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Geospatial distribution and anthropogenic litter impact on coastal mangrove ecosystems from the Saudi Arabia coast of the Gulf

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Mangrove ecosystems are significantly impacted by marine litter pollution, an increasingly important environmental problem. These ecosystems, situated at the interface between sea and land, serve as critical habitats and act as traps for plastic pollution. This study investigated the concentration, source, and composition of marine litter on both the mangrove bottom and canopy along the Saudi Arabia coast in the Gulf. The observed concentration of surface litter ranged from 0.98 ± 0.05 to 2.96 ± 0.25 items/m², with a mean concentration of 1.4 ± 0.61 items/m² (SD; *N* = 9). The mean trapped litter was 0.79 ± 0.45 items/tree, ranging from 0 to 7 items/tree. Plastic litter dominates the mangrove environment, accounting for 80% of debris items on the floor and 43% of those entangled in the canopy. Single-use plastics were the most prevalent type of litter detected across all surveyed locations. The sediments within the mangrove ecosystem serve as long-term repositories for plastic litter, evaluated through various indices, such as General Index, Clean Coast Index, Pollution Load Index, and Hazardous Litter Index, to assess the cleanliness of the mangrove floor. The Pollution Load Index shows a "Hazard level I," indicating that the mangrove floor is less contaminated. A higher concentration of litter was observed in urban areas with greater population density, likely originating from terrestrial activities like urban runoff and marine activities, particularly fishing.

Anthropogenic litter pollution is a significant hazard to mangrove ecosystems worldwide, especially on the western Gulf coast of Saudi Arabia[1,2]. Mangroves are distinctive, biodiverse coastal ecosystems that offer vital homes to microorganisms, animals, and plants[3]. In addition, they provide critical ecological services such as carbon sequestration, nutrient cycling[4], shoreline stabilization against tsunamis and storms[5]. However, the effects of human-induced pollution, particularly litter, render these essential habitats more vulnerable to destruction, which might have far-reaching environmental consequences. Anthropogenic litter in mangrove environments consists of various types of debris, including plastic bags, bottles, fishing gear, packaging materials, and other abandoned items[6]. Frequently, improper waste disposal, stormwater runoff, littering, and marine litter transported by currents and tides are how these items find their way into mangrove habitats[2]. Litter can remain in mangrove forests for years after being deposited, leading to several risks to the wildlife and surrounding environment[1,7].

One of the significant concerns about anthropogenic litter pollution in mangroves is its adverse effects on the ecosystem health. The mismanaged litter from landward and marine debris from tidal currents can be trapped and stored for a more extended period of time by the structural complexity of the mangrove canopy and pneumatophores[1]. In mangrove soils, litter accumulation can change the composition of the sediment and prevent nutrient cycling[4,8]. These effects can lower soil fertility and hinder plant growth[7,9]. Plastic waste can also physically suffocate mangrove roots, obstruct seed germination, and impede gas exchange mechanisms essential for root respiration[9]. Mangrove wildlife can also be impacted by anthropogenic litter both directly and indirectly. Plastic litter and fishing nets can entangle marine wildlife, including birds, fish, and turtles, causing

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harm, asphyxia, or even death[10–12]. Moreover, the pollution of the environment by plastic waste has the potential to emit toxic substances that may pose significant risks to both human health and biodiversity.

The plastics market is intricately linked to petroleum, chemicals, and other industries. The amount of plastic produced and consumed significantly impacts both industrial growth and living standards. Plastic usage and production have increased dramatically since the 1950 s. The global annual plastic production escalated from 1.5 million in 1950 to 400 million tons by 2015, with projections suggesting that by the year 2050, this figure will attain 1124 million tons[13]. The majority of plastics and non-biodegradable litter come from land-based sources, typically from industrialized or highly populated regions[14]. This issue has been exacerbated by inadequate waste management practices[15]. An estimated 12.7 million tons of mismanaged plastic litter were supposed to have ended up in the ocean in 2010[16]. The total plastic production from 1950 to 2015 is measured at 8300 million tons; out of the 8300 million tons of plastic, only 2% were recycled or burned, and the remaining 6300 million tons were disposed of or ended up in the environment[13]. A novel waste management strategy has been proposed in Saudi Arabia, wherein 42% of waste is designated for recycling, 35% is allocated for composting, and 19% is directed towards energy recovery, all of which are expected to be functional by the year 2035. (NCWM, 2023; https://mwan.gov.sa/en).

A recent study by Stofen-O'brien et[17] highlights that most of the research on marine litter in the Gulf has focused on countries such as Kuwait, Qatar, UAE, and Iran, leaving Saudi Arabia mostly underrepresented in the scientific literature. It is a fact that Saudi Arabia has the longest coastline in the Gulf region, which makes it a critical region to study the source, accumulation, and biological effects of marine litter. Without comprehensive studies on Saudi Arabia, the true extent of marine litter pollution in its marine environment remains unknown. For a deep understanding of marine litter, sources are necessary to prioritize future management and monitoring strategies for mismanaged waste. Further, a comprehensive inventory of the extent of litter accumulation and source identifications are required to design strategies to mitigate marine litter pollution along the coastal mangrove. Furthermore, Saudi Arabia lacks comprehensive marine litter management policies compared to the other Gulf countries. For example, the UAE has introduced national recycling and plastic waste management policies, but Saudi Arabia remains poorly documented in marine litter management. Therefore, the present study was to determine the distribution, source, abundance, and type of marine litter on the mangrove ground and trees along the Saudi Arabian coast in the western Gulf. Furthermore, various mangrove floor indices were calculated for the quality of the floor. Also, we prepared a numerical ocean model to understand the fate and transport of marine litter.

Materials and methods

Study region

The origin of this Gulf coastline is mainly due to the Arabian tectonic plate movement, which collided with a Eurasian plate in the middle to Late Cretaceous period. As a result of the compression brought on by this collision, the Arabian Plate subduction during the Tertiary formed what is now known as the Zagros Fault zone, which is situated in modern-day Iran[18]. This, together with the creation of the Gulf basin and the possible thinning of the crust leading to a northwesterly slope, caused the African continental plate to separate. Paleo deltaic characteristics were deposited in the present-day Eastern Province of Saudi Arabia due to the Erosion of the uplifted plate[19]. Massive ergs that are a significant landform of the Arabian Peninsula, such as the Rub Al Khali Desert, were formed due to the plate becoming more arid and having an aeolian impact during the Quaternary[20]. Because of their tectonic origins, the Gulf's east and west coasts have completely different geomorphologies and structures. The Oman line is present in the Empty Quarter of Saudi Arabia and has expanded into the Red Sea[21]. A central tectonic border between the Arabian and Eurasian plates is shown by this structural feature, which is a suture zone created during the closure of the Neotethys Ocean. This feature is essential for defining the underlying geology and affecting how sedimentary basins form and change over time[21]. The vertical movement of salt has been assisted by deep-seated basement faults, which have contributed to basin development and influenced hydrocarbon accumulation[22]. Given the structural connectivity between southern Iran and the Arabian Peninsula, these basement fault systems may extend into Saudi Arabia, impacting sedimentary basin evolution and regional geological processes[22].

The present study was conducted during November - December 2023 along the Saudi Arabian coast in the western Gulf, covering a latitudinal range of approximately 24°−30°N and a longitudinal range of 48°−56°E. The Gulf is a shallow basin with a 35-meter average water depth (Fig. 1; Table. S1). The coastline of Saudi waters of the Gulf covers natural and artificial rocky shores, as well as sandy beaches[23]. Its shores, the driest in the world, were formed 3,000–6000years ago[24]. Mangrove trees in the Western Gulf are patchy and are a limited protected area, wet, squishy, anaerobic mud[25]. Although they are only represented by one species, *Avicennia marina*, they provide a home and food source for most shrimp and fish of significant commercial value[26]. The diverse faunal assemblages of the communities sustain large numbers of invertebrates, including 50 species of mollusks and 40 species of crustaceans, as well as a lesser number of echinoderms, sponges, polychaetes, coelenterates, and ascidian species. Vertebrate species associated with mangroves comprise over 200 bird species, four species of mammals, three species of sea turtles, and over 86 fish species (with juveniles; 63). The mangroves are home to juvenile shrimp (Penaeus semisulcatus, Penaeus indicus, etc.) and other invertebrates[27]. It has been determined that the highest mangrove density on Tarut Island is 1,111 plants per 100 m^2. The primary productivity of mangroves is 8.8 tons of leaf litter/ha/year[28]. The loss of mangroves from 1973 to 2000 resulted in a decline in primary productivity of about 2041 tons of leaf litter/year. Due to the abundance of marine organisms in the Gulf, the loss of primary productivity can disturb the fragile ecological balance of the region[28].

