

## **Mangroves in the “Plasticene”: High exposure of coastal mangroves to anthropogenic litter pollution along the Central-West coast of India**

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### **Abstract**

Anthropogenic litter pollution is a ubiquitous stressor in the global ocean, and poses ominous threats to its biodiversity and ecosystem functioning. At the terrestrial-ocean interface, tropical mangrove forests are subject to substantial exposure to mismanaged litter from inland and marine sources. While the effects of litter in different marine ecosystems are well-documented, the possible ecological consequences on mangroves remain nascent. Here, we investigated anthropogenic litter concentration, composition, probable sources, and impact on coastal mangroves along the Central West coast of India. The mean concentration of trapped litter was measured  $8.5 \pm 1.9$  items/m<sup>2</sup> (ranged 1.4–26.9 items/m<sup>2</sup>), and  $10.6 \pm 0.5$  items/tree (ranged 0–85 items/tree) on the mangrove floor and mangrove canopy, respectively. Plastic dominated 83.02% of all litter deposited on the mangrove forest floor and 93.4% of all entangled litter on mangrove canopy. Most litter comprised single-use plastic products across all surveyed locations. Mangrove floor cleanliness was assessed using several indices, such as Clean Coast Index, General Index, Hazardous Items Index, and Pollution Load Index, reiterating an inferior cleanliness status. The pollution load index indicates “Hazard level I” plastic pollution risk across the mangroves. Litter concentration differed markedly across all sites. However, a significantly higher concentration of stranded litter was detected in the densely populated urban agglomeration and rural areas with inadequate solid waste management. Probable sources of litter indicate land-based (local) and sea-originated (fishing). Supportive information on the transport and accumulation of marine litter is examined based on the National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFS) model version 2 reanalysis of surface wind and current pattern across the Arabian Sea followed by MIKE simulated tide-induced coastal current. Mangrove pneumatophores and branches were found to be damaged by entangled plastics. Hence, determining litter quantum and their probable input source is pivotal in mitigating anthropogenic litter impact on mangrove ecosystems and fostering mangrove conservation. Overall, results envisage that stringent enforcement, implementation of an integrated solid waste management framework, and general behavioral change of the public are crucial to mitigate litter/plastic pollution.

**Keywords:** Coastal ecosystems, Plastic pollution, Mangrove, Indian Ocean, Solid waste management

## **Introduction**

The Anthropocene ocean is altered by human-induced climate change and pervasive environmental pollution that negatively impacted multiple oceanic ecosystems functioning and allied services (Lincoln et al., 2022; Ripple et al., 2017). At the interface of the terrestrial and marine environment, intertidal mangroves are considered foundation species, which form one of the most productive coastal ecosystems (Carugati et al., 2018; Friess et al., 2020). Globally mangrove forests cover ~132,000 km<sup>2</sup>, and the mangrove cover in Southeast Asia is most extensive and highly diverse (Hamilton and Casey, 2016). Mangroves are flagship ecosystems with immense societal importance and contribute to numerous high-value social, economic, and ecosystem services (Himes-Cornell et al., 2018). Mangroves act as bio-shield and provide nature-based coastal protection from disasters like tsunamis, storm surges, and flooding by protecting landward areas from wave impacts to ~15 million people globally (Barbier, 2016; Hochard et al., 2019; Walker et al., 2022), offer habitats for diverse biota and contribute an estimated 42 billion USD to fisheries (Bernardino et al., 2018; Walker et al., 2022). Mangroves also act as a significant source of ‘blue carbon’ or nature-based solutions for global climate change mitigation (Taillardat et al., 2018). However, the highly valued coastal mangrove ecosystems are rapidly regressing due to multifarious stressors, including climate change, coastal development activities, anthropogenic pollution, and over-extraction pressure (Gilman et al., 2008; Walker et al., 2022), which could lead to degradation of biodiversity, habitat loss, local scale extinctions and disrupt the ecosystem services (Friess et al., 2022, 2019; Polidoro et al., 2010).

In recent decades, anthropogenic marine litter and plastics have become contaminants of emerging concern and a growing threat to mangrove ecosystems globally (Debrot et al., 2013; Luo et al., 2021). Structural complexities of the mangrove canopy and pneumatophores can trap and retain marine-borne debris from tidal currents and mismanaged waste from landward for a prolonged period (Luo et al., 2021; Martin et al., 2019). Trapped litter covers the mangrove trees and pneumatophores, prohibiting sunlight and disrupting photosynthesis. It can cause local scale anoxia in mangrove sediment, create space constraints for new saplings, and affect the growth of pneumatophores and propagules (Selvam et al., 2021a; Smith, 2012; van Bijsterveldt et al., 2021). Marine litter, particularly plastics, poses a significant risk to mangrove species and mangrove-dwelling fauna by shedding, entanglement, and ingestion (Not et al., 2020; van Bijsterveldt et al., 2021), and the potential to incorporate into the food chain (Sarker et al., 2022). The accumulation of plastics in the mangrove ecosystems-aquatic-terrestrial transition zone has been raising particular concern as they accumulate at relatively high rates (Garcés-Ordóñez et al., 2019), highlighting

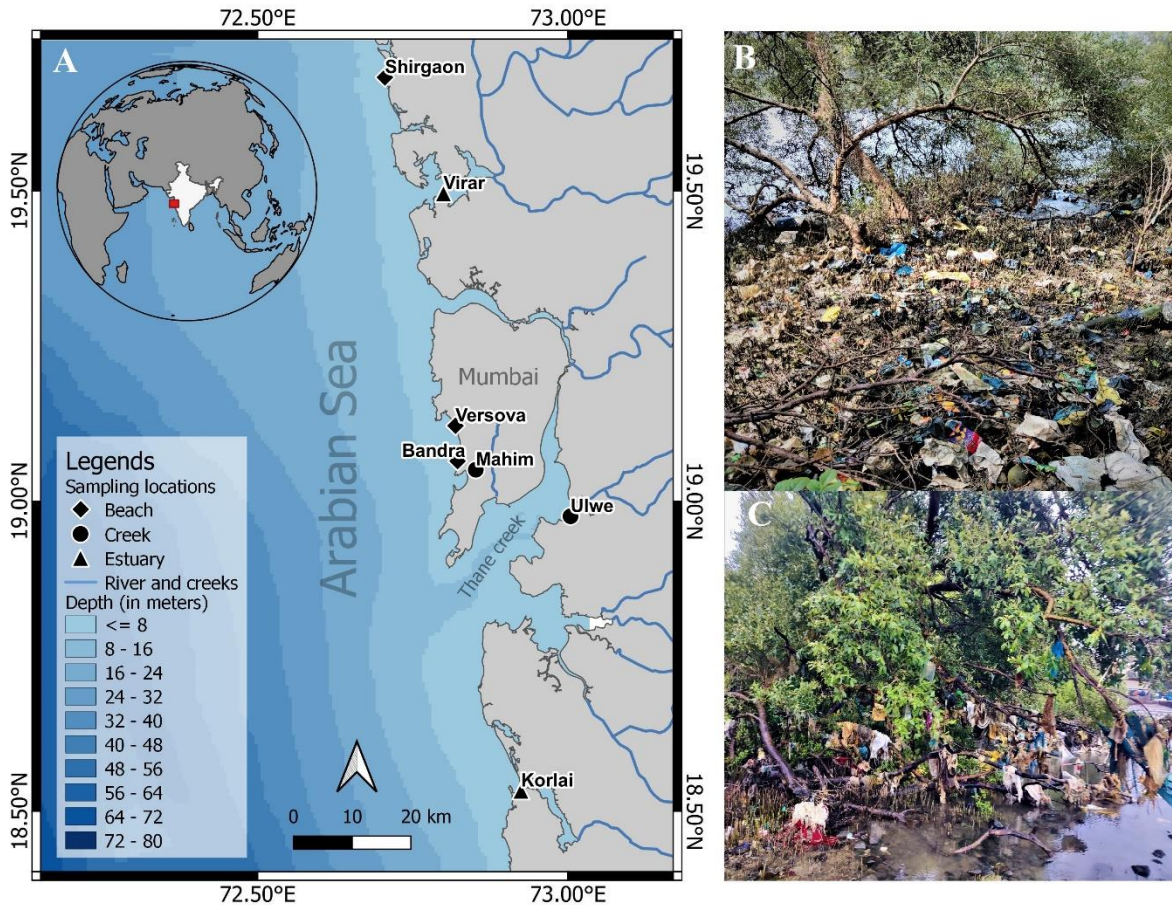
mangroves as a potential trap for plastics from inland activities (Luo et al., 2021; Martin et al., 2019). Still, very few studies have investigated this issue in mangroves (Luo et al., 2021), and much remains unknown about the detrimental effect of anthropogenic litter on mangroves.

Wasteful resource use, inadequate solid waste management, open disposal, and lack of recycling have emerged as significant global concerns in public discourse. Solid waste pollution poses great threats to global biodiversity and ecosystems. Among the mismanaged solid waste, plastics contribute the most and cause substantial ecological and social degradation. Since the 1940s, plastic products have become indispensable in modern life due to socio-economic development and represent major progress in human civilization. The use of plastics became widespread in industrial and domestic applications, including industrial and agricultural packaging, and manufacturing, due to low-cost, lightweight, water-resistant capacity, high durability, and thermal and electrical insulativity (Jacques and Prosser, 2021). The plastics industry has been growing with burgeoning production worldwide over the last few decades, from 1.7 MMT/year in the 1950s to 370 MMT/year in 2019 (PlasticsEurope, 2019). Approximately 6.3 billion metric tons of plastic waste were produced globally by 2015, and out of that, only 9% had been recycled, 12% were burnt, and 79% ended up in landfills or the environment (Geyer et al., 2017).

Moreover, worldwide plastic contamination has reached every compartment of the environment through different pathways and is responsible for 73% of litter in any aquatic habitat (Bergmann et al., 2017), which primarily originates from land-based sources (~80%) (Oliveira et al., 2019). Eventually, oceans emerged as a final sink for a significant portion of mismanaged litter and plastics from land sources (Jambeck et al., 2015; Lebreton et al., 2017; Thompson et al., 2004) and evidence of their detrimental impacts on marine organisms and ecosystem health has been documented (Doyle et al., 2022). Various studies reported that approximately 690 species are negatively impacted by marine litter globally, and according to the IUCN Red List, at least 17% of these species are registered as near-threatened or higher (Gall and Thompson, 2015).

The impact of mismanaged litter and plastics on marine biotope are under ongoing research and remain a critical unanswered question (Galgani et al., 2021). Marine litter is prevalent and well-acknowledged on the Indian coast, but investigation of their abundance and composition is mainly limited to sandy beaches (Ranjani et al., 2021; Sivadas et al., 2022). Other coastal habitats like mangroves remain understudied in India as well as globally regarding the ecological impacts of anthropogenic litter pollution. This could be due to mangroves not having the same aesthetic and economic charm as beaches, which hinders policy-making for protecting these endangered coastal ecosystems (Luo et al., 2021). This study was conducted along the central west coast of India, where

mangrove vegetation is sparse and confined to patches primarily due to coastal morphology, limited upstream freshwater supply, high silt-clay deposition, and low tidal fluctuation (Blasco and Aizpuru, 1997; Untawale, 1984). Mangrove vegetation in this region not only protects the coastline from erosion and adjoining human dwellings from natural calamities, but also offers enormous tangible and intangible services by supporting high biological diversity, contributing to nature-based climate solutions, and generating livelihood through fisheries and tourism (Selvam et al., 2021a; Untawale, 1984). However, the mangrove ecosystems in this part of the world are under pressure due to multiple stressors, including, but not limited to, habitat destruction due to climate change and urbanization, encroachments, conversion of mangroves to aquaculture farms, and illegal dumping of solid wastes (Abdul Azeez et al., 2022; Kantharajan et al., 2018). Therefore, immediate conservation and active restoration are needed to safeguard mangroves from further degradation. Further, considering the threat posed to mangroves by the mismanaged solid waste and marine litter, planning measures for mitigating litter pollution along the coastal mangroves requires a systematic inventory of the magnitude of litter accumulation and probable source identification. The present study attempts to provide critical information on (i) spatial distribution and quantification of litter pollution in mangroves (forest floor and canopy) stands along the Central West coast of India, (ii) identify the composition and the probable source of litter, (iii) investigate the environment quality and pollution risk by computing different indices, (iv) understand the influence of local hydrodynamics (winds and currents) on litter accumulation and transport, and (v) explore the avenues for management and mitigation of litter pollution in mangroves.



**Fig 1.** Figure illustrates- (A) the surveyed locations of the studied mangrove stands on the Central West Coast of India; (B-C) trapped litter on the mangrove forest floor and canopy.

## 2. Materials and methods

### 2.1. Study Site

The present study was conducted during May-June 2022 along the Central West coast of India in the Eastern Arabian Sea (EAS), spanning over ~150 km across the Maharashtra coast. Maharashtra has a coastline spread ~724 km, with sandy beaches and pockets of beaches fringed by rocky cliffs of Deccan basalt (Ratheesh et al., 2021). The coastline of Maharashtra is parallel to the Western Ghats mountain range, an area of significant biodiversity and one of the three most threatened global biodiversity hotspots by human activity (Cincotta et al., 2000). Likewise, the coastal ecosystems of Maharashtra are highly biodiverse, including critical ecosystems like sandy and rocky intertidal beaches, mudflats, salt marshes, coral reefs, and mangroves. Estuaries, creeks, and mudflats harbor patches of mangroves, which cover approximately 320 km<sup>2</sup> (Youdon, 2020). However, these important ecosystems are under pressure due to rapid urbanization, coastal development activities, and climate change (Abdul Azeez et al., 2022; De et al., 2022a; Sautya et al., 2022). Approximately 28.62 million populations live in this coastal region, with an average population density of 7,141

people/km<sup>2</sup>. Mumbai is one of the fastest-growing metropolitan cities and the business capital in India, which is also one of the most densely populated cities in the world with ~13 million population (population density of 20,925 people/km<sup>2</sup>) (Census, 2011).

We surveyed seven mangrove stands, strategically selected based on degrees of urban influence, the scale of anthropogenic activity such as population and industrial footprint, tourism, and the existence of solid waste management practice. Surveyed sites were further classified based on the- i) habitat type, i.e., beach, estuarine, and creek; ii) bottom substrate characteristics, i.e., rocky and mudflat; and iii) urbanization gradient, i.e., rural, peri-urban, and megacity. All the mangrove stands are primarily mono-species dominated, i.e., *Avicennia marina*, which develops complex aerial root systems or pneumatophores. *Avicennia marina* is known to be resilient to high salinity and pollution (Abdul Azeez et al., 2022). Three of the seven surveyed mangroves were situated adjacent to the densely populated Mumbai megacity shore, i.e., Bandra, Mahim creek, and Versova. They received polluted water and sewage from seaward-flowing creeks and city drainage that represented potential sources of litter.

