Assessment of potential ecological risk of microplastics in the coastal sediments of India: A meta-analysis

M. Ranjani, S. Veerasingam, R. Venkatachalapathy, M. Mugilarasan, Andrei Bagaev, Vladimir Mukhanov, P. Vethamony

Marine Pollution Bulletin 163 (2021) 111969

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Assessment of potential ecological risk of microplastics in the coastal sediments of India: A meta-analysis

M. Ranjani [a], S. Veerasingam [b,*], R. Venkatachalapathy [a], M. Mugilarasan [c], Andrei Bagaev [d], Vladimir Mukhanov [e], P. Vethamony [b]

[a] Department of Physics, Annamalai University, Annamalai Nagar 608 002, Tamil Nadu, India
[b] Environmental Science Center, Qatar University, P.O. Box: 2713, Qatar
[c] National Centre for Sustainable Coastal Management, Ministry of Environment, Forest and Climate Change, Chennai 600 025, Tamil Nadu, India
[d] Department of Shelf Hydrophysics, Federal Research Center Marine Hydrophysical Institute of RAS, Sevastopol 299011, Russia
[e] A.O. Kovalevsky Institute of Biology of the Southern Seas of RAS, Sevastopol, Russia

ARTICLE INFO

Keywords:
Microplastics
Sediments
Polymer hazard index
Pollution load index
Potential ecological risk index
Coast of India

ABSTRACT

Abundance, chemical composition and ecological risk of microplastics (MPs) in terrestrial and marine environments have merited substantial attention from the research communities. This is the first attempt to comprehend the ecological risk of MPs in sediments along the Indian coast using meta-data. Polymer hazard index (PHI), pollution load index (PLI) and potential ecological risk index (PERI) were used to evaluate the quality of sediments. Areas have high PHI values (>1000) due to the presence of polymers with high hazard scores such as polyamide (PA) and polystyrene (PS). According to PLI values, sediments along the west coast of India (WCI) are moderately contaminated with MPs (PLI: 3.03 to 15.5), whereas sediments along the east coast of India (ECI) are less contaminated (PLI: 1 to 6.14). The PERI values of sediments along the Indian coast showed higher ecological risk for the metropolitan cities, river mouths, potential fishing zones and the remote islands.

1. Introduction

Accumulation of plastic debris in the terrestrial and marine ecosystem from the poles to the deep ocean to the coast is found ubiquitously (Obbard et al., 2014; Veerasingam et al., 2020a; Cunningham et al., 2020). Meanwhile, petrochemical manufacturing industry has declared over 204 billion U.S. dollar investment to the shale gas boom, leading to a projected acceleration in virgin plastic production (ACC, 2020). Borrelle et al. (2020) evaluated influence of three comprehensive management strategies - plastic waste reduction, waste management, and environmental recovery - at diverse levels of effort to assess plastic emissions in 2030 for 173 countries. About 19 to 23 million metric tons of plastic waste, generated globally, entered into the aquatic ecosystems. Borrelle et al. (2020) found that the predicted growth in plastic waste exceeds efforts to mitigate plastic pollution around the world. Even with immediate and concerted action, 710 million tons of plastic waste cumulatively entered the aquatic and terrestrial ecosystems. Therefore, many countries around the world are struggling to manage the current volume of plastic waste and plastic contamination in the environment (UNEA, 2019; Lau et al., 2020).

Though large plastic debris present a visible environmental risk (Provencher et al., 2017), there is an increasing awareness and concern about the environmental and eco-toxicological impacts of tiny pieces of plastic debris (1 μm–5 mm) called 'microplastic' (MP) (Hartmann et al., 2019), originating from a variety of sources with different chemical properties. MP is found in different environmental matrices, including sediments (Veerasingam et al., 2016a, 2016b), water (Cozar et al., 2017), biota (Redondo-Hasselerharm et al., 2020), salt (Kim et al., 2018) and air/dust (Brahney et al., 2020) all over the world. It is estimated that ~8 million tons of MP (Jambeck et al., 2015) and 1.5 million tons of primary MP (Boucher and Friot, 2017) enter the ocean annually. Ingestion of MPs has been found in more than 2000 aquatic species worldwide, ranging from zooplankton to baleen whales (Savoca et al., 2016; Lamb et al., 2018; Zhu et al., 2019). Therefore, the resolutions of United Nations Environment Assembly on Marine litter and Microplastics (UNEA, 2019) and Goal 14.1 of the United Nations Sustainable Development Goals (UN-SDG, 2018) stressed the need to reduce plastic emission into the environment.

MPs are usually referred to as a 'cocktail of contaminants' due to their association with additives (added or produced during

* Corresponding author.
E-mail address: v.subramanian@qu.edu.qa (S. Veerasingam).

https://doi.org/10.1016/j.marpolbul.2021.111969
Received 17 November 2020; Received in revised form 4 January 2021; Accepted 6 January 2021
Available online 27 January 2021

manufacturing), heavy metals, and persistent organic pollutants present in the environment (Rochman, 2015). This mixture of contaminants can be bioavailable to various biota, including human upon ingestion (Hartmann et al., 2017). Therefore, it is of utmost importance to put efforts toward an eco-toxicological risk assessment of MPs to obtain a clear idea of the potential threat when they are ingested by biota. In India, in the past few decades due to rapid industrialization, economic development and climatic change, pollutants (organic and inorganic) have contaminated estuarine sediments via several pathways and resulted in associated coastal and marine environmental health problems (Chakraborty et al., 2014). For the past three years, the abundance and polymer composition of MPs in different environmental matrices in India have been studied extensively (Veerasingam et al., 2020b). However, ecological risk assessment of MPs in sediments, based on the observed results, has not received much attention. In this study, we conducted a meta-analysis of published work, and evaluated potential ecological risk of MPs in the terrestrial and marine sediments of India. The main objectives are (i) extracting data on concentration and polymer composition of MPs in sediments from the literature, (ii) identifying the potential sources of MPs and their controlling factors, (iii) assessing the degree of MP contamination using polymer hazard index, pollution load index and potential ecological risk and (iv) providing recommendations on the importance of ecological risk assessment of microplastic pollution.

2. Materials and methods

2.1. Study area

India has a coastline of ~7500 km, excluding its island territories and

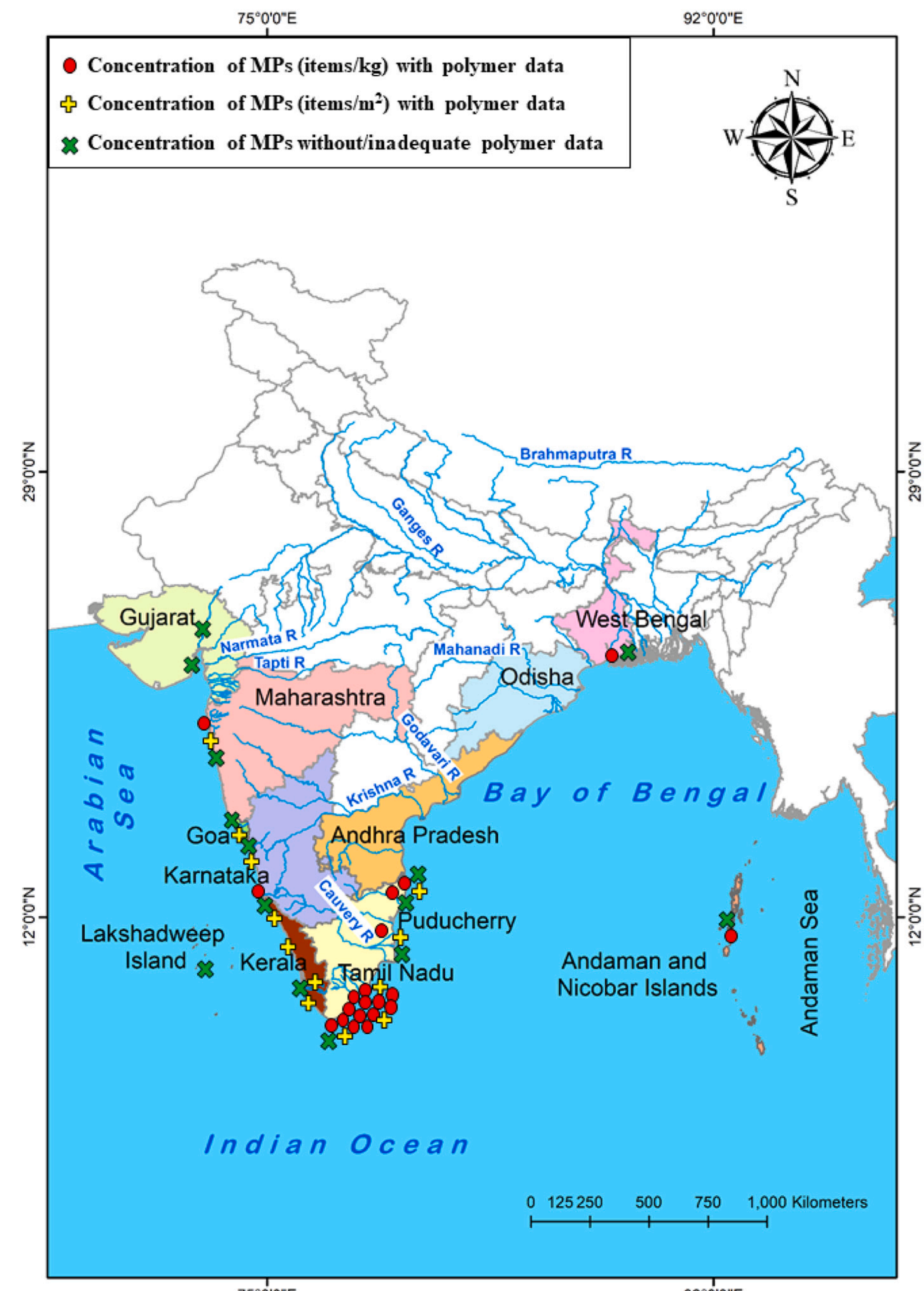

Fig. 1. The locations of sediment samples collected by the researchers for their works from the Indian coast. The geographical co-ordinates of sampling locations are extracted from the literature.

an exclusive economic zone (EEZ) of 2 million km^2. The climate of Indian sub-continent is dominated by monsoon systems. There are 11 major rivers (Ganga, Brahmaputra, Indus, Krishna, Godavari, Mahanadi, Cauvery, Palar, Pennar, Narmada, and Tapti), 47 medium rivers and 162 small rivers in India, having a mean annual run-off of 1645 km^3, although not all these rivers discharge into the sea (Sarkar et al., 2008).