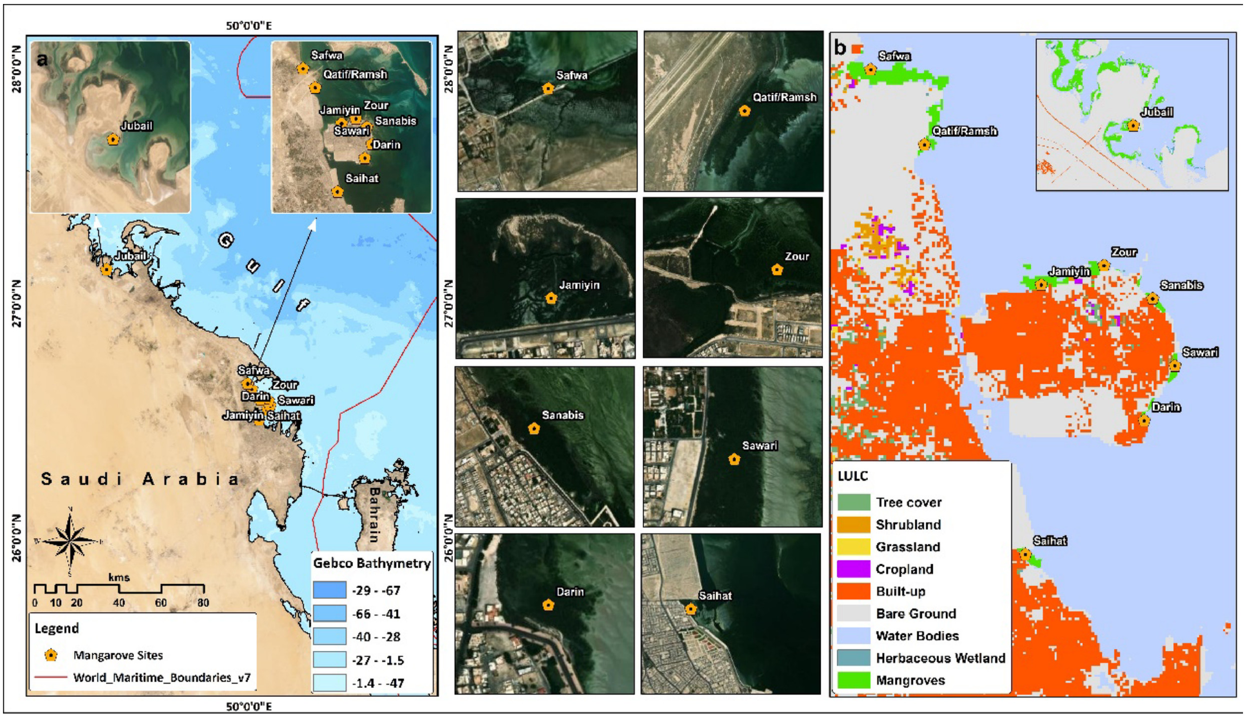


Fig. 1. (**a**) Map showing the study locations of the mangrove sites along the western Gulf (**b**) Land uses land cover types for 2021 for studied mangrove locations. The satellite imagery for panel (**a**) was obtained from USGS Earth Explorer (Landsat 8 OLI, 2024) processed in Arc GIS Pro for Layer Stacking of all the available bands. Bathymetry data were sourced from gebco bathymetry (https://www.gebco.net). (**b**) Land use and land cover classification were derived the European Space Agency (ESA) World cover 10 m data in Google Earth Engine (GEE), leveraging Sentinel-1&2 data. GEE, a is a cloud based geospatial processing platform, provides access to extensive earth observation datasets, including Landsat, Sentinel, MODIS, and ASTER archives, along with environmental, climate and socio-economic data.

Land use and land cover of sampling location

The Google Earth Engine (GEE) is a cloud computing platform for storing and processing earth observation big data and other ancillary datasets for geospatial studies[29]. The data catalog in GEE mainly includes satellite observations such as the entire Landsat archive, Sentinel-1&2, Modis, and Aster, land cover data, and many other environmental, climate forecasts, geophysical, and socio-economic datasets[29]. In assessing land use and land cover types for our area of interest, we used European Space Agency (ESA) World cover 10 m data in Google Earth Engine Interface. This dataset provides a global coverage map since 2021 at 10 m resolution using Sentinel-1 and Sentinel-2 data.

Survey of surficial litter in the mangrove areas

The survey was conducted during low tide from November to December 2023. A total of 36 belt transects was randomly surveyed to determine the habitat characteristics of six mangrove forests along the Saudi Arabian coast in the western Gulf, hereinafter referred to as a "station." A belt transect of 20.0 m in length and 2.0 m in width was used on the seaward side of the mangrove stand ($n = 6$ transects for each mangrove stand on the seaward and coast). To represent the litter that has accumulated from both land and sea-based activities, transect tapes were placed parallel to the shoreline at the landward fringes ($N= 20$), mangrove[14], and seaward fringes[26]. All nine mangrove stands were surveyed inside the stand, except Saihat and Tarut island (Jamiyin), which were inaccessible due to dense forest cover. 1080 m^2 of the mangrove floor was surveyed to quantify the surficial litter. All the visible marine litter objects above 2.5 cm (maximum diameter) in the transect area, whether trapped in mangrove aerial roots or pneumatophores or fully embedded in the surface sediment, partially buried litter were collected, counted, and classified according to OSPAR classification[30]. Logistical constraints prevented weighing all recorded litter, some partially buried in the sediment. A portable GPS Garmin (GPS Map276cx) was used to georeference each sampling location, and photos were captured with a digital camera for photo documentation.

Survey of trapped litter on the mangrove trees

For the trapped litter survey, 100 mangrove trees were randomly selected from each mangrove stand, and a total of 500 mangrove trees were chosen for the present study. Mangrove trees exceeding a height of 1.5 m were designated for inclusion in this survey following the method proposed by De et al.[6] and Selvam et al.[7]. The trapped litter objects were counted and characterized based on the category in the field. Litter items/tree is a unit for the litter density on the mangrove canopy.

Marine litter: quantification, typology, and source identification

The litter components were classified by the OSPAR methodology[30], except leather materials, and divided into six distinct categories, namely, glass, plastics, metals, textiles, footwear, rubber, leather, and timber. Plastic items were further categorized based on their operational origin, such as drink bottles, food wraps, bottle caps, cups, fishing nets, rope/handline, and bags., as suggested by Lippiatt et al.[31]. The number of litter items/m^2 was used to document the density of litter deposited on the mangrove floor using the following equation.

$$Density\ of\ marine\ litter = \frac{\sum Litter\ items\ in\ each\ transect}{Transect\ area}$$

The European Union (EU) Marine Strategy Framework Directive (MSFD) Good Environmental Status (GES) Marine litter Thematic Report methodology was used to classify the possible sources of the litter items[32].

Environmental quality of the mangrove ecosystems

Marine litter diversity Indies

Shannon-Wiener diversity index $(H')$and Evenness index (E) were calculated to assess the assembly of marine litter (species), their relative abundance and the diversity of sources[33,34].

$$H' = \sum fr \times 1n(fr)$$

where, fr represents the relative frequency of each litter 'species'.

The evenness index (E), which is based on the relative frequency of species distribution, shows the samples heterogeneity of an assembly[35]. The E index was calculated using the following formula:

$$E = \frac{H'}{H'_{max}}$$

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

Clean Coast Index

The Clean Coast Index (CCI) was used to measure the cleanliness of the coastal area and is exclusively used based on plastic litter deposition. It is based on the following formula[36].

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

Where, K is a correction coefficient with a value of 20.

Five categories are used by CCI to rank the cleanliness of beaches: (i) very clean (0–2); (ii) clean[2–5]; (iii) moderately clean[5–10]; (iv) dirty[10–16,23–26] and (v) extremely dirty (< 20)[36,37].

General Index

The General Index (GI) was used similar to the CCI. However, GI included all types of marine litter rather than just plastic litter[1].

Pollution Load Index

The pollution load index (PLI) was used to assess the level metal pollution in the marine environment. Recently, it has been used for microplastic pollution studies in marine[38], and freshwater lake ecosystems[39]. According to Pan et al.. (2021), PLI is classified into four hazard levels for microplastic pollution: Hazard level I, < 10; Hazard level II, 10–20; Hazard level III, 20–30; Hazard level IV, > 30. The macro and meso plastic pollution risk in the mangrove area was studied using the PLI, which is calculated using the following formula:

$$CF = \frac{C_1}{C_b}$$

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

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

Where, the CF stands for the plastic litter concentration factor, which is the ratio of the plastic litter concentration at each location to the background concentration of the plastic litter. The lowest concentration of plastic litter value observed at each mangrove stand was referred to as the background value[38,39].

