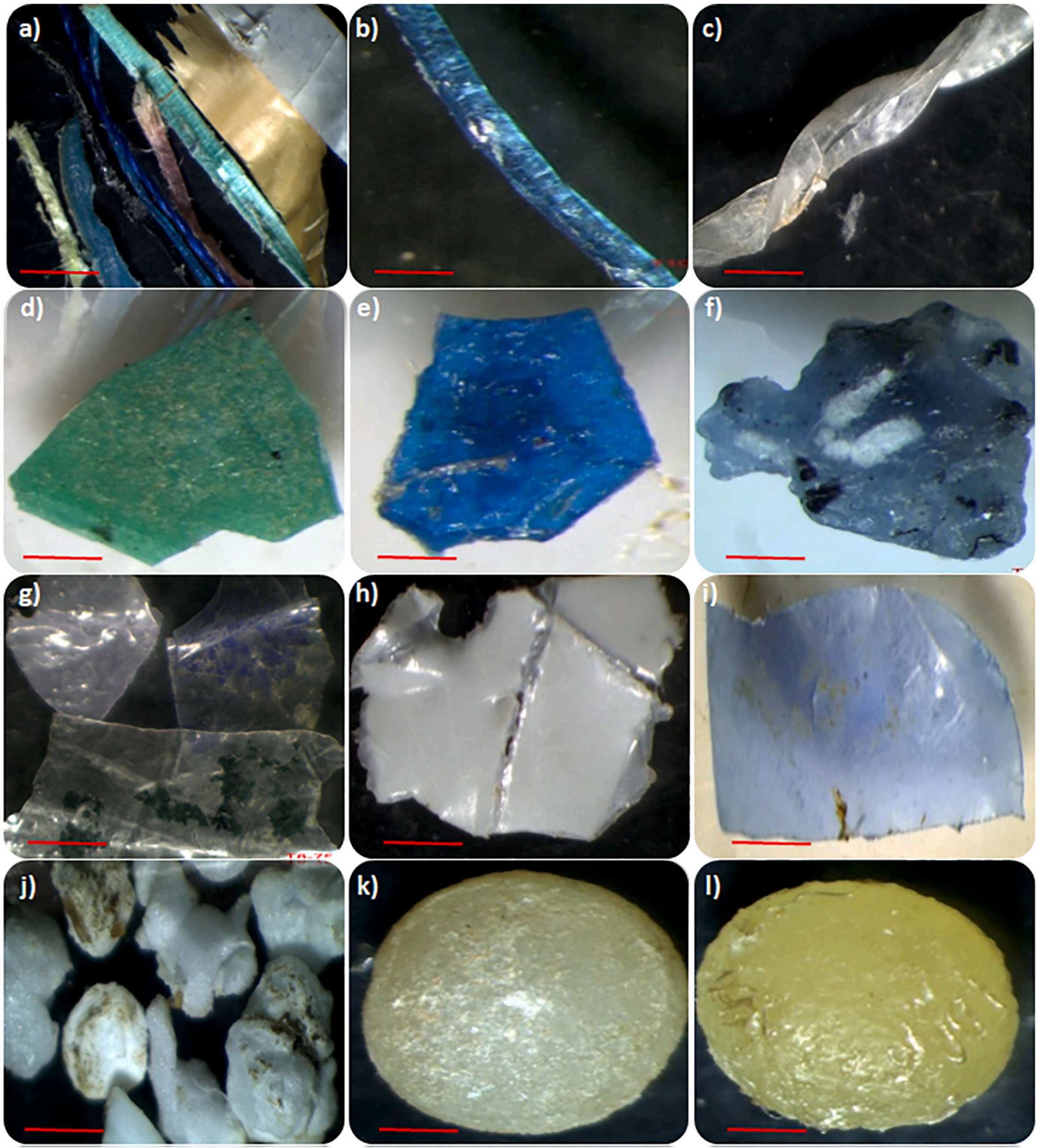

Fig. 4. Stereomicroscopic images of different types of microplastic particles found in surface waters of the eastern Arabian Sea i.e., a-c) fibre/line, d-f) fragments, g-i) films, j) foams and k & i pellets. Scale bars: 0.392 mm.