India has 28 states and 8 Union Territories with the total population of 1353 million. Among these states, 9 are coastal states (Gujarat, Maharashtra, Goa, Karnataka, Kerala, Tamil Nadu, Andhra Pradesh, Odisha, and West Bengal) and among the Territories, 4 are coastal Union Territories (Andaman and Nicobar Islands, Dadra and Nagar Haveli and Daman and Diu, Lakshadweep Islands and Puducherry) (Fig. 1). The coastline is rich in diverse ecosystems, including estuaries, lagoons mangroves, seagrasses, coral reefs, mudflats, and salt marshes. The coastal zone of India consists of widespread fertile delta plains, tourism related activities, industries, harbors, and land ports. In India, the annual plastic consumption is nearly 5.6 million tons (Naidu et al., 2018). Plastic litter related to fishing industry on the beaches is more prevalent along the Indian coast (Kaladharan et al., 2020). The dynamics of the Indian Ocean is controlled by the southwest (SW: June – September) and northeast (NE: November – February) monsoons. Due to run-off during SW and NE monsoons, large quantity of plastic waste enters into the Indian ocean through several perennial rivers along the Indian Ocean (Lebreton et al., 2017; van der Mheen et al., 2020).

2.2. Data collection, extraction and quality assessment

In order to extract concentration and polymer composition of MP data from the published literature, systematic literature search was conducted using the Web of Knowledge (all databases) with the keywords: "Sediment", "microplastic", "plastic debris" and "marine debris", "Arabian Sea", "Bay of Bengal", "India", and "Indian Ocean" from the year 2006 to October 2020. Review articles and book chapters were excluded. Our search resulted in a collection of literature spanning in the fields of environmental pollution, oceanography, marine biology, toxicology, and ecology. All the secondary data available in the peer-reviewed research articles focusing on different aspects of microplastic pollution in the surface sediments in the coastal regions of India were included in the analysis. For each study, we recorded information regarding polymer types of MPs and their identification techniques. Detailed sampling and analytical methods used for the study of MPs in different environmental matrices in India are explained by Veerasingam et al. (2020b). Fig. S1 summarizes the data collection and extraction process.

2.3. Polymer hazard index (PHI)

To evaluate the potential risks of MPs in surface sediments, we have considered both the concentration and the chemical composition of MPs (Xu et al., 2018). The chemical toxicity of different polymer types of MPs is considered to evaluate its ecological harm (Lithner et al., 2011). The polymer hazard assessment of MPs was calculated using the following formula:

$$PHI = \sum P_n \times S_n$$

where, 'PHI' is the calculated polymer hazard index caused by MP, 'P_n' is the percent of specific polymer types (Table 1) collected at each sampling location, and 'S_n' is the hazard scores of polymer types of MPs derived from Lithner et al. (2011).

2.4. Pollution load index (PLI)

To assess the degree of MP pollution in surface sediments from the estuarine, coastal and marine environment in India, an integrated pollution load index (PLI) was calculated based on Tomlinson et al. (1980). PLI at each location is related to MP concentration factors (CF_i) as given below:

$$CF_i = \frac{C_i}{C_{oi}}$$

$$PLI = \sqrt{CF_i}$$

CF_i of the MP is the quotient of the MP concentration at each location (C_i) and the background MP concentration (C_{oi}). The lowest concentration of MP value detected in the sediment sample was considered as a background value.

2.5. Potential ecological risk index (PERI)

Potential ecological risk index (PERI) is also used to assess the degree of contamination of MPs in the sediments (Peng et al., 2018). The equations used to calculate the PERI are as follows:

$$C_f^i = C^i \Big/ C_n^i$$

$$T_r^i = \sum_{n=1}^{n} \frac{P_n}{C^i} \times S_n$$

$$E_r^i = T_r^i \times C_f^i$$

where, C^i and C^i_n are the concentration of pollutant 'i' (i.e., microplastic) and unpolluted samples, respectively. The toxicity coefficient (T^i_r) represents toxicity level and biological sensitivity. The toxicity coefficient is the sum of the percentage of certain polymers in the total sample (P_n/C^i) multiplied by the hazard score of plastic polymers (S_n).

2.6. Hydrodynamics

Scatterometers are able to measure ocean surface wind vectors in both clear and cloudy conditions. Therefore, in this study, wind data during the southwest (SW) and northeast (NE) monsoons of 2019 from

Table 1
Detailed information for the primary hazard statements and scores of MP polymers found in sediments from the Indian coast.

Polymer	Monomer	Density (g cm^{-3})	Primary hazard statements	Hazard level	Score
Polyethylene (PE)	Ethylene	0.91–0.97	Extremely flammable gas	1	11
			May cause drowsiness or dizziness	2	
Polypropylene (PP)	Propylene	0.89–0.92	Extremely flammable gas	1	1
Polystyrene (PS)	Styrene	0.28–1.04	Flammable liquid and vapour	0	30
			Harmful if inhaled	2	
Polyethylene terephthalate (PET)	Ethanediol	1.37–1.38	Harmful if swallowed	2	4
Polyamide (PA)	Hexamethylenediamine	1.14–1.15	Harmful in contact with skin	2	47
			Harmful if swallowed	2	
			May cause respiratory irritation	2	
			Causes severe skin burns and eye damage	3	

(Data source: Lithner et al. (2011).)

the advanced Scatterometer (ASCAT) onboard the meteorological operational platform (MetOp-B) satellite (http://apdrc.soest.hawaii.edu/las/v6/dataset?catitem=12790) was used. The ASCAT sea surface wind product is a one-day composite product with a spatial resolution of 0.25° × 0.25°. The surface current patterns in the northern Indian Ocean during SW and NE monsoon of 2019 were obtained from the Ocean Surface Current Analysis Real-time (OSCAR) data (www.oscar.noaa.gov). OSCAR is an ocean-surface current data product, which is computed from satellite-derived measurements of sea level anomaly (SLA), sea surface wind (SSW), and sea surface temperature (SST). The data are available at 5-day intervals and at 1° × 1° spatial resolution (Veerasingam et al., 2016a).

3. Results and discussion

3.1. Abundance and polymer composition of MPs in the coastal and marine sediments

The concentration of MPs in the terrestrial and marine sediments of India is illustrated in Figs. 2a and 3a. The literature data shows that MP contamination is widespread in both terrestrial and marine environments. In most of the research papers, the concentrations of MPs in sediments are reported as 'MP items/kg' and 'MP items/m^2'. A few studies reported it in percentage and also provided the total number of MP items. The ranges of average MP concentration in sediments along the Indian coast varied between 12.22 items/kg and 439 items/kg (Fig. 2a) and between 2.2 items/m^2 and 526.5 items/m^2 (Fig. 3a). The highest concentration of MPs was found in the metropolitan cities (Mumbai along the WCI (Maharana et al., 2019), and Chennai along the ECI (Sathish et al., 2019)), and in the River Ganges (Sarkar et al., 2019). The remote islands (Andaman and Nicobar) situated in the East Indian Ocean is also highly contaminated by MPs (Goswami et al., 2020). Even in the terrestrial freshwater lakes such as Veeranam Lake (ECI) (Manikanda Bharath et al., 2021) and Vembanad Lake (WCI) (Sruthy and Ramasamy, 2017), we can find high concentration of MPs. The abundance of MPs is also found in the UNESCO Biosphere reserve (Gulf of Mannar). The lowest MP concentration is found in the Gulf of Mannar (12.22 items/kg) (Patterson et al., 2019) and Idinthakarai (2.2 items/m^2) (Karthik et al., 2018). Based on global modelling, Eriksen et al. (2014) estimated that there was approximately 59,130 tons of plastics in the surface waters across the Indian Ocean. Jambeck et al. (2015) estimated that about 4.49 million tons/year plastic waste was generated in 2010 from India, in which 85% of the waste was inadequately managed. Lebreton et al. (2017) showed that the River Ganges is the second largest contributor (115,000 tons) of plastic to the ocean. Though these model estimates were not validated due to inadequate monitoring data, the available field measurements and modelling studies do revealed that most of the terrestrial and marine sediments in India are contaminated with MPs. However, baseline level of MPs in most of the terrestrial regions, central and northeast coastal regions, nearshore and offshore regions have not yet been established. Therefore, in order to fill the knowledge gap in the distribution of MPs in terrestrial and marine systems of India, more studies are needed.