Along with the Mumbai coast, two other mangrove stands were selected in the nearby peri-urban area at Virar and Ulwe, respectively. Further, we studied litter accumulation in two rural mangrove stands in sparsely populated locations away from urban influences, i.e., Shirgaon and Korlai. Mumbai, Ulwe, and Virar have preexisting solid waste management systems among these sites. Details of the surveyed mangrove stands are described in Fig. 1 and electronic supplementary material table S1. Mangroves in the Mumbai and suburban regions reached the saturation phase and attained maximal growth in the landward direction (Abdul Azeez et al., 2022).

## **2.2.Survey of surficial litter on the mangrove floor (on the ground)**

Marine litter surveys were carried out in seven mangrove stands in May-June 2022 during low tide. Litter was quantified using a 20m long and 2m wide belt transect (n=3 transects at each mangrove stand). Transect tapes were laid perpendicular to the shoreline, each at the seaward fringe, mangrove basin, and landward fringe, representing litter accumulated from the land- and sea-based activities. For, mangroves in Mahim are situated on the narrow bank of the Mithi river; therefore, transect tape was laid parallel to the river bank with a distance of 50m between the transects. Overall, an 840 m<sup>2</sup> area of the mangrove floor was sampled to quantify the surficial litter. All the visual (entirely on the surface sediment or partially buried or trapped in mangrove aerial root or pneumatophores) marine litter objects above 2.5cm (maximum diameter) within the transect area were collected, counted, and

recorded category-wise. Each sampling site was georeferenced by using a handheld GPS, and digital photographs were taken for photo documentation using a digital camera.

### **2.3.Survey of entangled litter on the mangrove canopy (above ground)**

At each mangrove stand, 100 mangrove trees were selected randomly for the trapped litter survey, yielding a total of 700 mangrove trees for the present study. Mangrove plants with a height of >1.5 m were selected for sampling (Selvam et al., 2021a). Entangled litter objects on the entire mangrove canopy were collected, counted, and recorded category-wise in the field. The litter density on the mangrove canopy is represented as litter items/tree.

### **2.4.Quantification, typology, and source delineation of marine litter**

The litter items were segregated into six categories, i.e., plastics, glass, metals, textiles/fabrics, rubbers, leather, timbers, and footwear (other than leather items) as per the OSPAR protocol (Ospar, 2010). Plastic items were further sorted based on their functional origin, such as bags, food wraps, sachets, drink bottles, bottle caps, cups, straws, cutlery, fishing net, rope/line etc., following the standard guidelines (Lippiatt et al., 2013). The density of litter deposited on the mangrove floor was calculated following the formula and was documented as a number of litter items/m<sup>2</sup>.

$$\text{Density of marine debris} = \frac{\sum \text{Debris items in each transect}}{\text{Transect area}}$$

The probable sources of the litter objects were classified using the method described by the EU Marine Strategy Framework Directive (MSFD) Good Environmental Status (GES) Marine Litter Thematic Report (Veiga et al., 2016). Litters were categorized based on the possible input sources, i.e., (i) land-based, (ii) sea-based, and (iii) uncertain origin. Land-based litter from post-consumer used and industry-used solid waste escaped the management framework and was transported into marine environments by the drainage system or wind action (Veiga et al., 2016). Sea-based litters are from maritime activities, including mariculture, fishing, shipping, and offshore industries, that are accidentally or purposely released into the sea, drifted, and deposited on the coast (Veiga et al., 2016). The product's country of origin was also recorded for labeled litter objects. The litters of uncertain origin are those without any label for source identification (Galgani et al., 2015). All the classifications mentioned above were used for source identification in the current study.

### **2.5.Environmental quality of the studied mangrove habitats**

The environmental quality of the studied mangrove habitat was determined by using different indexes, namely the Clean coast index, General index, Hazardous item index, and Pollution load index, based on the abundance and characteristics of the litter.

### 2.5.1. Clean coast index

The clean coast index (CCI) evaluates the cleanliness state of the coastal area based on plastic litter deposition (Alkalay et al., 2007). The CCI score represents the cleanliness status 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).

$$CCI = \frac{\sum \text{Plastic objects in transect area}}{\text{Transect area}} \times K$$

Where, K represents a correction coefficient set at 20.

### 2.5.2. General index

The use of the general index (GI) is similar to the CCI. But, GI includes all types of marine litter, irrespective of plastic litter (Marin et al., 2019).

### 2.5.3. Hazardous item index

The hazardous item index (HII) is computed to measure the level of hazardous litter concentration on the mangrove floor. For instance, sharp metal objects and broken glasses may cause serious cuts and injury to the public and marine fauna. Medical waste, sanitary waste, and cigarette butts may induce environmental toxicity and pathogens (Rangel-Buitrago et al., 2019).

$$HII = \frac{\frac{\sum \text{Hazardous debris objects}}{\log_{10} \sum \text{Debris objects}}}{\text{Tansect area}} \times K$$

Where, K represents a correction coefficient set at 20.

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

HII value	Class	Description
0	I	No hazardous litter present
0.1 - 1	II	Presentence of some hazardous litter
1.1 - 4	III	Presentence of a considerable amount of hazardous litter
4.1 - 8	IV	Presentence of a lot of hazardous litter
>8	V	Presentence of most of the area by hazardous litter



#### 2.5.4. Pollution load index

The pollution load index (PLI) has been developed for monitoring metal pollution levels in estuarine environments (Tomlinson et al., 1980). However, recently it has been used for microplastic pollution studies in marine ecosystems (Pan et al., 2021; Ranjani et al., 2021; Xu et al., 2018). According to Tomlinson et al. (1980), a PLI value of zero denotes “no pollution”; a value of 1 denotes the presence of “baseline levels of pollutants”, and >1 indicates “progressive deterioration of estuarine quality”. However, Pan et al. (2021) categorized PLI into four levels of hazard for microplastic pollution as follows: <10 (Hazard level I), 10–20 (Hazard level II), 20–30 (Hazard level III), >30 (Hazard level IV). In the present study, we used the PLI to assess the macro plastic pollution risk in the mangroves, and it is computed using the following formula:

$$CF = C_i / C_b$$

$$PLI \text{ for site} = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \dots \times CF_n}$$

$$PLI \text{ for coast} = \sqrt[n]{PLI_1 \times PLI_2 \times PLI_3 \dots \times PLI_n}$$

Where, the PLI at each mangrove stand was computed based on the particular plastic debris contamination factors (CF), which is the quotient of the plastic debris density at each mangrove location ( $C_i$ ) /background value of the plastic debris ( $C_b$ ), which is theoretically a reference value of the concentration of plastics in the early stages of plastic industry. Due to a lack of background data, the lowest concentration of debris detected at the site was considered a base value (Ranjani et al., 2021).

#### 2.5.5. Marine litter diversity indices

Diversity indices were calculated to assess the assembly of marine litter in terms of litter identity/‘species’ (for this study, marine litter), their relative abundances, and diversity of sources (Battisti et al., 2018; Veerasingam et al., 2020a). Shannon-Wiener diversity index ( $H'$ )-a non-parametric diversity metric based on the number of species and relative frequency (Shannon and Weaver, 1949). Shannon-Wiener diversity index ( $H'$ ) is computed using the following formula

$$H' = -\sum fr \times \ln(fr),$$

where,  $fr$  is the relative frequency of occurrence of every litter ‘species’.

Evenness index ( $E$ ) represents the sample heterogeneity of an assemblage based on the relative frequency of distribution of species (Pielou, 1975). Evenness index was computed as:

$$E = H'/H'_{\max},$$

Where,  $H'_{\max} = \ln S$  and  $S$  is the total number of litters 'species'.

## **2.6. Wind and hydrodynamics**

In the oceanic system, winds and currents are the primary drivers of transportation and accumulation of floating plastic litter. The National Centers for Environmental Prediction (NCEP) Climate Forecast System Version 2 (CFSv2) monthly reanalysis data of January 2022 (north east monsoon) and June 2022 (south-west monsoon) are used for depicting the general pattern of wind and current in the Arabian sea. The data in the Arabian sea covers a rectangular domain from (50° E, 0°) to (80° E, 30° N). The wind at 10 m elevation from the sea surface and the ocean current at 5 m below the surface are considered in this study. The resolution of both wind and current data is 0.5° × 0.5° (Saha et al. 2011).

MIKE3 Flow model FM is executed across the Maharashtra coast in a rectangular domain from (72.5° E, 18° N) to (73.5° E, 20° N) to get the current pattern variation along with tidal fluctuation. The model simulation is carried out forced by the NCEP/CFSv2 hourly wind along with the boundary condition of predicted global tide model data.

## **2.7. Data Analysis**

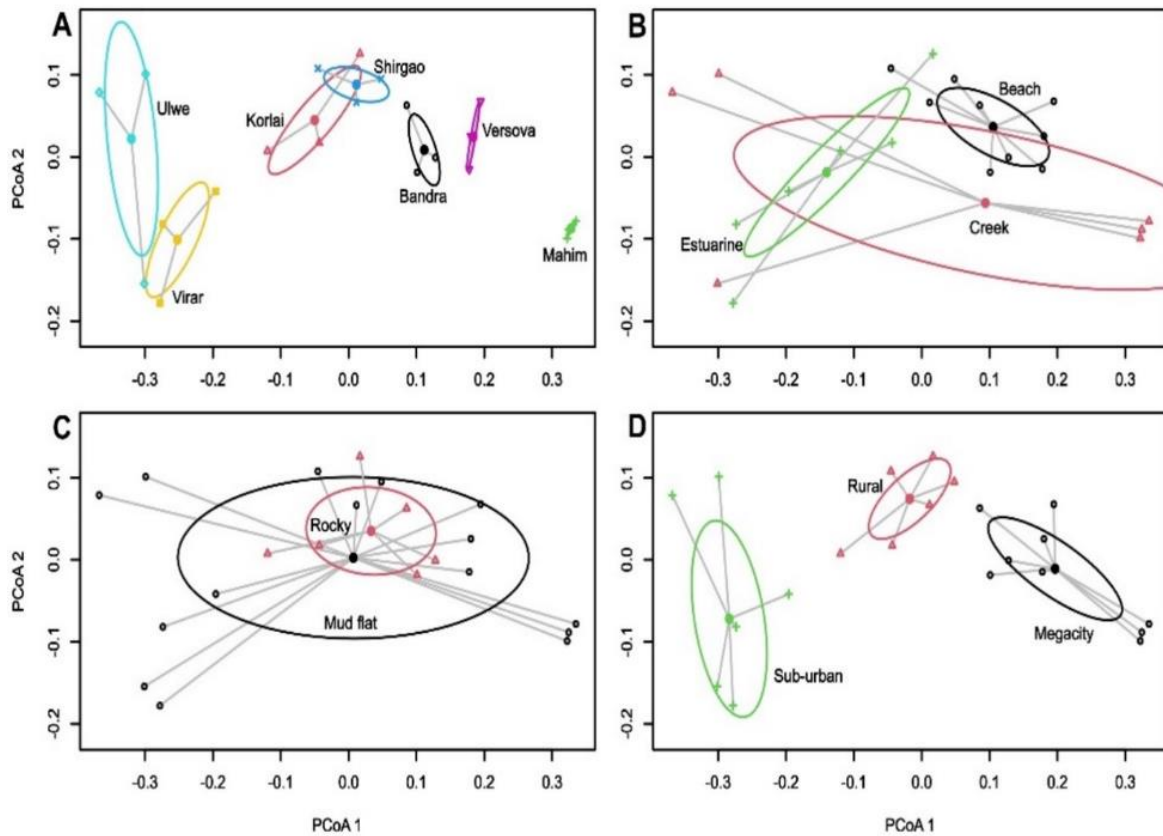
Data were assessed for normality and homogeneity of variances using the Shapiro-Wilk and Levene's tests, respectively. Results indicated that data were not normally distributed. Hence, the spatial variation of litter abundance among mangrove floors and mangrove canopies was tested by Kruskal–Wallis non-parametric test. Concentration differences between rural, peri-urban, and megacity regions were evaluated using the Kruskal–Wallis test. A post-hoc comparison using pairwise Mann-Whitney tests was conducted after the Kruskal–Wallis test. The significance of spatial variation difference of litter abundance among mangrove stands based on the habitat characteristics was tested by Permutational Multivariate Analysis of Variance (PERMANOVA) using 999 permutations and distance matrices (McArdle and Anderson, 2001). Prior to analysis, the data were square-root transformed, and the Bray-Curtis similarity matrix was created. The difference in  $\beta$ -diversity (homogenization) among different levels was analyzed using homogeneity tests for multivariate dispersions (Anderson et al., 2006). Bray-Curtis matrix was used to compute the centroid of each group of levels associated with one another, followed by the calculation of the distance of each site to their associated group centroid. Finally, to determine the significance of the dispersion (variance) of one or more groups, the permutation test for homogeneity of multivariate dispersion was applied on site distances to centroid with 999 permutations. All the statistical analysis was performed in R using the package "vegan" (Oksanen et al., 2020; R Core Team, 2021). The

PERMANOVA was performed using the function ‘*adonis2*’. The permutation test for homogeneity of multivariate dispersion was performed using the functions ‘*betadisper*’ and ‘*permutest*’. The box plots were made using the package “*ggplot2*” (Wickham et al., 2016). All statistical tests were conducted at the  $p < 0.05$  level of significance. The datasets were represented as means  $\pm$  standard error (SE), if not noted otherwise.

### **3. Results and discussion**

#### **3.1. Magnitude of litter abundance, and composition in the mangrove floor**

The belt transects survey in the mangrove floor along the studied sites yielded a total of 7143 litter items. The present study detected high litter concentration on the mangrove floor. Mean litter density ranged from 1.4 to 26.9 items/m<sup>2</sup> across the studied sites, with an average concentration ( $\pm 95\%$  confidence interval) of  $8.5 \pm 1.9$  items/m<sup>2</sup> (electronic supplementary material, Table S2). Globally, very few studies recorded the concentration of marine litter in mangrove forests (a summary of marine litter studies in mangrove ecosystems is provided in Table 2), possibly because of the difficulties in the sampling activities (Garcés-Ordóñez et al., 2019). The mean litter concentration from our result is comparable with the studies by Paulus et al. (2020) in Indonesia, which recorded a litter density of 9.62 items/m<sup>2</sup> in mangroves. However, our study revealed a significantly higher concentration of litter ( $15.94 \pm 2.86$  items/m<sup>2</sup>) in mangroves of the Mumbai region, than in the previous report by Selvam et al. (2021) in Mumbai ( $8.82 \pm 3.47$  items/m<sup>2</sup>). Noted litter concentrations of the present study were also higher than those reported by Martin et al. (2019) in the mangrove of the Red Sea ( $0.66 \pm 0.18$  items/m<sup>2</sup>), Arabian Gulf ( $1.21 \pm 0.53$  items/m<sup>2</sup>), respectively, and  $1.45 \pm 0.38$  items/m<sup>2</sup> in Hong Kong (Luo et al., 2022),  $1.29 \pm 0.67$  items/m<sup>2</sup> in Cebu Island, Philippines (Paler et al., 2022). In contrast, overall litter abundance was found to be lower than 12.6–73.1 items/m<sup>2</sup> in Penang Island, Malaysia (Yin et al., 2019),  $92 \pm 28$  items/m<sup>2</sup> in Ambon and Baguala Bay, Indonesia (Suyadi and Manullang, 2020), and 27 items/m<sup>2</sup> in Central Java (van Bijsterveldt et al., 2021).



