

Characterization of anthropogenic marine macro-debris affecting coral habitat in the highly urbanized seascape of Mumbai megacity

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Abstract:

Marine debris has become a major form of pollution and a serious ecosystem health concern. The present study evaluates the accumulation, origin, and fate of debris in intertidal coral habitats of Mumbai- one of the world's highly populated coastal cities on the west coast of India. Predominantly, seven hermatypic coral species belonging to seven genera and five families were identified and mainly represented by *Pseudosidastrea*, *Porites*, and *Bernardpora*. In terms of number, the mean density of marine debris was 1.60 ± 0.13 SE items/m², which is higher than the global average. The mean density of plastic debris was 1.46 ± 0.14 SE items/m². Approximately 9% of total coral colonies were in physical contact with debris, and 22% of these colonies showed visible signs of partial bleaching. Plastic bags and wrappers were dominant plastic debris. The study area was characterized as 'very poor cleanliness' according to the Beach Quality Indexes, which include the Clean Coast Index, General Index, and Hazardous Items Index. The numerical model indicates the influence of river discharge and probable areas of plastic accumulation with high tidal currents in this region, maneuvering the spatial advection of litter in the nearshore areas. Combined analysis of ground-truthing and model simulation implies that the possible contributing sources of litter were representatives of land-based and sea-originated. The overall results point to increasing anthropogenic stressors threatening coastal coral communities, including marine debris pollution. It is advocated to adopt an integrated coastal zone management approach supported by coordinated policy frameworks could guide the mitigation of the debris footprint in coastal environments.

Keywords: Plastic; Coral reef; Debris management; Conservation; Indian Ocean



Graphical abstract

1. Introduction:

Pollution by anthropogenic marine debris has become one of the most widespread environmental impacts in the world's oceans (Cózar et al., 2014; Derraik, 2002). Marine debris comprises any anthropogenic, manufactured or processed solid materials discarded in the environment and transported into the sea (Galgani et al., 2013). In marine debris, the large proportion of plastic raises particular concern because of its long persistence (Andrady, 2015). A substantial amount of plastic trash escapes recycling and waste management, which eventually enters the oceans, accumulating on the shoreline, water column, and sediments (Cózar et al., 2014; Galgani et al., 2021). The widespread presence of plastic has been reported from the ocean's deepest point (Mariana trench) (Peng et al., 2018) to the highest mountain peak (Mount Everest) (Napper et al., 2020). Over 10 million tons of mismanaged plastic debris find their way to the global oceans annually (Jambeck et al., 2015), and this mass is gradually increasing every year (Galgani et al., 2021).

Marine debris has extremely deleterious impacts on marine organisms and threatens marine life by ingestion, entanglement, and ghost fishing (Gregory, 2009). In recent years, marine debris has been recognized as one of the emerging pressures on coral reef ecosystems worldwide (reviewed in Huang et al., 2021; Soares et al., 2020) due to inflicting mechanical tissue damage, bleaching, disease diffusion, altering growth and several physiological processes (Chapron et al., 2018; Lamb et al., 2018; Savinelli et al., 2020; Tang et al., 2021). Globally, coral reefs are under threat due to the combined effects of climate change and chronic anthropogenic disturbances (e.g., overfishing, coastal

development, pollution) (Bellwood et al., 2019; Eakin et al., 2019), causing widespread coral mortality and disrupting ecosystem functioning (Hughes et al., 2019). Similarly, coral reefs in India are experiencing severe stress because of ongoing climate change and intensified environmental degradation prompted by human activities (De et al., 2021a; Nanajkar et al., 2019), which challenges the resilience of reef ecosystems and allied socioecological stability (De et al., 2017, 2020a). As one of the fastest-growing economies, India has witnessed significant growth in the production and consumption of plastic materials (Banerjee et al., 2013), which is expected to increase in the future (Bhattacharya et al., 2018). Consequently, Indian coasts accumulate considerable quantities of plastic debris (Kaladharan et al., 2017; Veerasingam et al., 2020). In the densely populated Indian coasts, pressure toward development and growth is immense, resulting in unabated littering and the release of debris that ultimately reaches the nearshore marine environment (Shaikh and Shaikh, 2021). Taking cognizance of the status, the Govt. of India had to launch the 'National Cleanliness Mission' to manage pollution to hygiene while strengthening the legal framework (GOI MOEFCC, 2021). Jambeck et al., (2015) ranked India at 12th in terms of plastic litter production and noted that 87% of plastic waste in India escapes the management framework, while 0.09 - 0.24 million metric tons enter the seas. However, the impact of the increasing debris on marine ecosystems in India is far from fully quantified (Ranjani et al., 2021). A large number of marine debris in Indian seas may pose an additional stressor that may cause adverse effects on corals (Patterson Edward et al., 2020; Patterson et al., 2020). Despite the increasing amount of marine debris pollution, sparse information is available on the transport, accumulation, distribution, and possible sources on the Indian coast and their impact on the coral ecosystems (Patterson Edward et al., 2020; Patterson et al., 2020).

The patchy distribution of hermatypic corals along the eastern coast of the Arabian Sea renders important traits of the population such as thermal tolerance and survival under harsh conditions (De et al., 2020b, 2021a). However, an information gap still exists on the ecological status and the potential threats from marine debris pollution in these coral habitats. The current work quantifies the occurrence of marine debris in a rocky reef covered by hermatypic corals in the highly urbanized Mumbai coast, along with the health status of both corals and their environment. Our study aims to address the following questions: 1) What is the abundance and composition of marine debris in the highly urbanized coastline of Mumbai megacity? 2) What are their probable sources? And (iii) What impact do they pose on fragile corals? We used numerical modeling, and particle tracking approaches to understand the influence of tidal currents, wind, and hydrodynamics on marine debris accumulation and transportation. Based on the density of marine debris, we also attempted to assess the quality of beach cleanliness by computing different beach quality indices (Marin et al., 2019). We further discuss

the need for the management and mitigation of marine debris pollution in India and other countries and how to safeguard coastal health, including fragile coral habitats.

2. Materials and methods:

2.1. Study Site:

The present study area (Mumbai) lies on the central-eastern coast of the Arabian Sea and is one of the largest megacities in India, with an area of approximately 437.71 km². Mumbai is one of the world's most populous metropolitan cities and the economic capital of India. The Mumbai coast has been under the collective pressure of increasing urbanization, industrialization, and population growth (Kamble and Vijay, 2011). The coastal seawater quality of the Mumbai coast is deteriorating rapidly due to the discharge of partially treated industrial effluents and domestic sewage from different points, and non-point sources (Vijay et al., 2015), which finally enter the shelf in the region. An extensive field survey was carried out at five locations on the intertidal region (Navy Nagar) during the fair-weather season in November-December 2020 (Supplementary Fig. 1). The present study site is located at the extreme south promontory of Mumbai city, at the mouth of Thane Creek, proximal to Jawaharlal Nehru Port (~10 km)- India's largest container port; hence, it is subjected to continuous anthropogenic pressure. Tides in this region are mixed semidiurnal type with an average maximum range of 5 m during spring and 3 m during neap at Apollo Bandar. The intertidal area of this region is surrounded by rocky reefs, composed of consolidated and unconsolidated boulders intermingled with loose rocks, sand, and gravel.

2.2. Survey method for assessment of coral abundance and health

In the present study, belt transects measuring 20 m long × 1 m width were laid perpendicular to the shoreline in the intertidal coral habitat for coral health assessment (English et al., 1997). A total of five locations were evaluated, and three replicate transects were made at each location. Transect lines were laid at approximately 10 m distance from each other. All coral colonies fell within the belt transect were identified at the genera level and enumerated. Photographs of corals and marine debris were taken and used to confirm the *in-situ* identification. Each of the coral colonies falling within transects was carefully examined for the occurrence of the following categories: (i) coral-marine debris contacts, (ii) symptoms of bleaching, and (iii) sediment deposition-mediated coral damage. The prevalence of impacted coral colonies was computed by the following formula and presented as a percentage.

$$\text{Prevalence of affected coral colonies} = \frac{\text{Number of affected colonies}}{\text{Total number of colonies in transect}} \times 100$$

Live coral cover was analyzed using the photo quadrat method described by English et al. (1997). Square-shaped quadrates of 1 m² area (n=5) were placed at every 5 m distance on the 20 m transect tape, and photographs were taken. The area coverage of each coral colony was enumerated by using the ImageJ software. Then, all the measurements were taken in cm² and the coral area coverage was expressed in cm²/m².