We have calculated the average percentage of polymer types of MPs found in the terrestrial and marine sediments (Figs. 2b and 3b) from the percentage value of polymer composition reported in the literature. Among the reviewed studies, the frequently identified polymer types of MPs in sediments include high-density/low-density polyethylene (HD/LD-PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET) and polyamide (PA). Overall, PE (47.7%) and PP (18.8%) were the most abundant polymer types found in the sediment samples. As per 2019 global plastic production data, PE (29.7%) and PP (19.3%) were the major composition of plastic material produced as short life-cycle products (Plastic Europe, 2019; Geyer et al., 2017). Therefore, the predominance of PE, PP and PET type of polymers might have been originated from the higher production rate and are widely used in food packaging, agricultural film, plastic bags and plastic bottles. The presence of PA type MPs in the northern Indian Ocean (Andaman

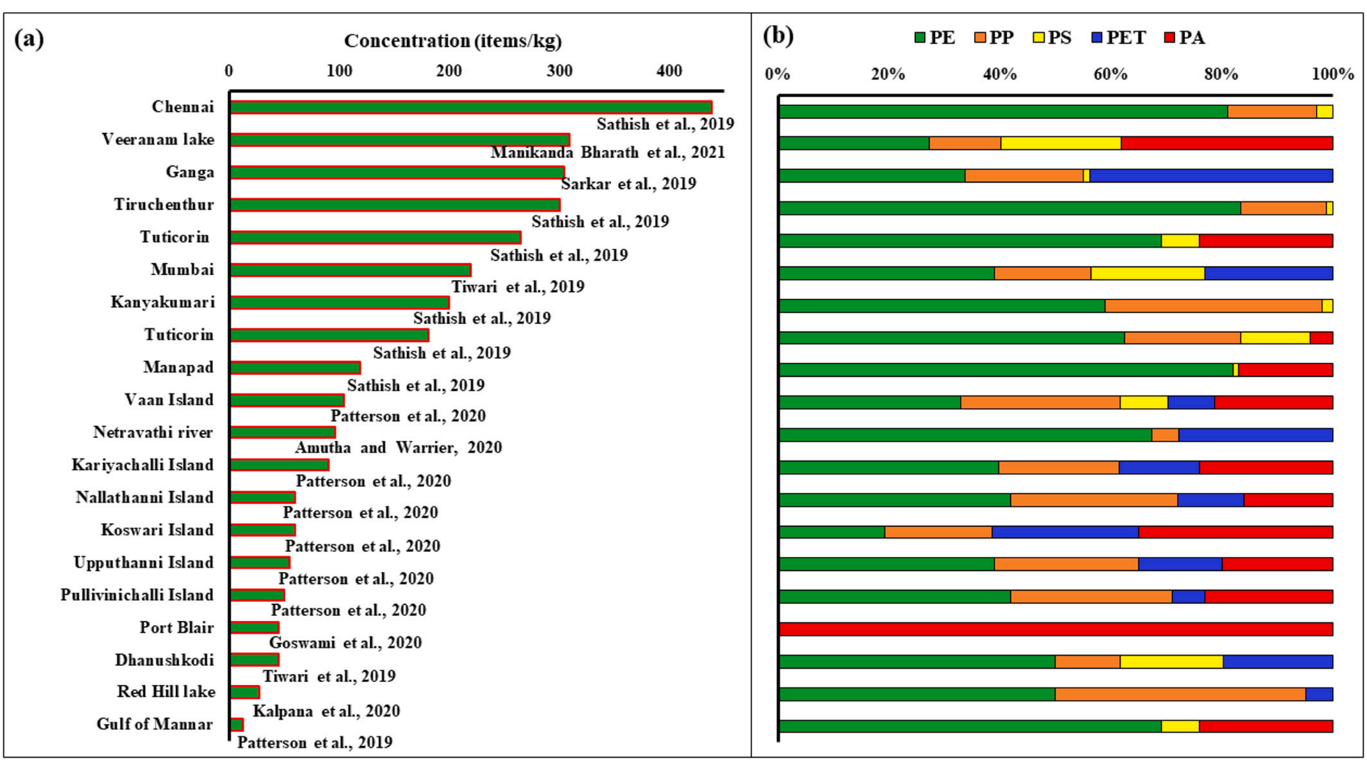

Fig. 2. (a) Average concentration of MPs (items/kg) and (b) their corresponding polymer composition in terrestrial and marine sediments in India. Data were extracted from Amrutha and Warrier (2020), Goswami et al. (2020), Kalpana et al. (2020), Manikanda Bharath et al. (2021), Patterson et al. (2019), Patterson et al. (2020), Sarkar et al. (2019), Sathish et al. (2019) and Tiwari et al. (2019).

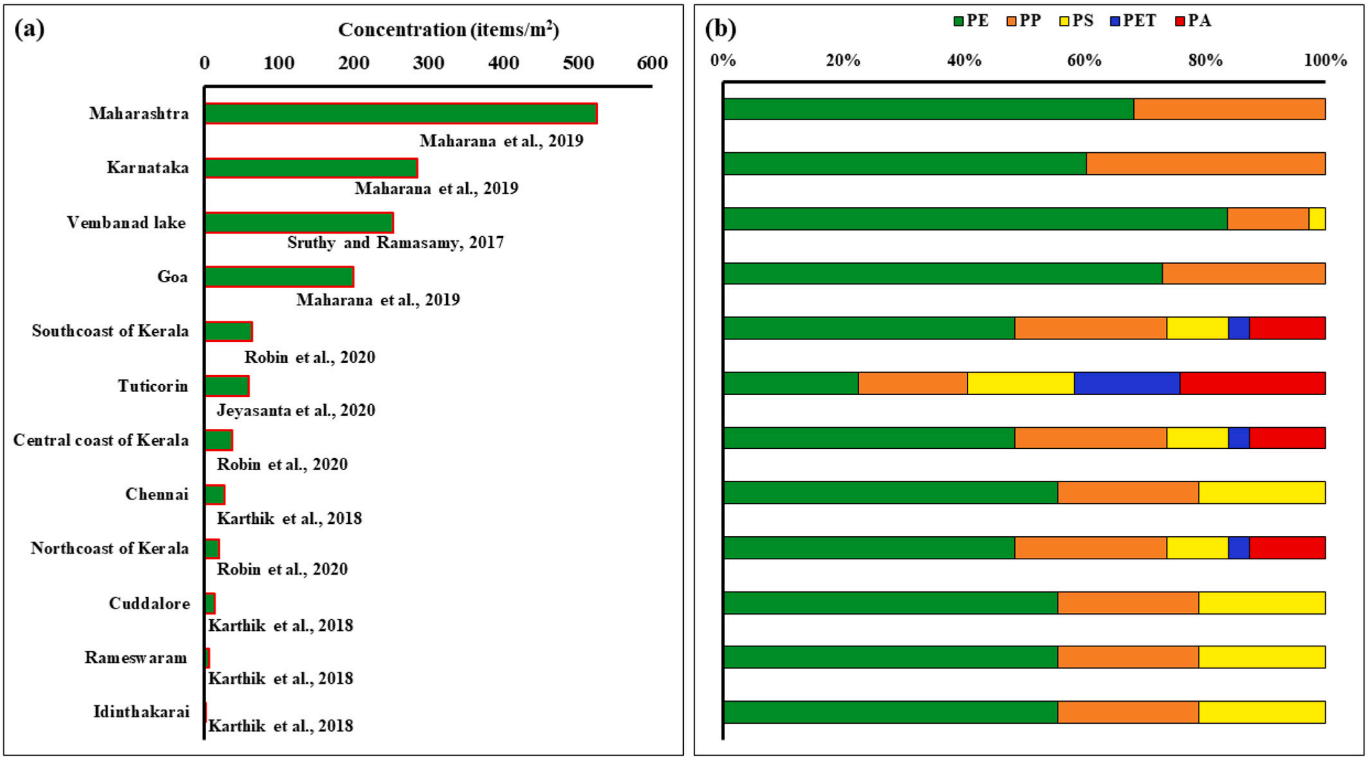

Fig. 3. (a) Average concentration of MPs (items/m2) and (b) their corresponding polymer composition in terrestrial and marine sediments in India. Data were extracted from Jeyasanta et al. (2020), Karthik et al. (2018), Maharana et al. (2019), Robin et al. (2020) and Sruthy and Ramasamy (2017).

and Nicobar Islands) were much higher than those found along the ECI and WCI.

