

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

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### **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.  $0.57 \pm 0.18$ ) while copepods had the lowest (av.  $0.03 \pm 0.01$ ). 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.  $22 \pm 7$  pieces/m<sup>3</sup>) 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.

**Keywords:** microplastics, zooplankton, food web, fish, corals, west coast of India, Arabian Sea

## 1. Introduction

Plastics were first mass-produced in the 1940s, and the present global production is at 348 million metric tonnes per year (Plastics Europe, 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 5mm (Arthur et al., 2009), and their buildup in the natural environment around the world has become a major worry in recent decades (Lonnstedt and Eklov, 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, colourants, 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., 2019). 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; 200-20000  $\mu\text{m}$ ), 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 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 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 (Goswamy 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 (Table 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 MP 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-meters in shelf waters, were selected for the study (Figure 1). The Indian western shelf extends 1,500 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, 0.6m diameter, 300  $\mu\text{m}$  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 minutes 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 multiplying 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 hours 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- $\mu\text{m}$  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 the following conditions: 532 nm excitation wavelength, 600 grooves/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; Stokr et al., 1982; Andreassen E, 1999; Sato et al., 2002; Anema et al., 2009; Rebollar et al., 2014; Bisticic et al., 2015; Ibrahim and Herman, 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<sup>3</sup>) was calculated by using the formula:

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

The zooplankton groups are indicated by the i<sup>th</sup> 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<sup>3</sup>.

### 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 (Figure 2). Pellets were the most common MPs (52.14%), followed by fibres (28.40%), films (10.51%), and fragments (8.95%). (Figure 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. Figure 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 colours, whereas the pellets were simply blue, black, and pink.

The lengths of all MPs observed were measured, and they ranged from 5- 3129  $\mu\text{m}$ . The length of different MPs differed. The longest length of fibre was 3129  $\mu\text{m}$ , and the shortest was 21  $\mu\text{m}$ , with an average length of av.  $829 \pm 723 \mu\text{m}$ . The fragments ranged in size from av. 17 – 424  $\mu\text{m}$ , with an average of av.  $124 \pm 120 \mu\text{m}$ . The film was av.  $475 \pm 409 \mu\text{m}$  long on average, with a maximum of 1711.3  $\mu\text{m}$  and a minimum of 52.53  $\mu\text{m}$ . Pellets ranged in length from 5 - 61  $\mu\text{m}$ , with an average of 13.5  $\mu\text{m}$ . Figure 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.  $195 \pm 42 \mu\text{m}$ , chaetognaths av.  $591 \pm 142 \mu\text{m}$ , decapods av.  $319 \pm 79 \mu\text{m}$ , and fish larvae av.  $245 \pm 49 \mu\text{m}$  in length. MPs were found in the largest size in chaetognaths (3129  $\mu\text{m}$ ) and the smallest size in fish larvae (5  $\mu\text{m}$ ).

#### 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.

$0.03 \pm 0.01$ , av.  $0.10 \pm 0.04$  for chaetognaths, av.  $0.14 \pm 0.06$  for decapods, and av.  $0.57 \pm 0.18$  for fish larvae (Figure 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**

Figure 5 shows the relative accumulation of MPs in different zooplankton groups, with a maximum in copepods (44.28%) and a minimum in fish larvae (13.85 %). MPs retention (pieces/m<sup>3</sup>) for copepods was av.  $9.9 \pm 2.5$ , chaetognaths av.  $5.35 \pm 2.7$ , decapods av.  $4.02 \pm 1.4$ , and fish larvae av.  $3.10 \pm 1.3$ . In the study region, the average MPs in the zooplankton community (16.5 - 35.3 pieces/m<sup>3</sup>) was av.  $22 \pm 7$  pieces/m<sup>3</sup> 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 (Figure 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 ( $1067\text{-}2881\text{ cm}^{-1}$ ), PP ( $810\text{-}2952\text{ cm}^{-1}$ ), PS ( $623\text{-}3053\text{ cm}^{-1}$ ) and PET ( $632\text{-}1729\text{ cm}^{-1}$ ) are known (Figure 6)

## **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 hours. 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, polyethylene 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.

#### **4.1. Characteristics of MPs in zooplankton in the EAS**

Despite the fact that all four MP 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., 2018; 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 (Gowsamy 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 MP 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 MP 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  $\mu\text{m}$ ) retrieved from zooplankton in this study from the EAS is slightly greater than that obtained from the northern south china sea [(167  $\mu\text{m}$ ) Sun et al., 2017] and the yellow sea [(154.62  $\mu\text{m}$ ) Sun et al., 2018 b], but it was significantly lower than that in the Bohai sea [(1300  $\mu\text{m}$ ) 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  $\mu\text{m}$ , 113.3  $\mu\text{m}$ ) was lower than that reported from the Northeast Pacific Ocean (951  $\mu\text{m}$ , 196  $\mu\text{m}$ , Desforges et al., 2015). For this study, the maximum length of microplastic observed was for fibre (3129 m). In actuality, fibres can be bent or twisted individually or grouped to 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 polyethylene (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., 2019; 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 ( $22 \pm 7$  pieces/m<sup>3</sup>) 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 copepod *Tigriopus japonicas* 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 20µm 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 *Arenicola 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 hemolymph of the crab (Farrell and Nelson, 2013). After 24 hours 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., 2016), 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. MP 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 Figure 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. 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. Figure 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 Figure 8. It is very clear in this figure that how MPs 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 and 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.

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## References

- Ajith, N., Arumugam, S., Parthasarathy, S., Manupoori, S., Janakiraman, S., 2020. Global distribution of microplastics and its impact on marine environment-a review. *Environ. Sci. Pollut. Res.* 27, 25970-25986. doi:10.1007/s11356-020-09015-5.
- Amelia, T.S.M., Wan Mohd Afiq Wan Mohd Khalik, Ong, M.C., Shao, Y.T., Pan, H.-J., Bhubalan, K., 2021. Marine microplastics as vectors of major ocean pollutants and its hazards to the marine ecosystem and humans. *Prog. Earth Planet. Sci.* 8. doi:10.1186/s40645-020-00405-4
- Amin, R.M., Sohaimi, E.S., Anuar, S.T., Bachok, Z., 2020. Microplastic ingestion by zooplankton in Terengganu coastal waters, southern South China Sea. *Mar. Pollut. Bull.* 150, 110616. doi:10.1016/j.marpolbul.2019.110616.
- Amrutha, K., Warriar, A.K., 2020. The first report on the source-to-sink characterization of microplastic pollution from a riverine environment in tropical India. *Sci. Total Environ.* 739, 140377. doi:10.1016/j.scitotenv.2020.140377.
- Andrady, A., Neal, M., 2009. Applications and societal benefits of plastics. *Phil. Trans. R. Soc. London* 364 (1526).
- Andrady, A.L., 2011. Microplastics in the marine environment. *Mar. Pollut. Bull.* 62, 1596-1605. <https://doi.org/10.1016/j.marpolbul.2011.05.030>.
- Andrady, A.L., 2017. The plastic in microplastics: A review. *Mar. Pollut. Bull.* 119, 12-22. doi:10.1016/j.marpolbul.2017.01.082.
- Andreassen, E., 1999. Infrared and Raman spectroscopy of polypropylene. *Polymer Science and Technology Series Polypropylene* 320–328. doi:10.1007/978-94-011-4421-6\_46.
- Anema, J.R., Brolo, A.G., Felten, A., Bittencourt, C., 2009. Surface-enhanced Raman scattering from polystyrene on gold clusters. *J Raman Spectrosc.* 41, 745-751. doi:10.1002/jrs.2504.
- Arthur, C., Baker, J., Bamford, H., 2009. Proceedings of the International Research Workshop on the Occurrence, Effects, and Fate of Microplastic Marine Debris. September 9-11, 2008. (NOAA Technical Memorandum NOS-OR&R-30).
- Ashwini S. K., Varghese, G.K., 2019. Environmental forensic analysis of the microplastic pollution at “Nattika” Beach, Kerala Coast, India. *Environ. Forensics.* 21, 21–36. doi:10.1080/15275922.2019.1693442.
- Athey, S.N., Albotra, S.D., Gordon, C.A., Monteleone, B., Seaton, P., Andrady, A.L., Taylor, A.R., Brander, S.M., 2020. Trophic transfer of microplastics in an estuarine food chain and the effects of a sorbed legacy pollutant. *Limnol. Oceanogr. Lett.* 5, 154-162.
- Avio, C.G., Gorbi, S., Regoli, F., 2016. Plastics and microplastics in the oceans: From emerging pollutants to emerged threat. *Mar. Environ. Res.* 128, 2–11. doi:10.1016/j.marenvres.2016.05.012.
- Ayukai, T., 1987. Discriminate feeding of the calanoid copepod *Acartia clausi* in mixtures of phytoplankton and inert particles. *Mar. Biol.* 94, 579e587.

- Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. M. Accumulation and fragmentation of plastic debris in global environments. *Philos Trans. R. Soc. B.* 364, 1985-1998. doi:10.1098/rstb.2008.0205.
- Besseling, E., Wang, B., Lürling, M., Koelmans, A.A., 2014. Nanoplastic Affects Growth of *S. obliquus* and Reproduction of *D. magna*. *Environ. Sci. Technol.* 48, 12336-12343. doi:10.1021/es503001d.
- Besseling, E., Wegner, A., Foekema, E.M., Van den Heuvel-Greve, M.J., Koelmans, A.A., 2013. Effects of microplastic on fitness and PCB bioaccumulation by the lugworm *Arenicola marina* (L.). *Environ. Sci. Technol.* 47, 593-600.
- Bharath M.K., Srinivasalu, S., Natesan, U., Ayyamperumal, R., Kalam, N., Anbalagan, S., Sujatha, K. and Alagarasan, C., 2021. Microplastics as an emerging threat to the freshwater ecosystems of Veeranam lake in south India: A multidimensional approach. *Chemosphere*, 264, p.128502.
- Bistričić, L., Borjanović, V., Leskovic, M., Mikac, L., Mcguire, G.E., Shenderova, O., Nunn, N., 2015. Raman spectra, thermal and mechanical properties of poly (ethylene terephthalate) carbon-based nanocomposite films. *J. Polym. Res.* 22. doi:10.1007/s10965-015-0680-z.
- Cheung, P.K., Fok, L., 2017. Characterisation of plastic microbeads in facial scrubs and their estimated emissions in Mainland China. *Water Res.* 122, 53-61. doi:10.1016/j.watres.2017.05.053.
- Cole, M., Lindeque, P., Fileman, E., Halsband, C., Galloway, T.S., 2015. The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod *Calanus helgolandicus*. *Environ. Sci. Technol.* 49 (2), 1130–1137. <https://doi.org/10.1021/es504525u>.
- Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., Galloway, T.S., 2013. Microplastic Ingestion by Zooplankton. *Environ. Sci. Technol.* 47, 6646–6655. doi:10.1021/es400663f.
- 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. doi:10.1016/j.marpolbul.2011.09.025.
- Cole, M., Lindeque, P.K., Fileman, E., Clark, J., Lewis, C., Halsband, C., Galloway, T.S., 2016. Microplastics alter the properties and sinking rates of zooplankton faecal pellets. *Environ. Sci. Technol.* 50 (6), 3239-3246. <https://doi.org/10.1021/acs.est.5b05905>.
- Cole, M., Webb, H., Lindeque, P.K., Fileman, E.S., Halsband, C., Galloway, T.S., 2014. Isolation of microplastics in biota-rich seawater samples and marine organisms. *Sci. Rep.* 4. doi:10.1038/srep04528.
- Collicutt, B., Juanes, F., Dudas, S.E., 2019. Microplastics in juvenile Chinook salmon and their nearshore environments on the east coast of Vancouver Island. *Environ. Pollut.* 244, 135-142. doi:10.1016/j.envpol.2018.09.137.
- Costa, E., Piazza, V., Lavorano, S., Faimali, M., Garaventa, F., Gambardella, C., 2020. Trophic Transfer of Microplastics From Copepods to Jellyfish in the Marine Environment. *Front. Environ. Sci.* 8. doi:10.3389/fenvs.2020.571732.



- Coyle, R., Hardiman, G., Driscoll, K.O., 2020. Microplastics in the marine environment: A review of their sources, distribution processes, uptake and exchange in ecosystems. *Case Stud. Therm. Eng.* 2, 100010. doi:10.1016/j.cscee.2020.100010.
- Crawford, C.B., Quinn, B., 2017. Microplastic collection techniques. *Microplastic Pollutants* 179–202. doi:10.1016/b978-0-12-809406-8.00008-6.
- Daniel, D.B., Ashraf, P.M., Thomas, S.N., 2020a. Abundance, characteristics and seasonal variation of microplastics in Indian white shrimps (*Fenneropenaeus indicus*) from coastal waters off Cochin, Kerala, India. *Sci. Total Environ.* 737, 139839. doi:10.1016/j.scitotenv.2020.139839.
- Daniel, D.B., Ashraf, P.M., Thomas, S.N., 2020b. Microplastics in the edible and inedible tissues of pelagic fishes sold for human consumption in Kerala, India. *Environ. Pollut.* 266, 115365. doi:10.1016/j.envpol.2020.115365.
- Daniel, D.B., Thomas, S.N., Thomson, K., 2020c. Assessment of fishing-related plastic debris along the beaches in Kerala Coast, India. *Mar. Pollut. Bull.* 150, 110696. doi:10.1016/j.marpolbul.2019.110696.
- Dehaut, A., Cassone, A.-L., Frère, L., Hermabessiere, L., Himber, C., Rinnert, E., Rivière, G., Lambert, C., Soudant, P., Huvet, A., Duflos, G., Paul-Pont, I., 2016. Microplastics in seafood: Benchmark protocol for their extraction and characterization. *Environ. Pollut.* 215, 223–233. doi:10.1016/j.envpol.2016.05.018.
- Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. *Mar. Pollut. Bull.* 44, 842–852.
- Desforges, J.-P.W., Galbraith, M., Dangerfield, N., Ross, P.S., 2014. Widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean. *Mar. Pollut. Bull.* 79, 94–99. doi:10.1016/j.marpolbul.2013.12.035.
- Desforges, J.P.W., Galbraith, M., Ross, P.S., 2015. Ingestion of microplastics by zooplankton in the Northeast Pacific Ocean. *Arch. Environ. Contam. Toxicol.* 69 (3), 320–330. <https://doi.org/10.1007/s00244-015-0172-5>.
- Devi, S.S., Sreedevi, A.V., Kumar, A.B., 2020. First report of microplastic ingestion by the alien fish *Pirapitinga* (*Piaractus brachypomus*) in the Ramsar site Vembanad Lake, south India. *Mar. Pollut. Bull.* 160, 111637. doi:10.1016/j.marpolbul.2020.111637.
- 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. doi:10.1016/j.marpolbul.2019.07.066.
- Dowarah, K., Patchaiyappan, A., Thirunavukkarasu, C., Jayakumar, S., Devipriya, S.P., 2020. Quantification of microplastics using Nile Red in two bivalve species *Perna viridis* and *Meretrix meretrix* from three estuaries in Pondicherry, India and microplastic uptake by local communities through bivalve diet. *Mar. Pollut. Bull.* 153, 110982. doi:10.1016/j.marpolbul.2020.110982.
- Enders, K., Lenz, R., Beer, S., Stedmon, C.A., 2016. Extraction of microplastic from biota: recommended acidic digestion destroys common plastic polymers. *ICES J. Mar. Sci.* 74, 326–331. doi:10.1093/icesjms/fsw173.

- Eriksen, M., Liboiron, M., Kiessling, T., Charron, L., Alling, A., Lebreton, L., Richards, H., Roth, B., Ory, N.C., Hidalgo-Ruz, V. and Meerhoff, E., 2018. Microplastic sampling with the AVANI trawl compared to two neuston trawls in the Bay of Bengal and South Pacific. *Environ. Pollut.* 232, pp.430-439.
- Farrell, P., Nelson, K., 2013. Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.). *Environ. Pollut.* 177, 1-3. <https://doi.org/10.1016/j.envpol.2013.01.046>.
- Fernández, D., López-Urrutia, Á., Fernández, A., Acuña, J., Harris, R., 2004. Retention efficiency of 0.2 to 6 µm particles by the appendicularians *Oikopleura dioica* and *Fritillaria borealis*. *Mar. Ecol. Prog. Ser.* 266, 89–101. doi:10.3354/meps266089.
- Frias, J.P.G.L., Otero, V., Sobral, P., 2014. Evidence of microplastics in samples of zooplankton from Portuguese coastal waters. *Mar. Environ. Res.* 95, 89-95. <https://doi.org/10.1016/j.marenvres.2014.01.001>.
- Gall, M.J, Hendra, P.J, Peacock, C.J, Cudby, M.E.A, Willis, H.A. The laser-Raman spectrum of polyethylene. The assignment of the spectrum to fundamental modes of vibration. *Spectrochim Acta.* 1972; 28:1485-96.
- Ganesan, M., Nallathambi, G., Srinivasalu, S., 2019. Fate and Transport of Microplastics from Water Sources. *Curr. Sci.* 117, 1879. doi:10.18520/cs/v117/i11/1879-1885
- GESAMP, 2016. Sources, fate and effects of microplastics in the marine environment: part two of a global assessment (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/ UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) In: Kershaw, P.J., Rochman, C.M. (Eds.), Rep. Stud. GESAMP No. 93, (220 p).
- Gopinath, K., Seshachalam, S., Neelavannan, K., Anburaj, V., Rachel, M., Ravi, S., Bharath, M., Achyuthan, H., 2020. Quantification of microplastic in Red Hills Lake of Chennai city, Tamil Nadu, India. *Environ. Sci. Pollut. Res.* 27, 33297–33306. doi:10.1007/s11356-020-09622-2.
- 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. <https://doi.org/10.1016/j.marpolbul.2020.111163>.
- Gregory, M.R., 2009. Environmental implications of plastic debris in marine settings—entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. *Philos. Trans. R. Soc. Lond., B, Biol. Sci.* 364 (1526), 2013–2025. <http://dx.doi.org/10.1098/rstb.2008.0265>.
- Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. *Environ. Sci. Technol.* 46, 3060-3075.
- Ibrahim, M., He, H. 2017. Classification of polyethylene by Raman spectroscopy. Thermo Scientific Application Note AN52301.
- Jagadeesan, L. Jyothibabu, R., Anjusha, A., Arya, P.M., Madhu. N.V et al., 2013. Ocean currents structuring the mesozooplankton in the Gulf of Mannar and the Palk Bay, southeast coast of India. *Prog. Oceanogr.* 110:27-48

