Marine Pollution Bulletin 173 (2021) 113042

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Microplastics in zooplankton in the eastern Arabian Sea: The threats they pose to fish and corals favoured by coastal currents

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ARTICLE INFO

Keywords:
Microplastics
Zooplankton
Food web
Fish
Corals
West coast of India
Arabian Sea

ABSTRACT

The baseline study of Microplastics (MPs) in zooplankton (copepods, chaetognaths, decapods, and fish larvae) from six different zones along India's west coast (off Kanyakumari/Cape Comorin, Kochi, Mangalore, Goa, Mumbai, and Okha) in the Eastern Arabian Sea (EAS) is presented here with their vast ecosystem impacts. This investigation revealed that zooplankton in all six zones accumulated MPs pellets (52.14%), fibres (28.40%), films (10.51%), and fragments (8.95%). The highest average retention of MPs (MPs/individual) was found in fish larvae (av. 0.57 ± 0.18) while copepods had the lowest (av. 0.03 ± 0.01). The presence of low-density polyethylene, polypropylene, polystyrene, and polyethylene terephthalate was confirmed by Raman Spectra of MPs. The MPs in zooplankton found in this study (av. 22 ± 7 pieces/m^3) were nearly 2-fold greater than those found in some of the world's most densely populated areas. It is shown that the strong southerly coastal currents could advect the MPs contaminated water mass too far away, having the potential to affect the fish and corals.

1. Introduction

Plastics were first mass-produced in the 1940s, and the present global production is at 348 million metric tonnes per year (Plastics – the Facts, 2018). Polyethylene (PE), Polypropylene (PP), Polyvinyl chloride (PVC), Polystyrene (PS), Polyethylene Terephthalate (PET), and Polyurethane (PU) are the six types of polymers that dominate global plastic manufacture (Lithner et al., 2011; GESAMP, 2016). Plastic debris has accumulated in both terrestrial and marine environments as a result of high production combined with its long durability and poor waste management (Barnes et al., 2009; Rillig, 2012). MPs are defined as plastic particles with a diameter of less than 5 mm (Arthur et al., 2009), and their buildup in the natural environment around the world has become a major worry in recent decades (Lönnstedt and Eklöv, 2016). Without a doubt, the growing marine pollution caused by MPs needs more attention because all trash generated on land eventually ends up in the ocean. Land-based sources such as landfills, rivers, runoff, domestic and industrial effluent, beach tourism, recreational and religious activities, and so on account for 60–80% of plastic litter in the ocean (Jambeck et al., 2015). Other notable sources include fishing, spills from vessels, ships, boats, oil rigs, and gas platforms (Naidu, 2019; Avio et al., 2016). Winds, currents, waves, and tides can transport this debris thousands of miles from its source to the ocean's surface, from the equator to the poles (Ryan et al., 2009; Barnes et al., 2009). Entanglement and ingestion of plastic waste have been documented to cause feeding inability, decreased locomotion, diminished reproduction, ulcerations, and mortality in marine mammals, birds, sea turtles, and fish (Laist, 1997; Derraik, 2002; Moore, 2008; Gregory, 2009).

To improve the performance of plastics, a variety of hazardous chemicals such as plasticizers, colorants, flame retardants, stabilisers, and antimicrobials are used (Barnes et al., 2009). MPs can adsorb and concentrate dissolved hazardous substances such as persistent organic pollutants (POPs) and heavy metals due to their huge surface-to-volume ratio and hydrophobicity (Wang et al., 2019a, 2019b). The uptake of MPs by aquatic species is a frequent mechanism for these dangerous compounds to enter the food chain (Teuten et al., 2009). Mesozooplankton (MSP; 200–20,000 μm), the aquatic environment's secondary producers, plays a critical role in the carbon transfer from phytoplankton (primary producers) to higher trophic levels (consumers) (Turner and Holmes, 2015). Many observations, both in the lab and in

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https://doi.org/10.1016/j.marpolbul.2021.113042
Received 4 August 2021; Received in revised form 4 October 2021; Accepted 6 October 2021
Available online 13 October 2021
0025-326X/

Table 1
Earlier studies of MPs from sediment, water, and biota from India.

Sample	Literature	Region
Sediment	Nigam, 1982	Goa
	Reddy et al., 2006	Alang-Sosia, Gujarat
	Ogata et al., 2009	Mumbai, Chennai, Sundarbans
	Jayasiri et al., 2013	Mumbai
	Jayasiri et al., 2015	Mumbai
	Veerasingam et al., 2016a	Goa coast
	Veerasingam et al., 2016b	Chennai coast
	Mugilarasan et al., 2017	Chennai
	Sruthy and Ramasamy, 2017	Vembanad Lake- Kerala
	Karthik et al., 2018	Tamil Nadu coast
	Vidyasakar et al., 2018	Rameswaram
	Ashwini and Varghese, 2019	Nattika, Kerala
	Tiwari et al., 2019	Mumbai, Tuticorin, Dhanushkodi
	Sarkar et al., 2019	Ganga River
	Dowarah and Devipriya, 2019	Puducherry
	Sathish et al., 2019	Chennai,Tuticorin,Tirichenthur, Manapad and Kanyakumari
	Patterson et al., 2019	Tuticorin coast, Gulf of Mannar
	Krishnakumar et al., 2020	Andaman and Nicobar Archipelago
	Robin et al., 2020	Kerala
	Daniel et al., 2020c	Kerala
	James et al., 2020	Kochi, Kerala
	Goswami et al., 2020	Port Blair Bay- Andaman Island
	Vidyasakar et al., 2020	Silver beach, Tamil Nadu
	Amrutha and Warrier, 2020	Netravathi River, Karnataka
	Jeyasanta et al., 2020	Tuticorin, Tamil Nadu
	Gopinath et al., 2020	Red hill lake, Tamil Nadu
	Sundar et al., 2020	Kanyakumari
	Patchaiyappan et al., 2020	Andaman
	Suresh et al., 2020	Kochi
	Patterson et al., 2020	Gulf of Mannar
	Maharana et al., 2020	Maharashtra, Karnataka, Goa
	Sathish et al., 2020b	Tuticorin coast, Gulf of Mannar
	Patel et al., 2020	Sabarmati River
	Ram and Kumar, 2020	Sabarmati River, Ahmedabad
	Kaviarasan et al., 2020	Lakshadweep Islands
	Sunitha et al., 2021	Marina beach, Tamil Nadu
	Bharath et al., 2021	Veeranam lake, Tamil Nadu
	James et al., 2021	Gulf of Mannar and Palk Bay
Water	Eriksen et al., 2018	Bay of bengal
	Ganesan et al., 2019	Kanyakumari, Chennai
	Patterson et al., 2019	Tuticorin coast, Gulf of Mannar
	Robin et al., 2020	Kerala
	James et al., 2020	Kerala
	Goswami et al., 2020	Port Blair Bay-Andaman Island
	Amrutha and Warrier, 2020	Netravathi river, Karnataka
	Gopinath et al., 2020	Red hill lake, Tamil Nadu
	Suresh et al., 2020	Kochi
	Patterson et al., 2020	Gulf of Mannar
	Sathish et al., 2020a	Tuticorin
	Sathish et al., 2020b	Tuticorin coast, Gulf of Mannar
	Sunitha et al., 2021	Marina beach, Tamil Nadu
	Bharath et al., 2021	Veeranam lake, Tamil Nadu
	James et al., 2021	Gulf of Mannar and Palk Bay
	Naidu et al., 2021	Eastern Arabian Sea
Biota	Karthik et al., 2018	Tamil Nadu coast
	Kumar et al., 2018	Tuticorin
	Naidu et al., 2018	Kochi, Kerala
	Naidu, 2019	Fishing harbor, Chennai
	Patterson et al., 2019	Tuticorin coast, Gulf of Mannar
	Robin et al., 2020	Kerala
	Karuppasamy et al., 2020	Chennai and Nagapattinam- Tamil Nadu
	Sathish et al., 2020a	Tuticorin
	Sathish et al., 2020b	Tuticorin coast, Gulf of Mannar
	Goswami et al., 2020	Port Blair Bay- Andaman Island
	James et al., 2020	Kochi, Kerala
	Devi et al., 2020	Vembanad Lake, Kerala
	Suresh et al., 2020	Kochi
	Daniel et al., 2020a	Kalamukku, Kerala
	Daniel et al., 2020b	Kochi, Kerala
	Umamaheswari et al., 2020	Tamil Nadu
	Dowarah et al., 2020	Pondicherry
	James et al., 2021	Gulf of Mannar and Palk Bay
	Nikki et al., 2021	Kochi backwaters

Table 2
Details of notable field-based research on MPs in zooplankton world over.