mesoplastics and microplastics with a range of colours (white, blue, yellow, green, black, green, transparent, brown) and shapes (fibre, fragment, film, foam, and pellets). The observed plastic debris was mainly in the form of fibre/fishing line and fragments were mainly sourced from fishing activities and the breakdown of large pieces, respectively. The high abundance of fractionated microplastics of observed size can enhance the bioavailability to fauna in different trophic levels and result in higher biomagnification. The leaching of additives/colourants and chemicals from the surface areas of microplastics (films/sheets) may be the result of various physical, chemical, and biological processes with more bioavailability. Further studies on the ingestion of plastic particles and colourants by marine biota, and their residence time in seafood in realistic marine environments will be useful to determine food quality and ecosystem health. Polyethylene, polypropylene, low-density polyethylene, polyethylene terephthalate, and nylon polymers were the most abundant; these may have originated from different sources such as fishing, packaging, clothing, domestic, and industrial activities. Hence, this present study demonstrates the need for administrative management strategies: educating the local fisher communities, framing regional action plans, and adopting good environmental practices to make coasts free from plastic contamination. Furthermore, freshwater and saline water mixing, stratification, riverine-coastal plumes, fronts, upwelling processes, and floodwaters are also important factors affecting transportation and accumulation of floating plastics both at spatial and temporal scales. Though this study reported low abundance of plastic debris when compared to other studies, the availability of monsoonal data on shelf/open ocean and the impact of plastic debris in marine ecosystem services is sparse. Hence, if undertaken during the monsoon season, a different result might be found.