- 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., Kripa, V., 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. <https://doi.org/10.1016/j.marpolbul.2020.111027>.
- James, K., Vasant, K., S.m., S.B., Padua, S., Jeyabaskaran, R., Thirumalaiselvan, S., G., V., Benjamin, L.V., 2021. Seasonal variability in the distribution of microplastics in the coastal ecosystems and in some commercially important fishes of the Gulf of Mannar and Palk Bay, Southeast coast of India. *Reg. Stud. Mar. Sci.* 41, 101558. doi:10.1016/j.rsma.2020.101558.
- Jayasiri, H.B., Purushothaman, C.S. and Vennila, A., 2015. Bimonthly variability of persistent organochlorines in plastic pellets from four beaches in Mumbai coast, India. *Environ. Monit. Assess.* 187(7), pp.1-13.
- Jayasiri, H.B., Purushothaman, C.S., Vennila, A., 2013. Quantitative analysis of plastic debris on recreational beaches in Mumbai, India. *Sci. Total Environ.* 645, 1388–1399. <https://doi.org/10.1016/j.scitotenv.2018.07.242>.
- Jeong, C.B., Kang, H.M., Lee, M.C., Kim, D.H., Han, J., Hwang, D.S., Souissi, S., Lee, S.J., Shin, K.H., Park, H.G., Lee, J.S., 2017. Adverse effects of microplastics and oxidative stress- induced MAPK/Nrf2 pathway-mediated defense mechanisms in the marine copepod *Paracyclops nana*. *Sci. Rep.* 7, 41323. <https://doi.org/10.1038/srep41323>.
- Jeyasanta, K.I., Sathish, N., Patterson, J., Edward, J.P., 2020. Macro-, meso- and microplastic debris in the beaches of Tuticorin district, Southeast coast of India. *Mar. Pollut. Bull.* 154, 111055. doi:10.1016/j.marpolbul.2020.111055.
- Jyothibabu, R., Madhu, N., Habeebrehman, H., Jayalakshmy, K., Nair, K., Achuthankutty, C., 2010. Re-evaluation of ‘paradox of mesozooplankton’ in the eastern Arabian Sea based on ship and satellite observations. *J. Mar. Syst.* 81, 235–251. doi: 10.1016/j.jmarsys.2009.12.019.
- Jyothibabu, R., Balachandran, K.K., Jagadeesan, L., Karnan, C et al., 2021. Why the Gulf of Mannar is a Marine Biological Paradise?. *Environ. Sci. Pollut. Res.* <https://doi.org/10.1007/s11356-021-15530-w>
- Kang, J.-H., Kwon, O.-Y., Shim, W.J., 2015. Potential Threat of Microplastics to Zooplanktivores in the Surface Waters of the Southern Sea of Korea. *Arch. Environ. Contam. Toxicol.* 69, 340–351. doi:10.1007/s00244-015-0210-3.
- Karthik, R., Robin, R.S., Purvaja, R., Ganguly, D., Anandavelu, I., Raghuraman, R., 2018. Microplastics along the beaches of southeast coast of India. *Sci. Total Environ.* 645 (2018), 1388-1399.
- Karuppasamy, P., Ravi, A., Vasudevan, L., Elangovan, M.P., Mary, P.D., Vincent, S.G., Palanisami, T., 2020. Baseline survey of micro and mesoplastics in the gastro-intestinal tract of commercial fish from Southeast coast of the Bay of Bengal. *Mar. Pollut. Bull.* 153, 110974. doi:10.1016/j.marpolbul.2020.110974.

Kaviarasan, T., Naik, S., Sivadas, S., Dhineka, K., Sambandam, M., Sivyer, D., Mishra, P., Murthy, M.R., 2020. Assessment of litter in the remote beaches of Lakshadweep Islands, Arabian Sea. *Mar. Pollut. Bull.* 161, 111760. doi:10.1016/j.marpolbul.2020.111760.

Kosore, C., Ojwang, L., Maghanga, J., Kamau, J., Kimeli, A., Omukoto, J., Ndirui, E., 2018. Occurrence and ingestion of microplastics by zooplankton in Kenya's marine environment: first documented evidence. *Afr. J. Mar. Sci.* 40 (3), 225-234. <https://doi.org/10.2989/1814232X.2018.1492969>.

Krishnakumar, S., Anbalagan, S., Kasilingam, K., Smrithi, P., Anbazhagi, S., Srinivasalu, S., 2020. Assessment of plastic debris in remote islands of the Andaman and Nicobar Archipelago, India. *Mar. Pollut. Bull.* 151, p.110841.

Kühn, S., Werven, B.V., Oyen, A.V., Meijboom, A., Rebolledo, E.L.B., Franeker, J.A.V., 2017. The use of potassium hydroxide (KOH) solution as a suitable approach to isolate plastics ingested by marine organisms. *Mar. Pollut. Bull.* 115, 86–90. doi:10.1016/j.marpolbul.2016.11.034.

Kumar, V.E., Ravikumar, G., Jeyasanta, K.I., 2018. Occurrence of microplastics in fishes from two landing sites in Tuticorin, South east coast of India. *Mar. Pollut. Bull.* 135, 889–894. doi:10.1016/j.marpolbul.2018.08.023.

Laist, D.W., 1997. Impacts of marine debris entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. In: Coe, J.M., Rogers, D.B. (Eds.), *Marine Debris-Sources, Impact and Solutions*. Springer-Verlag, New York, pp. 99-139.

Lee, K.W., Shim, W.J., Kwon, O.Y., Kang, J.H., 2013. Size-dependent effects of micro polystyrene particles in the marine copepod *Tigriopus japonicus*. *Environ. Sci. Technol.* 47, 11278-11283. <https://doi.org/10.1021/es401932b>.

Lithner, D., Larsson, A., Dave, G., 2011. Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition. *Sci. Total Environ.* 409, 3309-3324. doi:10.1016/j.scitotenv.2011.04.038.

Lönnstedt, O.M., Eklöv, P., 2016. Environmentally relevant concentrations of microplastic particles influence larval fish ecology. *Science* 352, 1213-1216. doi:10.1126/science.aad8828.

Maharana, D., Saha, M., Dar, J.Y., Rathore, C., Sreepada, R., Xu, X.-R., Koongolla, J.B., Li, H.-X., 2020. Assessment of micro and macroplastics along the west coast of India: Abundance, distribution, polymer type and toxicity. *Chemosphere* 246, 125708. doi:10.1016/j.chemosphere.2019.125708.

Mason, S.A., Garneau, D., Sutton, R., Chu, Y., Ehmann, K., Barnes, J., Fink, P., Papazissimos, D., Rogers, D.L., 2016. Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent. *Environ. Pollut.* 218, 1045–1054.

Ministry of Housing and Urban Affairs. 2019. *Plastic Waste Management- Issues, Solutions and Case Studies*. Retrieved from <http://164.100.228.143:8080/sbm/content/writereaddata/SBM%20Plastic%20Waste%20Book.pdf>.

Moore, C.J., 2008. Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. *Environ. Res.* 108, 131-139.