2.3. Survey method for quantification, typology assessment, and source identification of marine debris

Marine debris sampling was carried out during low tide, as debris accumulated in the intertidal zone. Debris were quantified using 15 belt transects (three transects at each location) measuring 20 m x 1 m area. All visually identifiable marine debris >2.5 cm (including caps, lids, and cigarette butts) within each transect area were enumerated and hand-picked in non-plastic bags for laboratory analysis (UNEP/MAP, 2015). Once in the laboratory, all the debris items were washed, air-dried, and the segregation of individual items was carried out. The collected debris were assorted into six categories according to the OSPAR guidelines, i.e., plastics, glass, metals, rubber, cloth/fabrics, and lumbers (Ospar, 2010). The plastic debris were characterized based on its functional origin following the standard protocol by Lippiatt et al., (2013), such as bags, cups, wrappers, bottles, etc. The density of marine debris was calculated following Lippiatt et al., (2013) and was recorded as number of items/m².

$$\text{Density of marine debris} = \frac{\text{Number of debris items counted in each transect}}{\text{Length (m)} \times \text{Width(m) of transect}}$$

The probable sources of the collected marine debris items were identified by employing the attribution-by-litter type method described by (Tudor and Williams, 2004). Marine debris items were characterized into the following groups based on probable sources: (i) land-based, (ii) sea-based, (iii) transboundary, and (iv) uncertain origin. Land-based marine debris consists of litter from user and industry discards transported into marine environments via river and drainage discharge, run-off, or wind action (Veiga et al., 2016). Sea-based debris includes litter from aquaculture, fishing, shipping, and marine industrial activities that drifted and deposited on the coast. The debris of uncertain origin has no label for suitable source identification (Galgani et al., 2015).

2.4. Model description for hydrodynamics and particle tracking

A coupled hydrodynamic-particle tracking model was run to determine the fate and transport of the plastic particles in the study region. The model is based on the two-dimensional depth-averaged shallow-water equations for continuity and momentum balance (Stoker, 1957). These equations have

been used to obtain the tidal circulation in the study region (Naidu and Sarma, 2001). The following equations are used for the model simulations:

2.4.1. Continuity and mass balance

$$\frac{\partial \eta}{\partial t} + \frac{\partial(HU)}{\partial x} + \frac{\partial(HV)}{\partial y} = Hm_v \quad \text{-----(1)}$$

where $\eta=H - h$, t =time coordinate, x, y = set of horizontal, mutually orthogonal Cartesian coordinates; H =total instantaneous water depth; and U, V =horizontal velocity components in x and y direction, respectively; m_v =vertically integrated average rate of mass injection or withdrawal of fluid per unit volume divided by the fluid density; and h =depth of water measured positively downwards from the reference datum plane.

2.4.2. Momentum balance equations

The vertically integrated momentum balance equations for a shallow water body are given by;

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} = -g \frac{\partial \eta}{\partial x} - \frac{1}{\rho} \frac{\partial P_a}{\partial x} + \Omega V + \frac{C_w W^2}{H} \cos \theta - \frac{C_f (U^2 + V^2)^{\frac{1}{2}}}{H} U + S_u \quad \text{----- (2)}$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} = -g \frac{\partial \eta}{\partial y} - \frac{1}{\rho} \frac{\partial P_a}{\partial y} - \Omega U + \frac{C_w W^2}{H} \sin \theta - \frac{C_f (U^2 + V^2)^{\frac{1}{2}}}{H} V + S_v \quad \text{----- (3)}$$

where g =acceleration due to gravity; η =tide elevation; ρ =fluid mass density; P_a = atmospheric pressure; Ω =Coriolis parameter; C_w =wind stress coefficient; W =wind speed; θ =wind angle measured from the positive direction of x toward the positive direction of y -axis; C_f =bottom friction coefficient; and S_u and S_v = average rate of momentum generated or dissipated per unit volume derived by the mass density of water in the x and y directions, respectively.

2.4.3. Lagrangian circulation

Lagrangian circulation was analyzed using a particle tracking method by releasing particles at a fixed time, tracking the path of these particles and the time they reach the boundary. It is performed in 2-D mode, using a 4th order Runge–Kutta (RK) scheme for particle advection. Lagrangian circulation was calculated using the following equation (Gong et al., 2008) .

$$\bar{x}(t + \Delta t) = \bar{x}(t) + U * \Delta t \quad (4)$$

where \bar{x} is the particle position, and Δt = time step. In this work, the diffusion term was neglected.

The model has also been used in several other locations on the west coast of India (Mitra et al., 2020; Naidu et al., 2016). The grid resolution was fixed to 500 m for model calibration. The model is barotropic and neglects horizon diffusion in the momentum balance equation since its contribution was negligible compared to the other terms. The eastern boundary of the model domain was closed, and boundary tides were applied at the northern, western, and southern boundaries. Because of the smaller water depth at the study location, the application of a depth-averaged numerical model is well justified.

2.4.4. Calibration and validation of hydrodynamic model

The model was calibrated and validated with the observed tide and current data for the successive application of the Lagrangian transport of marine debris. Boundary tides for model calibration and validation were specified at the southern, northern, and western periphery of the model domain. The modeled tide and current data were compared with field data collected at Colaba. The one-day model output was discarded due to the model instability during the first day of simulation. The model was run by varying the bottom friction coefficient, K . The modeled tides and currents were stored at 10-minute intervals and were compared with field observations. These datasets were in fair agreement with the observations and with average correlation coefficients of +0.98 and +0.65 for tides and currents, respectively (Supplementary Fig. 2).

2.5. Wind Data

The seasonal wind pattern was identified to determine the plausible correlation with debris transport in and around the study region. Wind for the entire study area at 10 m height, in 6-hour intervals, was obtained from the NOAA-CIRES Climate Diagnostics Centre, Boulder, Colorado (<http://www.cdc.noaa.gov>) (Kalnay et al., 1996).

2.6. Data analysis:

The datasets were stated as means \pm standard error (SE), if not noted otherwise.

2.6.1. Beach quality indexes (BQI)

The environmental quality of the study area was determined by using three indexes, based on the density and character of the litter, as follows:

Clean coast index (CCI)

The CCI is calculated to assess the cleanliness state of the studied beach from plastic debris accumulation (Alkalay et al., 2007). Based on the number of plastic debris, the values of the CCI scale represent the beach cleanliness state as follows: (i) 0-2: very clean, (ii) 2-5: clean, (iii) 5-10: moderately clean, (iv) 10-20: dirty, and (v) >20: extremely dirty (Alkalay et al., 2007; Kalnasa et al., 2019).

$$CCI = \frac{\text{Number of plastic items counted in transect area}}{\text{Total sampled area}} \times K$$

where K denotes a correction coefficient set at 20.

General index (GI)

The application and principle of the GI is analogous to the CCI. However, it considers every type of marine debris irrespective of plastic litters (Marin et al., 2019).

Hazardous Items Index (HII)

The HII is applied to assess the abundance of potentially hazardous waste in the beach environment. For example, sharp metal and glass items that can potentially inflict injury to beach users, and toxic waste (medical waste, sanitary waste, and cigarettes) may induce physiological harm (Rangel-Buitrago et al., 2019). HII encompasses five categories (Supplementary Table 1).

$$HII = \frac{\frac{\sum \text{Hazardous debris items counted in transects}}{\log_{10} \sum \text{total debris items}}}{\text{Total sampled area}} \times K$$

where K denotes a correction coefficient set at 20.

2.6.2. Marine debris diversity indices

Diversity indices were computed to investigate the structure in terms of items identity and their relative abundances of marine debris assemblages (Battisti et al., 2018). Shannon-Wiener diversity index (H') and Pieoul's evenness index (J') were computed using the PRIMER 6 software package (Clarke and Gorley, 2006).

3. Results

3.1. Coral communities of Mumbai coast

A total of 445 coral colonies belonging to seven genera and five families were found during the present study (Supplementary Fig. 3). The coral community was composed of encrusting and massive hermatypic corals. *Pseudosiderastrea* dominated the overall coral community, contributing 66.97% to the total generic composition of corals with a density of $0.99 \pm 0.16 \text{ m}^{-2}$, followed by *Bernardpora* (16.93%) with a density of $0.25 \pm 0.07 \text{ m}^{-2}$. Corals of the genera *Porites*, *Favites*, *Polycyanthus*, *Paracanthus*, *Cladangia* contribute 16.4% to the total generic composition of corals. The average live coral cover was $22.18 \text{ cm}^2 \text{ m}^{-2}$, wherein most of the area consisted of rocky substrate. Rocks were found to be smothered by sediment deposition and turf algae. We found that approximately 9.21% (n=41) of live coral colonies were in direct contact with marine debris. Among the corals interacting with marine debris, 21.95% (n=9) of colonies showed signs of partial bleaching or paling, representing

2.02% of the total colonies of the study area. Our results also found that an average of 38.2% (n=170) of the live corals seemed to be negatively impacted by sedimentation.

3.2. Abundance, typology and source identification of marine debris

Our results confirm the presence of marine debris throughout the intertidal region of the study area. A total of 481 macro-marine debris items were accounted. Average density of marine debris was estimated at 1.60 ± 0.13 items/m². Plastic materials were the most abundant of all debris registered in the study area, comprising 91.27% of the total debris, while other components were glass (3%), metal (2%), and fabrics (2.5%) (Fig.1A). The average density of plastic items was estimated at 1.46 ± 0.14 items/m². Sanitary waste, including sanitary pads and diapers (0.42% of total marine debris) and processed woods (0.42% of total marine debris) were also found in paltry amounts. Photographs of the marine debris encountered are shown in Supplementary Fig. 4A-L.