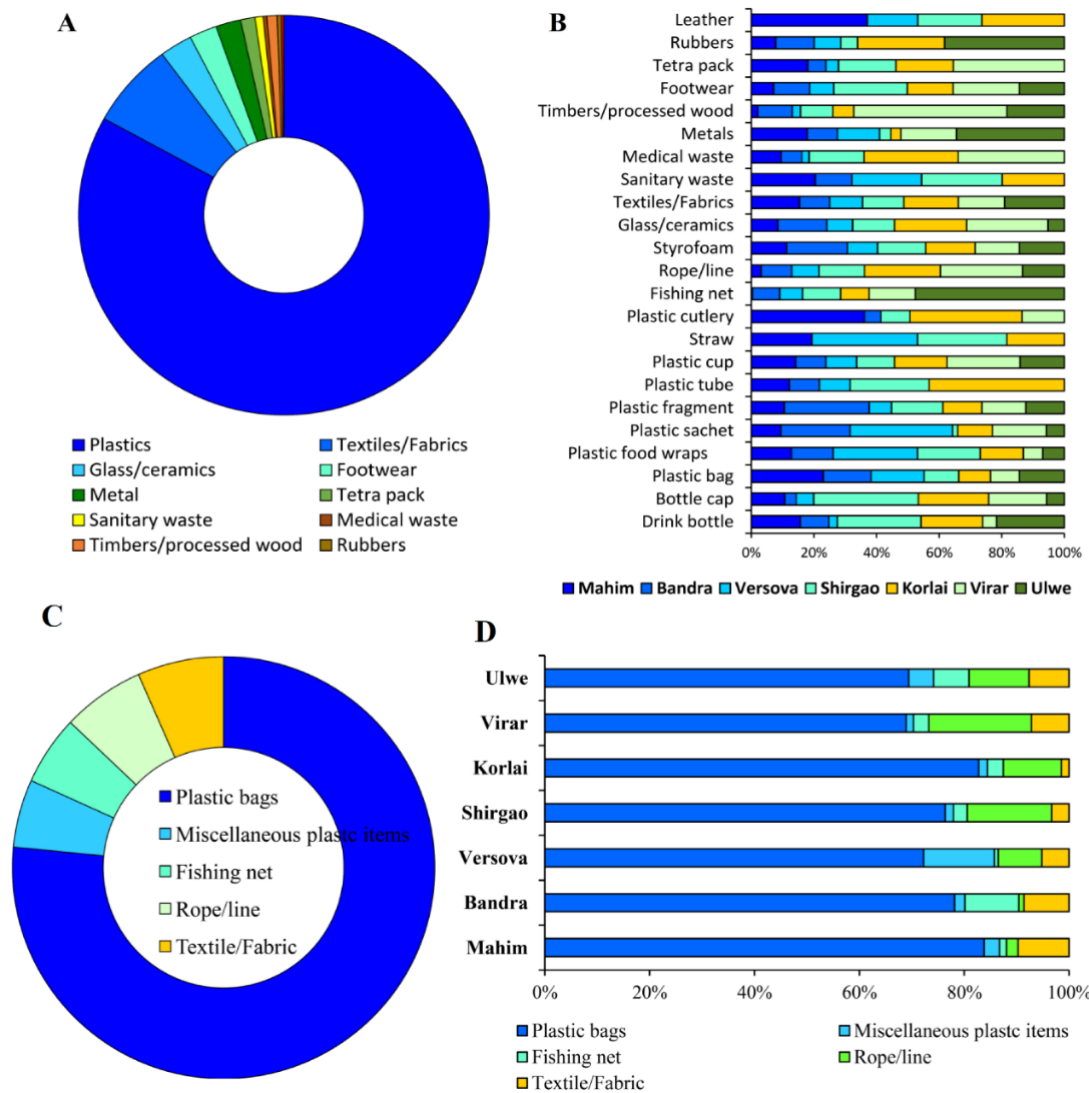
**Fig. 2.** The multivariate dispersion of litter composition among the mangrove floor, measured as the distance of sites to their group centroid, represented on the first two axes of a PCoA. Plots represent A) site-wise differences; B) habitat-wise differences; C) habitat substrate-wise differences; and D) variation according to urbanisation gradients

Litter density differed significantly among sites (Kruskal–Wallis test  $p < 0.5$ ) and urbanization gradients (Kruskal–Wallis test  $p < 0.5$ ). Litter density was highest at Mahim ( $26.88 \pm 2.03$  items/m<sup>2</sup>), and the lowest was recorded at Ulwe ( $1.38 \pm 0.09$ /m<sup>2</sup>) (electronic supplementary material, Fig. S1A, Table S2). According to the urbanization gradient, a significantly higher quantity of litter was observed in the mangrove stands located in the highly urban Mumbai megacity ( $15.9 \pm 2.9$  items/m<sup>2</sup>), followed by the rural area without proper solid waste management facilities ( $4.3 \pm 0.3$  items/m<sup>2</sup>). The lowest concentration of litter was observed in the peri-urban region ( $1.5 \pm 0.1$  items/m<sup>2</sup>) with a well-developed waste management facility (electronic supplementary material, Fig. S1D, Fig. S2). The PERMANOVA tests indicate significant variation in litter abundance among the sites (Fig. 2A) and urbanization state (Fig. 2D) of the sites (electronic supplementary material, Table S4). However, no significant differences were detected based on the habitat types (Fig. 2B), and habitat substrate characteristics (Fig. 2C). The dispersion was higher at creeks, estuaries, and mud flats (Fig. 2; ellipse size is in relation to the dispersion on PCoA ordination), which indicates that urbanization is the

primary driver for differentiation in litter density in the mangroves. Whereas habitats and their substrate property are not crucial for this distinctness; thus, showed homogeneity.

Plastic materials were the most widespread of all stranding litter on the mangrove floor, comprising 83.02% of the total litter, while other components were fabrics (6.87%), glass (2.58%), footwear (2.17%), metal (1.97%), tetra pack (1.13%), processed woods (0.81%), rubbers (0.32%), and leather items (0.2%) (Fig. 3A). Morales-Caselles et al. (2021) noted that plastics contributed ~80% of the litter in most of the marine environments. The average concentration of plastics was estimated at  $7.06 \pm 1.59$  items/m<sup>2</sup> across the sites, indicating plastic litter concentration is higher than the reported global average of 1 item/m<sup>2</sup> (Galgani et al., 2015). Plastic density ranged from  $22.28 \pm 1.95$  items/m<sup>2</sup> at Mahim to  $1.07 \pm 0.07$  items/m<sup>2</sup> at Ulwe (electronic supplementary material, Table S2). The most frequently occurring plastic item in mangroves were mainly lightweight single-use plastic bags, making up, on average 38.43% of total litter. Plastic food wraps were the second most abundant plastic type, making up on average 14.22%, followed by fragments (8.27%), sachets (4.98%), and plastic drink bottles (2.91%), Styrofoam particles (2.72%), and beverage cup (2.2%). Sanitary waste (diapers and sanitary pads) formed 0.63% of total litter, and medical waste (including face masks and syringes) contributed to 0.29% of total litter. Site-wise litter composition is shown in Fig.3B. The litter composition from our study well corroborated with the described composition of marine litter in other mangroves around the globe. For example, plastic forms a high proportion of marine debris, accounting for 70.31% of Hong Kong's mangrove forests (Luo et al., 2022), 70.2% in Cebu, Philippines (Paler et al., 2022), and 89% in Indonesian mangrove forests (Winarni et al., 2022). In mangroves of Mahim creek, Mumbai, plastics were the major dominating debris, contributing to 55%–71% of total solid waste, followed by synthetic rubber and glass items (Singare, 2012a). A similar observation was found in Thane creek, Mumbai, where the contribution of plastic was 76%–77%, followed by synthetic rubber (20%–21%), and glass (3%). Among the plastic items, milk/oil bags, plastic carry bags, and plastic bottles were dominant (Singare, 2012b). Our previous surveys on Mumbai's rocky intertidal region using a similar methodology recorded a litter concentration of  $1.60 \pm 0.13$  items/m<sup>2</sup> (De et al., 2022b). However, our result showed a high concentration of plastic debris in the coastal mangrove stands in the eastern Arabian sea, which confirms the assumption that mangrove vegetation contributes as a plastic trap and prevents plastic dispersal in the open seas. For the litter diversity indices, the Shannon-Wiener diversity index value was recorded 2 at Mahim and 2.6 at Korlai and Virar. Pielou's evenness index was recorded 0.6 at Mahim and 0.9 at Virar (electronic supplementary material, Table S5). The quantitative approach of diversity metrics offers

insights into litter accumulation, which could be helpful for policy makers for effective management decisions (Battisti et al., 2018, 2017).



**Fig. 3.** Percentage composition of marine litter along the studied mangroves. A) Average percentage composition of major litter types on the mangrove floor; B) composition of various litter types on the mangrove floor at different mangrove stands; C) Overall percentage composition of litter on mangrove canopy; D) variability in the composition of marine litter categories on mangrove canopy at different mangrove stands

### 3.2.Litter abundance and composition in mangrove canopy

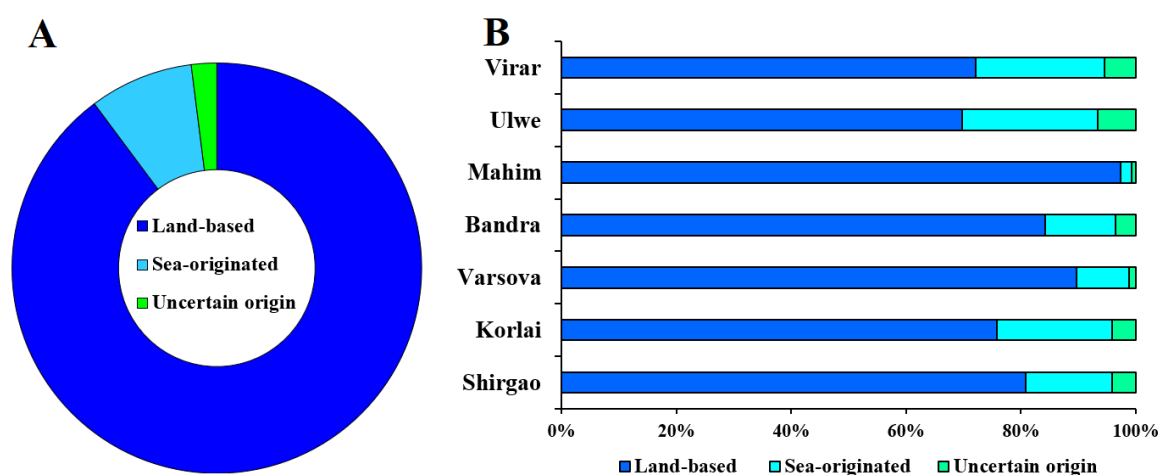
Studied mangrove canopies (n=700) contained 7437 entangled litter items. The mean concentration of litter was estimated  $10.62 \pm 0.48$  items/tree, range [0, 85 items/tree]. The mean concentration of plastic items was estimated  $9.92 \pm 0.45$  items/tree (n=6946). Plastic was the most dominant litter category at all study sites (Fig. 3C–D), occupying 93.4% of the total litter, while another major

component was cloths/fabrics (6.6%). Plastic bags dominated 81.98% of the overall composition of plastic litter, whereas miscellaneous plastic items, fishing nets, and rope/line comprised 5.57%, 5.69%, and 6.77%, respectively (Fig. 3C). The density of plastics on the mangrove canopy varied significantly among the study sites (Kruskal–Wallis  $p < 0.5$ ). The highest density of entangled plastics was found at Bandra ( $29.89 \pm 1.56$  items/tree), followed by Versova ( $20.02 \pm 1.04$  items/tree), Shirgaon ( $6.9 \pm 0.53$  items/tree), Korlai ( $6.21 \pm 0.91$  items/tree), Mahim ( $5.86 \pm 0.4$  items/tree), Ulwe ( $3.4 \pm 0.41$  items/tree), Virar ( $2.09 \pm 0.25$  items/tree) (electronic supplementary material, Table S3). We found that litter was mostly retained by mangrove pneumatophores, branches, and seedlings. Similar observations were noted in mangrove canopy in different mangrove forests (Luo et al., 2022; Martin et al., 2019; Paler et al., 2022; Selvam et al., 2021a; Suyadi and Manullang, 2020). Selvam et al. 2021a reported a mean litter density of  $35 \pm 10.4$  pieces/tree, collected from the 35 mangrove trees in the Bandstand, Mumbai. Further, a large number of pneumatophores were found to be covered by plastic litter (Fig. 7C–F). Similar findings were reported in mangroves from Colombia (Garcés-Ordóñez et al., 2019) and Saudi Arabia (Martin et al., 2019). The results indicate that the complex aerial root system and mangrove canopies act as traps for land-based litter from dispersing into the open ocean and prevent marine litter from invading the terrestrial environment (Li et al., 2021).