SL. No.	Literature	Region	Zooplankton groups
1	Desforges et al., 2015	Northeast Pacific Ocean	*Neocalanus Cristatus* (Copepod) *Euphausia pacifica* (Euphausiid)
2	Sun et al., 2017	Northern part of South China Sea	Copepods, Chaetognaths, Jellyfish, Shrimps, Fish larvae
3	Steer et al., 2017	Western English channel	*Merlangius merlangus, Microchirus variegatus, Trisopterus minutus, Callionymus lyra, Anguilla anguilla*
4	Sun et al., 2018a	East China Sea	Copepoda, Amphipoda, Chaetognatha, Euphasiacea, Cladocera, Medusozoa, Heteropoda, Luciferidea, Brachyura larva, Pteropoda
5	Sun et al., 2018b	Yellow sea	Copepods, Stomatopod larvae, Fish larvae,Medusa, Siphonophrea, Chaetognaths, Luciferidea, Brachyura larvae, Euphasiacea, Amphipoda, Thaliacea
6	Kosore et al., 2018	Kenya marine environment	Copepoda, Chaetognatha, Amphipoda, Fish larvae
7	Zheng et al., 2020	Bohai Sea, China	Brachyura larvae, Chaetognatha, Copepoda, Euphausia, Medusae, Fish larvae, Mantis shrimp, Amphipoda, Ctenophore, Siphonophorae
8	Amin et al., 2020	Terrengganu coastal waters, Southern south china sea	Calanoida, Cyclopoida, Ploychaeta, Shrimps and zoea, Chaetognths, Fish larvae
9	Goswami et al., 2020	Port Blair Bay, Andaman Islands	Copepods, Chaetognaths, Jellyfish, Shrimps, Fish larvae
10	Taha et al., 2021	Terengganu estuary and offshore, Malasya	Calanoida, Cyclopoida, Harpaticoida, Mysida, Decapoda,Cladocera, Aphragmophora

the field, show that zooplankton consumes MPs all over the world (Moore et al., 2001; Cole et al., 2013; Lee et al., 2013; Nobre et al., 2015; Setälä et al., 2014; Frias et al., 2014; Kang et al., 2015; Van Cauwenberghe and Janssen, 2014; Cole et al., 2016). The impact of MPs on the lifespan, behaviour, growth, and reproduction of zooplankton, as well as the impact on the marine food chain, is frequently highlighted in these studies.

The Indian subcontinent is bordered on the west by the Arabian Sea and the east by the Bay of Bengal, with a total coastline of 7516 km that includes 9 states, 2 union territories, and 2 island territories. It is the world's second-most populous country, with nearly one-third of the population living along the coast (Senapati and Gupta, 2014). It produces approximately 9.4 million tonnes of plastic garbage each year, with 40% of it remains uncollected (Ministry of Housing and Urban Affairs, 2019). Over the last four decades, numerous studies on MPs have been attempted in Indian waters, focused on sediment, water column, and major biota in the environment, and the bibliographic data of

Table 3
Details of notable experimental research on MPs in zooplankton world over.

SL. No.	Author	Zooplankton groups
1	Ayukai, 1987	*Acartia clausi*
2	Fernández et al., 2004	*Oikopleura diocia*, *Fritillaria borealis*
3	Cole et al., 2013	*Centropages typicus*, *Calanus helgolandicus*, *A. clausi*, *Temora longicornis*, *Parasagitta* sp, Obelia sp., *Euphausiidae* sp., Siphonophorae, Doliolidae, Bivalvia, Caridae, Paguridae, Porcellinidae, Brachyura
4	Lee et al., 2013	*Tigriopus japonicus*
5	Besseling et al., 2013	*Arenicola marina*
6	Wright et al., 2013	*A. marina*
7	Besseling et al., 2014	*Daphnia magna*
8	Setälä et al., 2014	*Acartia* spp, *Eurytemora affinis*, *Limnocalanus macrurus*, *Bosmina coregoni* maritime, *Evadne nordmannii*, *Neomysis integer*, *Mysis mixta*, *Mysis relicta*, *Tintinnopsis lobiancoi*, Marenzelleria spp., *Synchaeta* spp.
9	Cole et al., 2015	*C. helgolandicus*
10	Nobre et al., 2015	*Lytechinus variegatus*
11	Vroom et al., 2017	*Acartia longicornis*, *Calanus finmarchicus*, Pseudocalanus spp., Decapod larvae
12	Jeong et al., 2017	*Paracyclopina nana*
13	Athey et al., 2020	Silversides (*Menidia beryllina*), Tintinnids (Favella spp)
14	Costa et al., 2020	*Tigriopus fulvus* nauplii, *Aurelia* sp.

all such works are compiled in Table 1. Because zooplankton is a lower trophic level component, studies have shown that they respond quickly to changes in their environment (Jyothibabu et al., 2010 and the references therein). MPs have the potential to bioaccumulate in zooplankton because they float on the surface and overlap with the size range of zooplankton food (phytoplankton). However, there is no research on MPs in zooplankton from the Indian subcontinent's coastal waters, which are subjected to the greatest levels of MPs pollution.

The only data on MPs on zooplankton from this region comes from the Andaman Sea, which is an oceanic island ecosystem that is comparatively more pristine than the Indian mainland's coastal waters (Goswami et al., 2020). On the other hand, there are a wealth of MPs studies on zooplankton in the lower-level food web available around the world, both field-based and experimental, of which some of the most important are highlighted here (Tables 2 and 3). We conducted this investigation along the west coast of India because there is a paucity of information on MPs on zooplankton in Indian coastal waters. This baseline research of MPs from selected coastal locales along India's west coast focused on the following goals (a) determine whether MPs are present in zooplankton; (b) elucidate the properties of MPs in zooplankton if they are present; (c) determine whether MPs abundance varies among zooplankton groups and over spatial scale, and (d) propose plausible MPs sources in the research region and their potential implications.

2. Materials and methods

2.1. Study area

Six stations along the west coast of India in the EAS, with a depth range of 10 to 30-m in shelf waters, were selected for the study (Fig. 1). The Indian western shelf extends 1500 km from Cape Comorin in the south to Veraval in the north and is shared by Tamil Nadu, Kerala, Karnataka, Goa, Maharashtra, and Gujarat. This coastal area, which has a huge fishing potential, is home to millions of people. Tourism, festivals, and recreational activities are all popular on the beaches in this area. Several enterprises and factories are located near the coast. Household garbage from coastal and nearby urbanised communities, ports, harbours, various industries, factories, beaches, and oil rigs in the coastal area all contribute significantly to pollution in the marine environment, particularly in the coastal seas. Moreover, multiple rivers pour into this area, transporting more debris, especially plastic waste, into the coastal seas.

2.2. Sample collection

Zooplankton samples for the MPs study were collected onboard ORV *Sagar Kanya* at 6 sites along India's west coast in August 2018 as part of an oceanographic project. Horizontal tows were used to acquire zooplankton from the surface waters using a bongo net (Hydrobios, Kiel, 0.6 m diameter, 300 μm mesh). A standard oceanic flow meter placed to the mouth of the net was used to determine the volume of water filtered. To gather a sufficient number of zooplankton specimens, the net was towed at 1 knot for 10 min at each location. The nets were thoroughly cleaned after retrieval to prevent cross contamination of samples with MPs.

2.3. Analyzing and categorising zooplankton

All macroplankton and detritus were removed and a Folsom plankton splitter is used to divide the entire sample into two equal parts for analysis. One portion is sorted to the group level, while the other is used to quantify MPs. The zooplankton density was estimated by dividing the number of each zooplankton group by the volume of water filtered and then expressing the result as a number per cubic metre of water. This data was primarily used for estimating the MPs retention in different zooplankton groups considered in this study.