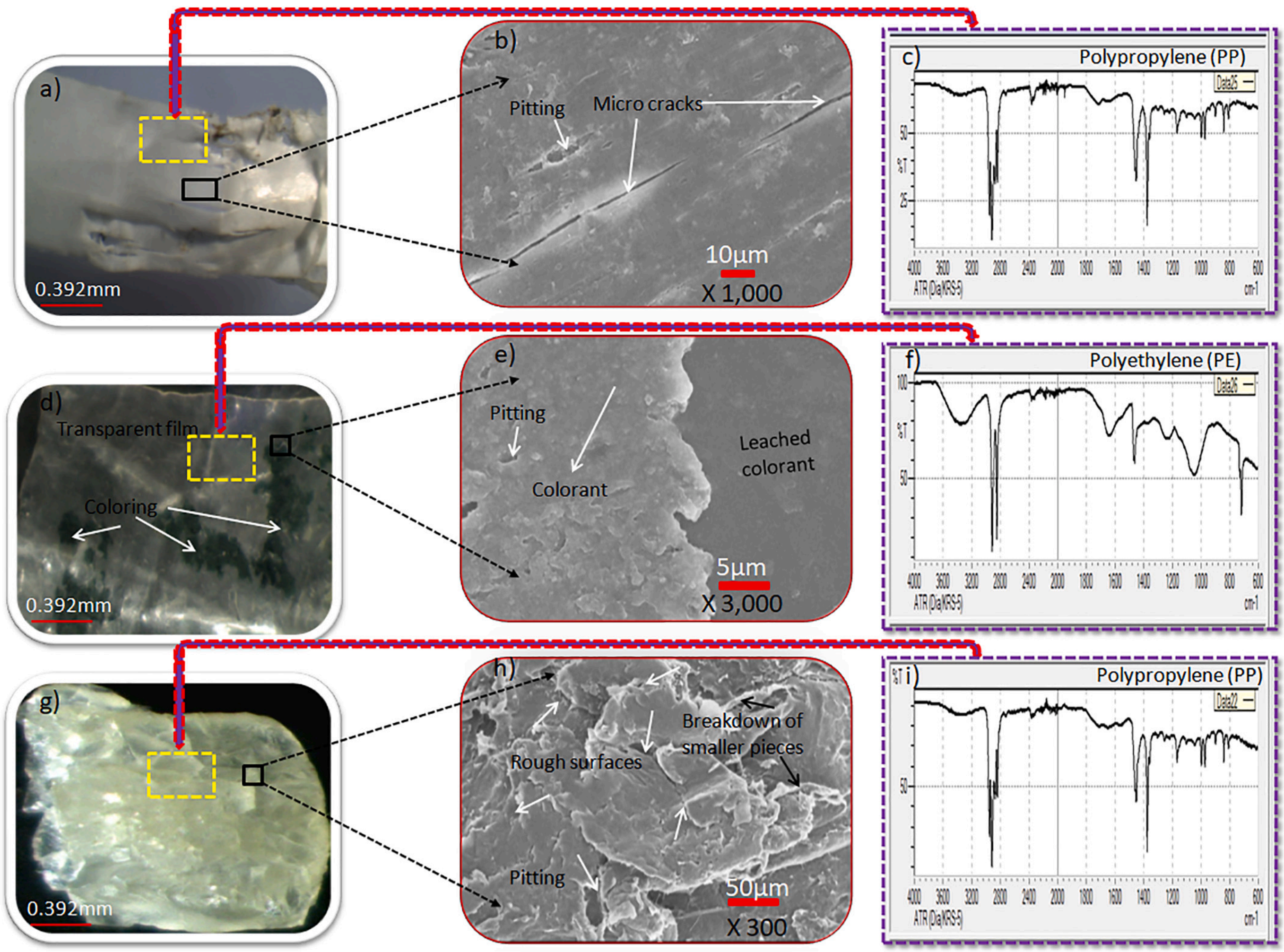

Fig. 5. SEM and FTIR analyses of microplastic samples. Microplastic images (a fibre; d film; g fragment) and corresponding images representing SEM analysis for morphology (b fibre with multiple cracks: zoomed in 1000 times; e film with multiple colour layers and leaching colorant on the film surface: zoomed in 3000 times; h fragment with a rough surface and many breakages on the fragment: zoomed in 300 times) and the FTIR spectral polymer images of the microplastics found in the surface waters of eastern Arabian Sea (c fibre-Polypropylene; f film-Polyethylene; i fragment-Polypropylene).

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CRediT authorship contribution statement

S.A. Naidu: conceptualization, methodology, sample collection, data analysis, writing original draft.

L. Mawii: data analysis.

V. Ranga Rao: supervision, software & review.

G. Anitha: supervision, review.

P. Mishra: review & editing.

Bhavani E. Narayanaswamy: methodology, review & editing.

Anil Kumar: chief scientist, review.

M.V. Ramana Murthy: Project Leader, Resources.

G.V.M. Gupta: Project Leader, Resources.

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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References

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 364, 1985–1998.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R., 2011. Accumulation of microplastic on shorelines worldwide: sources and sinks. Environ. Sci. Technol. 45, 9175–9179.

Castillo, A.B., Al-Maslamani, I., Obbard, J.P., 2016. Prevalence of microplastics in the marine waters of Qatar. Mar. Pollut. Bull. 111, 260–267.

Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62, 2588–2597.