- Moore, C.J., Moore, S.L., Leecaster, M.K., Weisberg, S.B., 2001. A comparison of plastic and plankton in the North Pacific Central Gyre. *Mar. Pollut. Bull.* 42 (12), 1297- 1300.
- Mugilarasan, M., Venkatachalapathy, R., Sharmila, N. and Gurumoorthi, K., 2017. Occurrence of microplastic resin pellets from Chennai and Tinnakkara Island: Towards the establishment of background level for plastic pollution. *Indian J. Geo Mar. Sci.* 46 (2017) 1210e1212.
- Murphy, F., Ewins, C., Carbonnier, F., Quinn, B., 2016. Wastewater Treatment Works (WwTW) as a Source of Microplastics in the Aquatic Environment. *Environ. Sci. Technol.* 50, 5800–5808. doi:10.1021/acs.est.5b05416.
- 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.
- Naidu, S.A., Mawii, L., Ranga Rao V., Anithaa, G., Mishra, P., Bhavani E.N., Anil Kumar, V., Ramana Murthya., M.V., Gupta, GVM., 2021. Characterization of plastic debris from surface waters of the eastern Arabian Sea–Indian Ocean. *Mar. Pollut. Bull.* 169, 112468.
- Nigam R., 1982. Plastic pellets on the Caranzalem beach sands, Goa, India, *Mahasagar Bulletin of the National Institute of Oceanography* 15(2), 125-127.
- Nikki, R., Abdul Jaleel, K.U., Ragesh, S., Shini, S., Saha, M., Dinesh Kumar, P.K., 2021. Abundance and characteristics of microplastics in commercially important bottom dwelling finfishes and shellfish of the Vembanad Lake, India. *Mar. Pollut. Bull.* 172,112803
- Nobre, C.R., Santana, M.F.M., Maluf, A., Cortez, F.S., Cesar, A., Pereira, C.D.S., Turra, A., 2015. Assessment of microplastic toxicity to embryonic development of the sea urchin *Lytechinus variegatus* (Echinodermata: echinoidea). *Mar. Pollut. Bull.* 92 (1–2), 99-104. <https://doi.org/10.1016/j.marpolbul.2014.12.050>.
- Ogata, Y., Takada, H., Mizukawa, K., Hirai, H., Iwasa, S., Endo, S., Mato, Y., Saha, M., Okuda, K., Nakashima, A. and Murakami, M., 2009. International Pellet Watch: Global monitoring of persistent organic pollutants (POPs) in coastal waters. 1. Initial phase data on PCBs, DDTs, and HCHs. *Mar. Pollut. Bull.* 58(10), pp.1437-1446.
- Patchaiyappan, A., Ahmed, S.Z., Dowarah, K., Jayakumar, S., Devipriya, S.P., 2020. Occurrence, distribution and composition of microplastics in the sediments of South Andaman beaches. *Mar. Pollut. Bull.* 156, 111227. doi:10.1016/j.marpolbul.2020.111227.
- Patel, A.K., Bhagat, C., Taki, K. and Kumar, M., 2020. Microplastic vulnerability in the sediments of the Sabarmati river of India. In *Resilience, Response, and Risk in Water Systems*, pp. 127-138. Springer, Singapore.
- Patterson, J., Jeyasanta, K.I., Sathish, N., Booth, A.M., Edward, J.K.P., 2019. Profiling microplastics in the Indian edible oyster, *Magallana bilineata* collected from the Tuticorin coast, gulf of Mannar, southeastern India. *Sci. Total Environ.* 691, 727-735. <https://doi.org/10.1016/j.scitotenv.2019.07.063>.

Patterson, J., Jeyasanta, K.I., Sathish, N., Edward, J.P., Booth, A.M., 2020. Microplastic and heavy metal distributions in an Indian coral reef ecosystem. *Sci. Total Environ.* 744, 140706. doi:10.1016/j.scitotenv.2020.140706.

Phillips, M.B., Bonner, T.H., 2015. Occurrence and amount of microplastic ingested by fishes in watersheds of the Gulf of Mexico. *Mar. Pollut. Bull.* 100, 264-269. doi:10.1016/j.marpolbul.2015.08.041.

Plastics – the Facts 2018. [https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics\\_the\\_facts\\_2018\\_AF\\_web.pdf](https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_the_facts_2018_AF_web.pdf).

Portesi, C., Visentin, D., Durbiano, F., Abete, M.C., Rizzi, M., Maurino, V., Rossi, A.M., 2019. Development of a rapid micro-Raman spectroscopy approach for detection of NIAS in LDPE pellets and extruded films for food packaging applications. *Polym. Test.* 80, 106098. doi:10.1016/j.polymertesting.2019.106098.

Ram, B., Kumar, M., 2020. Correlation appraisal of antibiotic resistance with fecal, metal and microplastic contamination in a tropical Indian river, lakes and sewage. *npj Clean Water*, 3(1),1-12.

Rebollar, E., Pérez, S., Hernández, M., Domingo, C., Martín, M., Ezquerro, T.A., García-Ruiz, J.P., Castillejo, M., 2014. Physicochemical modifications accompanying UV laser induced surface structures on poly (ethylene terephthalate) and their effect on adhesion of mesenchymal cells. *Phys. Chem. Chem. Phys.* 16, 17551. doi:10.1039/c4cp02434f.

Reddy, S.M., Basha, S., Adimurthy, S., Ramachandraiah, G., 2006. Description of small plastics fragments in marine sediments along the Alang - Soshiya ship-breaking yard, India. *Estuar. Coast. Shelf Sci.* 68, 656-660.

Rillig, M.C., 2012. Microplastic in Terrestrial Ecosystems and the Soil?. *Environ. Sci. Technol.* 46, 6453-6454. doi:10.1021/es302011r.

Robin, R., 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. doi:10.1016/j.scitotenv.2019.134947.

Ryan, P.G., Moore, C.J., van Franeker, J.A., Moloney, C.L., 2009. Monitoring the abundance of plastic debris in the marine environment. *Philos. Trans. R. Soc. Lond., B, Biol. Sci.* 364 (1526), 1999- 2012. <http://dx.doi.org/10.1098/rstb.2008.0207>.

Sarkar, D.J., Sarkar, S.D., Das, B.K., Manna, R.K., Behera, B.K., Samanta, S., 2019. Spatial distribution of meso and microplastics in the sediments of river Ganga at eastern India. *Sci. Total Environ.* 694, 133712. doi:10.1016/j.scitotenv.2019.133712.

Sathish, M.N., Jeyasanta, I., Patterson, J., 2020a. Occurrence of microplastics in epipelagic and mesopelagic fishes from Tuticorin, Southeast coast of India. *Sci. Total Environ.* 720, 137614. doi:10.1016/j.scitotenv.2020.137614.

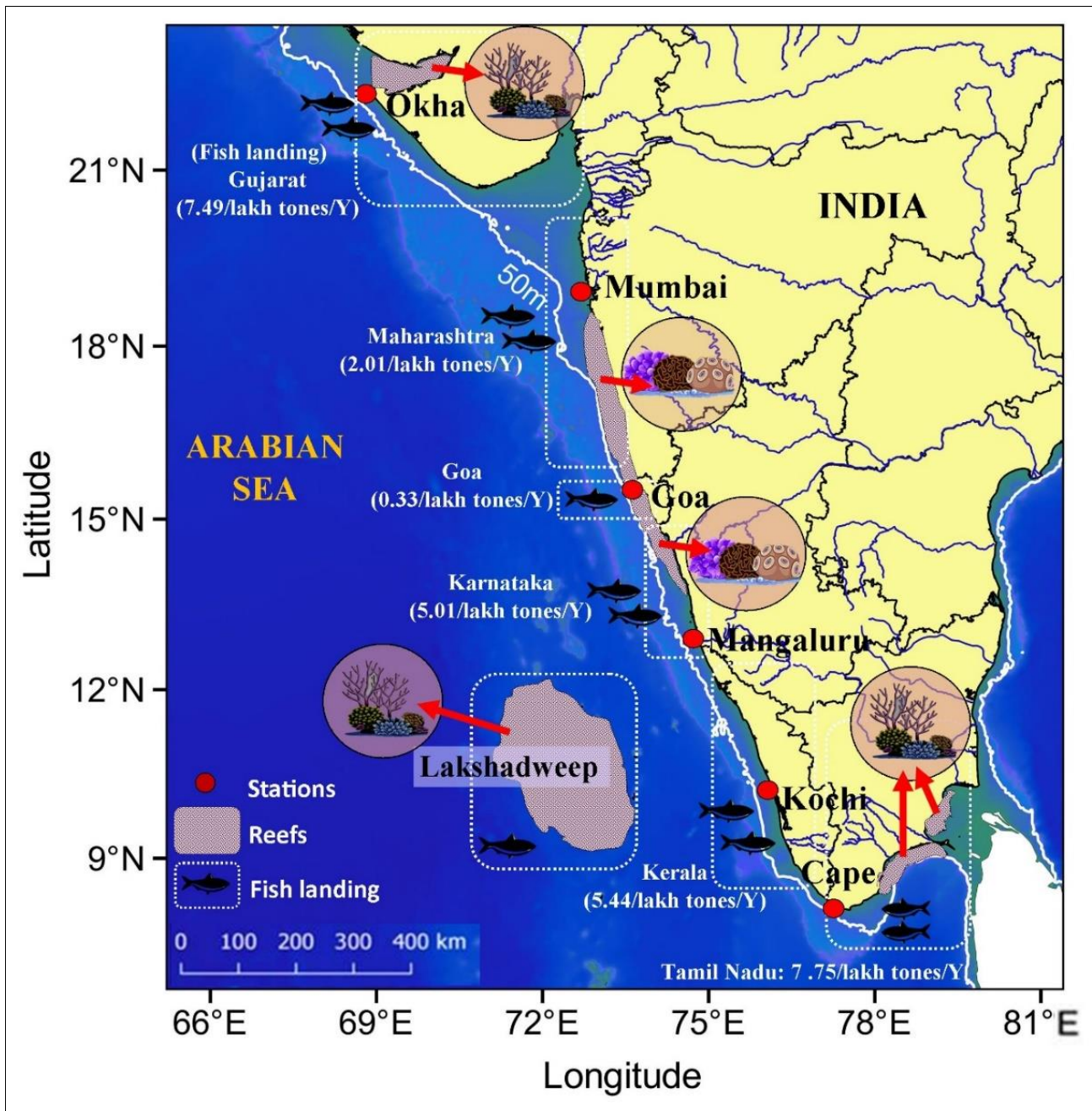
Sathish, M.N., Jeyasanta, K.I., Patterson, J., 2020b. Monitoring of microplastics in the clam *Donax cuneatus* and its habitat in Tuticorin coast of Gulf of Mannar (GoM), India. *Environ. Pollut.* 266, 115219. doi:10.1016/j.envpol.2020.115219.