Hazardous litter index

The hazardous litter index (HLI) has been developed to measure the level of hazardous litter concentration in the mangrove area. For example, broken glass and sharp metals can seriously injure and cut aquatic organisms and visitors. Cigarette butts, sanitary waste, and medical waste can cause environmental damage and disease[40]. HLI were classified into five categories: (i) 0 values indicate – no hazardous litter present, (ii) 0.1–1 values indicate the presence of some hazardous litter, (iii) 1.1–4 value indicates the presence of a considerable amount of hazardous litter, (iv) 4.1–8value indicates- presentence of a lot of hazardous litter, (v) >8 value indicates-presentence of most of the area by hazardous litter[40]. The HLI value of the location was determined using the following formula:

$$HLI = \frac{\frac{\sum Hazardous\ litter\ items}{log10 \sum Total\ Litter\ items}}{Transect\ area} \times K$$

Where, K is a correction coefficient with a value of 20.

Surface winds and ocean currents

Plastic pollutants are transported mainly in the coastal waters by the surface winds and ocean currents. In the present investigation, we employed the MIKE-21 computational model to replicate oceanic currents and tidal dynamics along the Saudi coastline of the Gulf. This model is configured specifically for the Gulf, encompassing the Saudi maritime territory with a high spatial resolution of 40 m near the coast and extending approximately 300 to 500 m offshore. The model is subjected to surface forcing from the ECMWF Reanalysis V5 (ERA5) wind data at a height of 10 m and near-surface pressure across a broader domain that encompasses the entire Gulf; this data is accessible and utilized at a horizontal resolution of 0.250 × 0.250 degree and a temporal frequency of one hour. The model domain boundary is forced with water level varying along the boundary from the predicted global tide models inbuilt in MIKE-21. The particle tracking model developed by the DHI works based on the lagrangian principle and used to simulate the marine litter fate and distribution over complex coastal environments. The coupled MIKE-21 hydrodynamic model simulations with particle tracking model drives the transport characteristic of these marine litter. The ocean surface currents over Gulf are taken from the Operational Mercator global ocean analysis and forecast system at 1/12-degree daily 3D data downloaded from Copernicus Marine Service (https://data.marine.copernicus.eu/product/GLOBAL_ANALYSIS -FORECAST_PHY_001_024/description).

Statistical analysis

Data were shown in mean values with their respective standard deviation for a more significant interpretation of marine litter assessment. SPSS was employed to execute all statistical analyses and the computation of descriptive statistics. One-way ANOVA was analyzed using Statistica and Principal coordinates analysis (PCO) was carried out using Primer 6. The satellite imagery used in Figs. 1 and 8 was downloaded from USGS Earth Explorer for year 2024 of Landsat 8 OLI which is then further processing in Arc GIS Pro Software for Layer Stacking of all the available bands. Further, the bathymetry data were obtained from gebco bathymetry (https://www.gebco.net/data_and_products/gridded_bathymetry_data/#global). The spatial surface winds, currents and wind rose diagrams (Fig. 7) are prepared using Matlab software version 2023b and the tidal currents (Fig. 8) over study region plotted using MIKE-21 plot composer (MIKE software version 2022).

Results and discussion

Distribution, abundance, composition, and morphology of marine litter on the Mangrove floor

The present study documents a total of 1509 litter items during the belt transect survey on the mangrove floor. The mean litter density varied between 0.98 ± 0.05 and 2.96 ± 0.25 items/m^2 and the average concentration was 1.4 ± 0.61 items/m^2 (SD; N = 9). The results are notably higher than earlier results reported by Martin et al.[1]for mangroves in the Gulf, which found that the mean litter density of the Gulf (was 1.21 ± 0.53 items/m^2). Globally, very few studies are available on marine litter in mangrove environments. (Table 1 provides reviews on marine litter in mangrove forests). Which may be due to challenges associated with sampling in these complex environments[41]. Similar results were observed from the studies conducted by Luo et al.[42]. in Hong Kong and Paler et al.[43]. in the Philippines which found that the mean concentration of litter in mangrove forests was 1.45 ± 0.38 items/m^2 and 1.29 ± 0.67 items/m^2, respectively. Overall, the present study noticed lower litter concentration than previously report in elsewhere, except Red Sea 0.66 ± 00.18 items/m^2[21], Tunda island, Indonesia 0.75 items/m^2[44]. In Central Java, 27 items/m^2[29], In Penang Island, Malaysia 12.6–73.1 items/m^2[45], In Ambon and Baguala Bay, Indonesia 92 ± 28 items/m^2[46], a Oman coast, sea of Oman 17.91 ± 17.61 items/m^2[47]. This study increase in litter density indicates a potential rise in waste mismanagement and plastic pollution along the Saudi Arabian coastline over the past five years. The previous study by Martin et al.[1] in 2019 reported a mean litter density of 1.21 items/m2. In contrast, the present study conducted in 2024 recorded a higher mean litter density of 1.4 items/m2. This notable increase in marine litter within five years indicates a worsening trend in plastic deposition in the mangrove ecosystem of the Gulf.

Among the studied mangrove sites, the highest litter density was noticed at Saihat (2.96 ± 0.25 items/m^2) and the lowest noticed at Sawari (0.98 ± 0.05 items/m^2; Table. S2). Marine litter variations between various surveyed locations were analyzed using one-way ANOVA. The results showing most of the locations (Sawari, Darin, Sanabis, Qatif/Ramsh, Jamiyin, Safwa, and Jubail) the variations in marine litter abundance between surveyed grounds are statistically significant (Table 2). Saihat is the only location where there is no significant variation, suggesting the relatively uniform litter abundance among the surveyed locations. Based on the urbanization gradient revealed that the mangrove stands in the densely populated Saihat urban area had considerably higher litter (2.96 ± 0.25 items/m^2) than the sub-urban area with the lack of waste management facilities at Ramsh (1 ± 0.06 items/m^2) and Safwa (1.33 ± 0.09 items/m^2; Table S1). On the other hand, the lower litter (1.03 ± 0.04 items/m^2) found in the densely populated Jubail urban area (4,74,679; https://database.stats.gov.sa/home/indicator/535) could be explained by the mangrove present at a remote location, which is about 17 km from the urban area. The higher litter density was observed in the Jamiyin (1.43 ± 0.09 items/m^2) and Sanabis (1.43 ± 0.08