Furthermore, plastic debris was categorized into seven categories, i.e., bottle, bottle cap, bag, wrapper, fishing net, fragments, and tubes. Plastic bags alone contributed 46.99% of the overall composition of plastic debris, followed by wrappers (23.49%), and fragments (11.85%) (Fig. 1B). The Shannon-Wiener diversity index and Pielou's evenness index ranged from 1-1.9 and 0.6-0.9, respectively (Fig. 2A). The present study revealed that over 59% of marine debris recorded were classified as land-based sources, followed by unclear origin (39%), and 2% belonged to sea-originated sources (1C-D).

3.3. Beach quality assessment

During the sampling period, the mean CCI value recorded was 29.27 ± 2.73 , range [18, 42]. According to CCI values, the studied rocky beaches could be classified as "extremely dirty" (Fig. 2B). Furthermore, the GI value was computed as 32.07 ± 2.68 , range [21, 41], which also indicates that the studied area fell under the "extremely dirty" category (Fig. 2B). The hazardous litter items constituted 5.82% of the total items collected (28 items of 481 marine debris items collected) during this study. The mean HII was recorded as 2.76 ± 0.64 , range [0, 9.34], which falls under the "class III" category, indicating a considerable amount of hazardous litter present on the beach (Fig.2C). The BQIs values highlighted that the studied area is under moderate risk from hazardous debris and at high risk by other types of marine debris as suggested by the GI and CCI.

3.4. Fate and transport of the marine debris

3.4.1. Hydrodynamics of the region

The coastal water off Mumbai is strongly influenced by the Indian monsoon system. Therefore, the wind, currents, and tidal patterns were identified as drivers of marine debris distribution. During the summer monsoon, the South-southwest winds prevail over this region (Fig. 3D), while north-northeast

winds dominate during the winter monsoon (Fig. 3E). The magnitude of the southwest-monsoonal wind was found to be maximum (>7 m/s) (Fig. 3D). Strong monthly averaged surface current vectors are observed along the nearshore water (Fig. 3A-C). The maximum monthly mean surface current speeds were 1.5 m/s, 2.0 m/s, and 1.8 m/s occurring in the pre-monsoon, southwest-monsoon, and northeast-monsoon seasons, respectively. Overall, the area experiences strong seasonality in the mean circulation pattern. During the southwest monsoon, the flow is southward mostly everywhere (Fig. 3A), whereas the current is northward during post-monsoon (Fig. 3B). Tides from the northern boundary play a significant role in these two seasons. However, during the pre-monsoon, there is a weakening of the northern boundary tide, and as a result, the eastern counterpart dominates (Fig. 3C). Simulations have revealed prominent spatiotemporal variability in water circulations around Mumbai due to the combined effect of bathymetry, tides, and seasonally reversing winds.

3.4.2. Lagrangian circulation

The Lagrangian connectivity of the study area elucidates mostly smooth trajectories in this region, and the average trails are presented in Supplementary Fig. 5A. Particles released from the northern region easily travel toward the south, and most of them escaped within the first ten days of simulation. During the monsoon, the system tends to flush out the particles mainly due to the combined action of tides and wind. In contrast, during the pre-monsoon season, it was hard for the particles to escape the domain, and a significant number of particles remained inside the system. The particles released in Thane Creek circulated inside for a considerable amount of time and finally came out of the creek after one month of simulation. A net southward flow was observed in the domain during the monsoon. Very few particles released in the nearshore region of the northern part of Mumbai moved southward and proceeded inside Thane Creek.

Numerical particle tracking experiments were continued by simulating the release of particles as sources of marine debris. The results were extracted after 10, 20, and 30 days of simulation (Fig. 3G-D). After ten days of simulation, the particles were primarily concentrated near the source region (Fig. 3G), which further dispersed after 20 days along the coastline (Fig. 3H), and the advection was found to be maximum after one month of simulation (Fig. 3I) leading to the decrease in the particle abundance near the source. The alongshore movement of particles in each of the experiments was due to the combined effect of the parallel running bathymetry contours along with the effects of tides and winds (Supplementary Fig. 5B). The northern boundary tide was found to dominate in each seasonal or tidal condition leading to larger southward advection. In contrast, the comparatively weaker southern boundary tide results in lower northward propagation of the particles. As shown in Supplementary Fig.

5A-B, the sea-surface current prevailing in the region might have led to the alongshore movement of the debris and their deployment in the nearshore region.

4. Discussion

4.1. Coral community structure in Mumbai coast

The present study demonstrates that hard corals in the intertidal coastline in Mumbai are exposed to marine debris. This study reports seven stony coral genera, indicating that the diversity of hermatypic corals in the Mumbai coast is comparatively low in a regional context. For example, in the southern part of the study area, the Malvan Marine Sanctuary (MMS) harbors 17 species of hard corals (De et al., 2021b), while in the northern part of the area, coral reefs of the Gulf of Kachchh (GoK) comprise 76 species of hard coral (De et al., 2020b). Reefs in close proximity to the urbanized coastline are characterized by less live coral cover and lower species heterogeneity than those away from the urban area (Heery et al., 2018; Ng et al., 2020). GoK and MMS could collectively provide the larval supply to Mumbai's rocky shore, where environmental conditions may favor larval recruitment and growth for stress-resilient species. The settlement of coral larvae and the distribution of corals largely depend on their substrate (Baird et al., 2003), and the presence of hard basaltic substrate along the Mumbai coast is suitable for coral larval settlement. The nearshore patch coral reefs on the central west coast of India are highly threatened due to multiple stressors, including climate change-driven coral bleaching events and coastal development activities (De et al., 2021a, 2020a). Furthermore, corals are regularly exposed to salinity fluctuations from monsoonal dilution of seawater, and high sedimentation results in increased turbidity from river discharge, organic matter enrichment, inorganic pollution, commercial fishing, and recreational diving activities (De et al., 2020b). Therefore, the occurrence of live corals in the present study area is important, as they manage to thrive in the face of wide variations in salinity, turbidity, and temperature regime.

4.2. Origins and fates of marine debris in the study area

The present study area is located adjacent to Thane Creek, which carries large quantities of anthropogenic litter, that is discharged in the coastal water of Mumbai (Kantharajan et al., 2018; Singare, 2012). The Mumbai urban area pours a major (Ulhas River) and four minor westward flowing rivers (Dahisar, Poisar, Oshiwara, and Mithi). These form a large estuary with mangroves and mudflats. Being landlocked by the hills of the Western Ghats on the east, the solid waste generated by the city itself is the major source of pollution in the adjacent coastal area (Kaladharan et al., 2020; Selvam et al., 2021a). The fate of marine debris is primarily dependent on the hydrodynamic conditions (such as tide, current and wind) of that region (Andrades et al., 2018; Auta et al., 2017). Our results

show that due to the nearshore morpho-dynamic of this region, marine debris could be advected toward the north or south within a month or more, depending upon the seasonal hydrodynamic. During the summer and winter monsoons, when the net water flow is towards the south, there is a possibility of the southward transport of marine debris. In contrast, during the pre-monsoon, debris circulate in the coastal waters of Mumbai due to the weakening of the current speed in the northern region. Our simulations of particle tracking model results indicate that the southern region of the domain is more prone to marine debris accumulation in the long run due to the alongshore current of this region. The Lagrangian track results displayed horizontal advection in the northern region of the model domain in every season. Due to the alongshore current off Mumbai, the north-south advection of particles was noticeable. The results also surmised an overall southward movement of the water parcel, reported earlier along the entire west coast, predominantly in the summer season (Shenoi and Antony, 1991). However, during the non-monsoonal months, the northern boundary tide deteriorates, leading to net water movement in and around the coast. High tidal currents and high wind speed collectively help the advection of marine debris in coastal waters. Jayasiri et al., (2013) also suggested that tides, currents, and waves bring the litters to the beaches along the Mumbai coast. The Lagrangian track indicates the alongshore drift of the released particles, with the possible drift of the marine debris in and around Mumbai (Fig.3 G-I). The model indicates that the city-generated waste is re-circulated and re-deposited. The alongshore dispersion of marine debris from the source region along with recirculation and redeposition would not only lead to difficulty for mitigation measures, but could also be potentially hazardous in the long run.