### **3.3. Source identification of marine litter**

The collected litter was classified based on MSFD GES TG Marine Litter Thematic Report (Veiga et al., 2016). Accurate identification of litter sources plays a crucial role in decision-making for successful prevention and mitigation of the litter problem at the sources (Galgani et al., 2013; Veiga et al., 2016). The input source of plastic litter is the coastal Arabian Sea (Fig. 1). This region is an area of high urbanization and industrialization, high population density, fisheries, tourism, and sewage disposal (Jayasiri et al., 2013; K. Selvam et al., 2021a), thus an important contributor of marine litter. Our surveys of trapped litter in mangrove canopy and floor confirm mainly two sources of litter: land-based (plastic bottles, plastic bags, plastic food wraps, household items, and plastic toiletries) and sea-originated (monofilament fishing line, nylon rope, fishing boxes, and small to large fishing nets) (Fig. 4A–B). Surficial litter on the mangrove floor was primarily composed of land-based sources, over 89.8% ( $n=6414$ ). Previous studies also pointed out land-based (households, tourism, industries) as a significant contributor to litter pollution in this region (Jayasiri et al., 2013; Selvam et al., 2021b), and globally most plastic in the coastal environment is sourced from land-based activities (Lebreton et al., 2017), indicating public littering and a gap in the waste management system (De et al., 2022b). The present study revealed that sea-originated litter contributed to 8.2% of total litter ( $n=586$ ), mainly from fishing-related activities. Notably, the Arabian Sea is an

economically important fishing ground for India; hence, the widespread use of synthetic polymer/plastics-based fishing gear is abundant. Abandoned, lost, and discarded fishing gear yields large quantities of litter and poses an adverse threat to marine biodiversity as it can trap and kill fish, elasmobranchs, crustaceans, marine mammals, reptiles, and seabirds (Enrichetti et al., 2021). Whereas 2% of litter (n=143) collected from the mangrove floor remains unidentified. Source identification of the litter encountered on the mangrove canopy revealed that 88.37% (n=6572) were from land-based sources and the remaining 11.63% of litter (n=865) were from fishing-related sources. Brand audit of the litter items with labels showing the brand name or country of origin to trace the origin of the litter, revealed that all (n=1236) were made in India. Other items remained untraceable due to the absence of fading of the labels.



**Fig. 4.** Probable sources of litter: A) overall percentage composition; B) site-wise percentage composition.

Coastal rivers are the major pathways for litter and plastic accumulation in the coastal marine environment (Harris et al., 2021; Lebreton et al., 2017). Schmidt et al. (2017) found that the amount of plastic litter in coastal areas positively correlates to the inadequately managed plastics in the river catchment areas. Further, population density and urbanization directly influence the quantity of river litter (Baldwin et al., 2016). The higher density of litter of the Mahim is most probably due to the surveyed area located in close vicinity to a densely populated area, which includes some of the densest localities of Mumbai like Dharavi (one of the largest slums in Asia, with approximately one million population and around 66,000 persons/km<sup>2</sup> population density), Kurla, and Sion. Large amounts of uncaptured waste from these catchment areas get trapped in the mangroves along the Mahim creek. Singare (2012) found that Mahim creek is one of the most polluted creeks in India.



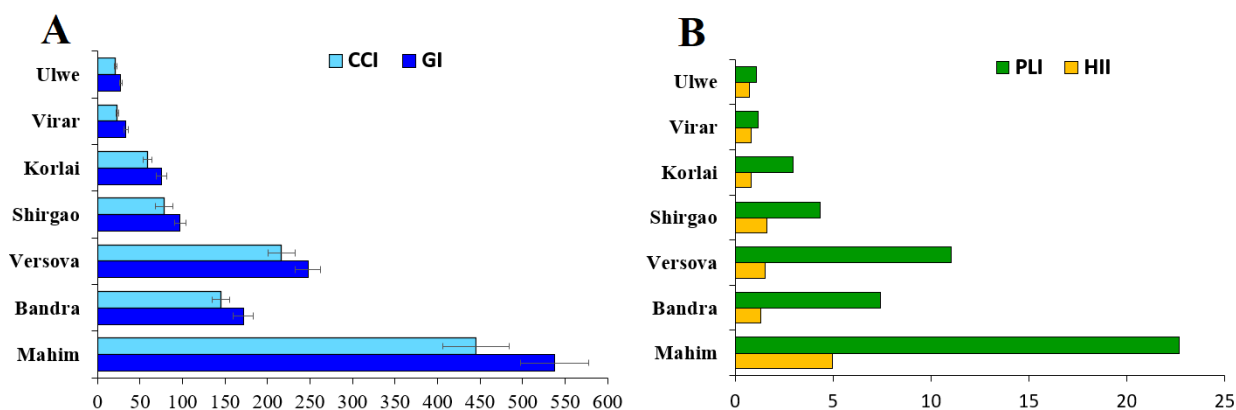
Another mangrove stands at Ulwe, located adjacent to Thane creek. Previous report highlighted that the mangrove ecosystems of this region are facing threats due to anthropogenic stress, particularly from industrial pollution (Pawar, 2013). Although mangroves in Korlai and Sirgao are far from urban pressure, we assumed that the locally generated solid waste might be lower compared to a megacity like Mumbai. However, due to the lack of adequate solid waste management facilities in rural areas, the collection remains low, and most of the household solid waste is disposed of in open areas that end up in the marine environment. In addition, the transfer and redistribution due to river discharge, wind, currents, and other climatic conditions could play an important role in litter accumulation in the mangroves.

### **3.4. Mangrove floor cleanliness assessment**

Here, CCI, GI, and HII were applied to assess the hazard associated with litter pollution on the mangrove floor. The mean CCI value was recorded as 141 across the studied mangroves during this study. The highest mean CCI value was recorded at Mahim ( $445.5 \pm 39$ ), and the lowest was at Ulwe ( $21.33 \pm 1.36$ ). Based on the CCI scores, all the mangrove stands could be classified as “extremely dirty” (Fig. 5A, and electronic supplementary material Table S6). Additionally, the highest GI score was recorded at Mahim ( $537.5 \pm 40.53$ ), and the lowest was recorded at Ulwe ( $27.5 \pm 1.89$ ), indicating that all the studied areas fell under the “extremely dirty” category (Fig. 5A, Table S6). Our previous study on litter abundance in Mumbai’s rocky intertidal region categorized the area as “extremely dirty”, based on GI and CCI values. Hazardous litter in mangroves may cause profound health implications to the public, such as cuts and injuries to people and fauna from sharp metals, tin cans, broken glasses, and syringes. Medical and sanitary waste (PPE face masks, syringes, sanitary pads, diapers, condoms) can cause significant health risks to the coastal community (Rangel-Buitrago et al., 2019). The hazardous litter constituted 2.6% of the total litter (186 items out of 7143 litter items). The highest HII was recorded at Mahim ( $4.99 \pm 1.15$ ), which falls under the “class IV” category, signifying the presence of much hazardous litter in the area. The lowest HII was recorded at Ulwe ( $0.75 \pm 0.41$ ), which falls under the “class II” category, indicating some hazardous litter on the mangrove floor (Fig. 5B, Table S6). The GI and CCI values highlighted that the studied areas were ‘Extremely dirty’ by the presence of different types of marine litter. CCI value in our study sites was significantly higher than other Indian coasts like Lakshadweep Islands, range [3.15, 10] (Kaviarasan et al., 2020) and Palk bay, range [4.3, 20.4] (Perumal et al., 2021), indicating a very low degree of cleanliness, also evident from the presence of highly weathered litter (personal observation). The higher values of CCI in the study area could be due to a large amount of land-based and sea-originated litter input in these regions, irregular litter cleaning activity, and inadequate solid waste management facilities. These indices are an informative tool for evaluating litter

accumulation in coastal environments and could also be helpful for coastal management framework and in evaluating the effectiveness of prevailing solid waste management systems (Semeoshenkova et al., 2017).

The PLI was developed for monitoring metal pollution levels in estuarine environments (Tomlinson et al., 1980). PLI has recently been applied to microplastic pollution studies in marine ecosystems (Pan et al., 2021; Ranjani et al., 2021; Xu et al., 2018). To the best of our knowledge, the present study employed the PLI for the first time to explore the ecological risks consociated with the macroplastic pollution load in mangroves. PLI values from Mahim (22.68), Versova (11.04), and Bandra (7.41) along the Mumbai coast showed high pollution risk (Fig.5, Table S6). According to PLI values, sediments along Virar (PLI=1.18), and Ulwe (PLI=1.09), were less contaminated with plastic litter. Overall, PLI values in the mangroves across the coast were relatively lower (i.e., 4.38), falling within the ‘Hazard level I’ categories. Nevertheless, additional research on the temporal variability of plastic litter pollution and associated ecological risk on mangrove systems is needed to validate our preliminary risk assessment results.



**Fig. 5.** Cleanliness indices based on marine litter at different sites, (A) Clean Coast Index (CCI) and General Index (GI), (B) Pollution load index (PLI) and Hazardous Items Index (HII)

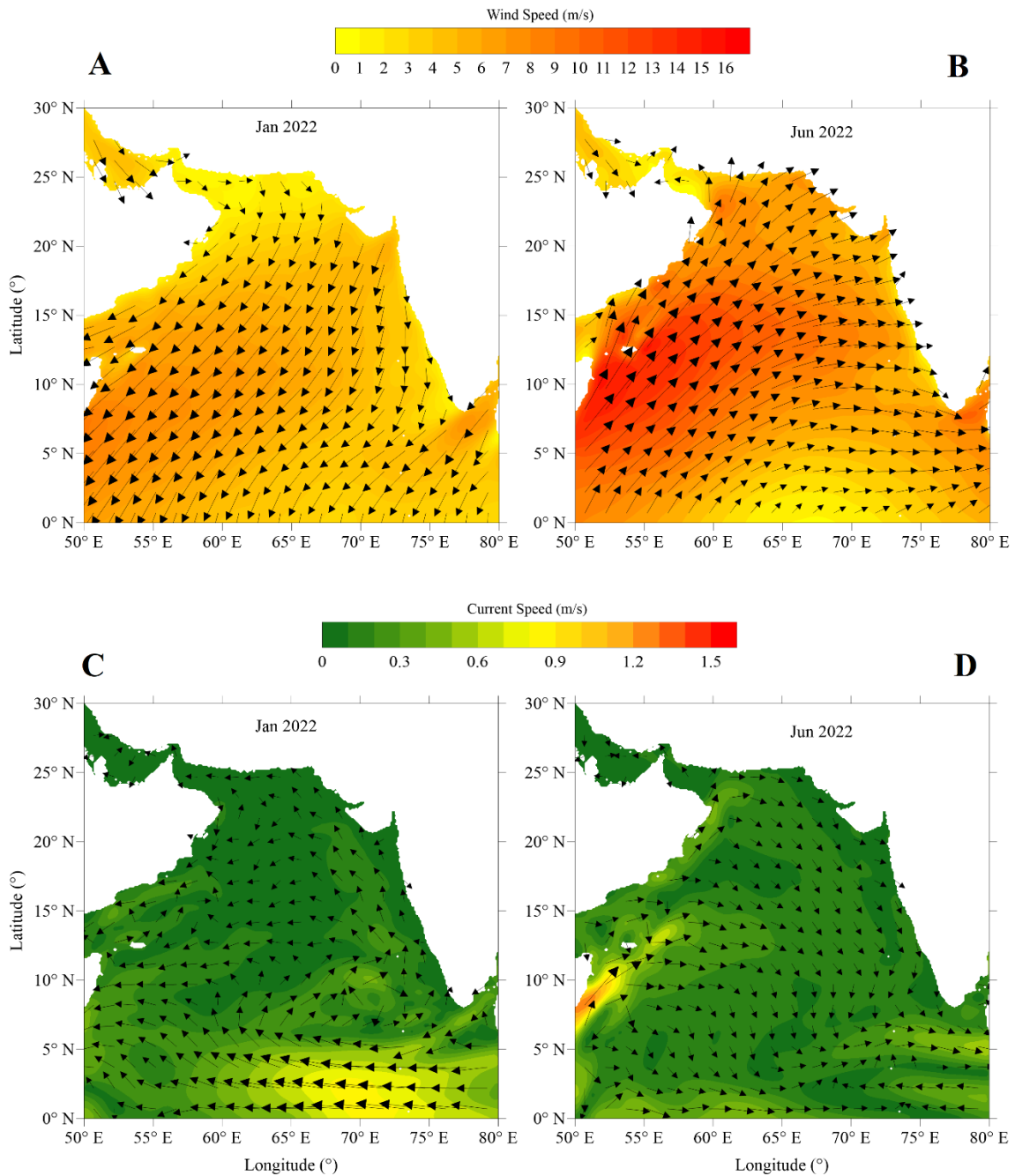
### 3.5. Factors impacting marine litter transport and accumulation in mangroves

Oceanographic physical processes along with atmospheric processes, which include tides, currents, waves, winds, Stokes' drift, longshore drift, and morphodynamics of the coast, play a key role in determining the transportation, accumulation, and retention of marine litter (Veerasingam et al., 2016; Zhang et al., 2020). Oceanic surface currents and waves transport the litter across the ocean and carry it from the open ocean toward the coast, where it accumulates in the swash zone. However, based on the beach morphodynamics, the litter may be accumulated across the beach or deeper into the sediments. Litter deposited on the mangrove forest floor is most likely washed off and

resuspended. The primary factor for the plastic litter deposited on the mangroves is the untreated waste dumped directly into creeks and city drainages from domestic sources in thickly populated catchment areas, about 77% of this litter consisted of plastic bags easily carried away by wind and tide (Manickavasagam et al., 2020).. Plastics littered by the public are an additional factor of ecological concern along the western coast of India. Rivers, creeks, and drainage systems transport terrigenous runoff driven by monsoonal rainfall and/or cyclonic events, accumulating massive amounts of plastic litter in the coastal area.

### **3.5.1. Hydrodynamics**

The seasonal reversal of wind systems during the southwest (SW) and northeast (NE) monsoon is a unique nature that primarily drives the northern Indian ocean hydrodynamics. The transport of plastic particles to the shore is affected by these seasonal winds and currents (Kim et al., 2015; Veerasingam et al., 2016). The open coast of Maharashtra is predominantly influenced by north-northeast wind during NE monsoon (Fig. 6A) and southwest-west wind during SW monsoon (Fig. 6B). Many researchers have pointed out that the wind speed and wind direction together play a crucial role in the spatial distribution and accumulation of marine litter (Kukulka et al., 2012; Pattiaratchi et al., 2022; Zhang, 2017). Most of the plastic litter was found to be accumulated towards the lee shore. However, further study is required to investigate the vertical distribution of plastic litter with wind effects in our studied region.