2.4. MPs extraction from zooplankton

Four primary groups of copepods, chaetognaths, decapods, and fish larvae were chosen for microplastic analysis based on the zooplankton composition in the study area. 15–215 individuals were hand-picked from each taxon at each station based on abundance and rinsed multiple times with Milli-Q water. Individuals in each group were then checked using a stereomicroscope (Stemi 305, ZEISS) to see if any microplastic particles had attached to them and if so, forceps were used to remove the particles. The materials were then digested in a 60 °C water bath for 48 h after being placed in 30 ml glass vials with ten millilitres of 10% KOH poured into each vial (Dehaut et al., 2016; Collicutt et al., 2019; Zheng et al., 2020). The samples were cooled to room temperature after digestion and vacuum-filtered through a 0.7-μm GF/F filter. Until microscopic analysis, the Whatman Filter Paper and the filter papers were kept in sealed Petri plates. All glassware and forceps were cleansed with distilled water before use, the workspace was cleaned before use, and sample vials were kept closed when not in use to avoid contamination by air-borne plastics and cross-contamination. During the studies, a nitrile glove was worn when handling samples, each batch of samples was given a procedural control (10 ml of 10% KOH in an empty vial), and there was no contamination of blanks.

2.5. Visual identification and enumeration of MPs

Under a stereomicroscope (OLYMPUS SZX16), all of the particles retained on the filter papers were examined, and the forms, colours, and sizes of probable MPs were documented and measured using image analysis software (Cell Sens software).

2.6. Polymer types of MPs

Using a Confocal Raman microscope (WITec Alpha 300R, Germany) and a Spectroscopic system (WITec UHTS), the polymer type of selected marine plastics was determined. The Raman microscope was used under

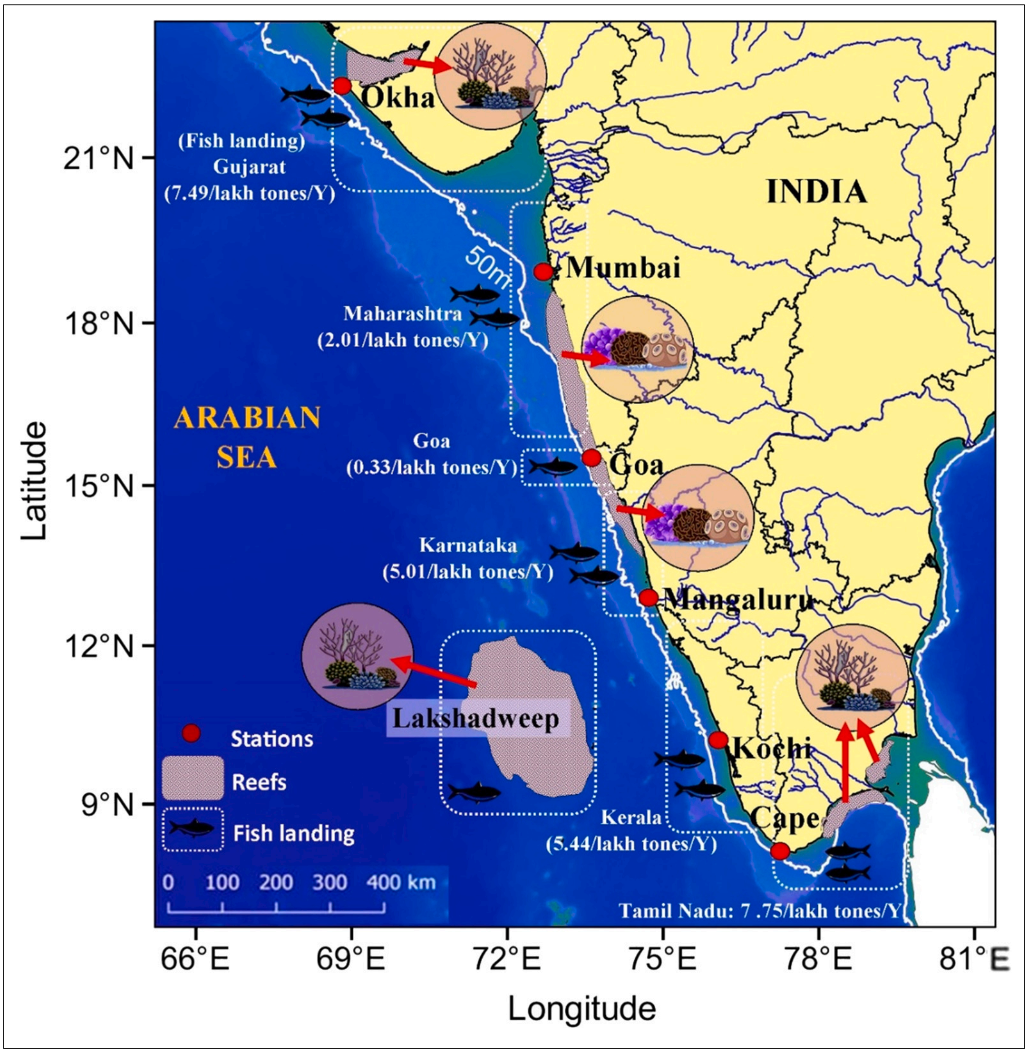

Fig. 1. Coastal waters off selected cities along India's west coast in the eastern Arabian Sea (Cape Comorin/Kanyakumari, Kochi, Mangalore, Goa, Mumbai and Okha) selected for sampling in this study. Red filled circles indicate sampling locations. Representative symbols have been used to denote areas of high fish landings and coral growth. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the following conditions: 532 nm excitation wavelength, 600 groves/mm grating, and a 20 X objective with a 10s integration time. Wiley's Know It All Raman spectrum library for polymers, as well as earlier literature, were used to confirm the reported spectra (Gall et al., 1972; Štokr et al., 1982; Andreassen, 1999; Sato et al., 2002; Anema et al., 2009; Rebollar et al., 2014; Bistričić et al., 2015; Ibrahim and He, 2017; Portesi et al., 2019; Stroe et al., 2020).

2.7. Retention of MPs by zooplankton

The number of MPs identified in zooplankton was divided by the number of zooplankton digested (MPs/individual) to determine MPs retention in each zooplankton group at each station (Sun et al., 2018a, 2018b). The zooplankton community's microplastic retention (pieces/m^3) for each station was calculated by using the formula:

$$\sum_{i=1}^{4}\left(\frac{Microplastics}{Zooplankton\ of\ Group\, i}\times Abundance\ of\ Zooplankton\ group\, i\right)$$

The zooplankton groups are indicated by the ith variable 1–4 (copepods, chaetognaths, decapods and fish larvae). MPs/Zooplankton group i denotes each group's retention and the abundance of each zooplankton group is calculated by dividing its total number present in the sample by the volume of water filtered through the net and is expressed as individual/m^3.

3. Results

3.1. MPs quality in zooplankton

MPs were found in all of the zooplankton groups studied. MPs found in zooplankton groups can be classified into four types: fibre, film, fragment and pellet (Fig. 2). Pellets were the most common MPs (52.14%), followed by fibres (28.40%), films (10.51%), and fragments (8.95%). (Fig. 3a). Pellets were plentiful at all stations (except Cape Comorin), with the highest concentration at Okha. The highest concentration of fibre was found in Cape Comorin, with the lowest concentrations in Goa and Mumbai. Fig. 3b depicts the distribution of MPs among zooplankton groups, which differed by taxon. Pellets constituted 16–76% of the total, with fish larvae accounting for the most and decapods for the least. Fibre content was lowest in fish larvae and highest in decapods (16.03–46.9%). Fish larvae (2.29, 6.11%) had the lowest fragments and films, while copepods had the highest (20.51%). Except for fish larvae, fibre predominated in all zooplankton groups. Blue was the most common colour (54.5%) among the different coloured MPs examined, followed by black (28.8%), pink (7%), transparent (5.1%), green (3.1%), and yellow (1.6%). The fibre came in a variety of