The present study revealed that the concentration of marine debris in the study area (1.67 ± 0.19 items/m²) is higher than the global mean concentration of 1.0 debris items/m² (Galgani et al., 2015). Our results also show that plastics contribute predominantly (91%) to the marine debris pollution of the Mumbai coast, which is significantly higher than the global average of 75% (Galgani et al., 2013). Our results corroborated those of a previous study, which reported that plastic items contributed 87.1% to the total marine debris in the coastal water of Mumbai (Selvam et al., 2021b). Recent studies from Mumbai's mangrove ecosystems reported a high abundance of surficial and trapped marine debris (8.82 ± 3.47 items/m²), primarily composed of plastic items (43.7%) (Selvam et al., 2021a). The marine debris on the Mumbai coast is primarily composed of single-use plastic bags, plastic wrappers, and plastic fragments (Fig. 1A-B). Reportedly, the major contributor to litter in Mumbai was land-based sources (Fig. 1C-D), reflecting inadequate disposal practices and littering behavior (Jayasiri et al., 2013a). A recent study identified that the land-based and recreational activities as primary sources (88.6%) of marine debris pollution in Mumbai coast, followed by sea-based activities (5.66%) (Selvam

et al., 2021b). Public negligence, intentional and unintentional discards of solid waste in combination with inadequate municipal waste management from several points and non-point sources could contribute to the occurrence of land-based marine debris items (Tudor and Williams, 2004). The presence of sea-originated marine debris (2%), mainly represented by nylon fishing nets, could be related to intensive fishing activities in the coastal water of Mumbai (Selvam et al., 2021b). Furthermore, the Thane creek and coastal water of Mumbai is known for intensive shipping and fishing activities, which could also be responsible for sea-based marine debris.

4.3. Implications of marine debris pollution on Mumbai's coral ecosystem

Our results show that the prevalence of direct contact between live corals and marine debris was 9.21%, which is higher than the Gulf of Mannar coral reefs (3.28%) (Patterson Edward et al., 2020). Notably, abandoned or lost fishing nets contributed to 1.80% of debris items in the study area (Fig. 1B). Fishing and related activities are significant contributors to marine debris to Indian coral reefs (Patterson Edward et al., 2020). Abandoned fishing gear and nets pose severe threats to corals and marine organisms as it entangles, leading to physical damage and mortality (Ballesteros et al., 2018). The sheer nature of coral morphology and protrusions make it vulnerable to entanglement with marine debris, especially large thin plastic sheets. The hydrodynamic force that brings the debris and locks them into corals may not necessarily decouple it once settled. Recent studies have revealed that coral reefs act as sinks of global plastic pollution through adhesion and suspension-feeding (Martin et al., 2019). Our results show partial bleaching of live coral colonies in contact with marine debris. Studies have shown the direct impact of plastics debris and microplastics on reef corals in the form of coral bleaching, diseases and tissue necrosis (Lamb et al., 2018; Reichert et al., 2018; Syakti et al., 2019). Marine debris impairs coral health by inflicting mechanical injury to coral tissue, thereby reducing growth and facilitating the advent of space competitors and invasive species (Al-Khayat et al., 2021; Reichert et al., 2019, 2018). A relationship between marine debris and diseases in corals has also been deciphered (Lamb et al., 2018). Experimental studies demonstrated that microplastics debris ingested by coral were retained in the tissue and skeleton, which may cause toxicity and facilitate trophic transfer (Allen et al., 2017; Hankins et al., 2018; Syakti et al., 2019). Additionally, plastic debris, including microplastics, was linked to impaired fertilization (Berry et al., 2019), reduced calcification and growth (Chapron et al., 2018; Hankins et al., 2021; Reichert et al., 2019), affected immune responses (Tang et al., 2018), disrupted food intake (Mouchi et al., 2019; Savinelli et al., 2020), altered photosynthetic performance (Syakti et al., 2019), and disrupted host-symbiont relationship in corals (Lanctôt et al., 2020; Tang et al., 2021). Several studies have reported the occurrence of marine debris

in Indian coral reefs (Supplementary Table 2); however, its impact on coral physiology and the community is not fully understood yet.

4.4.Perspective on the management of marine debris in the Mumbai coast

According to the calculated BQIs, the studied coastal region of Mumbai falls in the high-risk category pertaining to litter pollution and hazardous litter abundance. The CCI and GI suggest that Mumbai's beach fell under the "extremely dirty" category (Fig.2B-C). Along the West coast of India, the Mumbai coast had higher marine debris pollution (Tiwari et al., 2019), with a high proportion of plastic marine debris on recreational beaches (Jayasiri et al., 2013a, 2013b). As per HII, the study area falls under the class III category, indicating considerable quantities of hazardous marine debris on the beach. Hazardous marine debris on public beaches inflicts injuries from sharp objects (metal/ glass) and may spread disease and pathogens through exposure to medical and sanitary debris (Rangel-Buitrago et al., 2019; Williams et al., 2016). Considering BQIs in environmental health assessments could be a helpful tool in coastal management of marine debris and assessing the efficiency of existing waste management measures (Semeoshenkova et al., 2017).

Mumbai is the 7th largest city globally and has a population of 18 million (Census, 2011). The city produces approximately 700 mt plastic waste daily, ranking one of India's most prominent plastic waste generating cities (PIB Mumbai, 2020). Therefore, detailed mapping and understanding of the sources and nature of waste material is a prerequisite for preventing and mitigating environmental pressure and impact by plastic marine debris (de Ramos et al., 2021). The rapid development of this growing coastal city is not coupled to the implementation of adequate waste management. Unmanaged solid waste enters into drainages, river channels, and coastal areas ultimately becoming marine debris, as highlighted in the present study. Recent studies noted a high abundance of trapped debris in Mumbai's mangrove (Kantharajan et al., 2018; Selvam et al., 2021a). Selvam et al., (2021b) reported high abundance of marine debris on the coastal seabed. Therefore, in the case of Mumbai, conservation of coastal marine habitats depends upon adequate management of solid waste in the neighboring urban region. Actually, a considerable amount of solid waste often escapes the management process, primarily due to callus discard by the public, resulting in solid waste reaching the marine environments (Galgani et al., 2021; Li et al., 2016). Waste management of densely populated megacities in developing nations is a multilayered, multifaceted problem that requires an integrated management approach (Abalansa et al., 2020; Agamuthu et al., 2019). Such an approach demands the involvement of several stakeholders to tackle problems at each tier and must be dealt with independently (Löhr et al., 2017). A robust and comprehensive policy needs to be formulated that addresses an integrated socio-environmental approach specifically customized for parameters in Mumbai schematically

represented in Fig. 4. Increasing public funds is needed, with the involvement of more workforce and multistakeholder participation. Although the principle of '4R's: Reduce (both production and use), Reuse, Recycle and Recover can be helpful, its implementation in megacities require innovative and bold strategies to tackle solid waste (Prata et al., 2019). Increased taxation and large dedicated waste processing sites will contribute to the required measures (Convery et al., 2007; Prata et al., 2019). Efficient and innovative local management practices are needed to restrict the introduction of plastic waste into waterways (Löhr et al., 2017; Prata et al., 2019). Furthermore, large-scale clean-up campaigns before the monsoon season could reduce the marine debris through terrigenous run-off, since the monsoon triggers debris transport along the coastline. Considering the population of Mumbai and the level of awareness, clean-up campaigns engaging different stakeholders (industry, regulatory authorities, NGOs, and public) can be an effective management strategy specifically for open areas, beaches, and other accessible intertidal areas (Veiga et al., 2016). Furthermore, adopting a circular economy at the regional level for the long-term sustainability of specifically non-biodegradable waste could contribute to preserve coastal ecosystems (Frantzi et al., 2021).

4.5. Summary and conclusion

Notably, the highly urbanized coastal region of Mumbai harbors a great marine faunal diversity of conservation importance. However, coastal development, discharge of domestic sewage, industrial effluents, and solid waste in the studied area are probably the most severe local stressors for the intertidal coral communities. In recent years, Indian coral reefs have suffered mass mortality due to recurrent thermal bleaching events, significantly reducing live coral cover (Arora et al., 2021; De et al., 2017). Simultaneously, marine debris is emerging as an additional threat affecting corals in Indian coral reefs (Patterson Edward et al., 2020). The most dominant coral taxon found in this study was *Pseudosiderastrea tayamai*, classified in the near-threatened category according to the IUCN red list (Sheppard et al., 2008), which implies an urgent need for active conservation and management (Gaikwad et al., 2021). The present study provides some of the much-needed baseline information on anthropogenic environmental pollution by marine debris in the coral habitat of Mumbai. The obtained results call for a detailed study of the effects of marine debris on the recruitment, growth, and survival of corals, which might lead to better insight into the resilience of this coral community. Finally, well informed management and adequate measures for mitigating pollution by marine debris are required to provide a suitable environment to the otherwise sensible coral communities, such as the one studied along the coast of Mumbai, and other densely populated areas in developing nations.