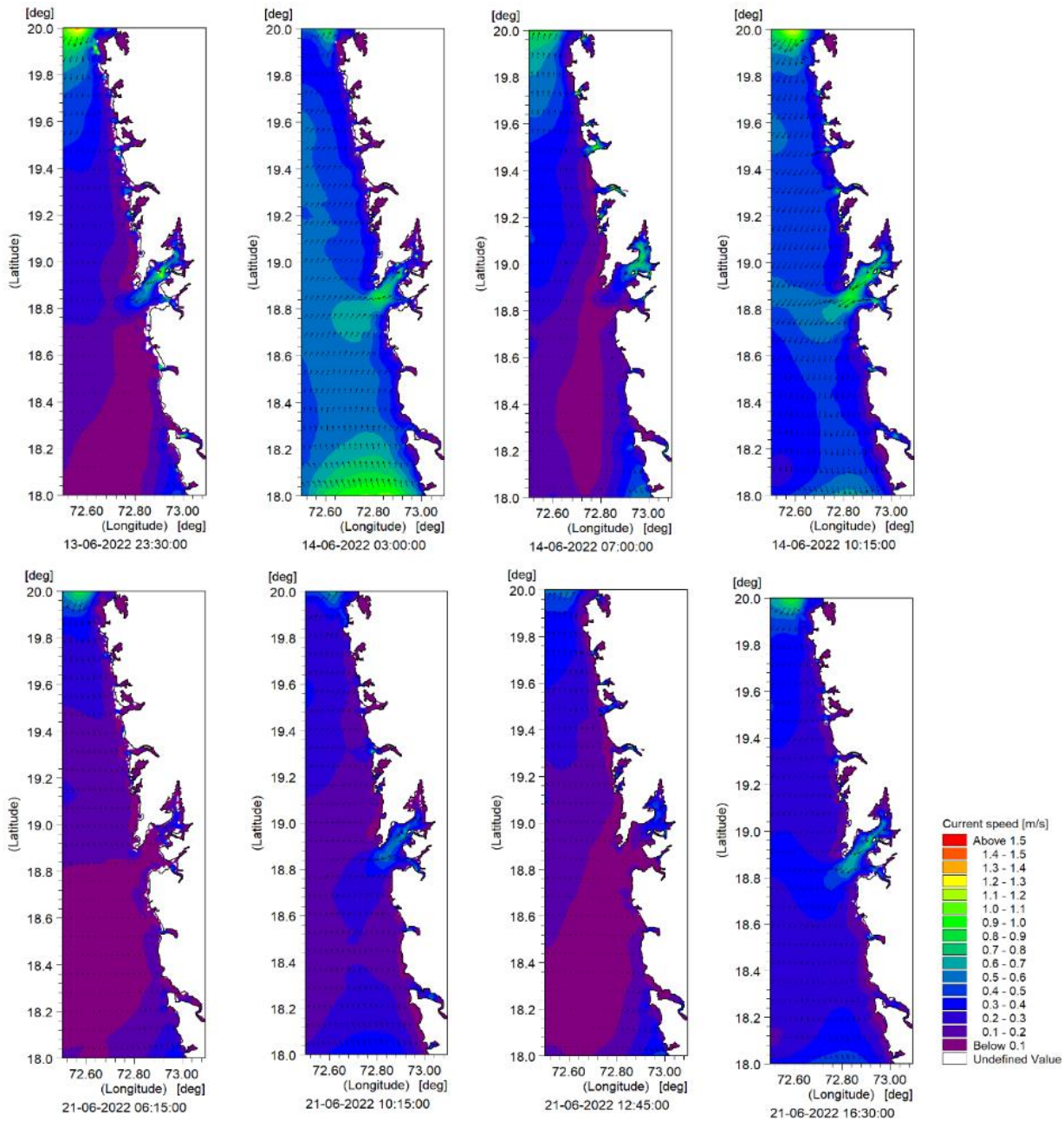


**Fig. 6.** Seasonal wind during- (A) northeast monsoon; (B) southwest monsoon. Seasonal current pattern during- (C) northeast monsoon; and (D) southwest monsoon in the Arabian Sea.

The current direction is the major factor that decides the distribution of marine litter along the shore. Seasonally reversing open ocean currents occur in the Arabian sea, known as SW monsoon currents and NE monsoon currents. The surface currents in the Arabian sea during the SW monsoon are the sum of the geostrophic current and Ekman drift. The Ekman velocity is stronger throughout the year compared to the geostrophic velocity and seasonally changes in its direction. The main driver of surface velocity fields in the Arabian sea is the wind-driven Ekman flow (Shankar et al., 2002). A similar reversal trend can be observed in the NCEP currents used in this study (Fig. 6C–D). During

January 2022, the currents are towards the west-northwest, away from the coast of Maharashtra (Fig. 6C), whereas during June 2022, currents are in the east-southeast direction, i.e., coastwards direction (Fig. 6D). The effect of Ekman drift on marine litter/debris have also been reported in earlier studies (Isobe et al., 2014; Zhang, 2017).

Along the coast, the waves are leading the littoral processes. Longshore currents associated with breaking waves and coastal breezes are the primary drivers influencing longshore drift (Komar, 1976). Similar to the transportation of sediment particles, longshore drift is also capable of marine litter transportation, which may be deposited or re-deposited along the coast based on the winds, currents, waves, shore morphology, and litter density. During June to July, net longshore drift moves toward the south along the west coast of India and towards the north for the rest of the year (Shanas and Sanil Kumar, 2014). Thus, the longshore drift has a unique contribution in transporting the deposited marine litter from one place to another; this also could be the cause for the high litter concentration during June (SW monsoon) in the study area. Maharashtra coast experiences reversing of the monsoon winds from June-September (SW monsoon) and November-February (NE monsoon), and the wind-induced surface ocean currents (Shankar and Shetye, 1997; Shenoi et al., 2004). While reaching the coast, the tide has a major contribution to the hydrodynamics, whereas the change in coastal morphology in creeks, rivers, bays, and engineering coastal structures may deviate transport direction. The simulated hydrodynamics across various phases of tidal conditions along the north part of the Maharashtra coast reveals that the current pattern is strongly associated with tidal fluctuations (Fig. 7). Additionally, the magnitude and direction along 10 m contour off the specific mangrove stands reveals the intensity of current gradually increases towards north, while the direction is almost similar across the locations along the 10 m contours (electronic supplementary material, Fig. S3). However, model simulation results exhibit that the current magnitude and direction varies abruptly in the swash zone across the different tidal phases along the sampling locations depending up on the surrounding morphology (Fig. 7). In the coastal domain, the water column mixing as well as stratification are responsible for the spatio-temporal distribution of plastic particles (Uurasjärvi et al., 2021).



**Fig. 7.** Coastal current along the Maharashtra coast at various tidal phases (Upper panel: Spring tide, Lower panel: Neap tide)

### 3.6. Ecological risk of marine litter on mangrove ecosystem

Our results support previous studies that noted mangroves trap floating litter, and complex aerial root systems act as a filter, preventing litter from being moved into the ocean by the flow of tides, currents, and waves (Luo et al., 2022, 2021; Martin et al., 2019; K. Selvam et al., 2021a). Systematic studies and standardized models on the environmental hazards caused by marine litter/plastics on coastal vegetation, like seagrass, macroalgae, and mangroves, are at a nascent stage. In the present study, we found that entangled plastic sheets, film, net, and rope can cause direct damage to

mangrove pneumatophores (Fig. 8C–D) and branches (Fig. 8E–H). Previous studies also showed that trapped plastics wrap branches and pneumatophores, barring sunlight exposure, disrupting photosynthesis, and affecting the growth of pneumatophores (Selvam et al., 2021a; Smith, 2012; van Bijsterveldt et al., 2021). Plastics also clog pneumatophores, disrupt proper gas exchange, and may cause local scale anoxia, leading to the suffocation and deformation of pneumatophores (Sandilyan and Kathiresan, 2012). van Bijsterveldt et al. (2021) found that continuous suffocation by trapped plastic is potential for rapid pneumatophore growth and leaf loss. Marine litter also negatively impacts the settlement and survival of mangrove propagules/seedlings by creating space constraints, inflicting physical damage, loss of foliage, crushing, and death (Garcés-Ordóñez et al., 2019).

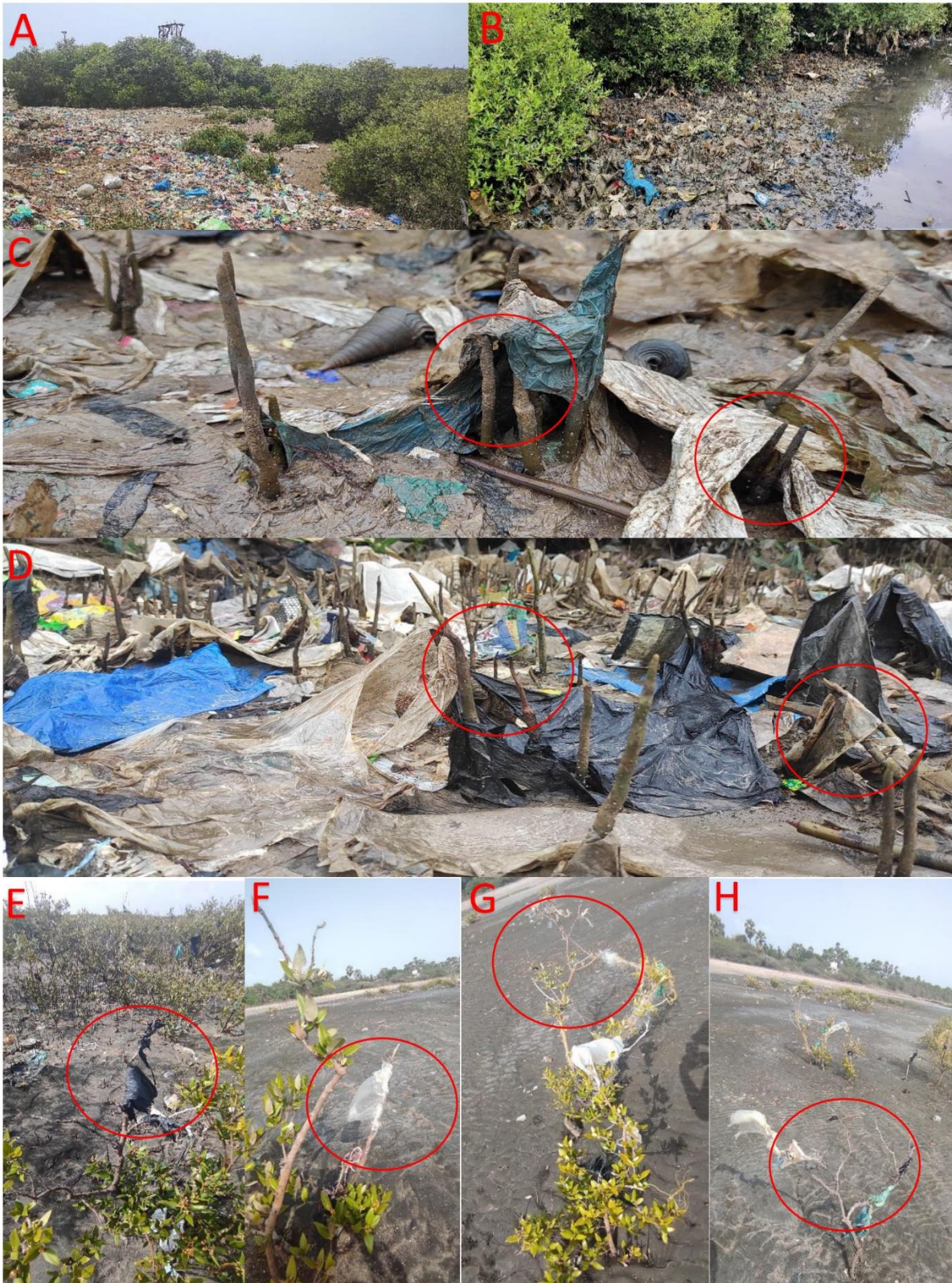
Since mangroves provide nursery ground and habitat to a large number of biota, thus it increases interaction between biota and plastics. Plastic sheets and bags negatively affect the species that live in the sediment associated with the mangrove roots. For example, Bulow and Ferdinand (2013) found a reduced number of crab (*Uca* sp.) burrows in areas covered by marine litter. Furthermore, plastics may cause entanglement, ingestion, and obstruction of the crab's hole (Ivar do Sul et al., 2014; Not et al., 2020). Sandilyan and Kathiresan (2012b) noted that the entangled plastic carry bags in mangroves produce a peculiar sound, which causes panic in the avifaunal community and keeps them away from that particular mangrove habitat. A recent study also confirmed that mangrove-dwelling avifaunal communities avoid litter-dominated mangrove habitats (Winarni et al., 2022). Our surveyed mangrove mudflat at Ulwe, located adjacent to Thane creek, is an important feeding ground for migratory bird species like Flamingos. Recently, Thane creek has been designated as a Ramsar site, indicating its importance for biodiversity and conservation. Hence, urgent solid waste and litter management is a prerequisite in this region.

Although the present study primarily focused on surficial litter (found only on the surface sediment or partially buried), our field observation found a large number of buried plastics (with scratches and damage on the external surface) in mangrove sediment at Versova and Mahim (Fig. 8B–D), indicating aging of plastics. Complex aerial root structures of mangroves trap both rigid and soft litter; subsequently, local hydrodynamics cause the burying of litter, which may remain buried for years (Costa et al., 2011). The ubiquitous presence of plastic objects in litter composition indicates that highly durable plastic may persist for hundreds of years before degrading or may never truly degrade as they transform into microplastics and nanoplastics (1 and 1000  $\mu\text{m}$  in size; Hartmann et al., 2019) by UV radiation exposure and other physical forces (Sipe et al., 2022). Micro and nano plastics are highly bioavailable due to their small size across different trophic levels (Guo et al., 2021), causing inescapable long-term intrusion into the food chain. Furthermore, according to the

hazard-ranking model of the United Nations' Globally Harmonized System of Classification and Labelling of Chemicals, over 50% of plastics contain several chemicals that are identified as hazardous (Lithner et al., 2011; Rochman et al., 2013). For example, Polycyclic aromatic hydrocarbons (PAHs), Polychlorinated biphenyls (PCBs), dichloro-diphenyl-trichloroethane (DDTs), polybrominated diphenyl ethers (PBDEs), alkylphenols and bisphenol A are some of the organic micro-pollutant presents in plastics (Hirai et al., 2011).

Additionally, plastic particles adsorb different pollutants (including persistent organic pollutants, trace, and toxic metals) from the surrounding environment (Groh et al., 2019). Mangrove-dwelling biota, especially commercially important fishes, crustaceans, and mollusks, have been found with ingested plastic particles, which may ultimately transfer up to humans via the food chain. For example, the microplastic trophic transfer is reported from primary consumers to tertiary consumers in the world's largest mangrove forest Sundarban (Sarker et al., 2022), indicating a potential health hazard to the human population as a consequence of bio-magnification. Large populations in low-income south Asian countries are highly dependent on mangrove fisheries; hence, further research is needed to elucidate the probable exposure routeways and toxic exposome of plastics (micro and nano plastics) from the mangrove ecosystem to humans.