Location of mangroves	Mangrove plant surveyed	Sampling method	Quantity	Major litter items	Contribution of plastic litte	References
Mangrove ecosystem of central West coast of India	Avicennia marina, Avicennia officinalis, Sonneratia apetala	20 × 2 m belt transect	Mean density of 8.5 ± 1.9 litter items/m^2 on mangrove floor, ranging from 1.4 to 26.9 items/m^2 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, fisfing nets, plastic cutlery, lines/ropes, styrofoam), ceramics/glass, fabrics/textiles, medical waste, sanitary waste, metals, processed woods/timbers, footwear, tetra packs, steel can	83.02% mangrove floor, 934% in mangrove canopy	De et al.,[6]
Mangrove forests, Kenya	Rhizophora mucronata, Ceriops tagal and Avicennia marina. Typically, Sonneratia alba, Bruguiera gymnorrhiza,	10 × 10 m transects	Mean density 0.088 ± 0.076 items m – ^{2}	Paper, cardboard, clothing, glass, e-waste, plastic, glass, metal, hygiene, cardboard, clothing, processed wood, foam, rubber, fishing gears	85.90%	Okuku et al.[92]
Ciénaga Grande de Santa Marta, Colombian Carib bean	Laguncularia racemosa, Avicennia germinans, Rhizophora mangle	50 m × 2 m transects	540 ± 137 and 31 ± 23 items/ha	Plastic, metal, glass, rubber, rubble, textile, processed wood, hospital, sanitary wastes	73 and 96%	Garcés-Ordóñezetal.,et al.[83]
Mangrove forest, Hong Kong	Kandelia obovata	1 × 25 m Belt transects	1.45 ± 0.38 items/m^2	Plastic, wood, metal, rubber, cloth, paper, glass, ceramic	70.31% by density and 49.1 % by area cover	Luo et al.[91]
Saudi Arabia (Red Sea and Gulf)	Avicenniamarina	4 m to 60 m long and 2 m to 8 m width transects	0.66 ± 0.18 items/m^2 in the Red Sea, 1.21 ± 0.53 items/m^2 in the Arabian Gulf	Plastic fragments, fishing lines, food wraps, bottle caps, ropes, polystyrene, plastic bags, buoys, mall 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.[1]
Cebu Island, Philippines	Rhizophora sp., Avicennia sp., Soneratia sp	Transect (100 to 600 m), 10 × 10 m plots	1.29 ± 0.67 items/m^2 (ranges 0–31.75 items/m^2), 18.07 ± 8.79 g/m^2	Plastic packaging, plastic bags, plastic fragments, buoys, fishing gear, and nets	78.10%	Paler et al.[43],0
Demak regency, Central Java	Avicennia alba, Avicennia marina	50 cm× 50 cmquadrats	0 to 236 items/m^2, mean 27 items/m^2	Plastic waste	Covering upto 50% of the forest floor	van Bijsterveldt et al.[9]
Ambon Bay (Passo, Waiheru, Nania) and Baguala Bay (Suli), Indonesia	Not stated	10 × 10 m Plot, 1 × 1 m Plot, 0.5 × 0.5 m quadrates along a 540 m line transects	10 ± 4 items/m^2 to 230 ± 75 items/m^2, Mean 92 ± 28 items/m^2	Fiber, foam, film, fragment	25–62%	Suyadi and Manullang[46].
PenangIsland, Malasia	Avicenniamarina, Bruguieracylindrica, Rhizophoraapiculate, Rhizophora mucronate, Sonneratiaalba	10 × 10 m quadrat	Urban: 12.6–73.1items/m^2, peri-urban: 2.1–10 items/m^2	Plastic (foam, sheet, film, fragment) glass, wood, paper, rubber	75.3 to 92.5%	Yin et al.[84]
Jakarta Bay, Indonesia	Avicennia marina, Rhizophora mucronate. Rhizophora stylosa, Sonneratia caseolaris, Excoecaria agallocha	Circular sampling area with a 10 m radius	2.06 items/m^2 to 5.41 items/m^2	Plastic (fragments, cups, food wrappers, plastic bags, plastic bottles, and bottle caps), metal, glass, rubber, processed wood, fabrics	89.00%	Winarni et al.[50]
Mumbai, India	Avicennia marina, Acanthus ilicifolius, Ceriops tagal, andBruguiera cylindrical	20 × 2 m belt-transects	8.82 ± 3.47 items/m^2 on mangrove floor, 35 ± 10.4 pieces/tree, 920 ± 317 g/m^2, 2514 ± 758 g/tree	Plastics, metal, glass, rubber, lumber, cloth	62.40%	Selvam et al.[7],
Xuan Thuy National Park, Nam Dinh province, Vietnam	Not stated	50 × 5 m or smaller transect	0.14 to 16.9 items/m^2, Mean 2.81 items/m^2	Plastic (food wrappers, fragments, plastic bags, pieces of plastic rope and nets), fabric pieces, foam	86.60%	Giles et al.[85],
Beilun estuary, Fangchenggang, China	Not stated	10 × 10 m quadrats	0.163 item/m^2, 21.123 g/m^2 (2.355–51.76)	Plastics, styrofoam, wood, paper, metal, rubber, fabric/fiber, glass, and other material	> 60%	Li et al.[86],
Panvel creek, Maharashtra, India	Not stated	Not stated	Not stated	Glass, plastic bottles, cans, bags, rubber, metal, fiberglass, cigarettes, fishing gear etc.	63.00%	Mayur et al.[87],
Kupang, Indonesia	Rhizophora mucronata, Rhizophora stylosa, Avicennia marina, Avicennia alba, Osbornia octodanta and Ceriops tagal	Line transects with 10 × 10 m plot	9.622 items/m^2	Plastic bags, foamed plastics, fabric, glass and ceramics, metal, paper and cardboard, rubber, wood, and other	92.30%	Paulus et al.[88],

Continued

Location of mangroves	Mangrove plant surveyed	Sampling method	Quantity	Major litter items	Contribution of plastic litte	References
Mangrove-ecosystem and estuaries of Kendari Bay, Indonesia	Not stated	5 × 5 m quadrats	1.76 to 3024 items/m^2	Plastic (bottles, bags, ropes, pipettes, cups), metals cans, rubber, glass bottles, cloth, paper, and others	159 to 378 items/m2	Rahim et al.[89],
Tunda Island, Indonesia	Not stated	100 m line transect	0.75 items/m^2, 0.075 kg/m^2	Plastic bottle, bottle caps, lids, straw beverage bottle, grocery bags, cigarette butt, can, straw	Not stated	Maharani et al.[44],
Pichavaram, Tamil Nadu, India	Not stated	Not stated	Not stated	Plastic carry bags, plastic bottles, food wrappers	Not stated	Sandilyan and Karthiresan[90],
Omani coast, Sea of Oman	Avicennia marina	10 × 10 m quadrats	133 items/m^2 to 10 items/m^2	Foamed plastics, hard plastics, soft plastics, plastic straps, clothes, fishing gears, glass, metals, rubbers, and wood	73–96%	Al-Tarshi et al.[47],
Saudi Arabia coast of the Gulf	Avicennia marina	20 × 2 m belt transect	Mean density of 0.98 ± 0.05 to 2.96 ± 0.25 items/m^2 and the average concentration 1.4 ± 0.61 items/m^2. Mean litter of 0.79 ± 0.45 items/tree with a range from 0 to 7 items/tree	Plastics (bottle caps, plastic bags, drink bottles, fisfing nets, lines/ropes, food wraps, beverage cups, fragments, buoys, styrofoam, sachets, oil containers, woods/timbers, metal, ceramics/glass, fabrics/textiles, tetra pack, rubbers, footwear, leather, medical waste, sanitary waste	80.05% mangrove floor 83.29% in mangrove canopy	Present study

Table 1. Marine litter studies from around the world in-mangrove ecosystem.

Locations	SS	df	MS	F	*P*
Saihat	599	1	599	18.720	0.145
	150	11	14		
Darin	497	1	497	68.591	**0.001**
	153	8	19		
Sawari	627	1	627	41.796	**0.008**
	137	9	15		
Sanabis	448	1	448	53.958	**0.002**
	149	8	19		
Zour	520	1	520	27.360	**0.003**
	87	7	12		
Jamiyin	486	1	486	37.846	**0.009**
	144	9	16		
Qatif/Ramsh	505	1	505	39.330	**0.008**
	144	9	16		
Safwa	560	1	560	39.078	**0.008**
	139	9	15		
Jubile	603	1	603	31.204	**0.011**
	124	9	14		

Table 2. Comparison of marine litter among surveyed Mangrove sites.

items/m^2) recorded higher litter density followed by Zour (1.26 ± 0.08 items/m^2), Darin (1.15 ± 0.07items/m^2), and Sawari (0.98 ± 0.05 items/m^2). Among the Tarut island mangrove stands, the Jamiyin and Sanabis showed higher litter concentrations than the other ones. This could be due to their morphological nature and the dense population around the stands where the litter was deposited more. The Jamiyin mangrove stand is distinguished by its tall growth and dense mangrove, which contains clayey sand.

Plastics litter (80.05%) were the most dominant materials of all the surveyed mangrove floor followed by other non-plastics litter were timbers/processed woods (5.37%), tetra pack (3.05%), rubbers (2.12%), glass/ceramics (2.05%), metal (1.92%), textile/fabrics (1.66%), footwear (1.39%), leather (1.06%), sanitary (0.66%) and medial items (0.66%; Fig 2a). The research finding indicates that the average concentration of plastic litter was 1.12 ± 0.57 items/m^2 at all sites, which is higher than the global average of 1 item/m^2[26,48]. The Plastic litter density ranged from 2.57 ± 0.31 items/m^2 at Saihat to 0.66 ± 0.05 items/m^2 at Safwa (Table S2). The lightweight, single-use plastic bags were the most common and abundant plastic item found in mangroves, accounting for 23.39% of all litter. A similar result was observed from Thoothukudi Coast in Southeast India, which has an average litter density of 6.7 items/m^2 on the mangrove ground and 8.6 items/tree, with plastic litter making up more than 81% of all collected items. Across all sites, single-use plastics were the most common[49].