3.2. Potential sources of MPs

MPs in the marine sediments along the Indian coast are originated from both land- and sea-based sources (Veerasingam et al., 2016a, 2016b). The abundance and polymer types of MPs along the Indian coast demonstrate a close association with inland sources such as urbanization, industrialization and sea-based sources such as fishing and shipping activities. Lebreton et al. (2012) found that 80% of plastic debris derived from the land-based sources (especially through coastal population and rivers) ended into the ocean. Fig. S2 shows that the population density along the WCI is relatively higher than those found along the ECI. It is reported that the population of India has doubled during 1975–2010 and the amount of municipal solid waste (MSW) has tripled (Singh et al., 2011). Based on the Central Pollution Control Board report (CPCB, 2018), in India, 62 MT of solid waste was generated in 2015, out of which 82% was collected (in this 28% was treated, and the remaining was dumped in the open) and 18% was treated as litter. It is estimated that about 300 million tons per year of MSW will be generated by 2051 due to increase in the population (≈1823 million), if urban local bodies (ULBs) in India continue to rely on landfill route for MSW management (Joshi and Ahmed, 2016). Open dumping causes surface water pollution due to material uncontrolled flows and leachate mismanagement. Therefore, urbanized and densely populated coastal areas around the Indian Ocean could be the major potential source of MPs (Li et al., 2021), which is in consistent with the modelling results obtained by Jambeck et al. (2015). However, we find that average annual discharges into the Indian Ocean from the rivers along the ECI are higher than that along the WCI (Table S1). The abundance and polymer composition of MPs along the Indian coast showed the highest polymer diversity pattern in metropolitan cities and river mouths along the Indian coast. This proves that the regional man-made activities influence the pollution characteristics of MPs in the nearshore marine environment. Nearly 20% of the plastic debris entered into the Indian Ocean are from sea-based sources (Veerasingam et al., 2017). MP polymers (i.e., abundance of PA) and shapes found along the southeast coast of India revealed that the sea-originated plastic debris from aquaculture and fisheries have become significant sources of MPs. Automatic Identification System (AIS) provided annually averaged traffic density map (Fig. S3), and that shows that congested shipping lanes are lower in the Bay of Bengal (ECI) than the Arabian Sea (WCI). The southern tip of India is situated very close to the International shipping routes. Moreover, Fig. S3 confirms that widespread fishing vessel activities are going on off ECI and WCI. Therefore, abundance of PA composition of MPs might have been derived from the unintentional and/or intentional discard of fishing nets and related debris. Recently, Kaladharan et al. (2020) confirmed that there is growing harmful effects of plastic waste in the potential fishing areas along the Indian coastal region. Moreover, cargo lost from merchant ships, and trash thrown overboard may also lead to an important input of plastics into the sea, particularly in the Strait of Malacca (Duis and Coors, 2016; Li et al., 2021). Airborne transport of MPs is also another important pathway for the plastics to move from land to ocean. Recently, Wang et al. (2020) found that MP in the atmosphere over the East Indian Ocean might have been originated from the MP emissions from the adjacent continent.

3.3. Factors influencing the distribution and transportation of MPs

PE and PP are produced in large quantities globally and widely used. MPs derived from both land and sea-based sources are transported mainly by winds and currents in the ocean (Law et al., 2010; Kane et al., 2020). The low specific densities of PE and PP allow them to float on water surface and travel long distances through ocean currents and winds, resulting in wide distribution, even in remote islands both uninhabited (Tinnakara Island, Lakshadweep) and inhabited (Andaman and Nicobar Islands). Fig. 4 shows the circulation in the northern Indian Ocean, influenced by both SW and NE monsoon winds (Schott et al., 2009). In summer, the clockwise ocean circulation is dominated by the

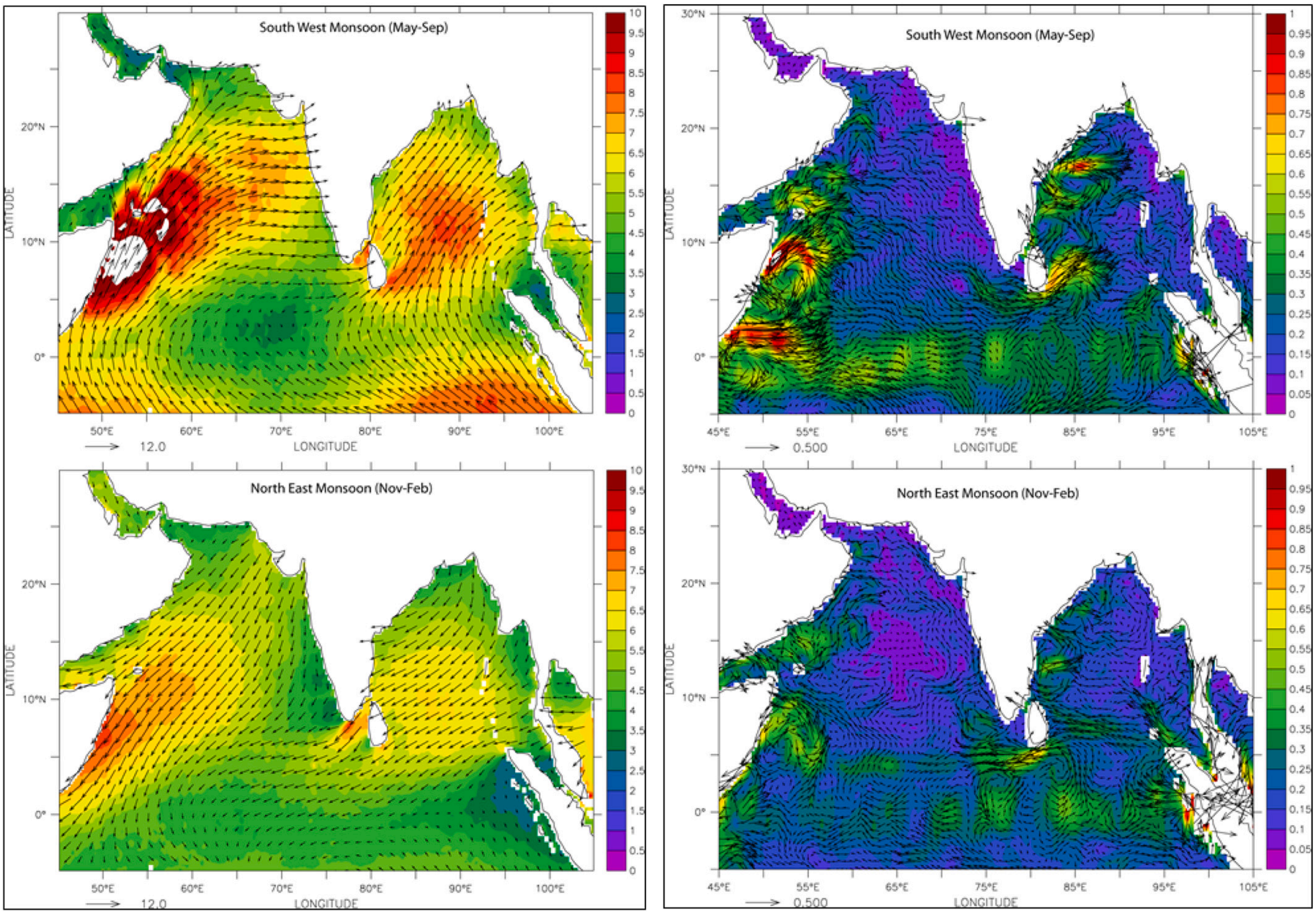

Fig. 4. The wind and current patterns during the southwest and northeast monsoon seasons in the north Indian Ocean.

SW monsoon, whereas the anticlockwise ocean circulation is formed under the influence of NE monsoon. The East Indian Coastal Current (EICC) and West Indian Coastal Current (WICC) play the important role on the transportation of floating debris between the Bay of Bengal and the Arabian Sea (Veerasingam et al., 2017). Dharani et al. (2003) found that the garbage generated in the coastal areas of Malaysia, Singapore, Sumatra, Indonesia and other SE Asian countries and in the international shipping routes (intentional/accidental release of waste) were transported by ocean currents and dispersed in the east Indian Ocean. Thus, the unique ocean dynamics and monsoon climate in the northern Indian Ocean influence the distribution and transportation of MPs.

As known, rain, flood, and storm events are the key drivers of MP transport and contamination in estuarine, coastal and marine environments (Veerasingam et al., 2016a; Hurley et al., 2018; Hitchcock, 2020). Storm surge is another major contributor of transportation of microplastics between ocean and land (Lo et al., 2020; Ockelford et al., 2020). The frequency and severity of storm surges occur along the ECI is higher than those on the WCI. In the Bay of Bengal and Arabian Sea, the storm surges generated by the tropical cyclones normally occur during pre-monsoon (March–May) and post-monsoon (October–November) seasons. Therefore, tropical cyclones and associated storm surges not only facilitate the adjustment/migration of shoreline, but also transport MPs from offshore to the beach. Recently, OceanParcels-v2 has been used in Lagrangian particle-tracking simulation of plastics released in the northern Indian Ocean (van der Mheen et al., 2020). Duncan et al. (2020) used Open-source tracking technology (using GPS cellular networks and satellite technology) to understand the transport and fate of plastics in the Ganges river system

3.4. Risk assessment of MPs in sediments

MPs are ingested by many terrestrial and marine organisms, such as mollusc (Naidu, 2019), fish (Kumar et al., 2018), shrimp (Daniel et al., 2020) and crab (Piarulli et al., 2019), which may transfer up to human via food chains. Therefore, it would pose significant risks to the biota as well as human health (Pan et al., 2021). MPs are composed of a variety of polymers synthesized from a chain of monomers through polymerization reaction, during which unreacted monomers and hazardous additives may be present. The sunlight and heat cause weathering of MPs in the beach and sea surface, and also releasing of hazardous additives. According to a hazard-ranking model based on the United Nations' Globally Harmonized System of classification and labelling of chemicals, the chemical ingredients of >50% of plastics are hazardous (Lithner et al., 2011; Rochman et al., 2013). The ecological risk assessment of MPs in terrestrial and marine sediments is assessed using PHI, PLI and PERI parameters. Based on PHI values, the overall risk of MP pollution in India was categorized as Hazard level IV to V (Table 2). The PHI values

Table 2
Terminology used to describe the hazard level criteria for MP pollution.