**Fig. 8.** The figures illustrate the exposure of mangroves to anthropogenic litter- A) litters dumped in the mangrove; (B) plastic accumulation on the mangrove sediment; (C, D) plastic-covered pneumatophore and damaged pneumatophore due to plastic wrapping; (E, F, G) trapped marine litter in the mangrove canopy and dead branches due to plastic wrapping ; (H) dead plant covered by plastic

1 **Table 2:** Summary of plastic litter studies in mangrove ecosystems around the world

Location of mangroves	Mangrove surveyed	plant	Sampling method	Quantity	Major litter items	Contribution of plastic litter	References
Mangrove forest, Hong Kong	<i>Kandelia obovata</i>		1 × 25 m Belt transects	1.45 ± 0.38 items/m <sup>2</sup>	Plastic, wood, metal, rubber, cloth, paper, glass, ceramic	70.31% density by cover 49.17% by area	Luo et al., 2022
Cebu Philippines	Island, <i>Rhizophora</i> <i>sp.</i> , <i>Avicennia</i> <i>sp.</i> , <i>Sonneratia sp.</i>		Transect (100 to 600 m), 10 × 10 m plots	1.29 ± 0.67 items/m <sup>2</sup> (ranges 0–31.75 items/m <sup>2</sup> ), 18.07 ± 8.79 g/m <sup>2</sup>	Plastic packaging, plastic bags, plastic fragments, buoys, fishing gear, and nets	78.1%	Paler et al., 2022
Jakarta Bay, Indonesia	<i>Avicennia marina</i> , <i>Rhizophora mucronate</i> , <i>Rhizophora stylosa</i> , <i>Sonneratia caseolaris</i> , <i>Excoecaria agallocha</i>		Circular sampling area with a 10 m radius	2.06 items/m <sup>2</sup> to 5.41 items/m <sup>2</sup>	Plastic (fragments, cups, food wrappers, plastic bags, plastic bottles, and bottle caps), metal, glass, rubber, processed wood, fabrics	89%	Winarni et al., 2022
Demak Central Java	regency, <i>Avicennia alba</i> , <i>Avicennia marina</i>		50cm × 50 cm quadrats	0 to 236 items/m <sup>2</sup> , mean 27 items/m <sup>2</sup>	Plastic waste	covering up to 50% of the forest floor	van Bijsterveldt et al., 2021
Seaflower Reserve in the north of the Caribbean	Biosphere Not stated		10 m × 10 m transects	0.4–1.4 items/m <sup>2</sup> and masses of 0.1–1.2 kg/m <sup>2</sup>	Plastics (food wrappers, sheets, plastic tiles, bottles), metals, glass, processed wood, paper/cardboard, textiles, electrical appliances, zinc mattresses, furniture, glass, clothing, boards, processed wood	>60%	Garcés-Ordóñez et al., 2021

Mumbai, India	<i>Avicennia marina</i> , <i>Acanthus ilicifolius</i> , <i>Ceriops tagal</i> , and <i>Bruguiera cylindrical</i>	20×2m belt- transects	8.82 ± 3.47 items/m <sup>2</sup> on mangrove floor, 35 ± 10.4 pieces/tree, 920 ± 317g/m <sup>2</sup> , 2514 ± 758 g/tree	Plastics, metal, glass, rubber, lumber, cloth	62.4%	Kesavan et al., 2021
Beilun estuary, Fangchenggang, China	Not stated	10 m × 10 m quadrats	0.163 item/m <sup>2</sup> , 21.123 g/m <sup>2</sup> (2.355~51.76)	Plastics, styrofoam, wood, paper, metal, rubber, fabric/fiber, glass, and other material	>60%	Li et al., 2021
Mahebourg and Ferney, south east coast of Mauritius	<i>Rhizophora mucronate</i> , <i>Brugueira gymnorrhiza</i>	70 m transects, 100 m <sup>2</sup> square quadrats	0.46 ± 0.24 at Mahebourg and 0.24 ± 0.22 at Ferney	Plastic, foam, cloth, glass, metal, paper, rubber, wood	42.92-43.66%	Seeruttun et al., 2021
Xuan Thuy National Park, Nam Dinh province, Vietnam	Not stated	50 × 5 m or smaller transects	0.14 to 16.9 items/m <sup>2</sup> , Mean 2.81 items/m <sup>2</sup>	Plastic (food wrappers, fragments, plastic bags, pieces of plastic rope and nets), fabric pieces, foam,	86.6%	Giles et al., 2021
Panvel creek, Maharashtra, India	Not stated	Not stated	Not stated	Glass, plastic bottles, cans, bags, rubber, metal, fiberglass, cigarettes, fishing gear etc	63%	Mayur et al., 2021
Mangrove-ecosystem and estuaries of Kendari Bay, Indonesia	Not stated	5×5m quadrats	1.76 to 3024 items/m <sup>2</sup>	Plastic (bottles, bags, ropes, pipettes, cups), metals cans, rubber, glass bottles, cloth, paper, and others	159 to 378 items/m <sup>2</sup>	Rahim et al., 2020
Ambon Bay (Passo, Waiheru, Nania) and Baguala Bay (Suli), Indonesia	Not stated	10 × 10 m Plot, 1 × 1 m Plot, 0.5×0.5m quadrates along a 540 m line	10 ± 4 items/m <sup>2</sup> to 230 ± 75 items/m <sup>2</sup> , Mean 92 ± 28 items/m <sup>2</sup>	Fiber, foam, film, fragment	25-62%	Suyadi and Manullang, 2020



transects

Kupang, Indonesia	<i>Rhizophora mucronata</i> , <i>Rhizophora stylosa</i> , <i>Avicennia marina</i> , <i>Avicennia alba</i> , <i>Osbornia octodanta</i> and <i>Ceriops tagal</i>	Line transects with 10×10m Plot	9.622 items/m <sup>2</sup>	Plastic bags, foamed plastics, fabric, glass and ceramics, metal, paper and cardboard, rubber, wood, and other	92.3%	Paulus et al., 2020
Penang Island, Malasia	<i>Avicennia marina</i> , <i>Bruguiera cylindrica</i> ,  <i>Rhizophora apiculate</i> ,  <i>Rhizophora mucronate</i> ,  <i>Sonneratia alba</i>	10×10m quadrat	Urban: 12.6-73.1 items/m <sup>2</sup> ,  peri-urban: 2.1-10 items/m <sup>2</sup>	Plastic (foam, sheet, film, fragment), glass, wood, paper, rubber	75.3% to 92.5%	Yin et al., 2019
Ciénaga Grande de Santa Marta, Colombian Caribbean	<i>Laguncularia</i> <i>racemosa</i> , <i>Avicennia</i> <i>germinans</i> , <i>Rhizophora</i> <i>mangle</i>	50m × 2m transects	540 ± 137 and 31 ± 23 items/ha	Plastic, metal, glass, rubber, rubble, textile, processed wood, hospital, sanitary wastes	73 and 96%	Garcés- Ordóñez et al., 2019
Saudi Arabia (Red Sea and Arabian Gulf coast)	<i>Avicennia marina</i>	4m to 60m long and 2m to 8m width transects	0.66 ± 0.18 items/m <sup>2</sup> in the Red Sea,  1.21 ± 0.53 items/m <sup>2</sup> in the Arabian Gulf	Plastic fragments, fishing lines, food wraps, bottle caps, ropes, polystyrene, plastic bags, buoys, small containers, drink bottles, nets, detergent bottles, oil containers, footwear, carboys, big containers	92.2 ± 1.4% in the Red Sea, and 95.5 ± 2.5% in the Arabian Gulf	Martin et al., 2019
Buenaventura bay, Colombia	<i>Rhizophora</i> sp.	154m <sup>2</sup> plots	0.22-35.5 items/m <sup>2</sup> ,  2 to 314 g/m <sup>2</sup>	Plastic cups, polypropylene woven bags, polyethylene plastic bags, rigid polyethylene containers, plasticized fabric,	86.86%	Riascos et al., 2019

					extruded polystyrene foam, disposable diapers, hard polypropylene, shoe (mixed materials), nylon, fiber, glass, fabric, glass, metal cans		
Tunda Indonesia	Island,	Not stated	100m line transect	0.75 items/m <sup>2</sup> , 0.075 kg/m <sup>2</sup>	Plastic bottle, bottle caps, lids, straw, beverage bottle, grocery bags, cigarette butt, can, straw	Not stated	Maharani et al., 2018
Pantai Indah Indonesia	Kapuk,	<i>Avicennia marina</i>	1×1m quadrat	20 to 533 items/m <sup>2</sup> , 108.7-5449.7 g/m <sup>2</sup>	Plastics, styrofoam, rubber cloth, glass, metal, foam, wood	77.7%	Hastuti et al., 2014
Goiana Estuary, Brazil		<i>Rizophora mangle</i>	20 m <sup>2</sup> plot	Not stated	Plastic bags, PET bottles, margarine tubs, plastic cups, polystyrene blocks	Not stated	Ivar do Sul et al., 2014
Lac Bay, Bonaire		Not stated	5m wide line transect	6.3, 5.8, and 23.2 items/m <sup>2</sup> , 0.71, 0.35, and 0.74 kg/m <sup>2</sup> surficial debris concentrations in the mangrove	Plastic bags, plastic beverage cups, polystyrene, rope, wood	72% abundance, 39% by mass	by Debrot et al., 2013
Ratones mangrove, Florianopolis, Santa Catarina Island, Brazil		<i>Laguncularia racemosa</i> , <i>Avicennia schaueriana</i> , <i>Spartina alterniflora</i> , <i>Rhizophora mangle</i>	50 m <sup>2</sup> plots	Not stated	Plastic, nylon, rubber, metal, wood, glass, tissue, ceramic, and other	63%	Vieira et al., 2013
Motupore Papua New Guinea	Island,	Not stated	1×2m quadrats along a 50m transect	1.2-78.3 items/m <sup>2</sup> , average of 15.3 items/m <sup>2</sup>	Plastic, rubber, textile, metal, wood, glass, paper	89.7%	Smith, 2012

Mahim creek, India	Not stated	Not stated	215.13 kg/Ha and 42.21 kg/Ha	Plastics, polystyrene, carry bags, plastic bottles, glass, synthetic rubber	55% to 71%	Singare, 2012
Pichavaram, Tamil Nadu, India	Not stated	Not stated	Not stated	Plastic carry bags, plastic bottles, food wrappers	Not stated	Sandilyan and Kathiresan, 2012
Sao Vicente Estuary Complex, Brazil	<i>Rhizophora mangle</i> , <i>Avicennia schauerian</i> , <i>Laguncularia racemosa</i>	10 × 10 m plots	129.66 g/m <sup>2</sup> , 1.33 items/m <sup>2</sup>	Rubber, foam, medical and personal hygiene, plastic, fabric	62.81%	Cordeiro and Costa, 2010
Kingston, Jamaica		1m <sup>2</sup> quadrats, along a line transect				Green and Webber, 1996
Mangrove ecosystem of Central West coast of India	<i>Avicennia marina</i> , <i>Avicennia officinalis</i> , <i>Sonneratia apetala</i>	20 × 2 m belt transect	Mean density of 8.5±1.9 litter items/m <sup>2</sup> on mangrove floor, ranging from 1.4 to 26.9 items/m <sup>2</sup> , and 10.6 ± 0.5 items/tree, ranging from 0 to 85 items/tree	Plastics (drink bottles, bottle caps, bags, food wraps, sachets, fragments, tubes, cups, straws, plastic cutlery, fishing nets, ropes/lines, styrofoam), glass/ceramics, textiles/fabrics, sanitary waste, medical waste, metals, timbers/processed woods, footwear, tetra packs, steel can	83.02% mangrove floor, 93.4% in mangrove canopy	Present study

### **3.7.Perspective on the mitigation of marine litter in the mangrove ecosystems**

Southeast Asia hosts the world's most diverse mangrove ecosystems and the highest mangrove cover (Giri et al., 2015). Conversely, Southeast Asia is also affected by the highest levels of marine plastic pollution (Omeyer et al., 2022). India has 4,975 km<sup>2</sup> of forest area under mangrove cover, i.e., 3.3% of global mangrove cover (FSI, 2019). In India, coastal protection and carbon sequestration provided by mangrove ecosystems alone contributed to INR 560-754 billion and INR 0.76-1.65 billion, respectively (Anneboina and Kavi Kumar, 2017; Kavi Kumar et al., 2016). However, the Indian mangrove forest cover is dwindling, and nearly 40% has been lost during the last 100 years because of rapid urbanization and over-resource extraction (Abdul Azeez et al., 2022; Youdon, 2020). Coastal developmental activities, including deforestation due to the construction of ports, road projects, and jetties, severely affect the natural resilience for regeneration and growth. Alongside, India is ranked among the top twelve plastic waste-generating countries (Jambeck et al., 2015), indicating that plastic litter management is apparently lagging behind the best practices (Chitra, 2021; Pathak, 2020; Shaikh and Shaikh, 2021). Rapid urbanization, industrialization, and increased consumption contribute to enhanced solid waste generation in India (Priti and Mandal, 2019; Sharma and Jain, 2018). In addition, decades-long unscientific handling and dumping of solid waste caused severe pollution due to uncontrolled flows and leachate mismanagement (Chitra, 2021). In India, 40% of plastic waste does not follow a properly integrated waste management approach and ends up in landfills (Rafey and Siddiqui, 2021). Hence, urbanized and densely populated coastal areas along the Indian coast are highly exposed to litter pollution and could be a potential source of micro (nano) plastics (Ranjani et al., 2021; Sivadas et al., 2022; Veerasingam et al., 2020b). Moreover, it is estimated that the global annual emission of plastic in the coastal ecosystems may increase by more than 50% by 2030, and for Indian cities, the projection indicates annual production of solid waste of 107.01 million tons by 2031 (Pal and Bhatia, 2022), which warrants extraordinary coordinated efforts to ameliorate plastic pollution (Borrelle et al., 2020). In developing countries like India, the expansion of decentralized solid waste processing units and bolstering of the recycling industry sector is essential to reduce the ever-increasing burden of solid waste (Joshi and Ahmed, 2016). Several countries have intervened plastic litter pollution by implementing bans on using and manufacturing single-use plastic (Schnurr et al., 2018). Likewise, India has institutionalized Plastic Waste Management Rules 2016, with the aim of plastic waste minimization, source segregation, and recycling (GOI MOEFCC, 2016). Recently, India has banned single-use plastics (less than 75µ) from 1<sup>st</sup> July 2022, and notified extended producers' responsibility (EPR) on plastic packaging, but the stringent implementation of regulation and effective plastic waste management is still a concern for

the country, and follow-up measures need to be taken. The lack of well-organized solid waste collection, the absence of adequate solid waste treatment infrastructures in rural areas and small towns, ineffectual monitoring mechanisms, population growth and a consumerism-centric lifestyle, suggest that the plastic problem is still far from the solution (Pal and Bhatia, 2022).