Author statement

Kalyan De: Conceptualization, Methodology, Data curation, Writing - original draft, Writing – review & editing. **Sabyasachi Sautya:** Project administration, Resources, Writing – review & editing. **Santosh Gaikwad:** Data curation, Writing – review & editing. **Aditi Mitra:** Numerical modeling, Writing – review & editing. **Mandar Nanajkar:** Project administration, Writing – review & editing

Conflict of 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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Figures:

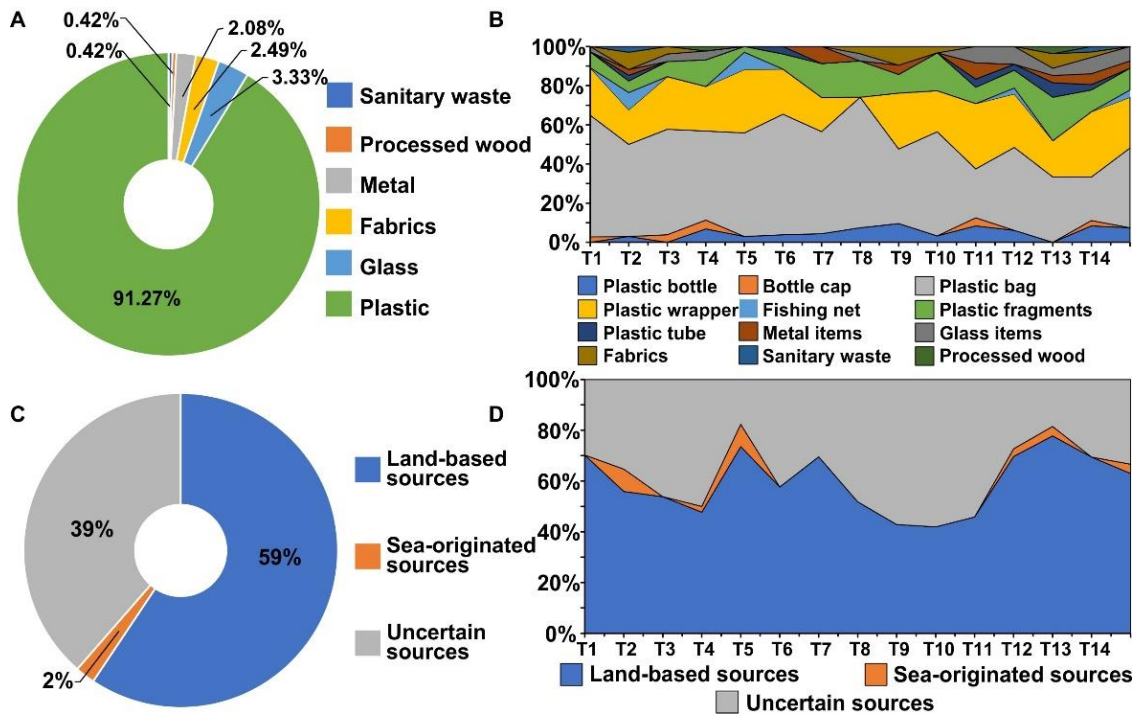


Fig. 1. Percentage composition of different marine debris parameters along the study area. A) Average percentage composition of major types of marine debris sampled; B) composition of various minor marine debris categories at each transect; C) average percentage composition of probable sources of MD; D) composition of probable sources of marine debris at each transect.

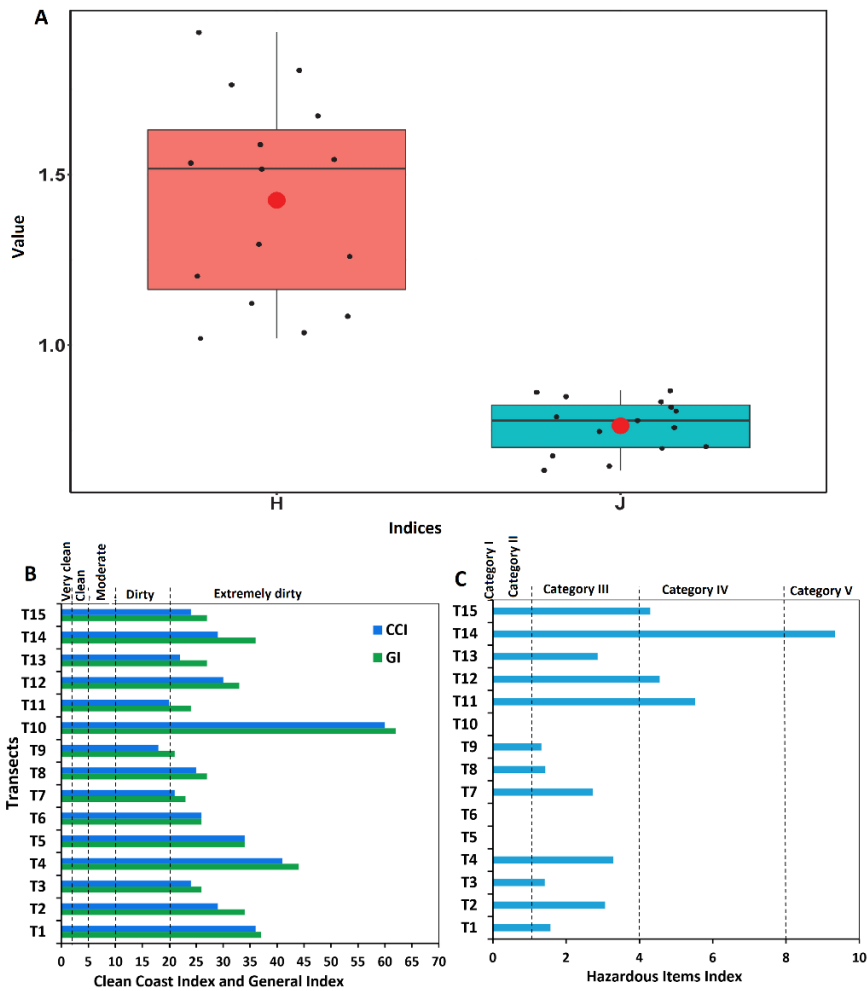


Fig. 2. (A) Shannon-Wiener (H) and Pieoul's evenness index (J) of marine debris. The red dot represents mean values. Beach quality indexes (BQIs) in the study area- (B) Clean Coast Index (CCI) and General Index (GI), (C) Hazardous Items Index (HII)