PHI	Hazard category	PLI	Hazard category	PERI	Risk category
0–1	I	<10	I	<150	Minor
1–10	II	–	–	150–300	Medium
10–100	III	10–20	II	300–600	High
100–1000	IV	20–30	III	600–1220	Danger
>1000	V	>30	IV	>1200	Extreme danger

of MPs (Fig. 5) in territorial and marine sediments exhibits serious MP pollution trend. For example, the coastal regions of Tamil Nadu, Maharashtra and Kerala have high PHI values (>1000) due to the presence of MPs with high hazard scores, such as PA and PS with high hazard scores. Though the hazard scores of PP, PET and PE are relatively lower than the hazard scores of PA and PS, we should not ignore them while calculating the risk. Moreover, even if the MP concentration is low, its chemical toxicity should not be ignored.

PLI is used to measure the degree of MP contamination (Pan et al., 2021). Based on PLI, the MP pollution load at each location was calculated (Fig. 6). The PLI values of sediments from ECI were less than 10, which indicate the 'Hazard level I'. However, PLI values from Maharashtra (15.5), Karnataka (11.4), and Vembanad Lake (10.45) along the west coast of India showed Hazard level II. According to PLI values, terrestrial and marine sediments along the WCI are moderately contaminated with MPs, while the sediments along the ECI are less contaminated. The chemical composition of MPs seems to have a minor effect on PLI, because PLI was calculated based on the ratio between abundance of measured MPs and the background value. The abundance of MPs in the marine environment is affected by regional human activities, including rate of industrialization, population density, economic development activities and sea-based activities (fishing and shipping) (Jang et al., 2020; Pan et al., 2021). However, the average PLI value found along the Indian coast (5.58) was relatively lower than those reported in China, especially in Changjiang estuary (18.4) (Xu et al., 2018) and Dongshan Bay (14.2) (Pan et al., 2021).

The potential ecological risk index (PERI) values of terrestrial and marine sediments along the Indian coast (Fig. 7) show high ecological risk (PERI: 300–600) from combined MP polymers in sediments from Tuticorin (835.7), Kerala coast (597.5), Tamil Nadu coast (476.2), Vembanad Lake (406.7), Goa (346.9), Maharashtra (332.1) and Karnataka (303.2). PERI is determined based on the hazard score and

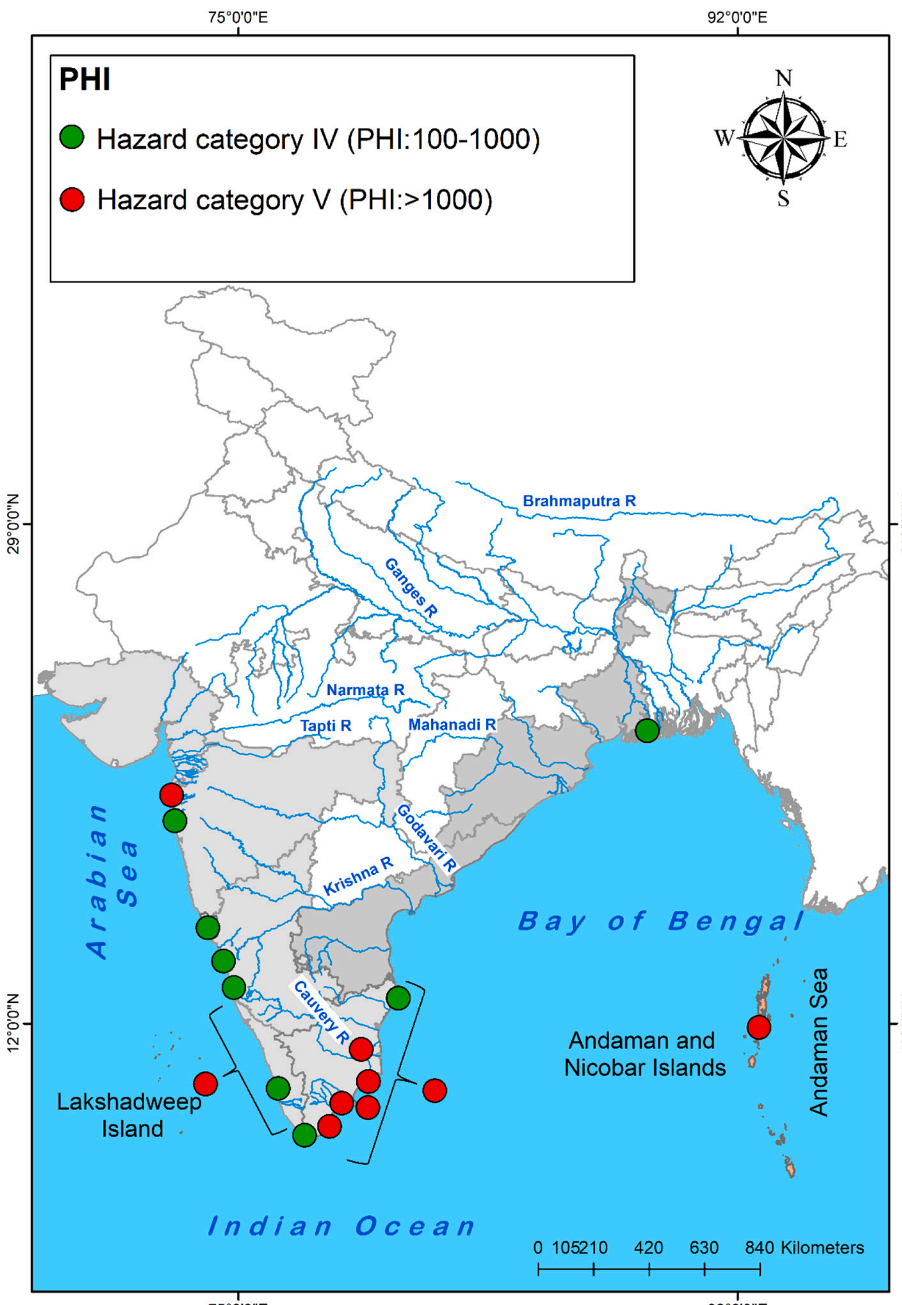

Fig. 5. Polymer hazard index along the Indian coast.

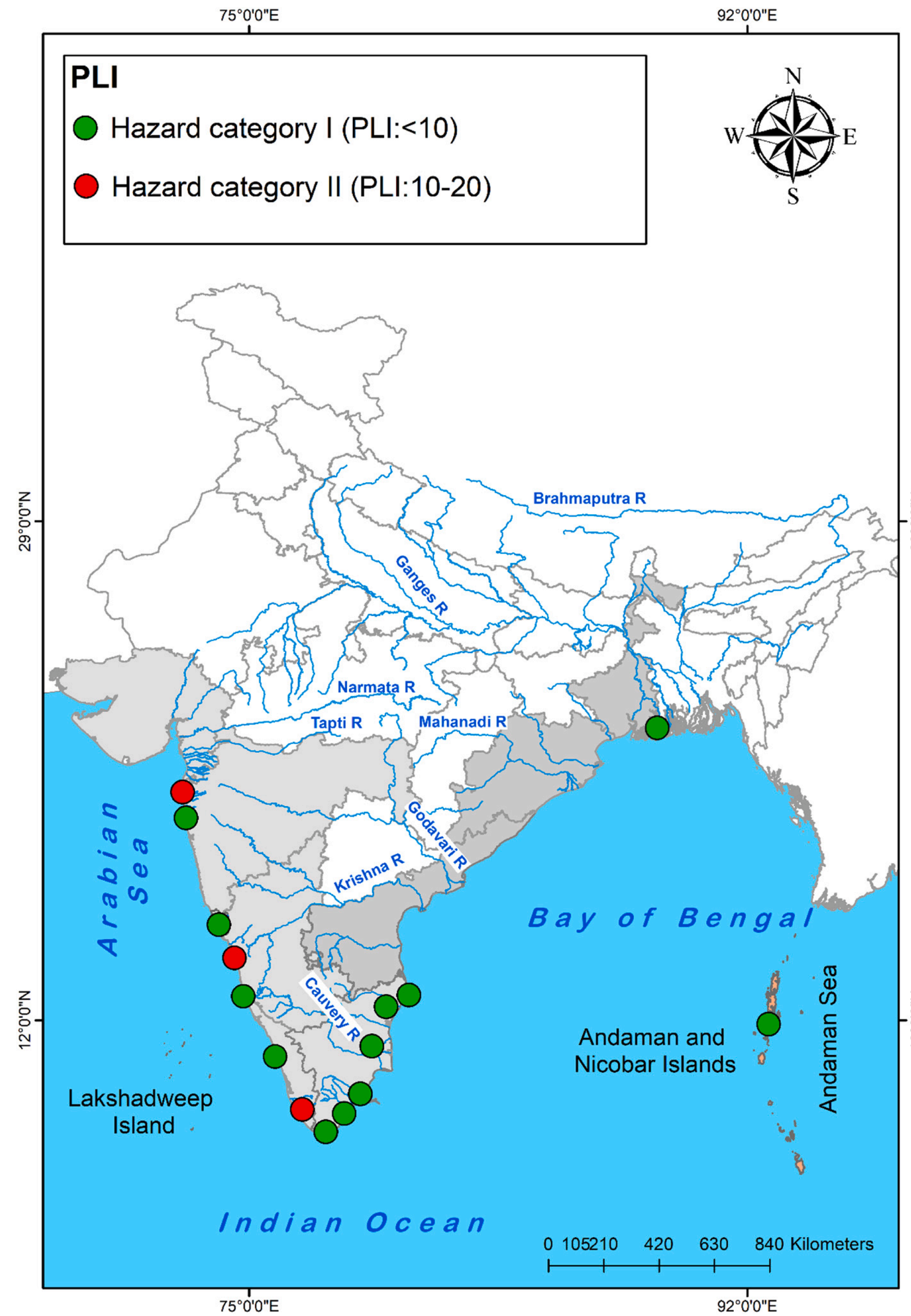

Fig. 6. Pollution load index along the Indian coast.

abundance of MP polymers. For example, in Tuticorin, the abundance of PA and PS are high, and that resulted in the highest PERI. Conversely, less abundance of PA and PS in other parts of Indian coast caused only minor (PERI<150) to medium (150–300) ecological risk. No noticeable correlation between the abundance of MPs (also, PLI) and PHI was observed, yet higher abundance of MPs may cause potential ecological risk. In this study, the combined use of PHI, PLI and PERI provided the preliminary ecological risk assessment caused by MP contamination in terrestrial and marine sediments along the Indian coast.