Rapid urban sprawling, economic development, and population growth are driving factors in burgeoning plastic waste generation in the Mumbai megacity (Chitra, 2021; Jayasiri et al., 2013; Pathak, 2020). Like most urban areas in India, a large amount of solid waste in Mumbai remains primarily untreated because of financial constrain and infrastructure shortfall (Sharma and Jain, 2018). The higher number of litter was recorded in mangrove stands on Mumbai city shore (at Mahim, Bandra, and Versova; Fig. S1D), points to the proximity of the megacity and the urban waterways (notably the Thane creek, Mithi river, Juhu creek, Versova creek, and numerous drainage) as a primary driver of marine litter accumulation (De et al., 2022b; Manickavasagam et al., 2020; Singare, 2012a, 2012b). It is known that urban mangrove sites have more litter concentrations than rural areas, as the density of plastic debris is significantly linked to surrounding socio-economic development and urban-related attributes, like high population density, anthropogenic and economic activities around mangroves (Garcés-Ordóñez et al., 2021; Li et al., 2020; Paler et al., 2022). Riascos et al. (2019) stated, “mangrove forests located close to the city are among the most polluted coastal areas in the world”. Like other developing nations in the global south, coastal natural ecosystems in India are witnessing a high degree of anthropogenic pressure due to the booming population, changes in land use, and rapid coastal development, which significantly enhanced the plastic pollution in the surrounding environment. Additionally, growing coastal tourism may elevate plastic pollution (Jayasiri et al., 2013). In rural areas, most domestic solid waste is primarily incinerated or burial in landfills due to a lack of proper waste collection and disposal facilities; that is flushed away during the rainy season or by the tidal currents, eventually entered in coastal water. For instance, our surveys in the rural areas (Korlai and Shirgaon) confirm that mangrove swamps were used as land fill or dumping sites for direct waste dumping (Fig. 8A). Subsequently, intertidal mangrove vegetations trap and retain these escaped litter and plastics that have entered to sea (Luo et al., 2022; Paler et al., 2022).

There are growing evidences that burgeoning plastic consumption and mismanaged litter elicited myriad challenges in Indian coastal ecosystems (reviewed in Sivadas et al., 2022). The projected plastic production and accumulation in the Indian oceans rim countries is alarming (Pattiaratchi et al., 2022; Sivadas et al., 2021), which could pose serious challenges to nation’s economy and environmental health and to United Nations-sustainable development goals (UNSDGs). The 26th



United Nations Climate Change Conference of the Parties (COP26), 2021, put plastics on its agenda, and emphasized on alleviating waste. Hence, environmental managers need to pursue sustainable solutions to tackle plastic problem urgently. Our study indicates that the trapped litter in the mangrove ecosystems is mostly single-use consumer plastic items, primarily composed of plastic bags, food wrappers, packaging materials, sachets, and beverage cups. These types of single-use plastic products could be checked by collective targeted actions by the public, industries, and political/government willingness and intervention (Winton et al., 2020). Additionally, the recent country-wide ban on single-use plastic products in India would positively impact the regulation of plastic waste. However, due to the transboundary nature of plastic litter, coordinated global actions for plastic management remain a prerequisite in addition to regional solid waste management. Additionally, environmentally responsible corporate practices, payments for ecosystem services (PES), and extended producers' responsibility for the non-biodegradable products manufacturing companies, and making the plastic producers accountable for waste collection, segregation, and recycling could ameliorate the litter problem. It is evident from the present study that most marine litter originates from land-based sources and allied activities. For example, through periodic clean-up programs, the Maharashtra forest department has removed more than 9,000 tonnes of plastics litters from Mumbai's mangrove stands (Chatterjee, 2018). Although periodic coastal and mangrove clean-up campaigns could momentarily reduce litter concentration, a global meta-analysis revealed that litter clean-up programs have negligible effects on long-term litter pollution due to the high magnitude of plastic emissions in the environment (Hohn et al., 2020). Hence, priority targets should be focused on source control and intercepting the inflow of litter into the water channels (city drainage, rivers) and reinforced collection at sea (Hohn et al., 2020).

Moreover, creating environmental literacy and littering awareness for the general public and coastal communities, building adequate solid waste management infrastructure, technological innovation and upscaling plastic litter recycling, and stringent enforcement of regulation would assist in practical solutions to prevent coastal litter. To reduce fishery-related litter, developing plastic waste management facilities near the fishing port and financial incentives to fishers may reduce the practice of discarding overboard end-of-life fishing gear. Financial incentives for collecting litter at sea or a 'buy back program' for end-of-life gear could help to ameliorate fishing-based litter.

#### **4. Conclusion**

In summary, our results indicate that mangroves are highly exposed to anthropogenic litter and plastics due to mismanaged land-based solid waste and fishing activities in the sea. Single-use plastics were most the abundant litter component across the mangrove stands. Mangroves play an

important role in trapping litter, restricting land-based litter dispersal in the marine environment, and vice-versa. However, results show that increased interaction between litter and mangroves could be detrimental to pneumatophores and tree health, severely impacting the overall ecological functioning of this important coastal ecosystem. Degradation of mangroves by litter pollution may directly interfere with mangrove health and allied ecosystem services, like coastal protection from coastal erosion and extreme weather events like cyclones, rising sea levels, and tsunamis. A high amount of litter accumulation in the mangroves could be attributed to inadequate solid waste management, fishing, tourism, public littering, and regional oceanographic conditions, including tides, winds, and currents. Hence, preventive, mitigating, and curative measures of litter pollution exposure and protective measures of mangrove stands at the highly urbanized city shore may benefit millions of peoples' livelihoods, income, and well-being. We hope current research will help policymakers formulate appropriate strategies and timely action for managing marine litter pollution and conserving ecologically important mangrove habitats.

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**Kalyan De:** Sampling, Data curation, Writing - original draft, Writing – review & editing. **Sabyasachi Sautya:** Project administration, Resources, Writing – review & editing. **Udhaba Dora:** Hydrodynamic modeling, writing – review & editing; **Santosh Gaikwad:** Sampling, Data curation, Writing – review & editing. **Dinesh Katke:** Sampling, Data curation. **Aditya Salvi:** Sampling, Data curation.

### **Ethical review**

This study does not involve any animal testing.

### **Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Submission declaration and verification

Authors declare that the article is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

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**Electronic supplementary material:**

**Table S1:** Characteristics of the studied mangrove habitats

Study site	Location coordinates (Latitude, longitude)	Forest setting	Surrounding environment	Population (Census 2011)	Mangrove species	Condition	Solid waste management status
Mahim	19° 3'12.65"N 72°51'52.92"E	Coastal creek	Megalopolis, bank of creek, muddy bottom	12,442,373 (Mumbai city)	<i>Avicennia marina</i> , <i>Rhizophora mucronata</i> , <i>Sonneratia apetala</i>	Anthropogenic disturbance, urban creek (Mithi river) discharge, highly polluted, dense population	Municipal solid waste management facility
Bandra	19° 3'51.50"N 72°49'18.93"E	Coastal, exposed to open sea	Megalopolis, open coast, rocky bottom	12,442,373 (Mumbai city)	<i>Avicennia marina</i>	Anthropogenic disturbance, dense population	Municipal solid waste management facility
Varsova	19° 7'16.79"N 72°49'6.81"E	Coastal, protected by sandy beach	Megalopolis, muddy bottom, mangrove stands located behind the sandy beach	12,442,373 (Mumbai city)	<i>Avicennia marina</i> , <i>Avicennia officinalis</i> , <i>Sonneratia apetala</i>	Anthropogenic disturbance, drainage from creek and urban sewage drainage	Municipal solid waste management facility
Virar	19°29'45.55"N	Estuarine	Peri-urban, large and	1,222,390	<i>Avicennia marina</i> ,	Mangrove in this site	Municipal solid waste



	72°47'57.14 "E		small fringes along a river estuary, muddy bottom, river bank		<i>Avicennia officinalis</i>	located within the Vaitarna estuarine system and near the mouth of river. Anthropogenic activities seam less dominant except fishing	management facility
Ulwe, Navi Mumbai i	18°58'31.58 "N 73° 0'14.32"E	Coastal creek	Peri-urban, satellite township. Continuous and fragmented stands along a river estuary, muddy bottom, river bank	1,80,464 (Panvel)	<i>Avicennia marina</i> , <i>Avicennia officinalis</i>	The mangrove habitat is located within Panvel creek, situated in the Thane creek, one of the mega creek systems on the west coast of India. The site is surrounded by dense	Municipal solid waste management facility

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						human population, and evidenced the many anthropogenic activities including nearby port activity, fishing, reclamation, infrastructure development, tourist and sewage discharge.	
Shirgao n	19°40'59.07 "N 72°42'17.62 "E	Coastal, expose to open sea	Rural, coastal fringes, sandy bottom, open coast	5,971	<i>Avicennia marina</i>	The mangrove patch is ~4 km away from the nearby village. The site was nearly free from the direct anthropogenic activities. The mangroves	No municipal solid waste management

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						were directly exposed the open coastal waters along the sandy beach.	
Korlai	18°31'58.15 "N 72°55'26.86 "E	Estuarine	Rural, small fringes along a river estuary, rocky bottom, estuary	2,864	<i>Avicennia marina</i> , <i>Avicennia officinalis</i>	This mangrove habitat is shaded by a rocky geological barrier formed (Korlai fort) near the mouth of the Kundalika river, which protects it from the open coastal currents and waves. The mangrove patch was less dense.	No municipal solid waste management

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**Table S2:** Mean concentration ( $\pm$  SE) of each object type to anthropogenic litter found in the eastern Arabian Sea mangrove forest floor (item/40 m<sup>2</sup> transect area).

Litter type	Shirgaon (n=584)	Korlai (n=454)	Virar (n=201)	Ulwe (n=165)	Mahim (n=3225)	Versova (n=1486)	Bandra (n=1028)
<b>Plastics</b>							
Drink bottles	11.67 $\pm$ 2.91	6.67 $\pm$ 2.33	0.67 $\pm$ 0.67	2.67 $\pm$ 1.76	37.67 $\pm$ 7.06	3 $\pm$ 0.58	7 $\pm$ 2.65
Bottle caps	7 $\pm$ 3.61	3.67 $\pm$ 2.33	1.33 $\pm$ 0.88	0.33 $\pm$ 0.33	12.33 $\pm$ 3.53	3 $\pm$ 2.08	1.33 $\pm$ 0.88
Plastic bags	45.33 $\pm$ 4.91	32.33 $\pm$ 4.67	13 $\pm$ 1.73	16.67 $\pm$ 2.6	520 $\pm$ 87.52	177.33 $\pm$ 23.96	110.33 $\pm$ 25.21
Food wraps	34.33 $\pm$ 8.41	18.33 $\pm$ 2.33	3.67 $\pm$ 2.03	3.33 $\pm$ 1.86	121.67 $\pm$ 23.14	117.33 $\pm$ 27.23	40 $\pm$ 14.57
Sachets	1 $\pm$ 1	5.33 $\pm$ 0.88	3.67 $\pm$ 0.67	1 $\pm$ 1	32.33 $\pm$ 12.91	51.33 $\pm$ 7.75	24 $\pm$ 6.56
Fragments	20.33 $\pm$ 5.36	12 $\pm$ 2.08	6 $\pm$ 2.52	4.33 $\pm$ 0.88	72.33 $\pm$ 9.02	22.67 $\pm$ 5.55	59.33 $\pm$ 7.84
Tubes	1 $\pm$ 0.58	1.33 $\pm$ 0.67	0 $\pm$ 0	0 $\pm$ 0	2.67 $\pm$ 2.67	1 $\pm$ 1	0.67 $\pm$ 0.67
Beverage cups	4 $\pm$ 2.08	4.33 $\pm$ 1.86	2.67 $\pm$ 1.76	1.33 $\pm$ 0.88	26 $\pm$ 5.69	8.33 $\pm$ 5.24	5.67 $\pm$ 3.18
Straws	1.33 $\pm$ 0.67	0.67 $\pm$ 0.67	0	0	5 $\pm$ 3.61	4 $\pm$ 1.73	0
Cutlery	0.67 $\pm$ 0.33	2 $\pm$ 1	0.33 $\pm$ 0.33	0	14.33 $\pm$ 5.46	0	0.67 $\pm$ 0.67
Fishing nets	6.33 $\pm$ 1.76	3.67 $\pm$ 1.2	2.67 $\pm$ 0.67	7 $\pm$ 2.31	1 $\pm$ 0.58	9.67 $\pm$ 2.03	8 $\pm$ 2.65
Rope/Line	16.67 $\pm$ 3.48	21.67 $\pm$ 2.91	10.33 $\pm$ 1.45	4.33 $\pm$ 1.45	20 $\pm$ 5.51	25.33 $\pm$ 5.04	19.67 $\pm$ 5.24
Styrofoam	6.33 $\pm$ 1.76	5 $\pm$ 2.52	2 $\pm$ 1	1.67 $\pm$ 0.88	25.67 $\pm$ 10.11	10 $\pm$ 3.79	14 $\pm$ 3.21
Glass/Ceramics	6 $\pm$ 1	0.67 $\pm$ 0.33	4 $\pm$ 1.73	0.67 $\pm$ 0.33	21 $\pm$ 4.16	9.33 $\pm$ 1.2	12.33 $\pm$ 3.71
Textile/Fabrics	13 $\pm$ 2.31	1.33 $\pm$ 0.88	5 $\pm$ 1.53	5.33 $\pm$ 1.45	84 $\pm$ 23.69	26.33 $\pm$ 4.33	16.67 $\pm$ 2.73
Sanitary waste	1.67 $\pm$ 0.88	1 $\pm$ 1	0	0	7.33 $\pm$ 2.6	3.67 $\pm$ 1.2	1.33 $\pm$ 0.88
Medical waste	1 $\pm$ 0.58	1.33 $\pm$ 0.67	0.67 $\pm$ 0.33	0	3 $\pm$ 1	0.33 $\pm$ 0.33	0.67 $\pm$ 0.67
Metal	1 $\pm$ 0.58	8 $\pm$ 2	1.67 $\pm$ 0.88	2.67 $\pm$ 1.45	27 $\pm$ 7.57	9.33 $\pm$ 4.33	4.67 $\pm$ 2.03
Timbers/	2.67 $\pm$ 1.45	1.33 $\pm$ 0.88	4.33 $\pm$ 1.45	1.33 $\pm$ 0.88	3 $\pm$ 2.52	1.67 $\pm$ 1.67	5 $\pm$ 1.15

Processed wood							
Footwear	9.67 ± 2.03	4.67 ± 2.19	3 ± 1.53	1.67 ± 1.2	16.33 ± 5.6	8 ± 1.73	8.33 ± 1.45
Tetra pack	3 ± 1.15	2.33 ± 1.33	2 ± 1.15	0	16.33 ± 4.37	1.67 ± 0.88	1.67 ± 0.88
Rubbers	0.33 ± 0.33	1.33 ± 0.67	0	0.67 ± 0.33	2.67 ± 1.45	1.37 ± 0.88	1.33 ± 0.88
Leather	0.33 ± 0.33	0.33 ± 0.33	0	0	3.33 ± 1.76	0.67 ± 0.67	0
Total plastics	149.67 ± 18.89	117 ± 10.44	46.33 ± 2.85	42.67 ± 2.73	891 ± 78	433 ± 32.01	290.67 ± 20.74
<b>Litter no/m<sup>2</sup></b>	4.87 ± 0.36	3.78 ± 0.31	1.68 ± 0.14	1.38 ± 0.09	26.88 ± 2.03	12.38 ± 0.75	8.57 ± 0.59
<b>Plastic item/ m<sup>2</sup></b>	3.9 ± 0.51	2.93 ± 0.26	1.16 ± 0.7	1.07 ± 0.07	22.28 ± 1.95	7.27 ± 0.52	10.83 ± 0.8

**Table S3:** Mean concentration ( $\pm$  SE) entangled of anthropogenic litter found on mangrove canopy (litter item/tree).