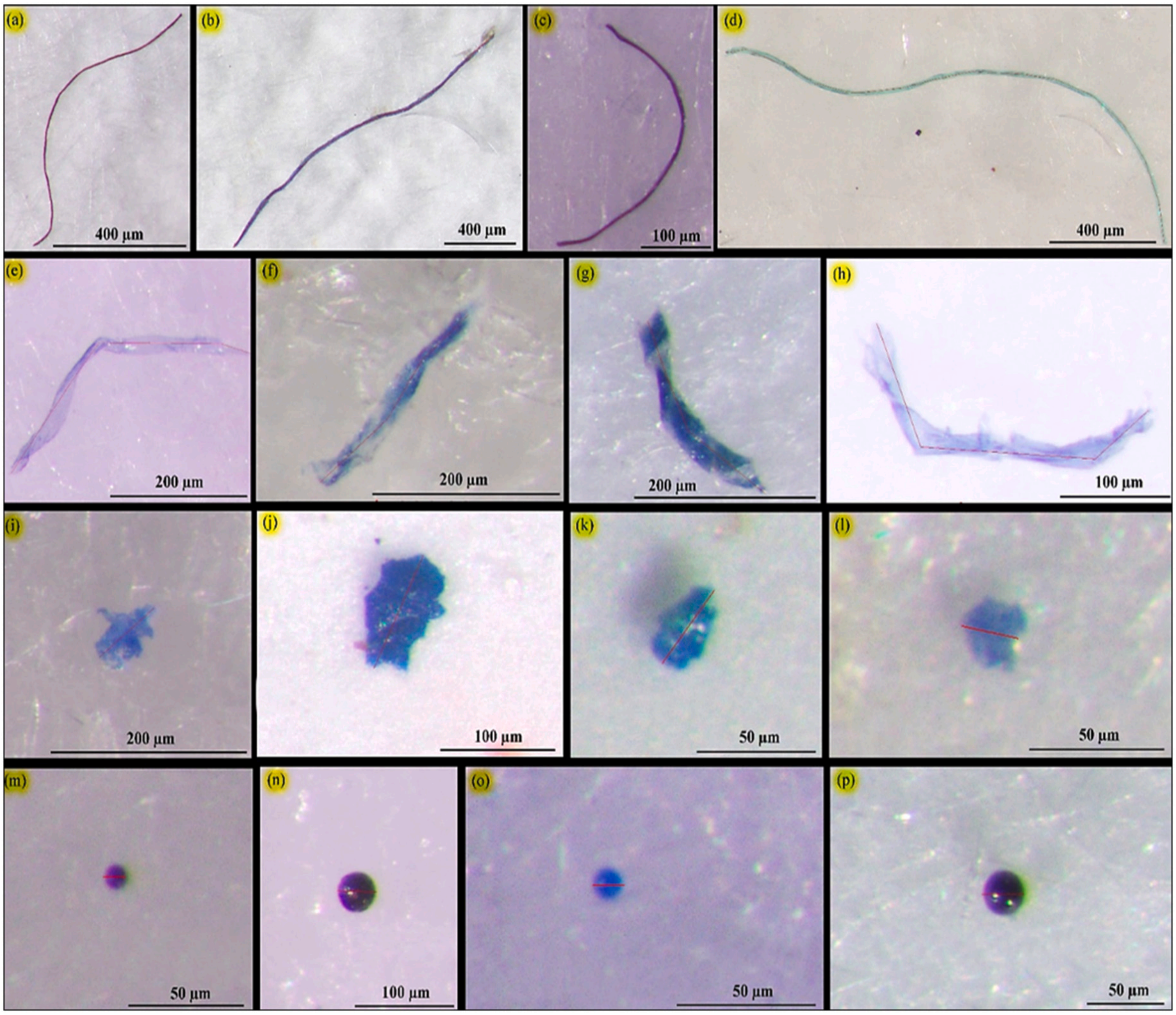

Fig. 2. Different forms of MPs ingested by zooplankton. (a–d) fibre, (e–h) film, (i–l) fragment, (m–p) pellet.

colours, whereas the pellets were simply blue, black, and pink.

The lengths of all MPs observed were measured, and they ranged from 5 to 3129 µm. The length of different MPs differed. The longest length of fibre was 3129 µm, and the shortest was 21 µm, with an average length of av. 829 ± 723 µm. The fragments ranged in size from av. 17–424 µm, with an average of av. 124 ± 120 µm. The film was av. 475 ± 409 µm long on average, with a maximum of 1711.3 µm and a minimum of 52.53 µm. Pellets ranged in length from 5 to 61 µm, with an average of 13.5 µm. Fig. 4a illustrates the average length of ingested MPs by different zooplankton groups, revealing a considerable difference in MPs length among different taxa. MPs in copepods were av. 195 ± 42 µm, chaetognaths av. 591 ± 142 µm, decapods av. 319 ± 79 µm, and fish larvae av. 245 ± 49 µm in length. MPs were found in the largest size in chaetognaths (3129 µm) and the smallest size in fish larvae (5 µm).

3.2. MPs quantity in zooplankton

The total number of MPs obtained from study locations and each zooplankton group and the total number of individuals examined are presented in Table 4, which shows spatial as well as group-specific variations in the occurrences of MPs. Okha, followed by Mumbai, had the highest concentration of MPs. The retention of MPs in zooplankton was estimated by dividing the number of MPs obtained by the number of digested individuals for each group and between different zooplankton taxa. As a result, overall, the average retention (MPs/individual) for copepods was av. 0.03 ± 0.01, av. 0.10 ± 0.04 for chaetognaths, av. 0.14 ± 0.06 for decapods, and av. 0.57 ± 0.18 for fish larvae (Fig. 4b). Okha (0.12 MPs/individual) had the highest total retention, whereas Mangaluru (0.07 MPs/ individual) had the lowest.

3.3. MPs retention in zooplankton

Fig. 5 shows the relative accumulation of MPs (pieces/m^3) in different groups in zooplankton community, with a maximum in copepods (44.28%) and a minimum in fish larvae (13.85%). MPs retention (pieces/m^3) for copepods was av. 9.9 ± 2.5, chaetognaths av. 5.35 ± 2.7, decapods av. 4.02 ± 1.4, and fish larvae av. 3.10 ± 1.3. In the study region, the average MPs in the zooplankton community (16.5–35.3 pieces/m^3) was av. 22 ± 7 pieces/m^3 with the highest in southernmost locations (Cape and Kochi).

3.4. Composition of MPs

Using a spectral library, a spectrum of various MPs obtained using Raman spectroscopy was identified (Fig. 6). Low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) were the four predominant types of MPs found in zooplankton samples. The Raman spectral ranges for LDPE (1067–2881 cm^{-1}), PP (810–2952 cm^{-1}), PS (623–3053 cm^{-1}) and PET (632–1729 cm^{-1}) are known (Fig. 6).

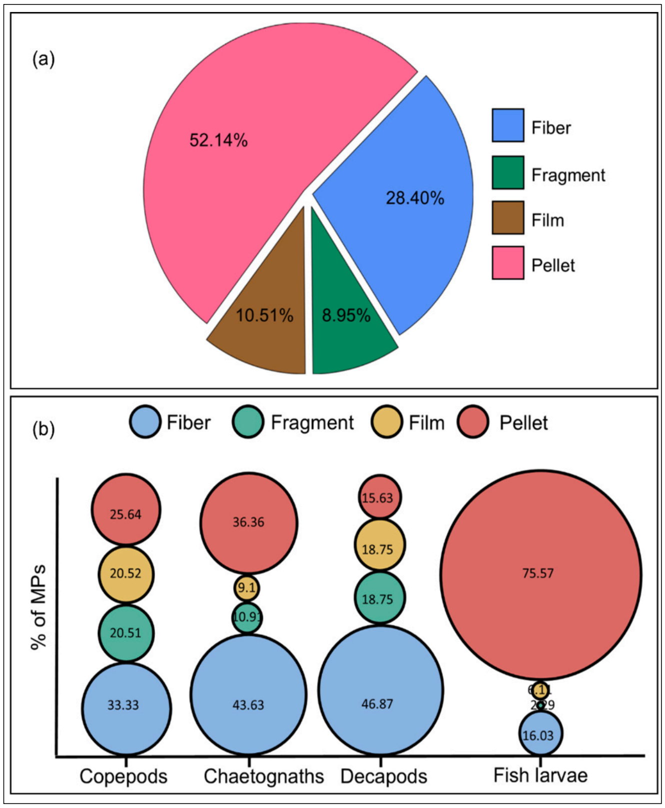

Fig. 3. The overall percentage contribution of MPs in (a) the whole zooplankton and (b) in different zooplankton groups.