3.5. Limitations and future research perspectives

The literature search clearly showed that very limited reliable data are available on the occurrence of MPs in terrestrial and marine sediments along the Indian coast, and different sampling and analytical methods were followed. The areas around major rivers (especially, Ganges) and metropolitans are not studied properly. Moreover, MPs in coastal sediments along the major parts of the ECI (especially, Andhra Pradesh and Odisha coastal region) have not yet been studied. MPs along the Indian coast exhibit high polymer hazard range (IV to V) and PERI values, indicating high ecological risk, of course with limited data. Although information is very limited to draw firm conclusion on the polymer hazards and their ecological risk, this study has given a pilot quantitative measure on the ecological risk caused by MPs in sediments. This prioritizes the importance of studying the complete risk assessment of MPs contamination to elucidate its potential adverse effects on human health.

Different sample collection and analytical techniques were used for the extraction, quantification and identification of polymers in sediments along the Indian coast (Fig. S4). In a previous work (Veerasingam et al., 2020b), we have highlighted the importance of harmonization and standardization of sampling and analytical methods of MPs in

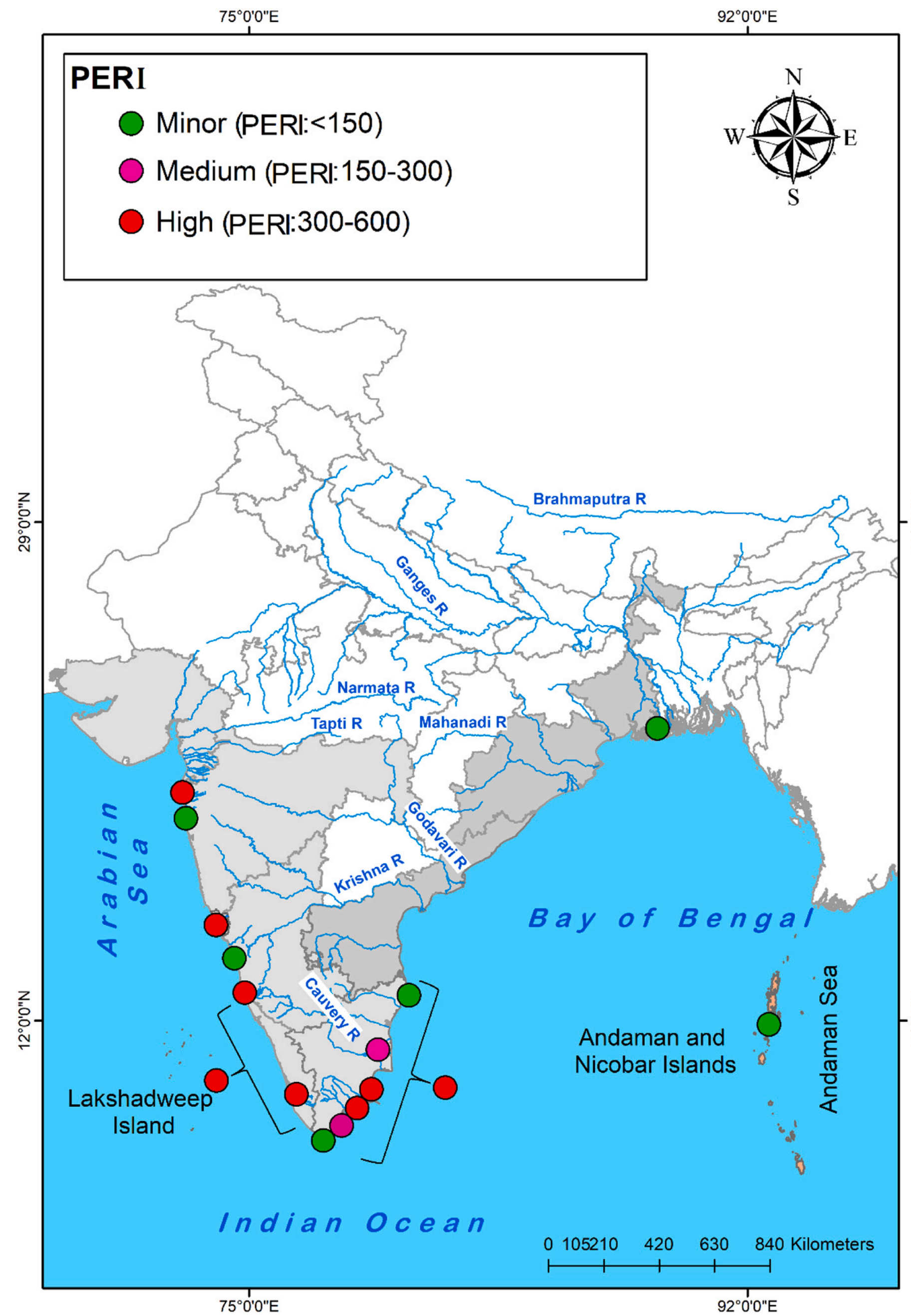

Fig. 7. Potential ecological risk index along the Indian coast.

different environmental compartments in India to compare the spatial and temporal variations around the world. Standardized analytical methods are required to assess the reliable abundance of MPs in sediments and their ecological risks in the major rivers, coastal and marine environments.

The choice of an appropriate background MP value plays a vital role in the understanding of PLI and PERI assessment. PLI was proposed by Tomlinson et al. (1980) to assess the level of heavy metal pollution load in the sediments with respect to the baseline metal levels. Since the distribution of metals in sediments is derived from both natural anthropogenic origins, the average values of Earth's continental crust (Taylor, 1964) or shale (Turekian and Wedepohl, 1961) have been widely used as the reference background levels. However, MPs are derived from anthropogenic origin alone. Therefore, setting up of reference background value for MP pollution load assessment is a crucial task. Moreover, most of the MP data provided in the literature have not either confirmed the polymer types or only a few samples were identified using FTIR/Raman spectroscopy (Veerasingam et al., 2020c). Therefore, the MP data could have contained both natural and synthetic fiber type MPs. In this study, the lowest concentration of MP value detected in the sediment sample was considered as a background value.

Background value is a comparative measure to discriminate between pristine and anthropogenically influenced concentrations of MPs in a given environmental sample. Two kinds of background values can be used: (i) Local Background (LBG), and (ii) Global Background (GBG). The LBG is the MP accumulation in the most pristine site or the MP value in the deeper part of the sediment core (Veerasingam et al., 2021), whereas GBG is an average MP concentration given in the literature around the world. GBG gives information concerning sediment quality to be considered at a global scale and allows comparisons beyond the local scale. However, due to rapid industrialization and urbanization, substantial inputs of human-derived MPs get deposited in the sediments, making it difficult or impossible to assess the level of contamination using only GBG. Therefore, LBG is suggested, particularly when the anthropogenic effect and high levels of pollution are suspected.

Most studies reported that fibers and/or particles <300 μm are the types of MPs ingested by terrestrial and marine organisms. However, majority of laboratory toxicology related studies have examined the impacts of MP ingestion on organisms by particles of <300 μm (often <100 μm microbeads) in diameter. Much of the existing data on the physiological and ecological effects of MPs is based on particle sizes that majority of seawater sampling studies are not quantified (Covernton et al., 2019; Kutralam-Muniasamy et al., 2020). Therefore, accurate quantification of MPs and their polymer types is important for planning relevant MP toxicology related investigations and linking the gap between field and laboratory analyses of potential ecological risk.

4. Conclusions

Abundance of different polymer compositions of MPs in the terrestrial and marine ecosystems is contaminating the seafood and may be leading to transfer of toxic chemicals to human beings. No information is available on the polymer hazard and ecological risk assessment of MPs in sediments. We used all the available peer-reviewed MP data in sediments along the Indian coast to evaluate the ecological risk assessment. Overall, the PHI values of MPs in terrestrial and marine sediments exhibited threat to the environment. The coastal regions of Tamil Nadu, Maharashtra and Kerala have high PHI values (>1000) due to the presence of polymers such as PA and PS with high hazard scores. According to PLI values, sediments along the WCI are moderately contaminated with MPs, whereas, the sediments along the ECI are less contaminated. However, the PLI values calculated in this study are relatively lower than those reported in China. The chemical composition of MPs seems to have a minor effect on PLI. The PERI values show high ecological risk in terrestrial and marine sediments along the Indian coast from combined the MP polymers in sediments. No noticeable correlation between abundance of MPs (also, PLI) and PHI was found, though higher concentration of MPs may cause potential ecological risks. The existence of unique ocean dynamics and monsoon climate in the northern Indian Ocean play a major role in the distribution and transportation of MPs. Abundance of various polymer composition of MPs along the Indian coast is closely related to different types of human activities on the land and sea. We recommend that policy makers and environmental managers may consider the ecological risk of MPs in sediments along the Indian coast and strict regulations for the discharge of plastic waste may be formed for the conservation of environment and human health.