- Sathish, N., Jeyasanta, K.I., Patterson, J., 2019. Abundance, characteristics and surface degradation features of microplastics in beach sediments of five coastal areas in Tamil Nadu, India. *Mar. Pollut. Bull.* 142, 112–118. doi:10.1016/j.marpolbul.2019.03.037.
- Sato, H., Shimoyama, M., Kamiya, T., Amari, T., Sasic, S., Ninomiya, T., Siesler, H.W., Ozaki, Y., 2002. Raman spectra of high-density, low-density, and linear low-density polyethylene pellets and prediction of their physical properties by multivariate data analysis. *J. Appl. Polym. Sci.* 86, 443-448. doi:10.1002/app.10999.
- Senapati, S., Gupta, V., 2014. Climate change and coastal ecosystem in India: issues in perspectives. *IJES* 5 (3), 531.
- Setälä, O., Fleming-Lehtinen, V., Lehtiniemi, M., 2014. Ingestion and transfer of microplastics in the planktonic food web. *Environ. Pollut.* 185, 77-83. <https://doi.org/10.1016/j.envpol.2013.10.013>.
- Sruthy, S., Ramasamy, E.V., 2017. Microplastic pollution in Vembanad Lake, Kerala, India, The first report of microplastics in lake and estuary sediments in India. *Environ. Pollut.* 222, 315-322. <https://doi.org/10.1016/j.envpol.2016.12.038>.
- Steer, M., Cole, M., Thompson, R.C., Lindeque, P.K., 2017. Microplastic ingestion in fish larvae in the western English Channel. *Environ. Pollut.* 226, 250-259. <https://doi.org/10.1016/j.envpol.2017.03.062>.
- Štokr, J., Schneider, B., Doskočilová, D., Lövy, J., Sedláček, P., 1982. Conformational structure of poly(ethylene terephthalate). Infra-red, Raman and n.m.r. spectra. *Polymer* 23, 714-721. doi:10.1016/0032-3861(82)90057-x.
- Stroe, M., Cristea, M., Matei, E., Galatanu, A., Cotet, L.C., Pop, L.C., Baia, M., Danciu, V., Anghel, I., Baia, L., Baibarac, M.A., 2020. Optical Properties of Composites Based on Graphene Oxide and Polystyrene. *Molecules* 25, 2419. doi:10.3390/molecules25102419.
- Sun, X., Li, Q., Zhu, M., Liang, J., Zheng, S., Zhao, Y., 2017. Ingestion of microplastics by natural zooplankton groups in the northern South China Sea. *Mar. Pollut. Bull.* 115, 217-224. doi:10.1016/j.marpolbul.2016.12.004.
- Sun, X., Liang, J., Zhu, M., Zhao, Y., Zhang, B., 2018b. Microplastics in seawater and zooplankton from the Yellow Sea. *Environ. Pollut.* 242 (Part A), 585–595. <https://doi.org/10.1016/j.envpol.2018.07.014>.
- Sun, X., Liu, T., Zhu, M., Liang, J., Zhao, Y., Zhang, B., 2018a. Retention and characteristics of microplastics in natural zooplankton taxa from the East China Sea. *Sci. Total Environ.* 640-641, 232–242. doi:10.1016/j.scitotenv.2018.05.308.
- Sundar, S., Chokkalingam, L., Roy, P.D., Usha, T., 2020. Estimation of microplastics in sediments at the southernmost coast of India (Kanyakumari). *Environ. Sci. Pollut. Res.* 28, 18495–18500. doi:10.1007/s11356-020-10333-x.
- Sunitha, T., Monisha, V., Sivanesan, S., Vasanthy, M., Prabhakaran, M., Omine, K., Sivasankar, V., Darchen, A., 2021. Micro-plastic pollution along the Bay of Bengal coastal stretch of Tamil Nadu, South India. *Sci. Total Environ.* 756, 144073. doi:10.1016/j.scitotenv.2020.144073.

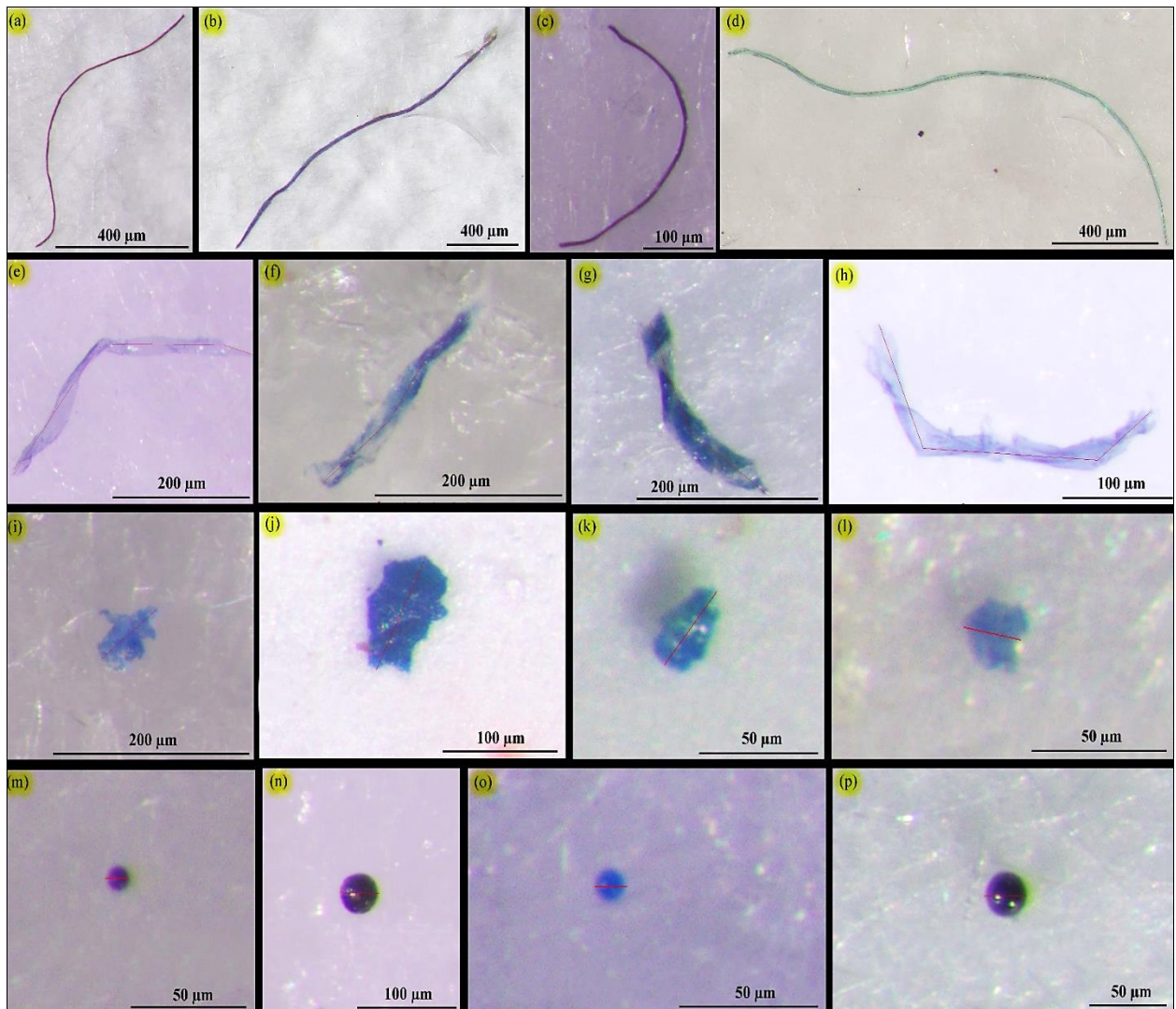
- Suresh, A., Vijayaraghavan, G., Saranya, K. S., Neethu, K. V., Aneesh, B. Nandan B. 2020.. Microplastics distribution and contamination from the Cochin coastal zone, India. *Reg. Stud. Mar. Sci.* 40, 101533. doi:10.1016/j.rsma.2020.101533.
- Taha, Z.D., Amin, R.M., Anuar, S.T., Nasser, A.A.A., Sohaimi, E.S., 2021. Microplastics in seawater and zooplankton: A case study from Terengganu estuary and offshore waters, Malaysia. *Science of The Total Environment* 786, 147466. doi:10.1016/j.scitotenv.2021.147466
- Teuten, E.L., Saquing, J.M., Knappe, D.R.U., Barlaz, M.A., Jonsson, S., Bjorn, A., Takada, H., 2009. Transport and release of chemicals from plastics to the environment and to wildlife. *Philos. Trans. R. Soc. Biol. Sci.* 364 (1526), 2027–2045. <https://doi.org/10.1098/rstb.2008.0284>.
- Thiele, C.J., Hudson, M.D., Russell, A.E., 2019. Evaluation of existing methods to extract microplastics from bivalve tissue: Adapted KOH digestion protocol improves filtration at single-digit pore size. *Mar. Pollut. Bull.* 142, 384-393. doi:10.1016/j.marpolbul.2019.03.003.
- Thompson, R.C., Moore, C.J., vom Saal, F.S., Swan, S.H., 2009b. Plastics, the environment and human health: current consensus and future trends. *Philos. Trans. R. Soc. Lond., B, Biol. Sci.* 364(1526), 2153-2166. <http://dx.doi.org/10.1098/rstb.2009.0053>.
- Thompson, R.C., Swan, S.H., Moore, C.J., vom Saal, F.S., 2009a. Our plastic age. *Philos. Trans. R. Soc. Lond., B, Biol. Sci.* 364 (1526), 1973-1976. <http://dx.doi.org/10.1098/rstb.2009.0054>.
- 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. <https://doi.org/10.1016/j.marpolbul.2019.01.055>.
- Turner, A., Holmes, L.A., 2015. Adsorption of trace metals by microplastic pellets in fresh water. *Environ. Chem.* 12, 600. doi:10.1071/en14143.
- Umamaheswari, S., Priyadarshinee, S., Bhattacharjee, M., Kadirvelu, K., Ramesh, M., 2020. Exposure to polystyrene microplastics induced gene modulated biological responses in zebrafish (*Danio rerio*). *Chemosphere* 128592. doi:10.1016/j.chemosphere.2020.128592.
- Van Cauwenberghe, L., Janssen, C.R., 2014. Microplastics in bivalves cultured for human consumption. *Environ. Pollut.* 193, 65-70. <https://doi.org/10.1016/j.envpol.2014.06.010>.
- 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 (1), 196-204.
- Veerasingam, S., Saha, M., Suneel, V., Vethamony, P., Rodrigues, A.C., Bhattacharyya, S., Naik, B., 2016b. Characteristics, seasonal distribution and surface degradation features of microplastic pellets along the Goa coast, India. *Chemosphere* 159, 496–505. doi:10.1016/j.chemosphere.2016.06.056.
- Vianello, A., Boldrin, A., Guerriero, P., Moschino, V., Rella, R., Sturaro, A., Da Ros, L., 2013. Microplastic particles in sediments of Lagoon of Venice, Italy: first observations on occurrence, spatial patterns and identification. *Estuar. Coast. Shelf Sci.* 130, 54-61. <https://doi.org/10.1016/j.ecss.2013.03.022>.