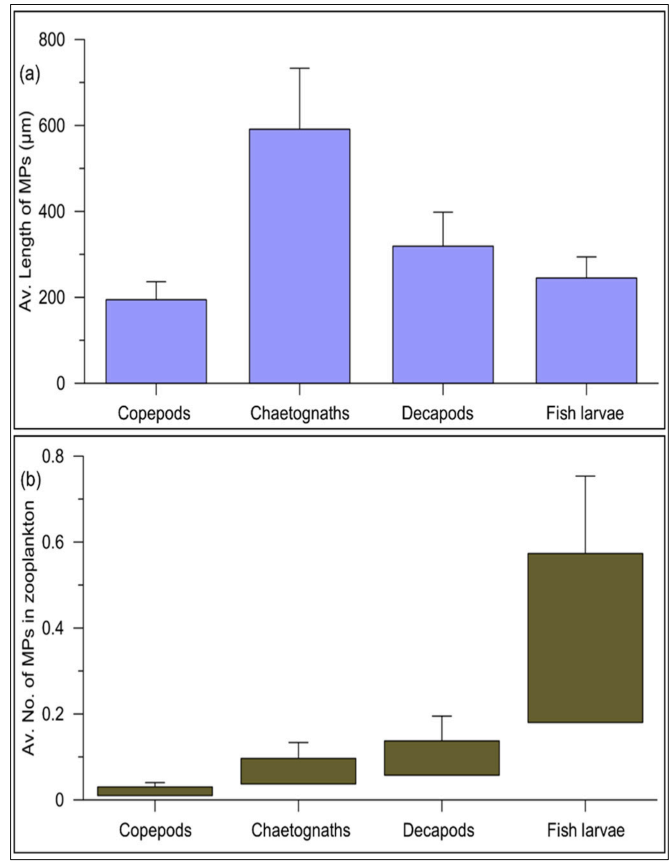

Fig. 4. (a) average size of MPs ingested by different zooplankton taxa and (b) their average number in various zooplankton groups.

4. Discussion

This study in the coastal waters off India's southwest coast found that MPs are highly bioavailable in the area and are commonly consumed by zooplankton. Copepods, chaetognaths, decapods, and fish larvae, which account for the majority of zooplankton biomass, all have absorbed MPs in their bodies, as have been reported in other areas (Frias et al., 2014; Desforges et al., 2015; Sun et al., 2017; Sun et al., 2018a, 2018b; Kosore et al., 2018; Zheng et al., 2020; Amin et al., 2020). MPs can be found in a variety of shapes and sizes in the natural environment (Hidalgo-Ruz et al., 2012; Wright et al., 2013), including pellets, fibres, irregular fragments, films, granules, and foam in the aquatic environment (Hidalgo-Ruz et al., 2012; Wright et al., 2013; Desforges et al., 2014; Crawford and Quinn, 2017). Marine MPs are divided into two types: primary and secondary MPs, which are defined by their source. Primary MPs are minute particles that are utilised as scrubbers in some personal care products or as resin pellets in the production of plastics (Cheung and Fok, 2017; Cole et al., 2011). Many waste treatment systems do not collect primary MPs, and they eventually end up in a water body (Murphy et al., 2016). Secondary MPs are formed when bigger particles, such as bags, bottles, fishing nets, and fabrics, deteriorate. Physical (wind, wave, and current), chemical (ultraviolet radiation), and biological (microbial) processes are all involved (Andrady, 2011). MPs are bioavailable to a wide range of marine organisms and can be ingested both actively and accidentally (Thompson et al., 2009a, 2009b), and their bright colour occasionally confuses visual predators, such as fish, as prey species (Phillips and Bonner, 2015). The size, shape, concentration, distribution, chemical features (i.e., density, a chemical signal, additives), and the animal's feeding habits all influence MPs particle ingestion and associated effects.

In this investigation, the MPs were determined using alkali digestion of the specimen tissue. Zooplankton is digested with 10% KOH and incubated at 60 °C for 48 h. For most MPs, KOH is the ideal choice for biological tissue digestion since it is less expensive, takes less time, and has a high recovery rate (Kühn et al., 2017; Thiele et al., 2019). In certain investigations, other procedures such as acid digestion and enzymatic digestion were also used. Nylon, polyethene terephthalate, and biopolymers are sensitive to concentrated nitric acid (Desforges et al., 2015; Enders et al., 2016), which is also more expensive than KOH and potentially dangerous to humans. Cole et al. (2014) investigated MPs in plankton using an enzymatic digestion approach. Even though this method can identify MPs, it necessitates the use of specialised equipment and materials, as well as time-consuming sample pretreatments.

Table 4
Total number of MPs obtained from study locations and each zooplankton group. The total number of individuals examined is also presented in parenthesis.

Location	Zooplankton groups				Total
	Copepods	Chaetognaths	Decapods	Fish larvae	
Kanyakumari	6 (215)	11 (90)	6 (15)	15 (20)	38 (340)
Kochi	6 (215)	6 (80)	5 (30)	22 (15)	39 (340)
Mangalore	3 (215)	10 (100)	9 (85)	15 (75)	37 (475)
Goa	4 (215)	17 (120)	2 (90)	16 (55)	39 (480)
Mumbai	9 (215)	8 (80)	7 (100)	25 (60)	49 (455)
Okha	11 (215)	3 (70)	3 (50)	38 (120)	55 (455)

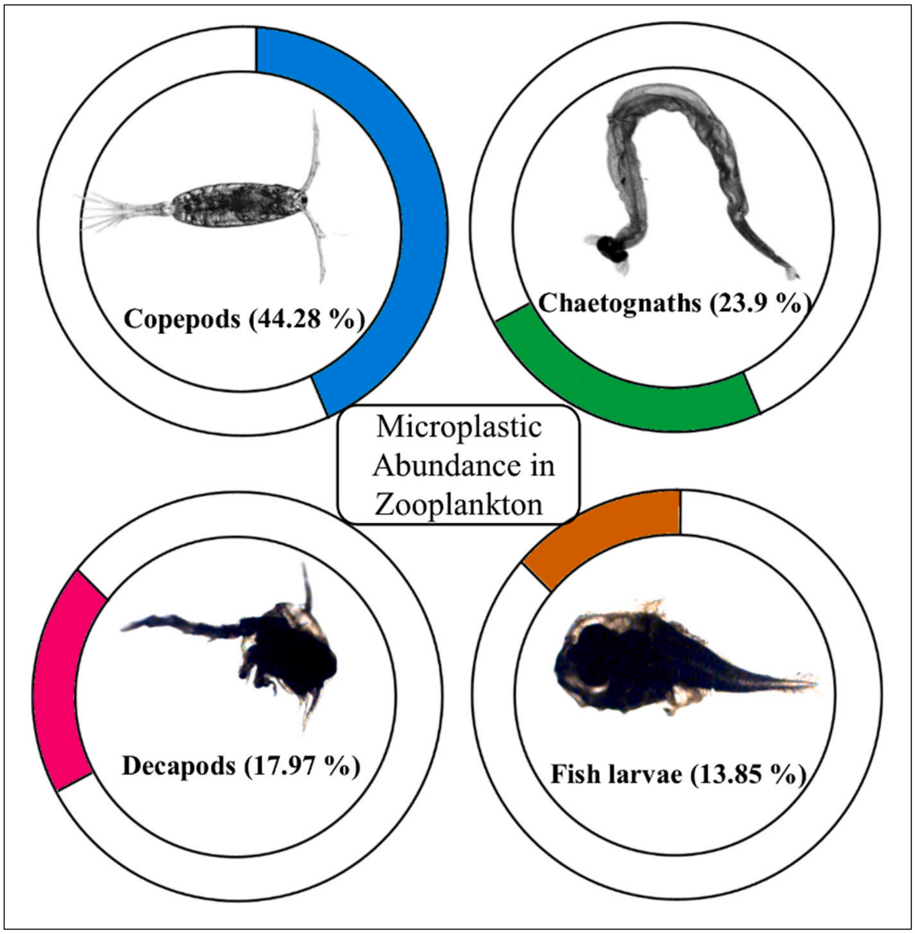

Fig. 5. A diagrammatic representation of the relative percentage of MPs retention in different groups in zooplankton community. The coloured outer circles represent the respective percentage of MPs in each group.

4.1. Characteristics of MPs in zooplankton in the EAS

Despite the fact that all four MPs types were identified in all of the zooplankton taxa studied, pellets accounted for 52.14% of the total, followed by fibres (28.10%), films (10.51%), and fragments (8.95%). Pellets were found to be the most prevalent plastic in this study, in contrast to previous reports that found fibres to be the most widespread (Sun et al., 2017; Sun et al., 2018a; Zheng et al., 2020), while filaments were numerous in zooplankton from Kenya's marine settings (Kosore et al., 2018). Similarly, fragment type MPs were found in greater numbers in zooplankton from Port Blair Bay, Andaman, than the fibres or pellets (Goswami et al., 2020). This means that zooplankton can eat all kinds of MPs, but their dominance is determined by the type of MPs available in the ecosystem. Pellets or microbeads are a type of primary MPs that is typically <100 μm in size and includes industrial 'scrubbers' for blast cleaning surfaces, plastic powders for moulding, and plastic nanoparticles used in several industrial operations. These are the primary ingredients in cleansing personal care products (cosmetics, body washes, cleansers, and toothpaste). When used as directed, these items are incorporated into wastewater, and some of these particles are likely to escape waste treatment plants and end up in the aquatic environment (Mason et al., 2016). Along India's west coast, the Mumbai and Gujarat coasts feature numerous large-scale industrial operations, which may be the major cause for the higher concentration of MPs observed in these locations, particularly in pellet form. In the maritime environment, the textile industry, home sewage, and fishing gear such as nets and rope are the main sources of fibre (Avio et al., 2016). Physical or chemical processes produce fragments and films from bigger plastic goods such as covers, bags, and bottles (Ajith et al., 2020). The lower abundance of MPs pellets observed in the Kanyakumari (Cape Comorin) region in this study could be the result of fewer industrial establishments in the region and also due to the turbulent sea environment existing there during the Southwest Monsoon due to heavy winds and strong currents which may be aiding in better dispersion of the MPs pellets in the region (Jyothibabu et al., 2021).