CRediT authorship contribution statement

M. Ranjani: Methodology, Investigation, Writing – original draft, Writing – review & editing. **S. Veerasingam:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Formal analysis, Visualization. **R. Venkatachalapathy:** Methodology, Investigation, Writing – review & editing, Resources, Funding acquisition, Supervision. **M. Mugilarasan:** Methodology, Investigation. **Andrei Bagaev:** Methodology, Investigation, Writing – review & editing. **Vladimir Mukhanov:** Methodology, Investigation, Writing – review & editing. **P. Vethamony:** Methodology, Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgment

Qatar University authors were partly supported by the IRCC International Research Co-Fund Collaboration Program of QU (Project No. IRCC-2019-002). This work is part of the joint Indo-Russian (DST-RFBR) research project (INT/RUS/RFBR/P-339). AB is supported by the state assignment of Marine Hydrophysical Institute, RAS (theme No. 0827-2018-0004). Open Access funding provided by the Qatar National Library.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2021.111969.

References

ACC, 2020. Shale gas is driving new chemical investment in the U.S., American Chemical Council. https://www.mericanchemistry.com/Policy/Energy/Shale-Gas/Fact-Sheet-US-Chemical-Investment-Linked-to-Shale-Gas.pdf.

Amrutha, K., Warrier, 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.

Borrelle, S.B., Ringma, J., Law, K.L., Monnahan, C.C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G.H., Hilleary, M.A., Eriksen, M., Possingham, H.P., Frond, H.D., Gerber, L.R., Polidoro, B., Tahir, A., Bernard, M., Mallos, N., Barnes, M., Rochman, C.M., 2020. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science 369, 1515–1518.

Boucher, J., Friot, D., 2017. Primary Microplastics in the Oceans: A Global Evaluation of Sources. IUCN, Gland, Switzerland (43 pp.).

Brahney, J., Hallerud, M., Heim, E., Hahnenberger, M., Sukumaran, S., 2020. Plastic rain in protected areas of the United States. Science 368, 1257–1260.

Chakraborty, P., Ramteke, D., Chakraborty, S., Nath, B.N., 2014. Changes in metal contamination levels in estuarine sediments around India–an assessment. Mar. Pollut. Bull. 78, 15–25.

Covernton, G.A., Pearce, C.M., Gurney-Smith, H.J., Chastain, S.G., Ross, P.S., Dower, J.F., Dudas, S.E., 2019. Size and shape matter: a preliminary analysis of microplastic sampling technique in seawater studies with implications for ecological risk assessment. Sci. Total Environ. 667, 124–132.

Cozar, A., Marti, E., Duarte, C.M., Garcia-de-Lomas, J., van Sebille, E., Ballatore, T.J., Eguiluz, V.M., Gonzalez-Gordillo, J.I., Pedrotti, M.L., Echevarria, F., Trouble, R., Irigoien, X., 2017. The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the Thermohaline circulation. Sci. Adv. 3, e1600582.

CPCB, 2018. Central pollution control board - consolidated annual report 2016-17 on implementation of solid waste management rules, 2016 (April 2018). Central Pollution Control Board, Ministry of Environment, Forests & Climate Change, Government of India, Delhi.

Cunningham, E.M., Ehlers, S.M., Dick, J.T.A., Sigwart, J.D., Linse, K., Dick, J.J., Kiriakoulakis, K., 2020. High abundances of microplastic pollution in deep-sea sediments: evidence from Antarctica and the Southern Ocean. Environ. Sci. Technol. 54 (21), 13661–13671.

Daniel, D.B., Ashraf, P.M., Thomas, S.N., 2020. 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.

Dharani, G., Abdul Nazar, A.K., Venkatesan, R., Ravindran, M., 2003. Marine debris in Great Nicobar. Curr. Sci. 85, 574–575.

Duis, K., Coors, A., 2016. Microplastics in the aquatic and terrestrial environment: sources (with a specific focus on personal care products), fate and effects. Environ. Sci. Eur. 28, 1–25.

Duncan, E.M., Davies, A., Brooks, A., Chowdhury, W., Godley, B.J., Jambeck, J., Maddalene, T., Napper, I., Nelms, S.E., Rackstraw, C., Koldewey, H., 2020. Message in a bottle: open source technology to track the movement of plastic pollution. PLoS One 15, e0242459.

Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G., Reisser, J., 2014. Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS One 9, e111913.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Science Advances, e1700782. https://doi.org/10.1126/sciadv.1700782pmid:28776036.

Goswami, P., Vinithkumar, N.V., Dharani, G., 2020. First evidence of microplastics bioaccumulation by marine organisms in the Port Blair Bay, Andaman Islands. Mar. Pollut. Bull. 155, 111163.

Hartmann, N.B., Rist, S., Bodin, J., Jensen, L.H., Schmidt, S.N., Mayer, P., Meibom, A., Baun, A., 2017. Microplastics as vectors for environmental contaminants: exploring sorption, desorption, and transfer to biota. Integr. Environ. Assess. Manag. 13, 488–493.

Hartmann, N.B., Huffer, T., Thompson, R.C., Hasselloy, M., Verschoor, A., Daugaard, A.E., Rist, S., Karlsson, T., Brennholdt, N., Cole, M., Herrling, M.P., Hess, M.C., Ivleva, N.P., Lusher, A.L., Wagner, M., 2019. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. Environ. Sci. Technol. 53, 1039–1047.

Hitchcock, J.N., 2020. Storm events as key moments of microplastic contamination in aquatic ecosystems. Sci. Total Environ. 734, 139436.

Hurley, R., Woodward, J., Rothwell, J., 2018. Microplastic contamination of river beds significantly reduced by catchment-wide flooding. Nat. Geosci. 11, 251–257.