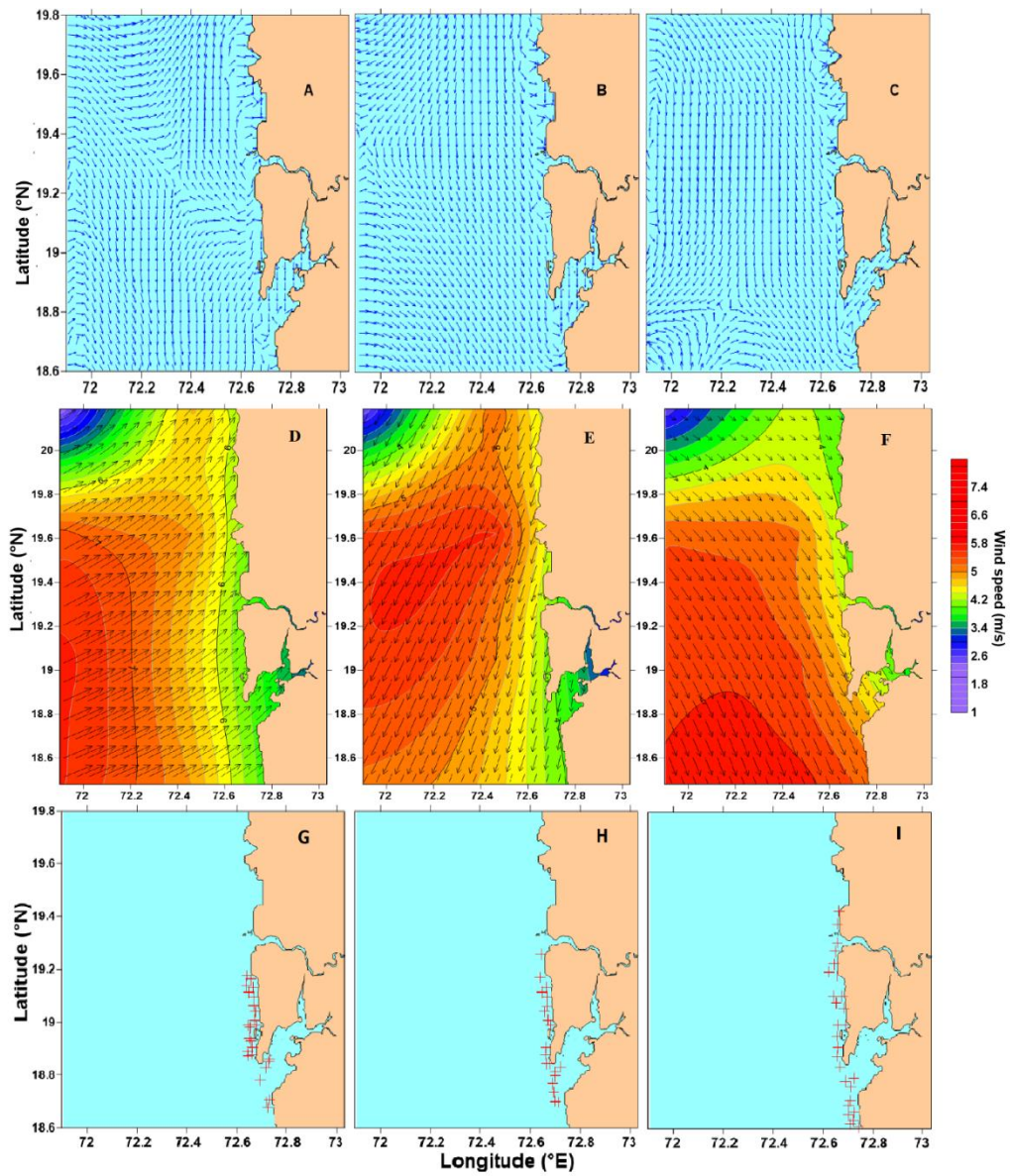


Fig. 3. Seasonal-averaged circulation during the- A) southwest monsoon, B) post-monsoon, C) pre-monsoon; and seasonal-averaged wind speed during- D) southwest monsoon, E) northeast-monsoon, F) pre-monsoon of Mumbai and the surrounding region. Prediction of trajectory and cumulative distribution of particles after- G) 10 days, H) 20 days, and I) 30 days of simulation

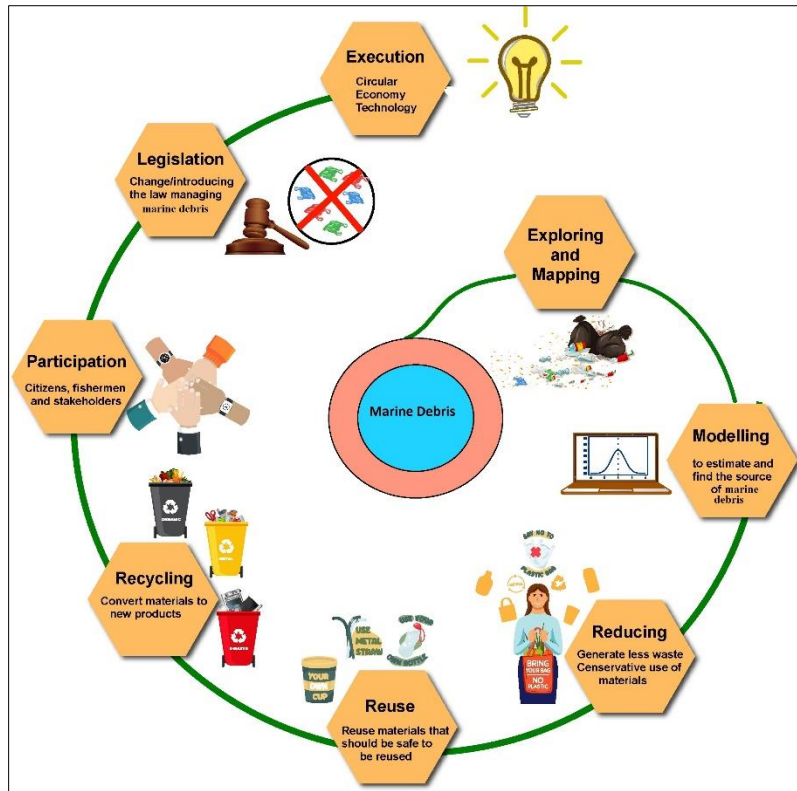


Fig. 4. Schematic representation of potential marine plastic debris management strategies

Supplementary material:

Supplementary File

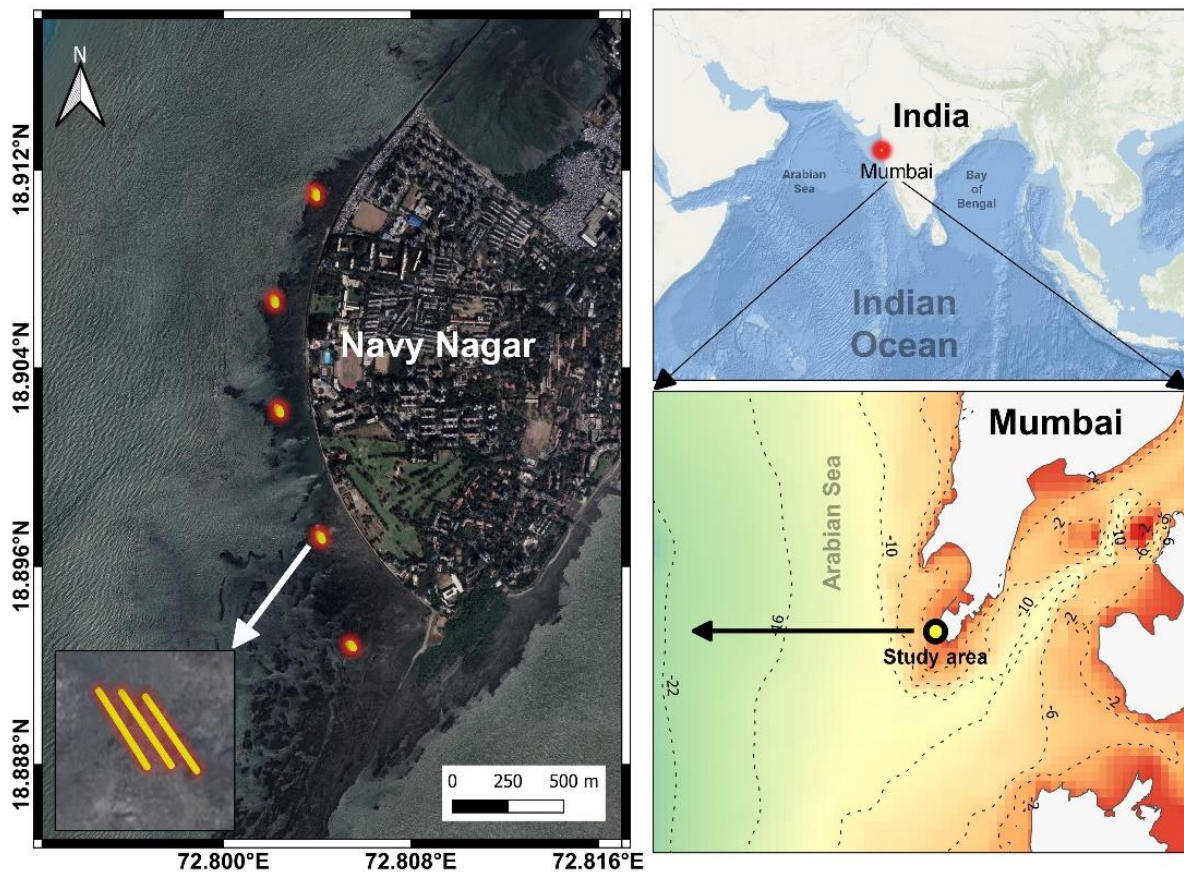
Characterization of anthropogenic marine macro-debris affecting coral habitat in the highly urbanized seascape of Mumbai megacity

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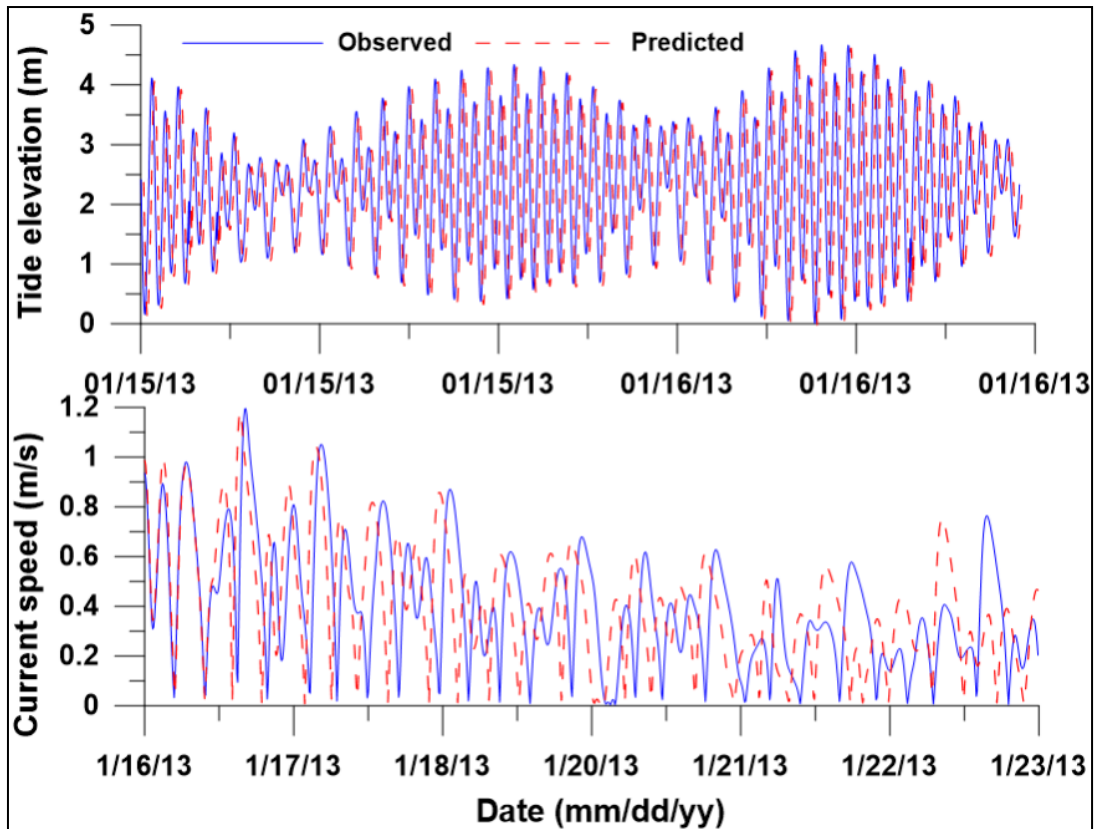
¹CSIR- National Institute of Oceanography, Dona Paula, Goa-403002, India.