MPs of six different colours, including blue, black, pink, yellow, green, and transparent, were discovered to be ingested by zooplankton in this study. Blue is the most common colour, accounting for 54.4% of the total, which is similar to the findings of Zheng et al. (2020) and Steer et al. (2017). Due to their resemblance to prey items, such as visual raptorial animals (Wright et al., 2013), MPs' colour may increase their bioavailability, making it an intriguing area for further research. The average size of MPs (326 μm) retrieved from zooplankton in this study from the EAS is slightly greater than that obtained from the northern south china sea [(167 μm) Sun et al., 2017] and the yellow sea [(154.62 μm) Sun et al., 2018b], but it was significantly lower than that in the Bohai sea [(1300 μm) Zheng et al., 2020]. However, the average length of various types of MPs obtained from EAS is comparable to prior reports (Desforges et al., 2015; Sun et al., 2018a; Amin et al., 2020). When the average length of different types of MPs in each zooplankton group was compared to that of earlier research, some differences were found. In the present study, the average length of fibre and fragments for copepods (335.5 μm, 113.3 μm) was lower than that reported from the Northeast Pacific Ocean (951 μm, 196 μm, Desforges et al., 2015). For this study, the maximum length of microplastic observed was for fibre (3129 μm). In actuality, fibres can be bent or twisted individually or grouped to

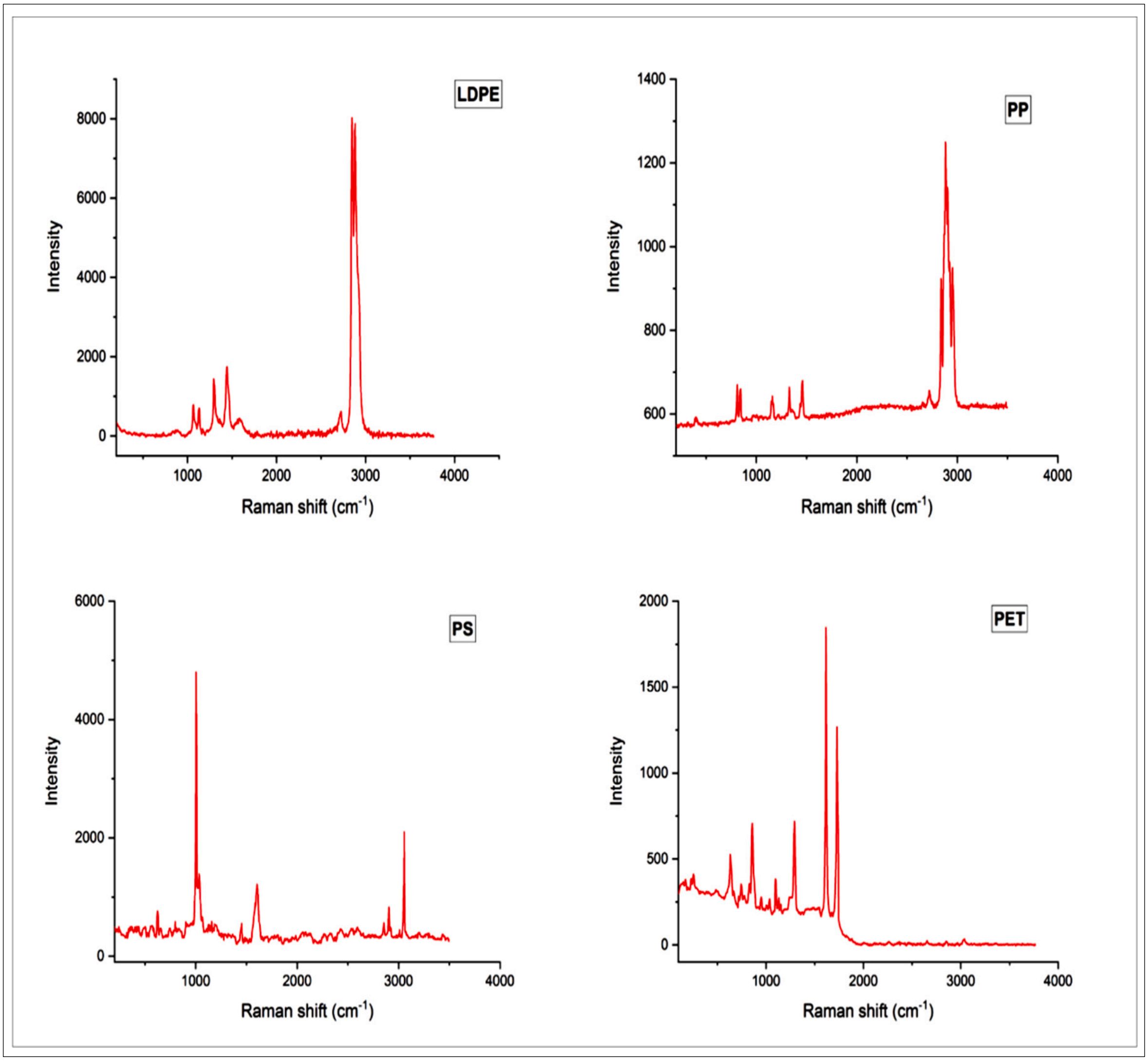

Fig. 6. Raman spectra of the MPs: Low density polyethylene (LDPE), Polypropylene (PP), Polystyrene (PS), Polyethylene terephthalate (PET).

reduce their overall size and potentially increase bioavailability (Desforges et al., 2015).

The MPs found in this study are the most typically detected polymers, and they are remarkably similar to those found in the marine environment in various Indian studies (Tiwari et al., 2019; James et al., 2020; Robin et al., 2020; Devi et al., 2020). Packaging film, wire and cable insulation, garbage and grocery bags, toys, squeeze bottles, housewares, and frozen food bags are all made of low-density polyethene (LDPE). Rope, bottle caps, fishing gear, strapping, packaging, carpets, drinking straws, and microbeads in personal care products are all made of polypropylene (PP). Food containers, disposable cups, plates, fast food cartons, CD covers, and other items are made of polystyrene (PS). PET is utilised in the manufacture of bottles, strapping, food packaging, and thermal insulation (Andrady and Neal, 2009; Vianello et al., 2013; Andrady, 2017; Wang et al., 2019a, 2019b; Coyle et al., 2020).

In this study, the number of MPs per individual (0.03–0.57) is slightly greater than in most other studies [(0.04–0.14) Frias et al., 2014; (0.03–0.06) Desforges et al., 2015; (0.16–0.46) Kosore et al., 2018; (0.003–0.14) Amin et al., 2020]. However, it was slightly lower than the Yellow Sea study [0.07–1.17 (Sun et al., 2018b)]. Copepods had the lowest ingestion rate, followed by chaetognaths, decapods, and fish larvae. This could be due to biological dilution effects, as described by Desforges et al. (2015), where MPs become less available due to competing with a large number of individuals. Furthermore, the rate of ingestion is influenced by feeding behaviour. Bioaccumulation is indicated by the greater ingestion rate of carnivorous zooplankton such as chaetognaths and fish larvae, which can feed directly on MPs by misunderstanding the food item or devouring prey that has already eaten the MPs.