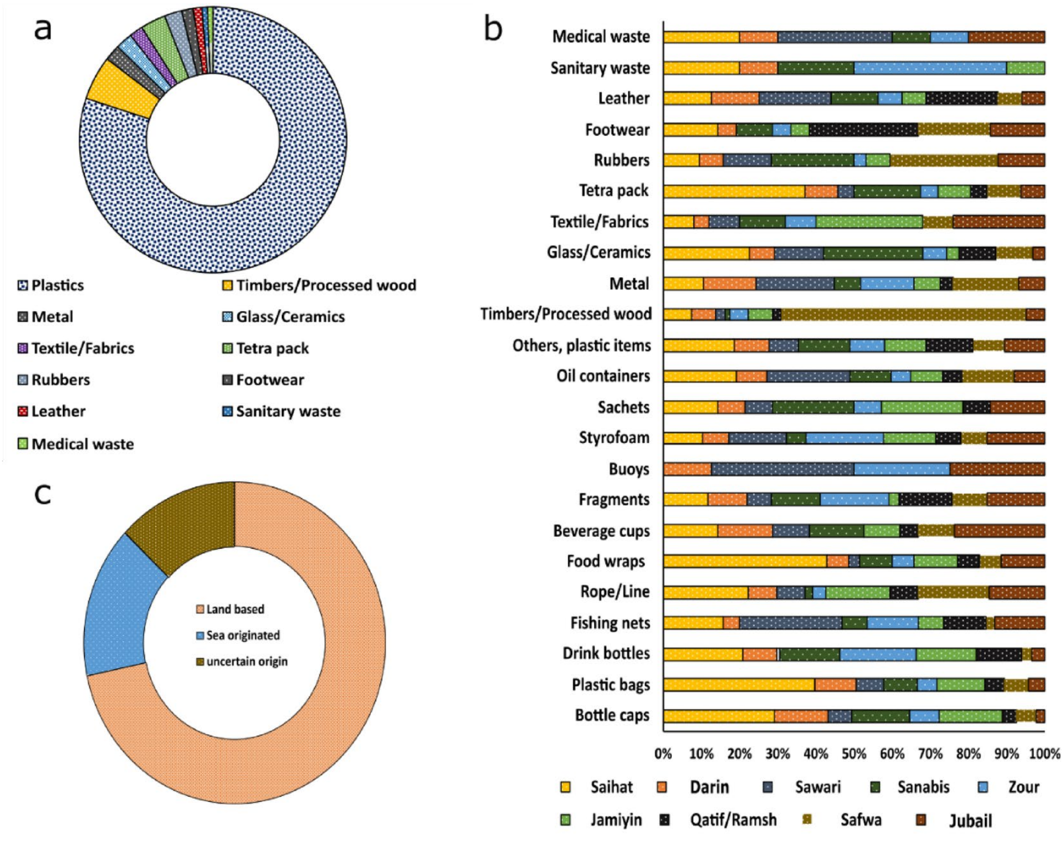


Fig. 2. Marine Litter Composition and Distribution on the Mangrove Floor. (**a**) Percentage composition of major litter types. (**b**) Abundance, composition, and spatial distribution of marine litter. (**c**) Percentage contribution of land-based, sea-based, and uncertain origin litter.

The second most abundant plastic litter is drink bottles, which account for 15.24% followed by other plastic litters (12.92%), bottle caps (5.24%), fragments (5.17%), Styrofoam (3.91%), rope/line (3.58%), tetra pack (3.05%), fishing net (2.98%) and timbers/processed woods (5.37%). The composition of the litter density by the site is shown in Fig 2b. The marine litter composition from the present study is well correlated with other studies on mangrove ecosystems around the globe (Table 1). For example, plastics litter was high a proportion of 70% in the Philippines mangrove forest[43], 89% in Indonesian mangrove[50], 83.02% noticed on the central west coast of India, Arabian Sea[6] and 92.2% on the Rea Sea coast mangrove forests[1]. The west coast of India and the Kerala coast contributed 77.6% and 73.8% of the plastic, as noticed by Mugilarasan et al.[51]. and Daniel et al.[52]. respectively. According to previous observations by Martin et al.[1]., 95.5% of the marine litter in the Gulf mangrove forests was plastics. Most of the studies conducted in other regions have shown a comparable percentage of plastic litter between 50 and 90% (Table 1). Based on the earlier study on the mangrove forests along the western Gulf revealed a litter density range from 0.22 ± 0.53 items/m^2 to 3.0 ± 2.0 items/m^2 and an average 1.21 ± 0.53 items/m^2[21]. Our present findings (0.98 ± 0.05 to 2.96 ± 0.25 items/m^2 and the average concentration of 1.4 ± 0.61 items/m^2) are slightly higher than that reported by Martin et al.[1]. However, overall, its show a higher concentration of plastic litter in the coastal mangrove stands in the western Gulf, which support the theory that mangrove vegetation acts as a plastic trap and stops plastic from dispersing into the open sea. Shannon-Wiener diversity index values for litter diversity indices were 2.2 at Saihat and 2.7 at Jubail. Pielous evenness index was recorded at 0.7 Saihat and 0.8 at Jubail (Table. S5). Policymakers may find the quantitative method of diversity measurement useful in making informed decisions about effective management since it provides insights into the accumulation of litter[53]. Field observation are shown in the Fig. 6a-l.

Distribution, abundance, composition, and morphology of marine litter on the Mangrove canopy

A total of 500 mangrove trees were surveyed and 395 entangled litter items were recorded. An estimation of the mean concentration of litter was 0.79 ± 0.45 items/tree with a range from 0 to 7 items/tree. At all study sites, plastic bags were the most dominant litter type (Table S3. Figure 3a), accounting for 43% of the total litter, followed by other litter (16.0%), fishing nets (14.4%), rope/line (13.4%), food wraps (7.1%) and Styrofoam (5.3%). The highest density of entangled litter was observed in Saihat (1.42 ± 0.27), followed by Tarut Island (1.38 ± 0.23), Jubail (1.27 ± 0.26), Qatif (1.09 ± 0.15) and Safwa (1.01 ± 0.54; Table. S3). The majority of the litter was found to be retained by branches, pneumatophores, and seedings. Similar findings in the mangrove canopy were observed

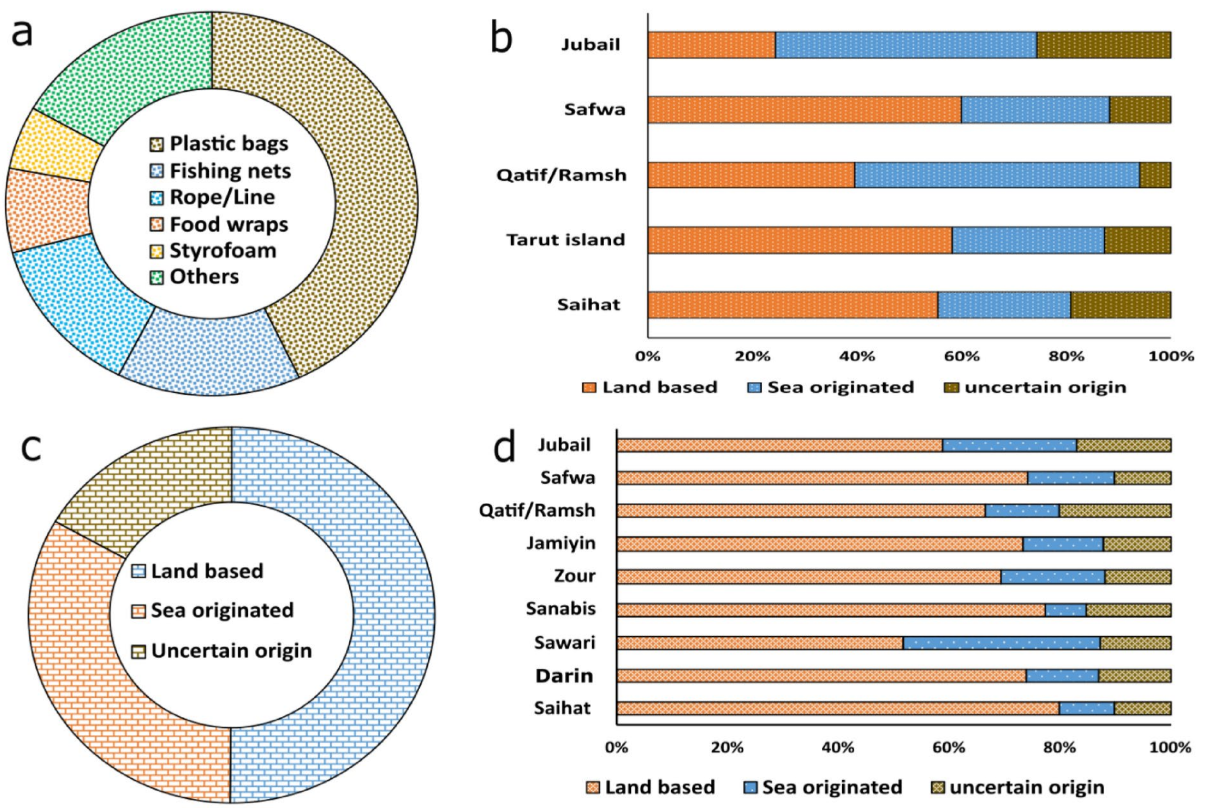


Fig. 3. Marine Litter Composition and Distribution in the Mangrove Canopy. (**a**) Percentage composition of major litter types. (**b**) Abundance, composition, and spatial distribution of marine litter at different mangrove sites. (**c**) Percentage contribution of land-based, sea-based, and uncertain origin litter at different mangrove sites. (**d**) Percentage contribution of land-based, sea-based, and uncertain origin litter across all studied sites.

in several mangrove habitats[1,6,43,46]. De et al.[6]., documented an average litter density was 10.62 ± 0.48 items/tree from 700 mangrove canopies along the Mumbai coast. Additionally, it was noticed large number of plastic litter were endangered in pneumatophores. A similar result was documented in Mumbai coastal mangroves[6,7]. The finding suggests that the intricate network of aerial roots and mangrove canopies functions as a barrier to stop land-based waste from floating out to sea and to stop marine waste from entering the terrestrial ecosystem[54].