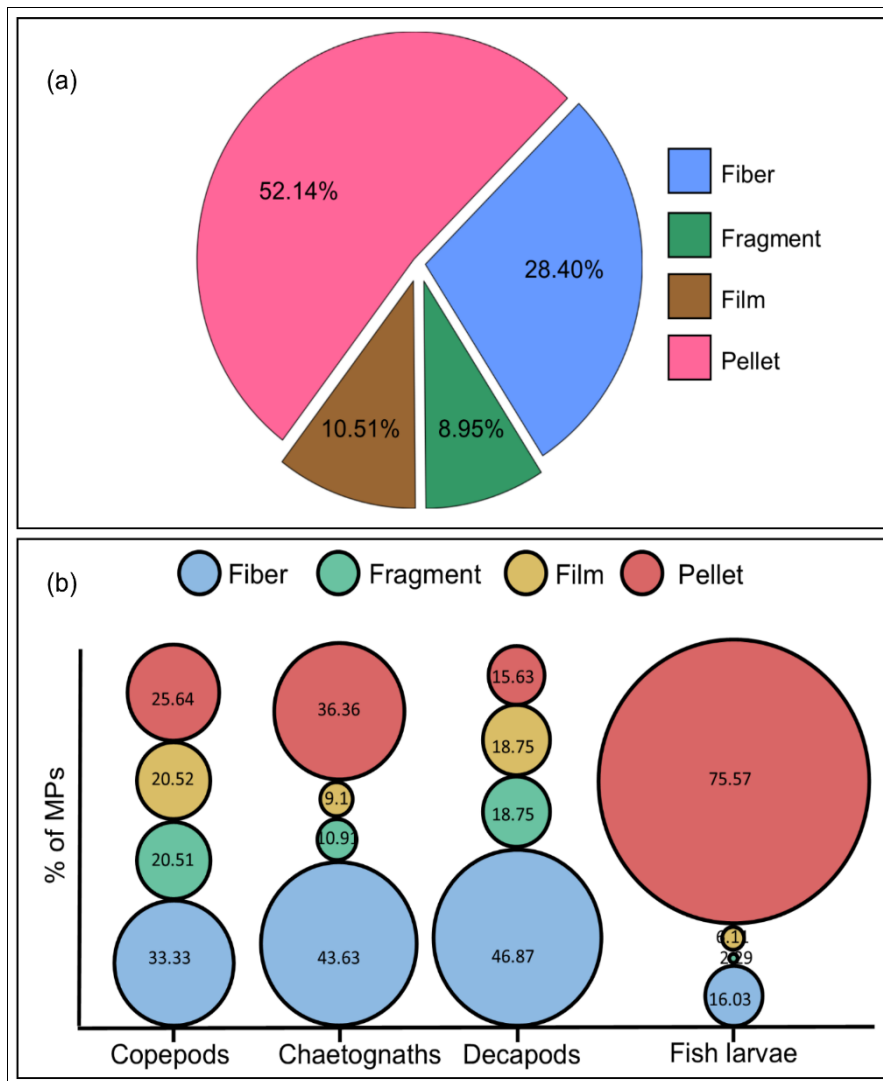
- Vidyasakar, A., Krishnakumar, S., Kasilingam, K., Neelavannan, K., Bharathi, V.A., Godson, P.S., Prabha, K., Magesh, N., 2020. Characterization and distribution of microplastics and plastic debris along Silver Beach, Southern India. *Mar. Pollut. Bull.* 158, 111421. doi:10.1016/j.marpolbul.2020.111421.
- Vidyasakar, A., Neelavannan, K., Krishnakumar, S., Prabakaran, G., Priyanka, T.S.A., Magesh, N., Godson, P.S., Srinivasalu, S., 2018. Macrodebris and microplastic distribution in the beaches of Rameswaram Coral Island, Gulf of Mannar, Southeast coast of India: A first report. *Mar. Pollut. Bull.* 137, 610–616. doi:10.1016/j.marpolbul.2018.11.007.
- Vroom, R.J., Koelmans, A.A., Besseling, E., Halsband, C., 2017. Aging of microplastics promotes their ingestion by marine zooplankton. *Environ. Pollut.* 231, 987e996. <https://doi.org/10.1016/j.envpol.2017.08.088>.
- Wang, J., Liu, X., Li, Y., Powell, T., Wang, X., Wang, G., Zhang, P., 2019. Microplastics as contaminants in the soil environment: A mini-review. *Sci. Total Environ.* 691, 848–857. doi:10.1016/j.scitotenv.2019.07.209.
- Wang, W., Gao, H., Jin, S., Li, R., Na, G., 2019. The ecotoxicological effects of microplastics on aquatic food web, from primary producer to human: A review. *Ecotoxicol Environ Saf.* 173, 110–117. doi:10.1016/j.ecoenv.2019.01.113.
- Wright, S.L., Rowe, D., Thompson, R.C., Galloway, T.S., 2013. Microplastic ingestion decreases energy reserves in marine worms. *Curr. Biol.* 23. doi:10.1016/j.cub.2013.10.068.
- Zheng, S., Zhao, Y., Liangwei, W., Liang, J., Liu, T., Zhu, M., Li, Q., Sun, X., 2020. Characteristics of microplastics ingested by zooplankton from the Bohai Sea, China. *Sci. Total Environ.* 713, 136357. doi:10.1016/j.scitotenv.2019.136357.