4.2. MPs in zooplankton and their implication in EAS

Because MPs are abundant in the EAS, the average abundance of MPs in the zooplankton community recorded in this study (22 ± 7 pieces/m^3) is higher than in earlier findings. When the average abundance of MPs in each group is compared to the previous study, all results demonstrate an increase in abundance. The MPs abundance for copepods (the most abundant and widely distributed zooplankton group) was 0.41 in the Bohai Sea (Zheng et al., 2020), 1.71 in Terengganu coastal water (Amin et al., 2020), 2.19 in the Northern South China Sea (Sun et al., 2017), 2.44 in the West Yellow Sea (Sun et al., 2018b), and 9.91 in the EAS (this study). The higher abundance shows that MPs have a significant impact on EAS, necessitating further comprehensive research in this area.

Although MPs in zooplankton have been described in numerous studies, little is known about their impact on zooplankton health and survival. MPs have been found to have a deleterious impact on zooplankton in several recent laboratory investigations. For the marine

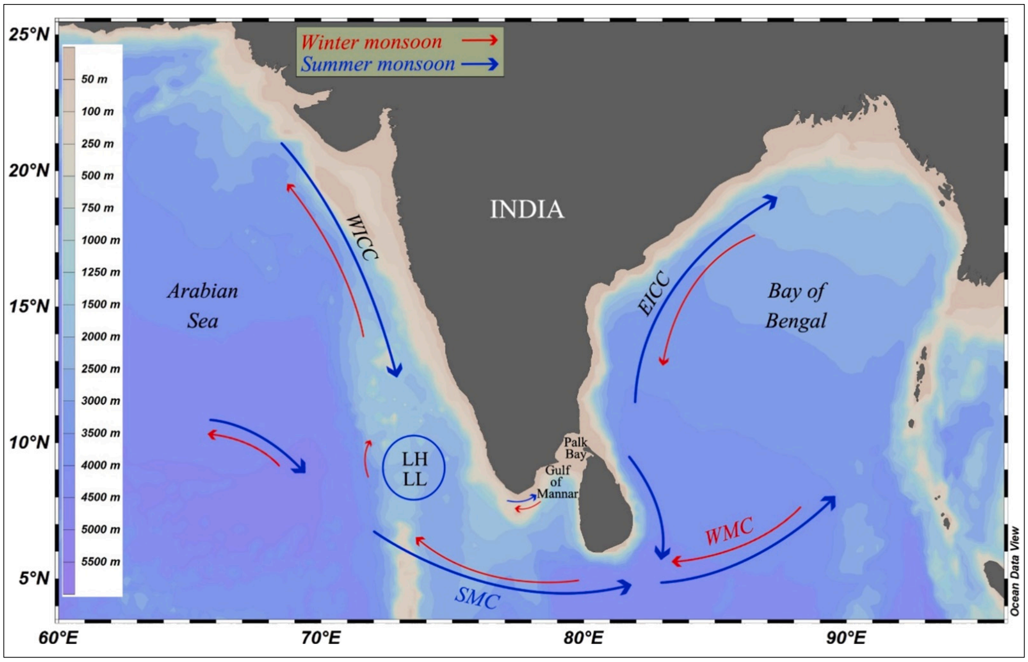

Fig. 7. Seasonal circulation of coastal currents around the Indian subcontinent, which is the exchange of water masses between the Southeastern Arabian Sea and the Southwestern Bay of Bengal. This peculiar circulation system is capable of expanding the spread of MPs pollution in a particular area to a widespread region. All linked currents during the Northeast/Winter Monsoon are in red and all those during the Southwest/Summer Monsoon are in blue. WICC-West India Coastal Currect, LH-Lakshwadweep High, LL-Lakshwadweep Low, SMC- Summer Monsoon Current, WMS-Winter Monsoon Current, EICC-East India Coastal Current. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

copepod *Tigriopus japonicus* and the freshwater cladoceran *Daphnia magna*, the effects of nano and MPs on body growth, survival, reproduction, and mortality have been documented at varying concentrations of polystyrene beads (Lee et al., 2013; Besseling et al., 2014). The copepod *Centropages typicus* reduced its algal ingestion rate after ingesting polystyrene microbeads (0.4–30.6 μm) (Cole et al., 2013) Another study on the copepod *Calanus helgolandicus* found that consuming 20 μm beads lowered their feeding capacity and that extended exposure affected their reproductive production (Cole et al., 2015). The exposure of polystyrene beads to *Arenicola marina* resulted in weight loss and reduced eating (Besseling et al., 2013). Another study on *A. marina* found that persistent exposure to tiny unplasticised polyvinylchloride (UPVC) lowered energy reserves due to decreased food intake, and increased phagocytic activity, indicating increased inflammatory activity. All of this suggests that MPs may harm zooplankton on a variety of levels, including feeding, growth, body size, reproduction, and even survival.

The potential impact of MPs trophic transfer across the marine food web is a major concern, and this is an area that has received little research. Because zooplankton are secondary producers and carriers of MPs, there is a greater likelihood that MPs would be transferred to higher trophic levels, such as fish. We investigated MPs in copepods, chaetognaths, decapods, and fish larvae in this work. Copepods are herbivores that feed phytoplankton and are usually filter feeders. Because MPs and copepod prey sizes overlap, the likelihood of ingestion is high. Copepods are preyed upon by chaetognaths and fish larvae. Chaetognaths are higher in the food chain than copepods, and fish larvae are higher than chaetognaths. Due to difficulty in identifying their food, carnivorous zooplankton may consume MPs directly from saltwater. They could also consume MPs by devouring lower trophic level species like copepods that have already consumed MPs. This study shows that the increase in the encounter rate with trophic levels is suggestive of the transfer of MPs along with the planktonic food web in this sea domain. The trophic transfer of MPs in the food web by ingestion has been observed in several laboratory investigations. Setälä et al. (2014) showed that luminous PS spheres (10 μm) can be transferred trophically from mesozooplankton to mysid shrimp *Mysis relicta*. When mussels (*Mytilus edulis*) were exposed to 0.5 μm fluorescent polystyrene microspheres and then fed to crabs, trophic transfer from mussel to crab also was detected (*Carcinus maenas*). MPs labelled in the mussel were found to be translocated into the tissues and heamolymph of the crab (Farrell and Nelson, 2013). After 24 h of feeding, the highest concentration of MPs was found in the hemolymph, and it was retained for up to 21 days (Farrell and Nelson, 2013). LDPE microsphere (10–20 μm) trophic transmission from unicellular tintinnid (*Favella* spp.) to larval inland silversides (*Menidia beryllina*) was described by Athey et al. (2020).

Plastic contamination is particularly prevalent along the coast and on the shelf. According to several studies conducted on India's west coast, land-based activities are the primary source of MPs in the marine environment. Domestic sewage, municipal wastewaters, industrial effluents, and wastewater treatment plant effluents released in drains, canals, and rivers eventually reach the sea, partially or untreated. In addition, rain, floods, and drainage contribute to MPs in the sea. Studies on the beaches of Mumbai (Jayasiri et al., 2013; Tiwari et al., 2019), Goa (Veerasingam et al., 2016b), Kerala (Daniel et al., 2020a; Robin et al., 2020), and Tamil Nadu indicated a significant abundance of MPs (Karthik et al., 2018; Tiwari et al., 2019; Jeyasanta et al., 2020). Upwelling, eddies, and currents are all common hydrodynamic processes in the EAS, and they may all be contributing to the redistribution of MPs in the region. In addition, zooplankton migration contributes to the redistribution of MPs in the coastal, open ocean, and water column. The western coastal areas have a lot of fishing and other maritime activity, and it's also an important shipping route. In western coastal areas, plastics from all of these sources contribute a significant quantity of MPs buildup. Because zooplankton is a favoured food for many finfish and shellfish, MPs ingested by zooplankton are likely to be passed to humans via the food chain. This is a major worry, and as a result, there is a lot of study potential in this area that should be examined in future studies.

4.3. MPs dispersion in EAS is aided by coastal currents

A schematic of the seasonally reversing chain of coastal currents that exchange water masses between the Arabian Sea and the Bay of Bengal around the Indian subcontinent is presented in Fig. 7. During the Southwest Monsoon (present sampling time), water masses from the eastern Arabian Sea get transported to the Bay of Bengal, and during the Northeast Monsoon, just the reverse is the case, wherein the low saline Bay of Bengal intrudes and spreads into the southeastern Arabian Sea.