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.
Jang, M., Shim, W.J., Cho, Y., Han, G.M., Song, Y.K., Hong, S.H., 2020. A close relationship between microplastic contamination and coastal area use pattern. Water Res. 171, 115400.
Jeyasanta, K.I., Sathish, N., Patterson, J., Edward, J.K.P., 2020. Macro-, meso- and microplastic debris in the beaches of Tuticorin district, Southeast coast of India. Mar. Pollut. Bull. 154, 111055.
Joshi, R., Ahmed, S., 2016. Status and challenges of municipal solid waste management in India: a review. Cogent Environ. Sci. 2, 1139434.
Kaladharan, P., Singh, V.V., Asha, P.S., Edward, L., Sukhadane, K.S., 2020. Marine plastic litter in certain trawl grounds along the peninsular coasts of India. Mar. Pollut. Bull. 157, 111299.
Kalpana, G., Srinivasalu, S., Neelavannan, K., Vidyasakar, A., 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.
Kane, I.A., Clare, M.A., Miramontes, E., Wogelius, R., Rothwell, J.J., Garreau, P., Pohl, F., 2020. Seafloor microplastic hotspots controlled by deep-sea circulation. Science 368, 1140–1145.
Karthik, R., Robin, R.S., Purvaja, R., Ganguly, D., Anandavelu, I., Raghuraman, R., Hariharan, G., Ramakrishna, A., Ramesh, R., 2018. Microplastics along the beaches of southeast coast of India. Sci. Total Environ. 645, 1388–1399.
Kim, J.-S., Lee, H.-J., Kim, S.K., Kim, H.-J., 2018. Global pattern of microplastics (MPs) in commercial food-grade salts: sea salt as an indicator of seawater MP pollution. Environ. Sci. Technol. 52, 12819–12828.
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. Pollu. Bull. 135, 889–894.
Kutralam-Muniasamy, G., Perez-Guevara, F., Elizalde-Martinez, I., Shruti, V.C., 2020. An overview of recent advances in micro/nano beads and microfibers research: critical assessment and promoting the less known. Sci. Total Environ. 740, 139991.
Lamb, J.B., Willis, B.L., Fiorenza, E.A., Couch, C.S., Howard, R., Rader, D.N., True, J.D., Kelly, L.A., Ahmad, A., Jompa, J., Harvell, C.D., 2018. Plastic waste associated with disease on coral reefs. Science 359, 460–462.
Lau, W.W.Y., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., Koskella, J., Velis, C.A., Godfrey, L., Boucher, J., Murphy, M.B., Thompson, R.C., Jankowska, E., Castillo, A. C., Pilditch, T.D., Dixon, B., Koerselman, L., Kosior, E., Favoino, E., Gutberlet, J., Baulch, S., Atreya, M.E., Fischer, D., He, K.K., Petit, M.M., Sumaila, U.R., Neil, E., Bernhofen, M.V., Lawrence, K., Palardy, J.E., 2020. Evaluation scenarios toward zero plastic pollution. Science 369, 1455–1461.
Law, K.L., Moret-Ferguson, S., Maximenko, N.A., Proskurowski, G., Peacock, E.E., Hafner, J., Reddy, C.M., 2010. Plastic accumulation in the North Atlantic subtropical gyre. Science 329, 1185–1188.
Lebreton, L.C.M., Greer, S.D., Borrero, J., 2012. Numerical modelling of floating debris in the world's oceans. Mar. Pollut. Bull. 64, 653–661.
Lebreton, L.C.M., der Zwet, J.V., Damsteeg, J.-W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nat. Commun. 8, 15611.
Li, C., Wang, X., Liu, K., Zhu, L., Wei, N., Zong, C., Li, D., 2021. Pelagic microplastics in surface water of the Eastern Indian Ocean during monsoon transition period: abundance, distribution, and characteristics. Sci. Total Environ. 755, 142629.
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.
Lo, H.-S., Lee, Y.-K., Po, B.H.-K., Wong, L.-C., Xu, X., Wong, C.-F., Wong, C.-Y., Tam, N.F.-Y., Cheung, S.-G., 2020. Impacts of Typhoon Mangkhut in 2018 on the deposition of marine debris and microplastics on beaches in Hong Kong. Sci. Total Environ. 716, 137172.
Maharana, D., Saha, M., Dar, J.Y., Rathore, C., Sreepada, R.A., Xu, X.-R., Koongolla, J.B., Li, H.-X., 2019. Assessment of micro and macroplastics along the west coast of India: abundance, distribution, polymer type and toxicity. Chemosphere 246, 125708.
Manikanda Bharath, K., Srinivasalu, S., Natesan, U., Ayyamperumal, R., Nirmal Kalam, S., Anbalagan, S., Sujatha, K., Alagarasan, C., 2021. Microplastics as an emerging threat to the freshwater ecosystems of Veeranam lake in south India: a multidimensional approach. Chemosphere 264, 128502.
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., Rao, V.R., Ramu, K., 2018. Microplastics in the benthic invertebrates from the coastal waters of Kochi, Southeastern Arabian Sea. Environ. Geochem. Health 40, 1377–1383.
Obbard, R.W., Sadri, S., Wong, Y.Q., Khitun, A.A., Baker, I., Thompson, R.C., 2014. Global warming releases microplastic legacy frozen in Arctic Sea ice. Earth's Future 2, 315–320.
Ockelford, A., Cundy, A., Ebdon, J.E., 2020. Storm response of fluvial sedimentary microplastics. Sci. Rep. 10, 1865.
Pan, Z., Liu, Q., Jiang, R., Li, W., Sun, X., Lin, H., Jiang, S., Huang, H., 2021. Microplastic pollution and ecological risk assessment in an estuarine environment: the Dongshan Bay of China. Chemosphere 262, 127876.
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.
Patterson, J., Jeyasantha, K.I., Sathish, N., Edward, J.K.P., Booth, A.M., 2020. Microplastic and heavy metal distributions in an Indian coral reef ecosystem. Sci. Total Environ. 744, 140706.
Peng, G., Xu, P., Zhu, B., Bai, M., Li, D., 2018. Microplastics in freshwater river sediments in Shanghai, China: a case study of risk assessment in mega-cities. Environ. Pollut. 234, 448–456.
Piarulli, S., Scapinello, S., Comandini, P., Magnusson, K., Granberg, M., Wong, J.X.W., Sciutto, G., Prati, S., Mazzeo, R., Booth, A.M., Airoldi, L., 2019. Microplastic in wild populations of the omnivorous crab *Carcinus aestuarii*: a review and a regional-scale test of extraction methods, including microfibres. Environ. Pollut. 251, 117–127.
Plastics Europe, 2019. Plastics – The Facts 2019: An Analysis of European Plastic Production. Demand and Waste Data, European Association of Plastics Manufacturers, Brussels, Belgium.
Provencher, J.F., Bond, A.L., Avery-Gomm, S., Borrelle, S.B., Bravo Rebolledo, E.L., Hammer, S., Kuhn, S., Lavers, J.L., Mallory, M.L., Trevail, A., van Franeker, J.A., 2017. Quantifying ingested debris in marine megafauna: a review and recommendations for standardization. Anal. Methods 9, 1454–1469.
Redondo-Hasselerharm, P.E., Gort, G., Peeters, E.T.H.M., Koelmans, A.A., 2020. Nano- and microplastics affect the composition of freshwater benthic communities in the long term. Science Advances 6, eaay4054.
Robin, R.S., Karthik, R., Purvaja, R., Ganguly, D., Anandavelu, I., Mugilarasan, M., Ramesh, R., 2020. Holistic assessment of microplastics in various coastal environmental matrices, southwest coast of India. Sci. Total Environ. 703, 134947.
Rochman, C.M., 2015. The complex mixture, fate and toxicity of chemicals associated with plastic debris in the marine environment. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer, Cham, pp. 117–140pp.
Rochman, C.M., Browne, M.A., Halpern, B.S., Hentschel, B.T., Hoh, E., Karapanagioti, H. K., Rios-Mendoza, L.M., Takada, H., Teh, S., Thompson, R.C., 2013. Classify plastic waste as hazardous. Nature 494, 169–171.
Sarkar, S.K., Bhattacharya, B.D., Bhattacharya, A., Chatterjee, M., Alam, A., Satpathy, K. K., Jonathan, M.P., 2008. Occurrence, distribution and possible sources of organochlorine pesticide residues in tropical coastal environment of India: an overview. Environ. Pollut. 34, 1062–1071.
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.
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.
Savoca, M.S., Wohlfeil, M.E., Ebeler, S.E., Nevitt, G.A., 2016. Marine plastic debris emits a keystone infochemical for olfactory foraging seabirds. Sci. Adv. 2, e1600395.
Schott, F.A., Xie, S.-P., McCreary Jr., J.P., 2009. Indian Ocean circulation and climate variability. Rev. Geophys. 47, RG1002.
Singh, R.P., Tyagi, V.V., Allen, T., Ibrahim, M.H., Kothari, R., 2011. An overview for exploring the possibilities of energy generation from municipal solid waste (MSW) in Indian scenario. Renew. Sust. Energ. Rev. 15, 4797–4808.
Sruthy, S., Ramasamy, E.V., 2017. Microplastic pollution in Vembanad Lake, Kerala, India: the first report of microplastics in lake and estuarine sediments in India. Environ. Pollut. 222, 315–322.
Taylor, S.R., 1964. Abundance of chemical elements in the continental crust: a new table. Geochim. Cosmochim. Acta 28, 1273–1285.
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.
Tomlinson, D.L., Wilson, J.G., Harris, C.R., Jeffrey, D.W., 1980. Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. Helgolander Meeresun. 33, 566–575.
Turekian, K.K., Wedepohl, K.H., 1961. Distribution of the elements in some major units of the earth's crust. Geol. Soc. Am. 72, 175–192.
UNEA, 2019. UNEA resolutions: marine litter and microplastics (1/6, 2/11, 3/7, 4/6), United Nations Environment Assemble. https://papersmart.unon.org/resolution/uploads/unep.aheg_.2019.3.inf_.2_compilation_of_resolutions.pdf (United Nations, 2019).
UN-SDG, 2018. Sustainable development goal 14, United Nations. https://sustainabledevelopment.un.org/sdg14.
van der Mheen, M., van Sebille, E., Pattiaratchi, C., 2020. Beaching patterns of plastic debris along the Indian Ocean rim. Ocean Sci. 16, 1317–1336.
Veerasingam, S., Mugilarasan, M., Venkatachalapathy, R., Vethamony, P., 2016a. Influence of 2015 flood on the distribution and occurrence of microplastic pellets along the Chennai coast, India. Mar. Pollut. Bull. 109, 196–204.
Veerasingam, S., Saha, M., Suneel, V., Vethamony, P., Rodrigues, A.C., Bhattacharyya, S., Naik, B.G., 2016b. Characteristics, seasonal distribution and surface degradation features of microplastic pellets along the Goa coast, India. Chemosphere 159, 496–505.
Veerasingam, S., Saha, M., Suneel, V., Vethamony, P., 2017. Microplastic pollution: a serious threat to the marine ecosystem, Blue Waters Newlett. Mar. Environ. Prot. 18, 6–9.
Veerasingam, S., Al-Khayat, Jassim A., Aboobacker, V.M., Hamza, S., Vethamony, P., 2020a. Sources, spatial distribution and characteristics of marine litter along the west coast of Qatar. Mar. Pollut. Bull. 159, 111478.
Veerasingam, S., Ranjani, M., Venkatachalapathy, R., Bagaev, A., Mukhanov, V., Litvinyuk, D., Verzhevskaia, L., Guganathan, L., Vethamony, P., 2020b. Microplastics in different environmental compartments in India: current understanding and future challenges. Trends Anal. Chem. 133, 116071.
Veerasingam, S., Ranjani, M., Venkatachalapathy, R., Bagaev, A., Mukhanov, V., Litvinyuk, D., Mugilarasan, M., Gurumoorthi, K., Guganathan, L., Aboobacker, V.M., Vethamony, P., 2020c. Contributions of Fourier transform infrared spectroscopy in microplastic pollution research: a review. Critical Reviews in Environmental Science and Technology. https://doi.org/10.1080/10643389.2020.1807450.

Veerasingam, S., Vethamony, P., Aboobacker, V.M., Giraldes, A.E., Dib, S., Al-Khayat, J., 2021. Factors influencing the vertical distribution of microplastics in the beach sediments around the Ras Rakan Island, Qatar. Environmental Science and Pollution Research. https://doi.org/10.1007/s11356-020-12100-4.

Wang, X., Li, C., Liu, K., Zhu, L., Song, Z., Li, D., 2020. Atmospheric microplastic over the South China Sea and East Indian Ocean: abundance, distribution and source. J. Hazard. Mater. 389, 121846.

Xu, P., Peng, G., Su, L., Gao, Y., Gao, L., Li, D., 2018. Microplastic risk assessment in surface waters: a case study in the Changjiang estuary, China. Mar. Pollut. Bull. 133, 647–654.

Zhu, J., Zhang, Q., Li, Y., Tan, S., Kang, Z., Yu, X., Lan, W., Cai, I., Wang, J., Shi, H., 2019. Microplastic pollution in the Maowei Sea, a typical mariculture bay of China. Sci. Total Environ. 658, 62–68.