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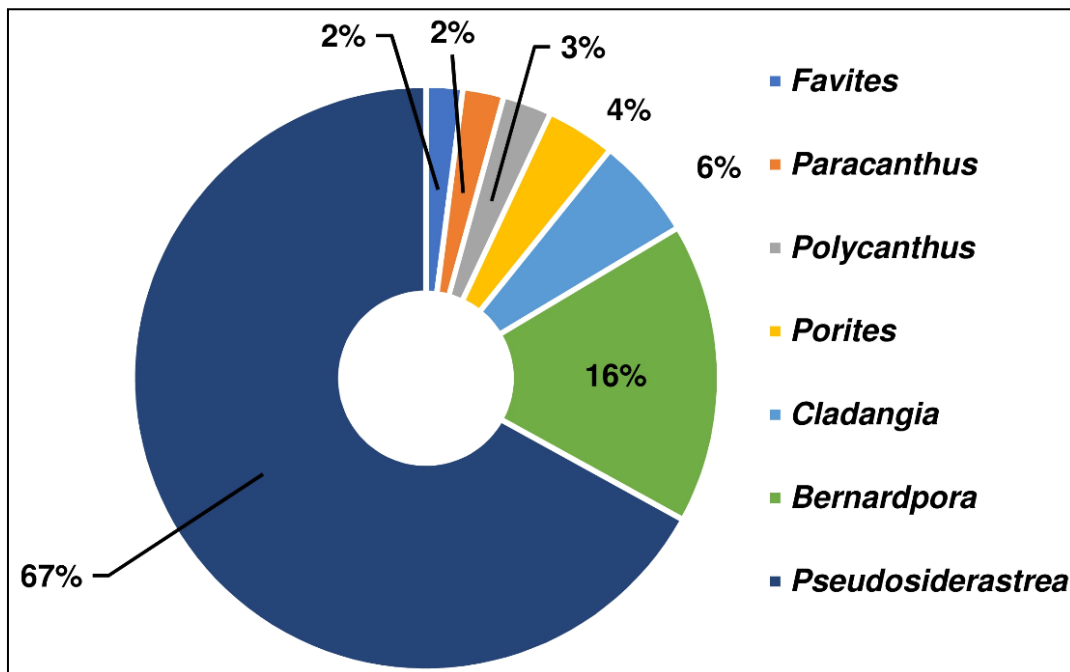
*Corresponding: sautya@nio.org



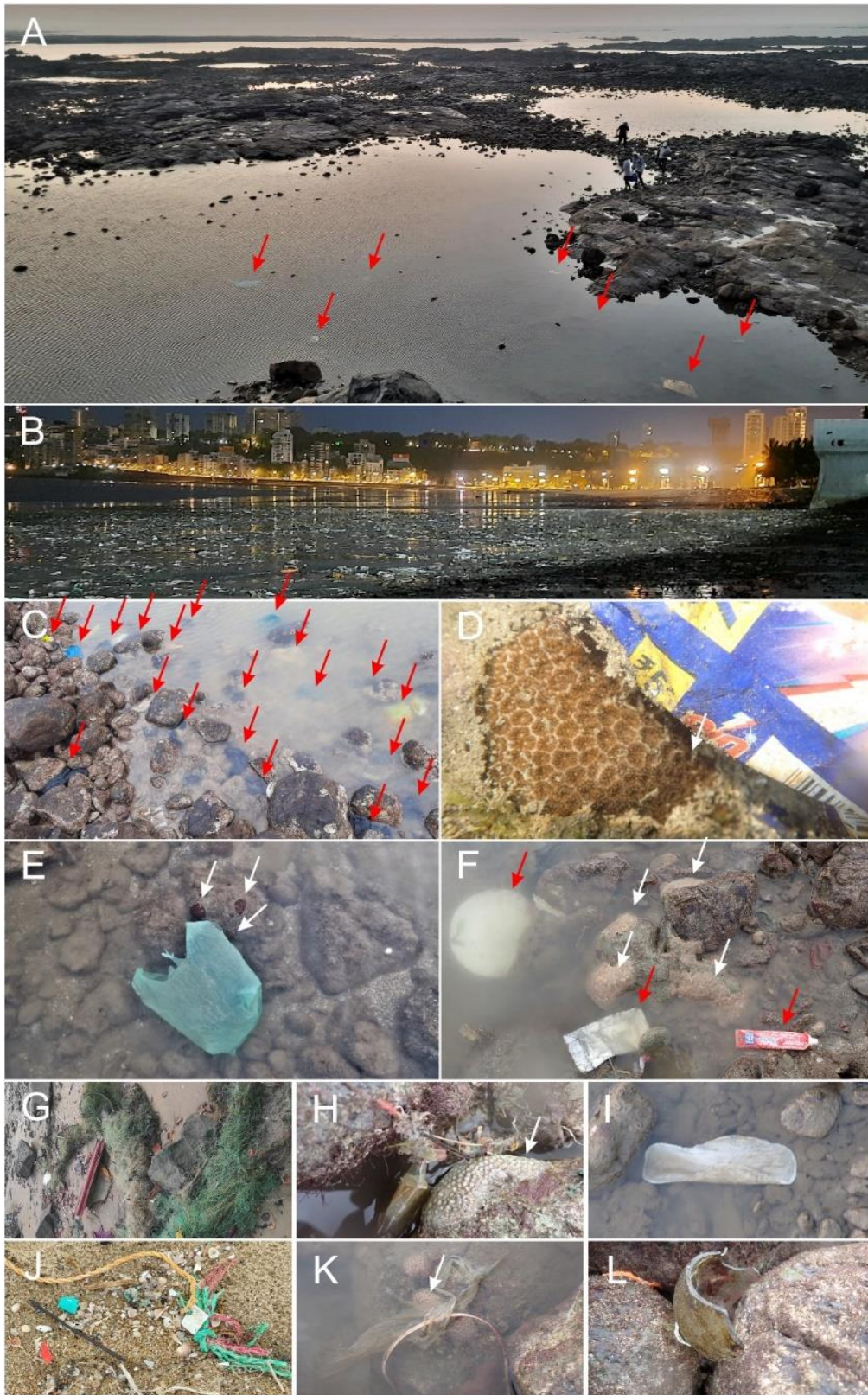
Supplementary Fig. 1. Geographic location and bathymetric map of the study site, Mumbai and surrounding region, Eastern Arabian Sea.



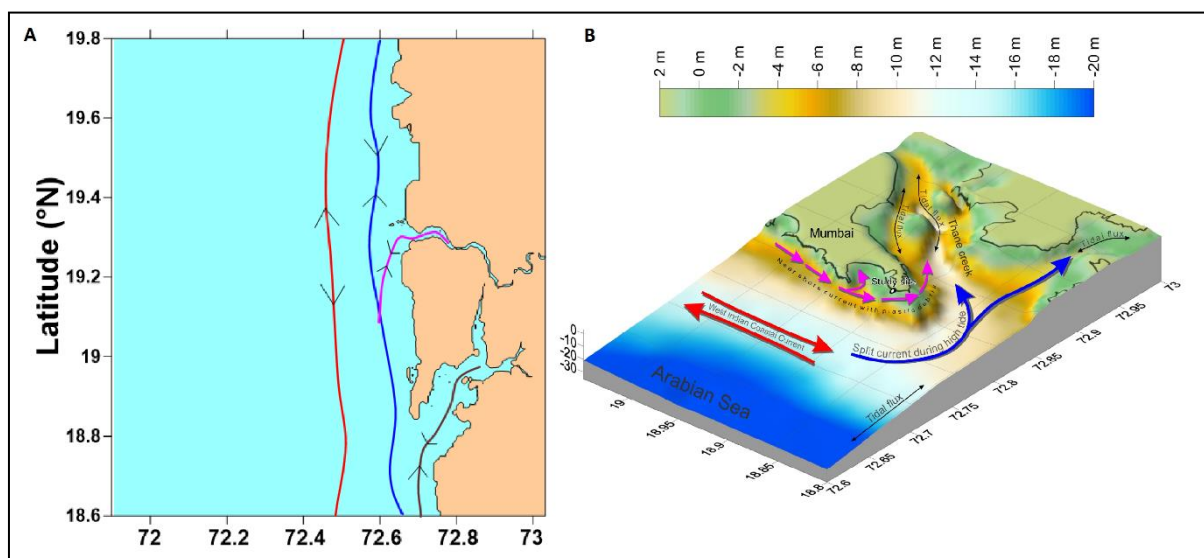
Supplementary Fig. 2. Calibration and validation of the numerical model with observed tide and current of this region.