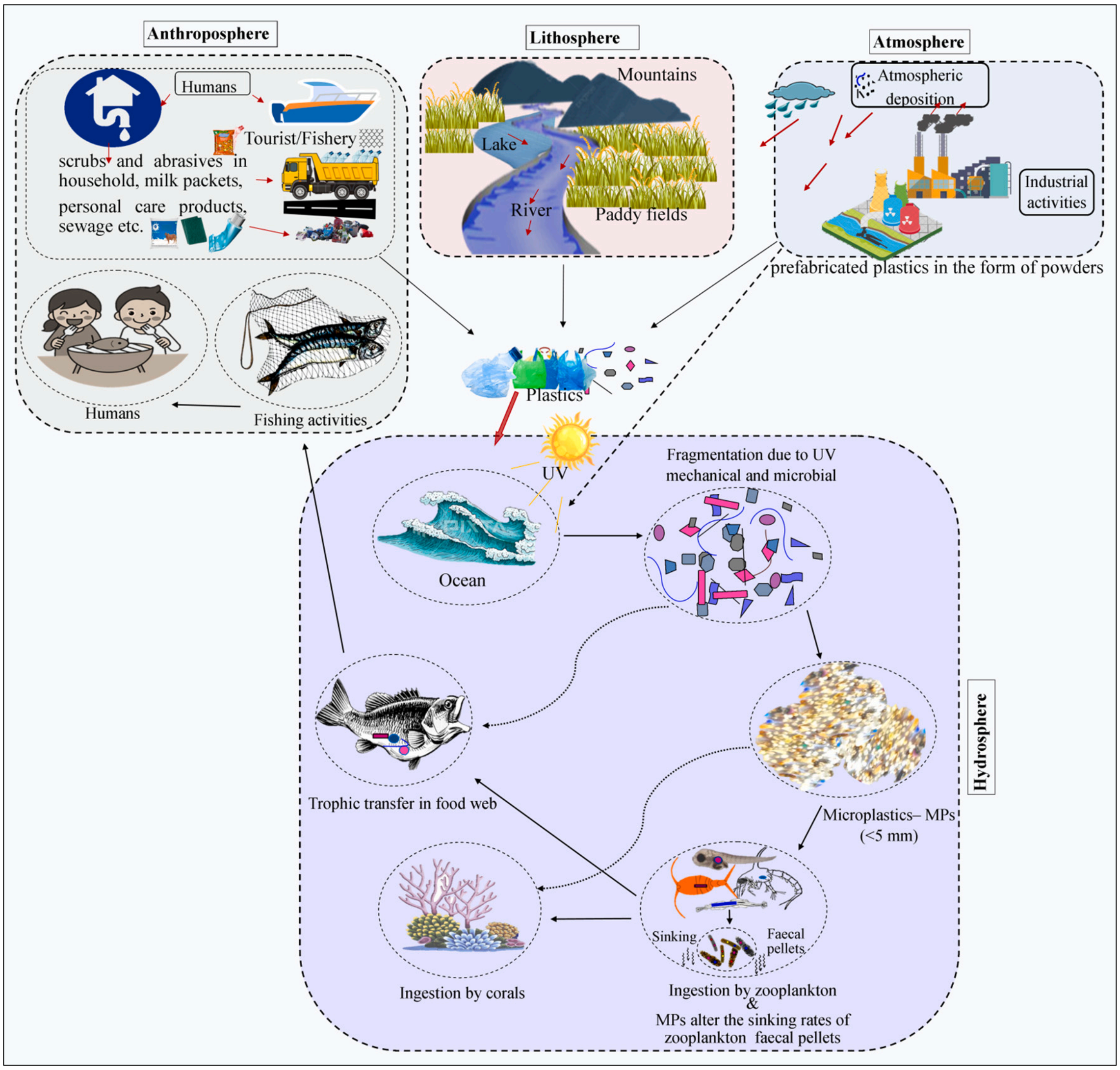

Fig. 8. The transfer pathway of MPs from the anthroposphere to other spheres of the environment, as well as interactions in the marine environment via trophic transfer, eventually reaching the top consumer humans in the chain, are depicted schematically.

Recent studies have shown that these coastal currents have the potential to transport zooplankton communities from one region to another, and it was noted that during the southwest monsoon, *Temora turbinata*, which is an upwelling indicator along the southwest coast of India, gets transported to the adjacent Gulf of Mannar, where no coastal upwelling occurs (Jagadeesan et al., 2013). Similarly, the copepod *Paracalanus parvus*, typical of the coastal environments, gets transported to Palk Bay and the Gulf of Mannar during the Northeast Monsoon as a part of the coastal currents existing in the region (Jagadeesan et al., 2013). A very recent study by Jyothibabu et al. (2021) showed that the upwelled plankton-rich water mass advected to the Gulf of Mannar during the Southwest Monsoon is crucial in sustaining the astonishing marine life existing there. All these indicate that the seasonally reversing coastal currents play a pivotal role in maintaining the biogeographic continuity of plankton communities between the Eastern Arabian Sea and the western Bay of Bengal throughout the year.

It's critical to consider the MPs contamination of zooplankton found in this study against the backdrop of the region's prevalent coastal currents. The prevailing coastal currents can transport the polluted zooplankton community around the Indian peninsula, connecting all of the study domain's highly profitable fishing and coral-resource-rich locations. Fig. 1 depicts the peculiarities of the current sample sites, as well as the locations of important fish landings and the occurrence of corals and their reef formations. All of the research locations are close to important fishing landing ports along the Indian coastline. Similarly, important coral formations (Gulf of Katchh-Okha, Mumbai-Goa coast, Lakshadweep Islands, Gulf of Mannar, and Palk Bay) are all close to the study sites or on the track of coastal currents that could transport polluted water mass and zooplankton from the MPs to these areas. Researchers began to explore the possibility of MPs pollution being dispersed by coastal currents on a global scale. In this line, it was recently reported that floating microplastics were brought into the North Yellow Sea via the Chinese coastline current and the Korean coastal current (Amelia et al., 2021). It is alarming to note that the MPs observed in this study were nearly 2-fold higher than those reported by the zooplankton in the subtropical regions. This indicates a possible threat of MPs to higher trophic levels, as zooplankton is the preferred food of all pelagic fishes and corals. Also, we propose that the southerly currents prevalent along the western shelf of India during the present sampling during the Southwest Monsoon could advect the MPs contaminated water mass and zooplankton to the adjacent Gulf of Mannar, Palk Bay, and the western Bay of Bengal, thereby extending the MPs contamination to biota to a further geographical extent. A summary diagram of ecosystem impacts of MPs at multiple levels and ultimately harming the human health is presented in Fig. 8. It is very clear in this figure that how MPs in interact in different spheres of the earth how their trophic transfer pathway is structured from the source to the humans top in the trophic chain. As this is a baseline study, we urge the need for detailed further studies on MPs in the environment, fishes and corals in the region.

5. Conclusion

This study on MPs reveals a significant level of MPs contamination in zooplankton in the lower-level food web along the southwest coast of India, which is very productive and supports a large number of fishing resources. The MPs were found to be abundant in pellets (52.14%), with the greatest concentration in fish larvae (0.573) being greater than previously reported. This is the first study to document MPs concentrations in the lowest food web of the EAS, which is rich in fish and coral. The implication could be that these MPs are easily transmitted to higher trophic levels of fish, eventually reaching humans through the food chain. We also showed that the prevailing coastal currents in the region have a great potential to spread MPs pollution to extended regions, affecting the fish and coral resources surviving in the entire study domain. Hence, we urge that further investigations should be coordinated to determine the extent of MPs levels in the food chain as well as in common fishes in the region, as well as their ecological consequences on both short and long-time scales.

CRediT authorship contribution statement

C.P. Rashid: Conceptualization, Methodology, Data curation, Writing – original draft, Visualization, Funding acquisition. **R. Jyothibabu:** Conceptualization, Methodology, Data curation, Visualization, Writing – review & editing, Supervision, Funding acquisition. **N. Arunpandi:** Conceptualization, Methodology, Visualization, Formal analysis. **V.T. Abhijith:** Methodology, Visualization. **M.P. Josna:** Methodology, Visualization. **V. Vidhya:** Methodology, Visualization. **G. V.M. Gupta:** Methodology, Visualization, Data curation. **M.V. Ramanamurty:** Methodology, Visualization, Data curation.

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.

Acknowledgements

The authors thank the Director of the CSIR-National Institute of Oceanography for the facility and support. This study is part of the SWQM-MEDAS programme funded by the Ministry of Earth Sciences, India. The authors thank the Ministry of Earth Sciences, New Delhi for supporting this work. We thank DST-SAIF, Mahatma Gandhi University, Kottayam, India for the qualitative identification of microplastic materials using Raman Spectroscopy. This is CSIR-NIO, CMLRE and NCCR contribution numbers 6815, 143 and 377, respectively.

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