Collignon, J.H., Hecq, F., Galgani, P., Voisin, F., Collard, A. Goffart, 2012. Neustonic microplastic and zooplankton in the North Western Mediterranean Sea. Mar. Pollut. Bull. 64, 861–864.
Courtene-Jones, W., Quinn, B., Gary, S.F., Mogg, A.O.M., Narayanaswamy, B.E., 2017. Microplastic pollution identified in deep-sea water and ingested by benthic invertebrates in the Rockall Through, North Atlantic Ocean. Environ. Pollut. 231, 271–280.
Courtene-Jones, W., Quinn, B., Ewin, C., Gary, S.F., Narayanaswamy, B.E., 2020. Microplastic accumulation in deep-sea sediments from the Rockall Trough. Mar. Pollut. Bull. 154, 111092.
Cox, K.D., Covernton, G.A., Davies, H.L., Dower, J.F., Juanes, F., Dudas, S.E., Dower, J.F., 2020. Correction to human consumption of microplastics. Environ. Sci. Technol. 54, 10974–707410.
Daniel, D.B., Ashraf, P.M., Thomas, S.N., 2020. Microplastics in the edible and inedible tissues of pelagic fishes sold for human consumption in Kerala, India. Environ. Pollut. 266, 115365.
Dileepkumar, M., 2006. Biogeochemistry of the North Indian Ocean; IGBP-WCRP-SCOPE Rep. Ser. 1. Indian Natl. Sci. Acad, New Delhi, India.
Doyle, M.J., Watson, W., Bowlin, N.M., Sheavly, S.B., 2011. Plastic particles in coastal pelagic ecosystems of the Northeast Pacific Ocean. Mar. Environ. Res. 71, 41–52.
ENCORE, 2019. http://sicom.nic.in/sites/default/files/ESMF%20-%20Vol-%20I.pdf.
Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G., Reisser, J., 2014. Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS One (9e111913).
Galgani, F., Hanke, G., Maes, T., 2015. Global distribution, composition and abundance of marine litter. In: Marine Anthropogenic Litter, pp. 29–56.
Galloway, T.S., Cole, M., Lewis, C., 2017. Interactions of microplastic debris throughout the marine ecosystem. Nat. Ecol. Evol. 1, 0116.
GESAMP, 2019. Guidelines or the monitoring and assessment of plastic litter and microplastics in the ocean. In: Kershaw, P.J., Turra, A., Galgani, F. (Eds.), IMO/FAO/UNESCO IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection. Rep. Stud. GESAMP No. 99, p. 130.
Goswami, P., Vinithkumar, N.V., Dharani, G., 2020. First evidence of microplastics bioaccumulation by marine organisms in the port Blair Bay, Andaman islands. Mar. Pollut. Bull. 155, 111163.
Gupta, G.V.M., Sudheesh, V., Sudharma, K.V., Saravanane, N., Dhanya, V., Dhanya, K.R., Lakshmi, G., Sudhakar, M., Naqvi, S.W.A., 2016. Evolution to decay of upwelling and associated biogeochemistry over the southeastern Arabian Sea shelf. J. Geophys. Res. Biogeosci. 121, 159–175.
Hurley, R., Woodward, J., Rothwell, J.J., 2018. Microplastic contamination of river beds significantly reduced by catchment-wide flooding. Nat. Geosci. 11, 251–257.
Isobe, A., Kubo, K., Tamura, Y., Nakashima, E., Fujii, N., 2014. Selective transport of microplastics and mesoplastics by drifting in coastal waters. Mar. Pollut. Bull. 89, 324–330.
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.
James, K., Vasant, K., Padua, S., Gopinath, V., Abilash, K.S., Jeyabaskaran, R., Babu, A., John, S., 2020. An assessment of microplastics in the ecosystem and selected commercially important fishes off Kochi, south eastern Arabian Sea, India. Mar. Pollut. Bull. 154, 111027.
Jayasiri, H.B., Purushothaman, C.S., Vennila, A., 2013. Plastic litter accumulation on high-water strandline of urban beaches in Mumbai, India. Environ. Monit. Assess. 185, 7709–7719.
Khalik, M., Ibrahim, W.M.A.W., Anuar, Y.S., Govindasamy, S.T., Baharuddin, N.F., 2018. Microplasics analysis in Malaysian marine waters: a field study of Kuala Nerus and Kuantan. Mar. Pollut. Bull. 135, 451–457.
KIMO, 2007. Small Plastic Particles in Coastal Swedish Waters, N-Research Report, Commissioned by KIMO Sweden (Submitted to BDC).
Koongolla, B.J., Andrady, A.L., Terney Pradeep Kumara, P.B., Gangabadage, C.S., 2018. Evidence of microplastics pollution in coastal beaches and waters in southern Sri Lanka. Mar. Pollut. Bull. 137, 277–284.
Kosore, C., Ojwang, L., Maghanga, J., Kamau, J., Kimeli, A., Omukoto, J., Ngisiag'e, N., Mwaluma, J., Ong'ada, H., Magori, C., Ndirui, E., 2018. Occurrence and ingestion of microplastics by zooplankton in Kenya's marine environment: first documented evidence. African. J. Mar. Sci. 40, 225–234.
Law, K.L., Thompson, R.C., 2014. Microplastics in the seas. Science 345, 144–145.
Lee, J., Hong, S., Song, Y.K., Hong, S.H., Jang, Y.C., Jang, M., Heo, N.W., Han, G.M., Lee, M.J., Kang, D., Shim, W.J., 2013. Relationships among the abundances of plastic debris in different size classes on beaches in South Korea. Mar. Pollut. Bull. 77, 349–354.
Li, C., Wang, X., Liu, K., Zhu, L., Wei, N., Zong, C., Li, D., 2021. Pelagic microplastics in surface water of the eastern Indian Ocean during monsoon transition period: abundance, distribution and characteristics. Sci. Total Environ. 755, 142629.