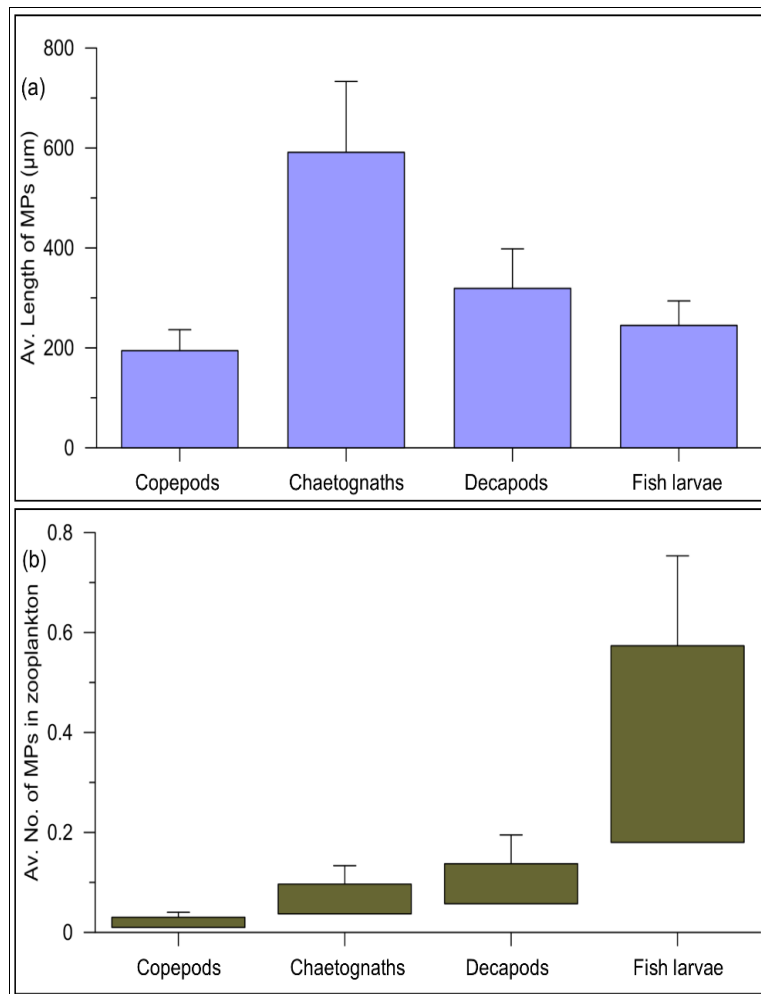
**Figure 1** - Coastal waters off selected cities along India's west coast in the eastern Arabian Sea (Cape Comorin/Kanyakumari, Kochi, Mangalore, Goa, Mumbai and Okha) selected for sampling in this study. Red filled circles indicate sampling locations. Representative symbols have been used to denote areas of high fish landings and coral growth.



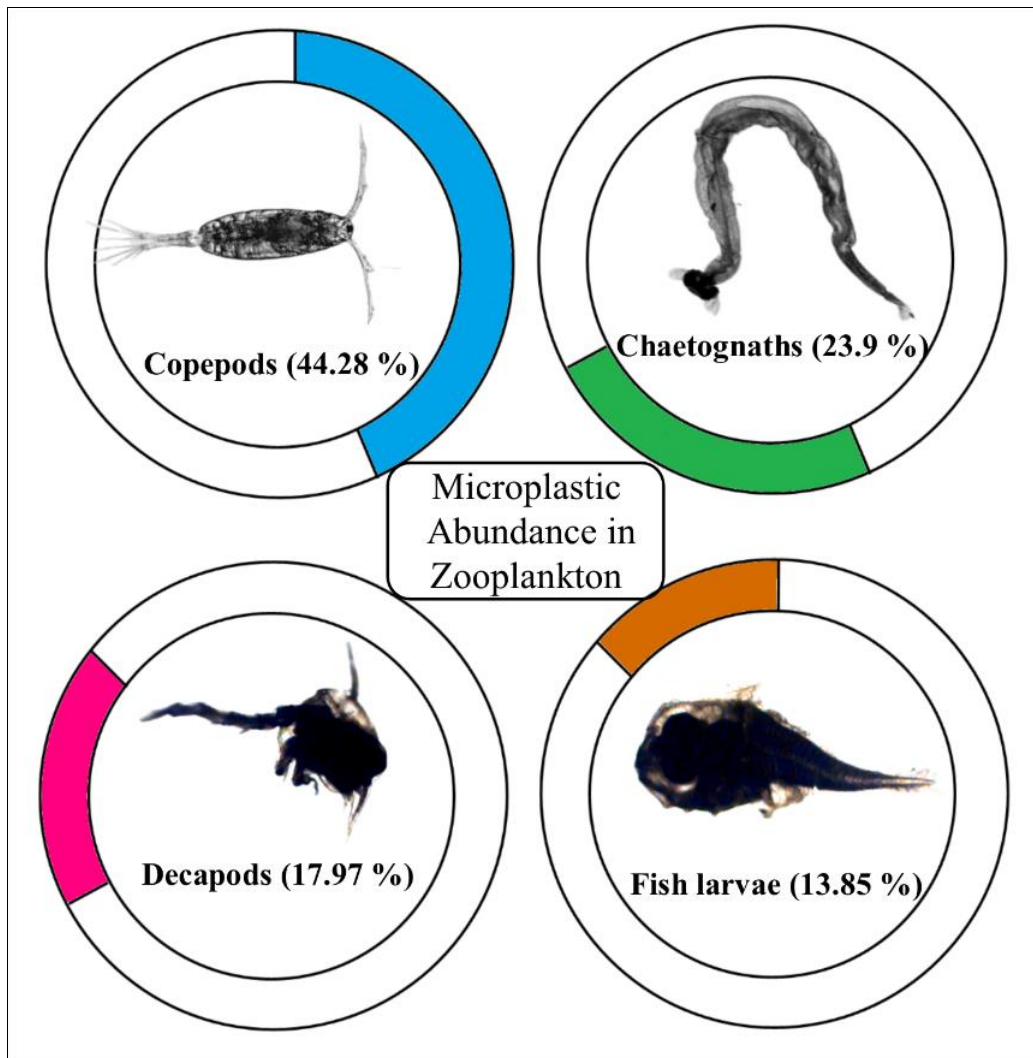
**Figure 2** - Different forms of MPs ingested by zooplankton. (a-d) fibre, (e-h) film, (i-l) fragment, (m-p) pellet



**Figure 3** - The overall percentage contribution of MPs in (a) the whole zooplankton and (b) in different zooplankton groups

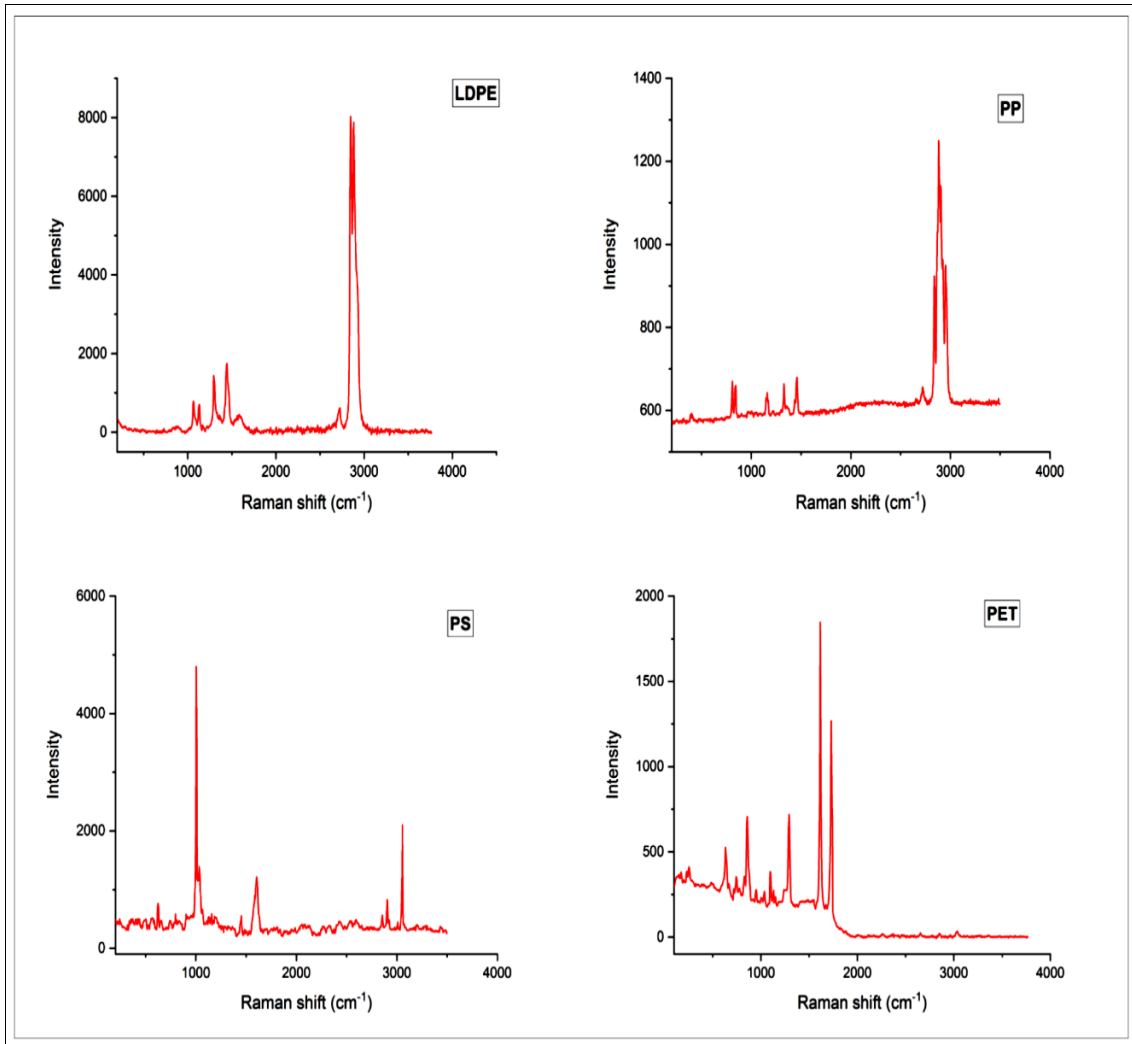


**Figure 4** - (a) average size of MPs ingested by different zooplankton taxa and (b) their average number in various zooplankton groups.