Litter type	Shirgao n (n=690)	Virar (n=209)	Ulwe (n=340)	Korlai (n=621)	Mahim (n=586)	Bandra (n=2989 )	Versova (n=2002 )
Plastic bags	5.27 $\pm$ 0.49	1.44 $\pm$ 0.18	2.36 $\pm$ 0.35	5.14 $\pm$ 0.84	4.91 $\pm$ 0.42	23.36 $\pm$ 1.08	14.46 $\pm$ 0.95
Miscellaneous plastic items	0.11 $\pm$ 0.05	0.03 $\pm$ 0.01	0.16 $\pm$ 0.05	0.1 $\pm$ 0.04	0.17 $\pm$ 0.06	0.59 $\pm$ 0.14	2.71 $\pm$ 0.41
Fishing net	0.18 $\pm$ 0.06	0.06 $\pm$ 0.03	0.23 $\pm$ 0.06	0.19 $\pm$ 0.05	0.08 $\pm$ 0.03	3.07 $\pm$ 0.41	0.14 $\pm$ 0.05
Ropes/lines	1.11 $\pm$ 0.23	0.41 $\pm$ 0.1	0.39 $\pm$ 0.1	0.69 $\pm$ 0.1	0.13 $\pm$ 0.06	0.3 $\pm$ 0.09	1.67 $\pm$ 0.28
Texttile/Fabric s	0.23 $\pm$ 0.06	0.15 $\pm$ 0.06	0.26 $\pm$ 0.08	0.09 $\pm$ 0.03	0.57 $\pm$ 0.12	2.6 $\pm$ 0.26	1.04 $\pm$ 0.18
Average litter items/tree	6.9 $\pm$ 0.53	2.09 $\pm$ 0.25	3.4 $\pm$ 0.41	6.21 $\pm$ 0.91	5.86 $\pm$ 0.46	29.89 $\pm$ 1.56	20.02 $\pm$ 1.04

**Table S4:** Results of permutational multivariate analysis of variance (PERMANOVA) and permutational tests of multivariate dispersion around centroid between sites, habitats, habitat substrate characteristic and urbanisation gradient for composition and  $\beta$ -diversity of plastic items

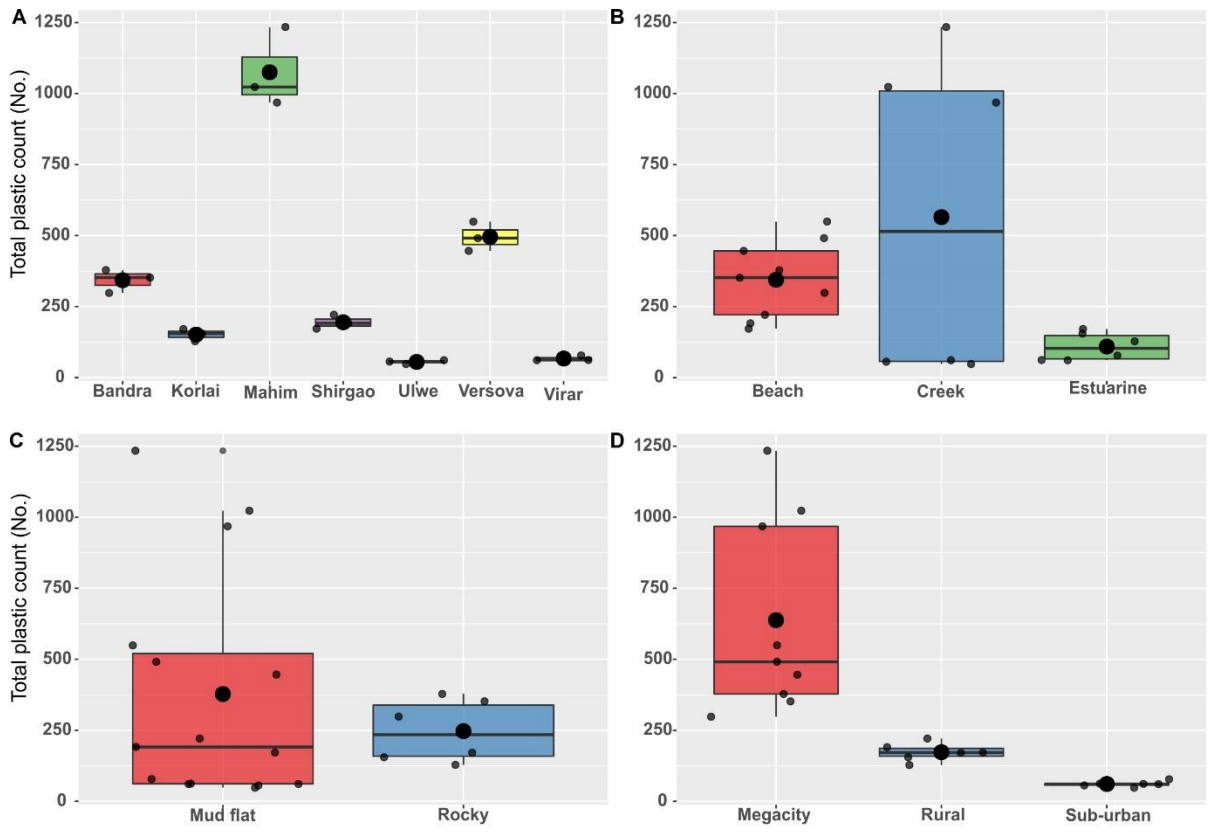
Groups	Df	Sum Sq	Mean Sq /R2	F	N.Perm	Pr(>F)
Permutational multivariate analysis of variance						
Sites	6	1.2745	0.73693	6.5364		0.001*
Habitat type	2	0.36307	0.20993	2.3914		0.06
Habitat substrate characteristic	1	0.05261	0.03042	0.5962		0.665
Urbanisation gradient	2	0.98943	0.5721	12.033		0.001*
Permutation test for homogeneity of multivariate dispersion						
Sites	6	0.020878	0.0034796	2.3795	999	0.103
Habitat type	2	0.13713	0.068565	13.253	999	0.001*
Habitat substrate characteristic	1	0.074547	0.074547	13.478	999	0.002*
Urbanisation gradient	2	0.011792	0.0058959	2.401	999	0.117

**Table S5:** Shannon-Wiener (H') and Pielou's evenness index (J') of marine litter along the mangrove sites

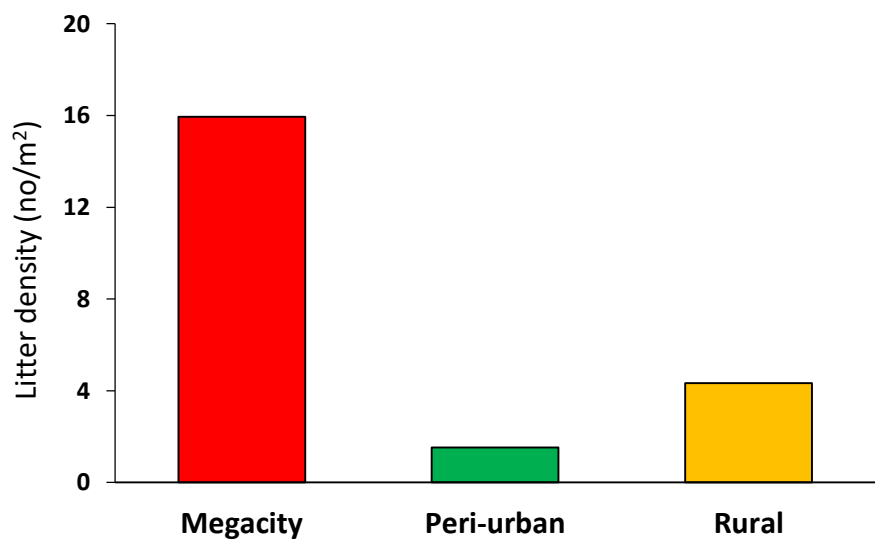
Mangrove site	Pielou's evenness index (J')	Shannon-Wiener diversity index (H')
Shirgaon	0.77	2.45
Korlai	0.82	2.60
Virar	0.90	2.60
Ulwe	0.84	2.32
Mahim	0.63	2.03
Bandra	0.72	2.27
Versova	0.65	2.07

**Table S6:** Hazard level and potential ecological risk of marine litter in mangroves of Eastern Arabian Sea.

Mangrove site	GI	CCI	CCI grade	HII	HII grade	PLI	Risk category
Shirgaon	97.3	78	Extremely dirty	1.6	III	4.3	I
Korlai	75.7	58.5	Extremely dirty	0.8	II	3	I
Virar	33.5	23.2	Extremely dirty	0.8	II	1.2	I
Ulwe	27.5	21.3	Extremely dirty	0.8	II	1.1	I
Mahim, Mumbai	537.5	445.5	Extremely dirty	5	IV	22.7	III
Bandra, Mumbai	171.3	145.3	Extremely dirty	1.3	III	7.4	I
Varsova, Mumbai	247.7	216.5	Extremely dirty	1.5	III	11	II

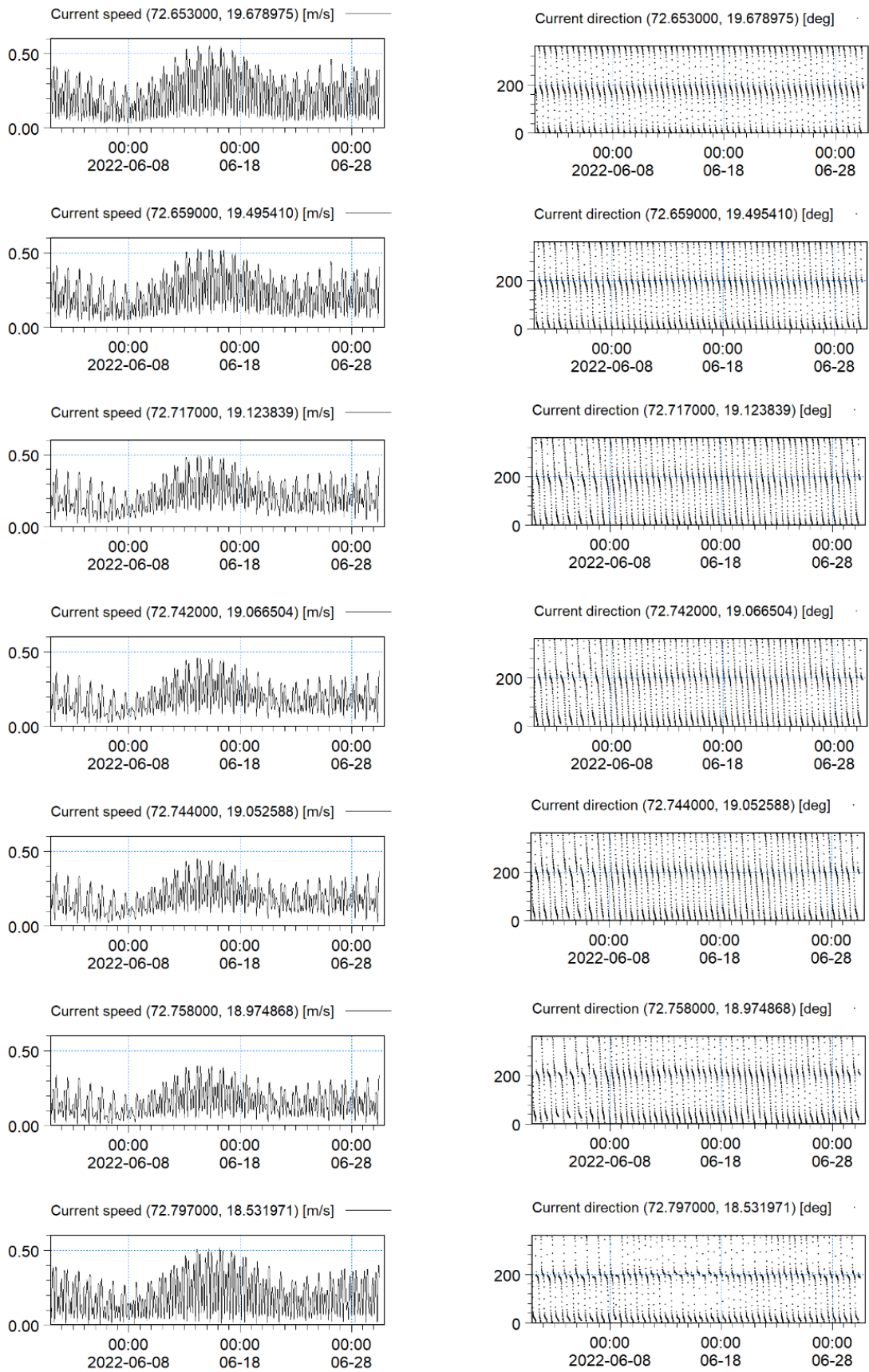


**Fig. S1.** A. Litter abundance along the mangrove stands; B. variation of litter abundance according to habitat type of the mangrove stands; C. variation of litter abundance according to bottom substrate characteristic of the surveyed mangrove; D. variation of litter abundance according to urbanization gradient



**Fig. S2.** Variation of litter density (no/m<sup>2</sup>) on mangrove forest floor according to urbanization gradient





**Fig. S3.** Time series coastal current along 10 m contour off the surveyed mangrove locations