Supplementary Fig. 3. Average percent composition of various coral genera recorded in the study area



Supplementary Fig. 4. Plastic junk in a highly susceptible environment of fragile urban coral ecosystem. A) habitat overview along with plastic debris at Navy Nagar, South Mumbai; B) stockpile of plastic and other debris along the sandy beach Girgaon Chawpatty, Mumbai; C-F) evidence of direct plastic landing in the vicinity or on the corals; G-L) different categories of MD observed within transect areas such as polythene bags, toothpaste tubes, fishing nets, nylon ropes, food wrappings, sanitary waste, and broken glass.



Supplementary Fig. 5. (A) Average Lagrangian particle trajectories of Mumbai and surrounding region, (B) A schematic model of average Lagrangian particle trajectories along West Indian Coastal Current (WICC) and split current entering inside the Thane creek ecosystems triggered by tidal flux at regional scale.

Supplementary Table 1. Hazardous Items Index (HII) classification (Rangel-Buitrago et al., 2019).

HII value	Category	Description
0	I	Number of hazardous marine debris is nil
0.1 - 1	II	Some hazardous marine debris is present
1.1 - 4	III	A considerable amount of hazardous marine debris is present
4.1 - 8	IV	A lot of hazardous marine debris items are present
>8	V	Most of the area is covered by hazardous marine debris

Supplementary Table 2: Studies on plastic litter pollution in Indian coral reef environments and potential impact

Reef location	Type of plastic litter	Density	Impacted species name	Harmful impact	Reference
Gulf of Mannar	Macroplastics (Nylon, Polyester, Polypropylene, Polyethylene)	No observation	<i>Porites</i> sp.	Coral's annual growth band impregnated by microplastics.	Krishnakumar al., 2021
Gulf of Mannar	Macroplastics Fishing nets (43.17 ± 5.48%), fishing traps (16.68 ± 4.01%), ropes (12.43 ± 0.2%), lines (8.05 ± 2.82%), other debris (19.66 ± 2.22%)	No observation	Prevalence of corals in contact with debris: <i>Acropora</i> (8.23 ± 1.29%), <i>Montipora</i> (4.63 ± 1.29%)	An area of 1152 m ² has been affected by MD. Among the corals in contact with MD, 47.56% were found fragmented and 34% were found with tissue loss	Patterson Edward al., 2020
Tuticorin and Vembar groups of Islands, Gulf of Mannar	Microplastics	Mean density from 60±54 to 126.6±97 items/l in water, 50±29 to 103.8± 87 items/kg in sediment	No observation	Corals in the region are exposed microplastics and associated metal	Patterson et al., 2020
Tuticorin coast, Gulf of Mannar	Microplastics	Mean density 0.6-1.3 items/g (wet weight) in clams, 10-30 items/l in water, and 24-235 items/kg in sediment	Microplastics measured in the clam <i>Donax cuneatus</i>	Microplastics of fiber (100-250 mm) detected in clams	Sathish et al., 2020

Tuticorin coast, Gulf of Mannar	Microplastics	Mean density 6.9 ± 3.84 items/ind. oyster and the mean density to be 0.81 ± 0.45 items/g of tissue	<i>Magallana bilineata</i>	Microplastics bioavailability increases with increasing size of oysters.	Patterson et al., 2019
Tuticorin coast, Gulf of Mannar	Microplastics	Mean density 3.1 ± 2.3 to 23.7 ± 4.2 items/l water, 0.11 ± 0.06 to 3.64 ± 1.7 items/ind. fish, 0.0002 ± 0.0001 to 0.2 ± 0.03 items/g gut weight	<i>Harpodon nehereus</i> , <i>Chirocentrus dorab</i> , <i>Sardinella albella</i> , <i>Rastrelliger kanagurta</i> , <i>Katsuwonus pelamis</i> , <i>Istiophorus platypterus</i>	Shallow water fishes had higher ingestion rate of microplastics.	Sathish et al., 2020
Tuticorin coast, Gulf of Mannar	Macroplastics: (0.138-0.616 items/m ² , Mesoplastics: (9.375 ± 0.5 items/m ²), Microplastics: (25 ± 18 to 83 ± 49 items/m ²)	Water: 24 ± 9 to 96 ± 57 items/L Sediment: 55 ± 21 to 259 ± 88 items/kg	No observation	No observation	Jeyasanta et al., 2020
Nallathanni Island, Gulf of Mannar	Macro litter	505 MP items/kg	No observation	Not known. Water bottles and polystyrene pieces also found in the inner part of the coral island	Krishnakumar et al., 2018
Rameswaram Coral Island, Gulf of Mannar	Microplastic (60.8%), mesoplastic (~30%) and macroplastic (~9.2%)	403 pieces	No observation	No observation	Vidyasakar et al., 2018
Kadmat, Par, and Minicoy	Suheli Hard plastic (87%), rubber (5%), glass (3%), foamed plastic and metal (2%), and others (1%)	Kadmat (193 ± 97 items 400 m ⁻²),	No observation	No observation	Kaviarasan et al., 2020

Islands,
Lakshadweep
archipelago

Suheli Par (154 ± 31 items 400 m^{-2}),
Minicoy islands
(65 ± 49 items 400 m^{-2})

Tinnakkara Island,
Lakshadweep
archipelago

White, black, yellow, gray and blue plastic pallets

Total 603 items

No observation

No observation

Mugilarasan et al., 2017

Lakshadweep
archipelago

PET (polyethylene terephthalate), plastic bags, HDPE (high density polyethylene) and nylon ropes, net pieces, long lines, cigarette lighters, footwear and insulators like PUF (polyurethane foam), styrofoam, thermocol pieces, and glass bottles

Agathi (7.674 g/m^2),
Amini (8.213 g/m^2),
Androth (5.51 g/m^2),
Bitra (5.29 g/m^2),
Chetlat (11.32 g/m^2),
Kadamat (7.94 g/m^2),
Kalpeni (13.35 g/m^2),
Kavarathi (10.11 g/m^2),
Minicoy (31.73 g/m^2),
Kiltan (4.53 g/m^2)

No observation

No observation

Kaladharan et al., 2020
Anasukoya, 2020

Great Nicobar
Island

Macro plastic debris

High quantity of plastic debris on the beach

No observation

No observation

Das et al., 2019
Dharani et al., 2020
Sahu and Baska, 2019

Andaman and
Nicobar Islands

Macro litter (0.2 - 20 cm).
Nylon from fishing activities contributed to 68% of the total plastic pollution

Mean density of 358 to 925 particles/ m^2 ,
Karmatang

No observation

No observation

Krishnakumar et al., 2020

Port Blair Bay, Andaman Islands	Microplastics including fiber, fragment, and pellet	Beach (44.3%), Sound Island (26.4%), Reef Island (9.2%), Lamba Balu (9.2%), Pocket Beach– Mayabhandar Bay (5.9%), Elizabeth Bay (5.04%)	Water (0.93 ± 0.59 particles per m ³), Sediment (45.17 ± 25.23 particles per kilogram), Zooplankton (0.12 ± 0.07 pieces per zooplankter), Finfish and shellfishes (10.65 ± 7.83 particles per specimen)	Zooplanktons and fishes (<i>Carangoides malabaricus</i> , <i>Alepes djedaba</i> , <i>Saurida tumbil</i> , <i>Gerres filamentous</i> , <i>Nemipterus peronei</i> , <i>Upeneus vittatus</i>), <i>Portunus pelagicus</i> , <i>Penaeus indicus</i>	Bioaccumulation in zooplankton ranged from 18.89 pieces/m ³ to 502.26 pieces/m ³ . 45.83% of the total fish samples showed bioaccumulation of microplastics with mean 10.65 (±7.83) particles per specimen.	Goswami et al 2020
Indian coasts	Plastic debris (40%)	Mean density of 10.97 g/m ² at Lakshadweep and 19.23 g/m ² at Andaman:	No observation	No observation	Kaladharan et al 2017	

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