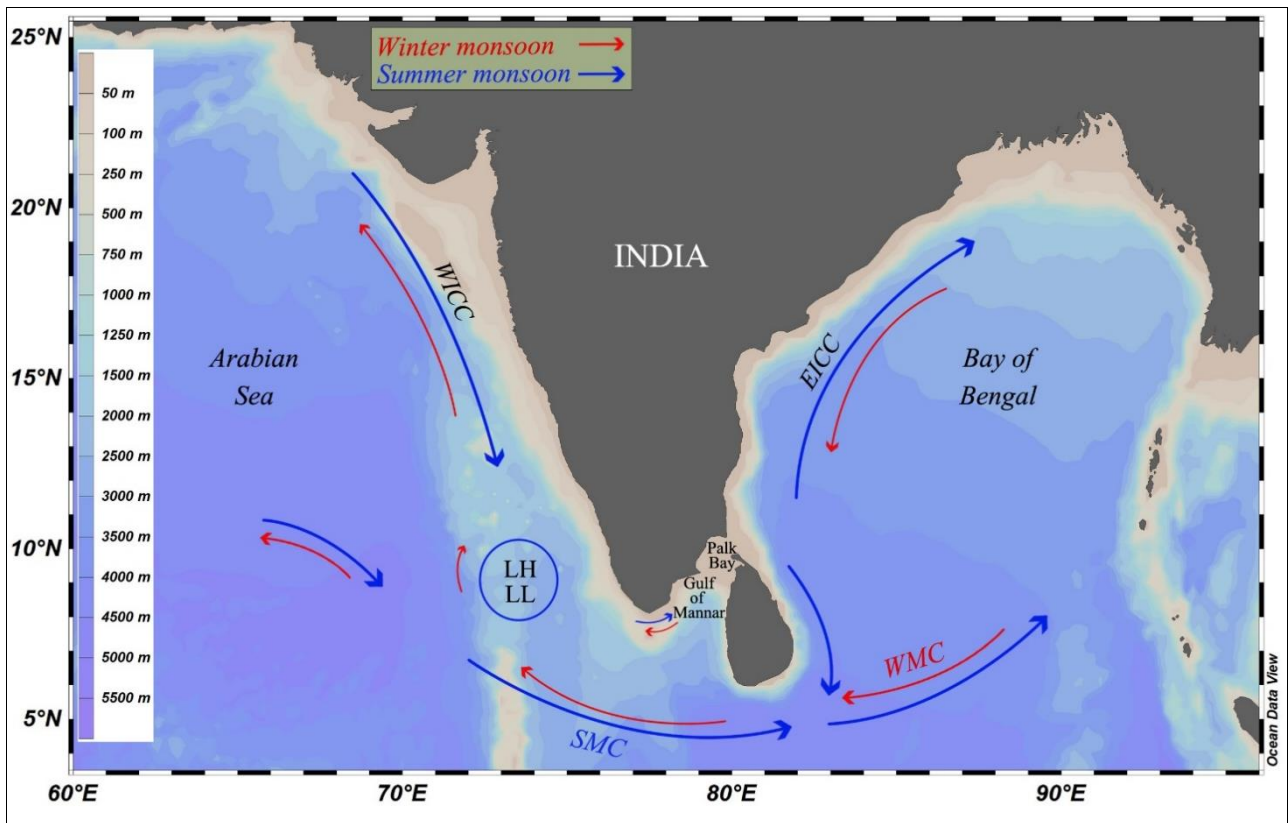


**Figure 5** – A diagrammatic representation of the relative percentage of MPs retention in different groups in zooplankton community. The coloured outer circles represent the respective percentage of MPs in each group



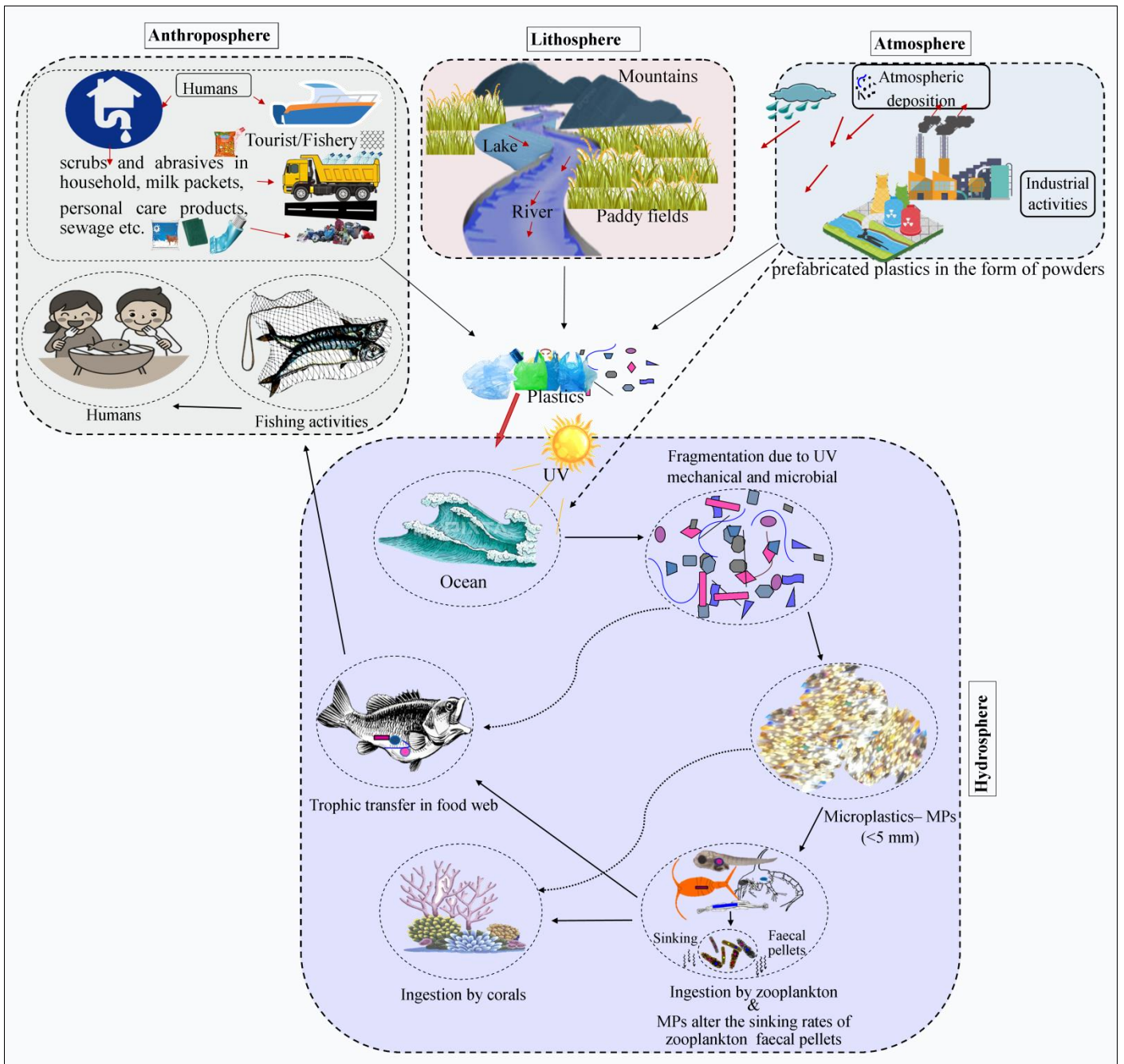


**Figure 6** - Raman spectra of the MPs: Low density polyethylene (LDPE), Polypropylene (PP), Polystyrene (PS), Polyethylene terephthalate (PET).



**Figure 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 Current, LH-Lakshwadweep High, LL-Lakshwadweep Low, SMC- Summer Monsoon Current, WMS-Winter Monsoon Current, EICC-East India Coastal Current.





**Figure 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.

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	
	Ozata 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 Ramaswami., 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	Pudicherry	
	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 Anish kumar., 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	Sabarnati River	
	Ram and Kumar, 2020	Sabarnati 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	Erikson 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 Anish kumar., 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	
Biota	Naidu et al., 2021	Eastern Arabian Sea	
	Karthik et al., 2018	Tamil Nadu coast	
	Kumar et al., 2018	Tuticorin	
	Naidu et al., 2018	Kochi, Kerala	
	Naidu et al., 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.

<b>SL. No.</b>	<b>Literature</b>	<b>Region</b>	<b>Zooplankton groups</b>
1	Desforges et al., 2015	Northeast Pacific Ocean	<i>Neocalanus Cristatus</i> (Copepod) <i>Euphausia pacifica</i> (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	<i>Merlangius merlangus</i> , <i>Microchirus variegatus</i> , <i>Trisopterus minutus</i> , <i>Callionymus lyra</i> , <i>Anguilla anguilla</i>
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

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

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

**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)