Source of marine litter

Principal coordinates analysis (PCO) in different surveyed locations based on marine litter abundance. PCOs of nine surveyed locations of marine litter distributions are shown in Fig 4. The results show that PCO1 accounts for 41.3% of the total variation and PCO2 accounts for 36.8% of the total variation. Those two axes show substantial variation in marine litter in the surveyed mangroves. Levels of similarity (60%, 70%, and 80%) are represented by ellipses, which show similar litter composition among the surveyed locations. PCOs show three main clusters of surveyed location based on the marine litter abundance. Saihat, Sanabis, Jamiyin, and Darin form a closely related group, indicating similar litter composition. Safwa, Jubail, and Sawari are shown as another distinct group, with Qatif/Ramsh and Zour falling in between. More than 78% of variation occurred by two axes (PCO1 And PCO2), indicating significant differences in litter composition and distribution across these sites, potentially driven by different sources. The marine litter present in the Gulf was contributed by land-based sources (plastic bags, plastic bottles, bottle caps, household items, and food wraps), sea-originated sources (fishing line, rope, nets, and Styrofoam), and unidentified sources. Over 71.7% (n = 1082) of the surficial litter on the mangrove floor and 50.1% (n = 198) of litter found on the mangrove canopy originated from land-based sources (Figs. 2c and 3b and d). The previous research also indicated that the major source of litter pollution in this region was from is land-based sources[1,37].

The majority of plastic found in coastal environments worldwide originates from land-based actions[55], suggesting that there is a deficiency in the waste management system and awareness against public littering[6]. Our finding shows that fishing related activities accounted for the majority of the sea-originated litter, which is 15.37% (n = 232) on the mangrove floor and 33.2% (n = 131) on the mangrove canopy. The Gulf is one of the primary sources of fish production in Saudi Arabia. Present-day fisheries are multi-species and multi-gear and mostly artisanal, except of trawlers in the Kingdom, that target shrimp a few months out of the year. Many of fishing gears are used to capture fish, and most of them are made of synthetic polymers.

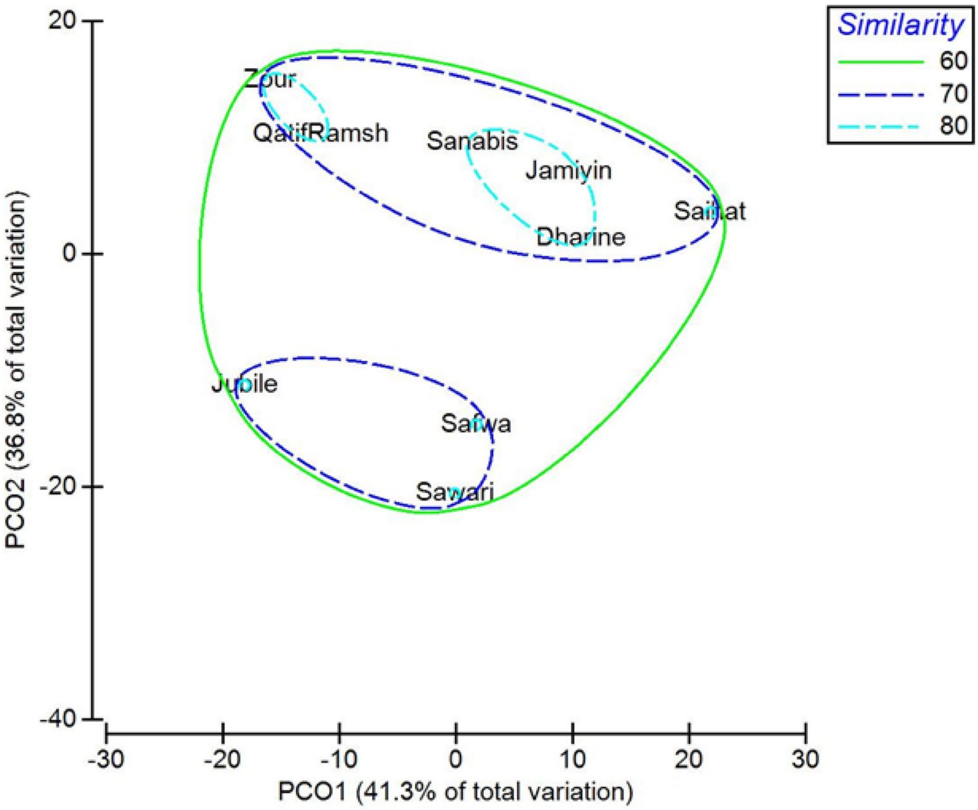
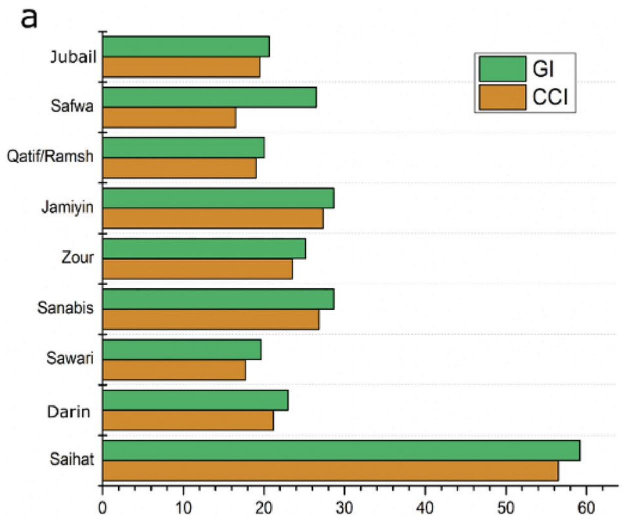


Fig. 4. Principal coordinates analysis (PCO) based on the among the studied sites.

Large amounts of litter are produced by abandoned, lost, and discarded fishing gear (ALDFG) or ghost gear, which also poses a hazard to marine ecosystems since it may entangle and kill aquatic animals, including crabs, elasmobranchs, reptiles, and seabirds[7,56] The ALDFG entangling the whole mangrove tree and blocking it from sunlight will may adversely affect the mangrove tree growth (Fig. 6b-f). Additionally, research on similar habitats have shown that entanglement in ALDFG may cause tissue damage and an increase the epibiotic fouling organisms, indicating a high probability of mortality once entangled[57]. Mangrove ecosystem are sensitive to physical disturbances that affect their productivity and nutrient dynamics. Hydrological and deforestation changes have been identified as important disruptors to soil nutrient plant relations and productivity of the mangrove. Although not specific to ALDFG, these findings indicate that physical obstructions, such as debris entanglement, can have negative impact on mangrove health by disrupting essential ecological processes[58]. Studies conducted in Java, Indonesia, revealed that up to 50% of the mangrove forest floor was covered in plastics debris, which deprivation for the trees[9]. A field experiment revealed that varying the percentage of pneumatophores (aerial roots) covered with plastics showed that within six weeks, mangrove tree considerable leaf loss and increased mortality rates corresponding to the extent of the plastics coverage (0%, 50%, and 100%; 9). However, 12.92% (n = 195) of the litter collected on the mangrove floor and 16.7% (n = 66) on the mangrove canopy remain unidentified. The nation of origin of marine litter was identified by the language, manufacturing location and barcode. It shows that most of the PET bottles (n = 150) were made in Saudi Arabia, and other items could not be traced because of the fading of the label. Some of the marine litter may have been derived from neighboring countries, UAE, Bahtain, Iraq, and Qatar. Veerasingam et al.[37]. have observed notable amount of marine litter found on the beaches of the Qatar coast, which originated from the neighboring countries. Previous research showed that current, stokes drift and wind regulate the movement of marine litter in the Gulf region[59,60].