Lusher, A.L., Tirelli, V., Connor, I.O., Officer, R., 2015. Microplastics in Arctic polar waters: the first reported values of particles in surface and sub-surface samples. Sci. Rep. 5, 14947.
Lusher, A.L., Hollman, P.C.H., Mendoza-Hill, J.J., 2017. Microplastics in fisheries and aquaculture: status of knowledge on their occurrence and implications for aquatic organisms and food safety. In: FAO Fisheries and Aquaculture Technical Paper. No. 615. Rome, Italy.
Moore, C.J., Moore, S.L., Weisberg, S.B., Lattin, G.L., Zellers, A.F., 2002. A comparison of neustonic plastic and zooplankton abundance in southern California's coastal waters. Mar. Pollut. Bull. 44, 1035–1038.
Naidu, S.A., 2019. Preliminary study and first evidence of presence of microplastics and colorants in green mussel, Perna viridis (Linnaeus, 1758), from southeast coast of India. Mar. Pollut. Bull. 140, 416–422.
Naidu, S.A., Ranga Rao, V., Ramu, K., 2018. Microplastics in the benthic invertebrates from the coastal waters of Kochi, southeastern Arabian Sea. Environ. Geochem. Health 40, 1377–1383.
PlasticsEurope, 2018. Annual Report 2018 "Plastics – the Facts 2018. An Analysis of European Latest Plastics Production, Demand and Waste Data".
Robin, R.S., Karthik, R., Purvaja, R., Ganguly, D., Anandavelu, I., Mugilarasan, M., Ramesh, R., 2020. Holistic assessment of microplastics in various coastal environmental matrices, southwest coast of India. Sci. Total Environ. 703, 134947.
Saliu, F., Montano, S., Garavaglia, M.G., Lasagni, M., Seveso, D., Galli, P., 2018. Microplastic and charred microplastic in the Faafu Atoll, Maldives. Mar. Pollut. Bull. 136, 464–471.
Seena, G., Muraleedharan, K.R., Revichandran, C., Abdul Azeez, S., John, S., 2019. Seasonal spreading and transport of buoyant plumes in the shelf off Kochi, South west coast of India- a modeling approach. Sci. Rep. 9.
Seetharaman, G., Bureau, E.T., 2019. https://economictimes.indiatimes.com/industry/indl-goods/svs/paper-/-wood-/-glass/-plastic/marbles/how-plastic-ban-will-affect-businesses-and-consumers/articleshow/71236532.cms.
Selvam, K., Xavier, K.A.M., Shivakrishna, A., Bhutia, T.P., Kamat, S., Shenoy, L., 2021. Abundance, composition and sources of marine debris trawled-up in the fishing grounds along the north-east Arabian coast. Sci. Total Environ. 751, 141771.
Shankar, D., Shetye, S.R., 1997. On the dynamics of the Lakshadweep high and low in the southeastern Arabian Sea. J. Geophys. Res. Ocean. 102, 12551–12562.
Shenoi, S.S.C., Shankar, D., Shetye, S.R., 2004. Remote forcing annihilates barrier layer in southeastern Arabian Sea. Geophys. Res. Lett. L05507.
Sruthy, S., Ramasamy, E.V., 2017. Microplastic pollution in Vembanad Lake, Kerala, India: the first report of microplastics in lake and estuarine sediments in India. Environ. Pollut. 222, 315–322.
Syakti, A.D., Bouhroum, R., Hidayati, N.V., Koenawan, C.J., Boulkamh, A., Sulistyo, I., Lebarillier, S., Akhlus, S., Doumenq, P., Wong-Wah-Chung, P., 2017. Beach macro-litter monitoring and floating microplastic in a coastal area of Indonesia. Mar. Pollut. Bull. 122, 217–225.
Thompson, R.C., Olson, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304, 838.
Tiwari, M., Rathod, T.D., Ajmal, P.Y., Bhangare, R.C., Sahu, S.K., 2019. Distribution and characterization of microplastics in beach sand from three different Indian coastal environments. Mar. Pollut. Bull. 140, 262–273.
UNEP, 2005. https://wedocs.unep.org/handle/20.500.11822/8348.
Veerasingam, S., Mugilarasan, M., Venkatachalapathy, R., Vethamony, P., 2016a. Influence of 2015 flood on the distribution and occurrence of microplastic pellets along the Chennai coast, India. Mar. Pollut. Bull. 109, 196–204.
Veerasingam, S., Saha, M., Suneel, V., Vethamony, P., Rodrigues, A.C., Bhattacharyya, S., Naik, B.G., 2016b. Seasonal distribution and surface degradation features of microplastic pellets along the Goa coast, India. Chemosphere 159, 496–505.
Veerasingam, S., Ranjani, M., Venkatachalapathy, R., Bagaev, A., Mukhanov, V., Litvinyuk, D., Mugilarasan, M., Gurumoorthi, K., Aboobacker, V.M., Vethamony, P., 2020a. Contributions of Fourier transform infrared spectroscopy in microplastic pollution research: a review. Crit. Rev. Environ. Sci. Technol. 0, 1–62.
Veerasingam, S., Ranjani, M., Venkatachalapathy, R., Bagaev, A., Mukhanov, V., Litvinyuk, D., Verzhevskaia, L., Guganathan, L., Vethamony, P., 2020b. Microplastics in different environmental compartments in India : analytical methods, distribution, associated contaminants and research needs. Trends Anal. Chem. 133, 11607.
Wang, J., Wang, M., Ru, S., Liu, X., 2019. High levels of microplastic pollution in the sediments and benthic organisms of the South Yellow Sea, China. Sci. Total. Environ. 651, 1661–1669.
Wright, S.L., Rowe, D., Thompson, R.C., Galloway, T.S., 2013. Microplastic ingestion decreases energy reserves in marine worms. Curr. Biol. 23, 1031–1033.
Zhang, H., 2017. Transport of microplastics in coastal seas. Estuar. Coast. Shelf Sci. 199, 74–86.