Assessment of Mangrove floor quality

GI, CCI, and HLI were used to evaluate the risk associated with litter pollution on the mangrove floor. Among the studied sites based on CCI value, it fell under two categories "extremely dirty" and "Dirty". The highest CCI value was noticed at Saihat (56.5) followed by Jamiyin, Sanabis, Zour, and Darin, which fell under the "extremely dirty" group. Sawari, Qatif, Safwa, and Jubile fell under the 'dirty' category (Fig.5a; Table S4). Based on the GI rating, most of the mangrove sites fell under "extremely dirty" except Sawari and Qatif (Figure. 5a; Table. S4). Hazardous litter materials may impact human health, such as metal cans and sharp-edged broken glass injuries to people. Sanitary and medical waste (diapers, syringe needles, face masks, condoms, sanitary pads) can cause, serious health concerns to the coastal community[6,37]. 80 out of the 1530 litter items were classified as hazardous litter, making 5.1% of all litter. The entire HII value falls into the "class II" category, indicating that there is a



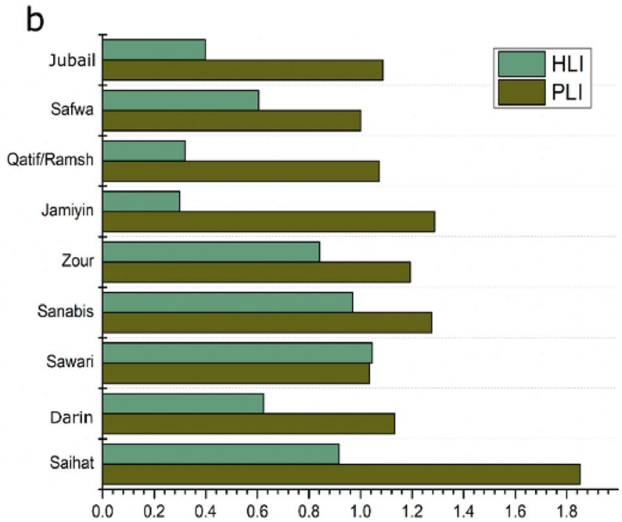


Fig. 5. Indices of cleanliness based on marine litter in mangrove forest. (**a**) General Index (GI) and Clean Coast Index (CCI), (**b**) Hazardous Items Index (HII) and Pollution load Index (PLI).

presentence of some hazardous litter on the studied mangrove floor (Fig. 5b; Table S4). The CCI and GI grades show that the studied mangrove floor was dirty to extremely dirty condition. Overall, 68.1% (CCI) and 84.2% (GI) of the studied mangrove floor were "extremely dirty", 31.9% (CCI) and 15.8% (GI) were dirty. PLI values of all the studied mangrove floors show less than 10, which showed "Hazard level I" (Fig. 5b; Table S4). Based on the PLI result, the mangrove floor is less contaminated. These indices are useful for assessing the amount of litter that accumulates in coastal regions. They can also be useful in developing a framework for coastal management and assessing how well the current solid waste management system is performing.

Biofouling organisms in marine litter

Ocean currents may transport fouling organisms on marine litter, but atmospheric circulation greatly modifies the intensities and direction of those currents on both larger and local scales. As a result, ocean currents can transport a few meters to many thousands of kilometers from any place of origin[61]. In the present study, most of the marine litter (bottles) looking fresh may have been manufactured in the last ten years, around 15% of litter was deteriorated and covered by encrusting organisms. *Amphibalanus amphitrite* is the most common rafting species found in eastern Saudi Arabian coast mangrove environments (Fig 6k-l). Recently, Veerasingam et al.[37]. and Al-Khayat et al.[59]. noticed that beaches on Qatar's west coast had huge amounts of befouled litter, which negatively impacts biodiversity. The current study also supports the possibility that transboundary litter may serve as a vector for an intro of non-native species in the Saudi territorial waters in the Gulf.

Transport mechanisms of floating marine litter

The Gulf is a shallow, enclosed basin connected to the Arabian Sea through a narrow channel, the Strait of Hormuz; circulation over the basin is mostly contributed by the tides, waves, and winds. The mean seasonal

Fig. 6. Impacts of Marine Litter on Mangrove Ecosystems along the Western Gulf. (**a-f**) Abandoned fishing gear entangled in and damaging pneumatophores. (**g, j**) Accumulation of styrofoam and other debris within the mangrove habitat. (**h**) Processed wood debris accumulating in the mangrove. (**i**) Dead bird observed on the Uqair coast. (**k-l**) Marine litter colonized by biofouling organisms. Photographs taken by Kannaiyan Neelavannan.

winds over the basin display north westerlies in both seasons, with maximum wind stress extending from north to central Gulf during summer (Fig. 7a). The maximum wind stress was noticed in the central parts, and the effect was reduced near northern parts during winter (Fig. 7d). According to Kamranzad[62], the Shamal wind events produce high winds and strong waves in early summer and winter, consequently contributing to surface currents in the Gulf (Fig. 7c, f). A wide cyclonic overturning circulation established during spring and early summer later disintegrated into mesoscale eddies. In winter, the wide cyclonic circulation weakens and is more dominated by mesoscale eddies[63]. These seasonal winds and currents impact the transfer of plastic litter to the coastline[64]. Further, the seasonal Windrose pattern shows the majority of wind-induced drift towards south during both summer and winter (Fig. 7b, e) over current study region, that more possibility of the observed marine litter could be from the nearby northern fishing ports. Winds (due to Stokes drift), currents, and the geometry of the floating marine litter all work together to signify the transport and distribution of the marine litter in the Gulf. For example, the surface wind stress distributes the floating marine litter that extends over the sea surface[65]. Though, according to Fazey and Ryan[66], the buoyancy of the litter has a big impact on how quickly and far they disperse. These floating marine litter are transported to the nearshore area by the Stokes drift, however, at a

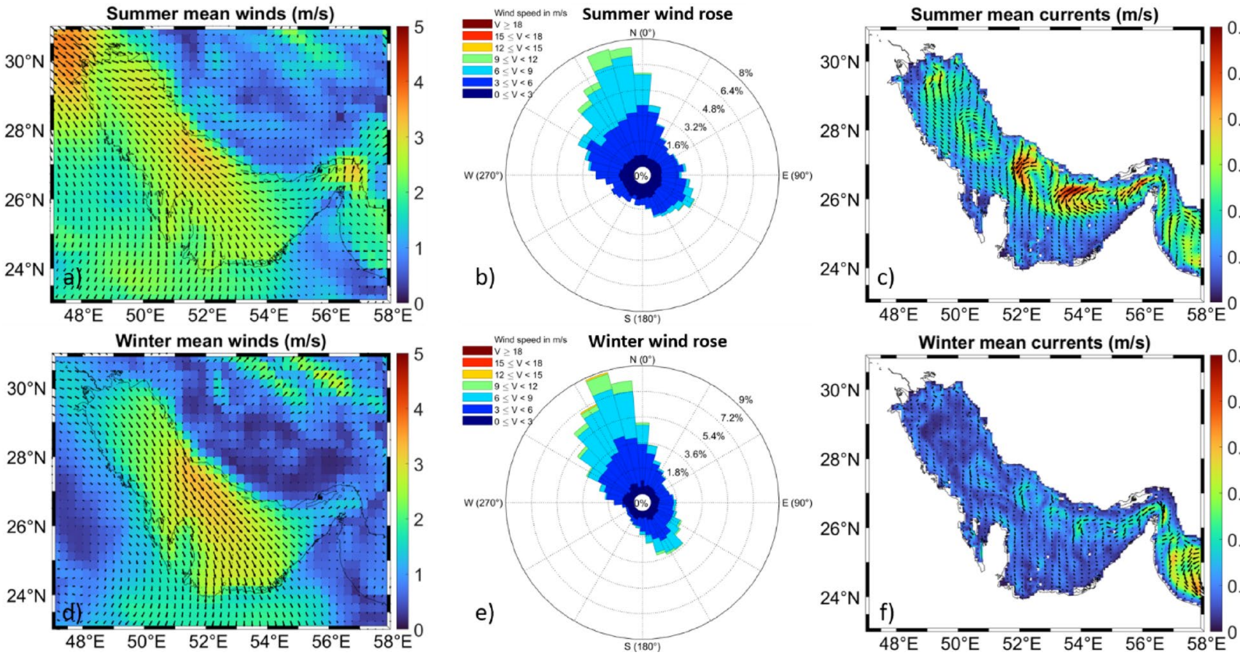


Fig. 7. Seasonal surface wind and current variation. Mean wind speed (color scale) and direction (arrows) during summer (**a**) and winter **d**). The wind rose diagram displays wind variation over Tarut Bay during summer (**b**) and winter **e**). Mean current speed (color scale) and direction (arrows) during summer (**c**) and winter **f**). The spatial surface winds, currents and wind rose diagrams (Fig. 7) are prepared using Matlab software version 2023b.

slow speed[67]. This allows for a relatively faster surface drift in comparison to the transport in the sub-surface. In addition to the wind influence, the tidal currents also play an important role in transporting marine litter from offshore to coast and vice-versa far away from the origin place. In the Gulf, the tide is very complex and dominant due to the shallowness of the basin, varying from semi-diurnal to diurnal. The amphidromic point of semi-diurnal tides is one in the north-western basin and the other in the southern basin. In contrast, the diurnal amphidromic point is located in between two semi-diurnal points the central Gulf near Bahrain. Due to the existence of the different tidal patterns within a shallow basin produces mixed semidiurnal tides all along the Saudi coastal regions of the Gulf, the tidal hydrodynamic model predicted current rage from tidal 0.3–0.6 m/s over most of the coastal waters, whereas high tidal flow observed along the northern head of the Gulf and near Strait of Hormuz. In the Saihat mangrove forest, we observed a lot of Ghost gear or abandoned lost and discarded fishing gear (ALDFG), due to the strong tidal current and the geomorphology of the coastal area favorable for accumulation and transport of marine litter to the marine environment. Also observed are high tidal ranges (Figure. 8a-b) in this area; during high tide, the water reaches a maximum, and the floating litter is trapped with mangrove trees (trapped ALDFG are shown in Fig. 6a-f). Saihat is more prone to trapping floating litter over the mangrove tree in comparison with other studied forests. Figure 8 shows semi-diurnal tidal patterns with strong tidal current in the study region favorable for further transport of the marine litter towards coastal and offshore areas apart from the wind-induced circulations over the Gulf.

To determine the fate and dispersion of marine litter during the sampling month, a MIKE-21 particle tracking model was simulated for 15 days coupled with MIKE21 hydrodynamic model. The results demonstrated the influence of high tidal ranges with strong currents and southward winds across the study region. Here, we choose one location for particle tracking modeling at Taruth Island's fishing harbor to provide a brief review of the transport mechanisms influencing the fate of the anthropogenic litter. The starting particle position of marine litter on December 1, 2023, as well as on the fifth, tenth, and fifteenth days, is shown in Fig. 9. The paths of the marine litter propagation from the source corresponding to the flow patterns over the region were displayed in the model simulations. The dispersion of litter in island habitats is influenced by various factors, including sources, hydrodynamic conditions, gusty winds, and currents[68,69]. Because of their distinct geomorphology and strong tidal currents, the mainland coastal regions south of the island serve as a sink where much marine litter, especially fishing gear and other items associated with fishing activities, accumulates. After ten days, the litter outflow from this source moves further offshore following the increasing magnitudes of spring tidal currents during that period.

Ghost gear or abandoned lost and discarded fishing gear (ALDFG)

The term ghost gear refers to abandoned, lost, and discarded fishing gear (ALDFG) which is a major source of marine litter[70]. Significant negative effects on the environment, economy, and community can result from ALDFG, such as indiscriminate fishing, habitat destruction, sea safety hazards, entanglements, vessel damage,

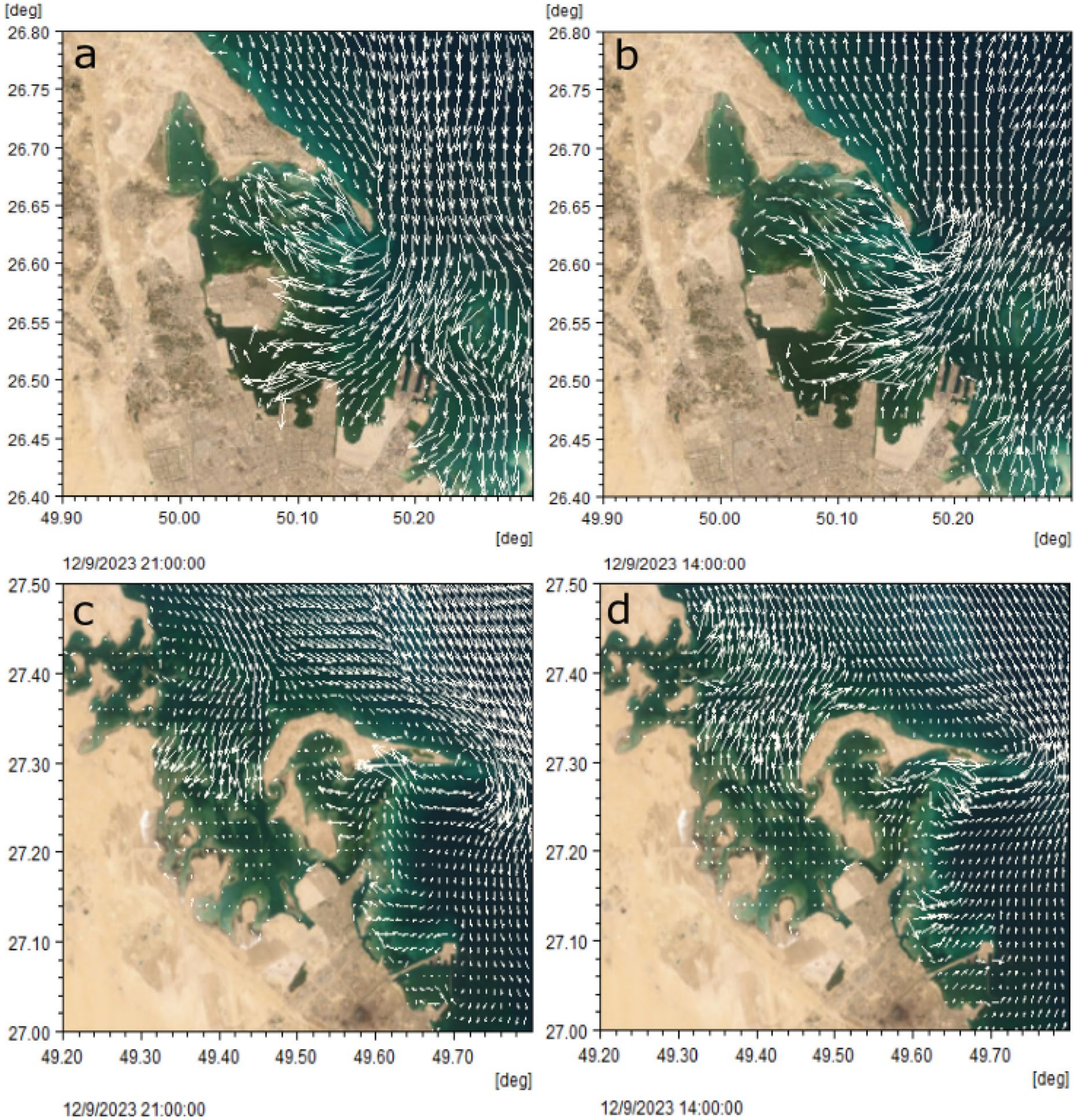


Fig. 8. Tidal Current Patterns near Tarut Island and Jubail. Surface current patterns during flood tide (**a, c**) and ebb tide (**b, d**) near Tarut Island (**a, b**) and Jubail (**c, d**). The ocean surface currents over Gulf is taken from the Operational Mercator global ocean analysis and forecast system at 1/12-degree daily 3D data downloaded from Copernicus Marine Service (https://data.marine.copernicus.eu/product/GLOBAL_ANALYSISFORECAST_PHY_001_024/description). The satellite imagery used in the figure was downloaded from USGS Earth Explorer for year 2024 of Landsat 8 OLI which is then further processing in Arc GIS Pro for Layer Stacking of all the available band, generated using MIKE-21 plot composer (MIKE software version 2022).

fewer catches, increase in marine litter and microplastics[71]. The Taiwan Marine Debris Management Act (I), which includes 34 future act goals and 67 strategies, was issued in 2018 by the Environmental Protection Administration of Taiwan in cooperation with NGOs. The 67 strategies covered issues like developing policies, education, increasing producer responsibility, preventing litter from entering the sea, and waste collection. Further, the Management Act underwent additional revisions in 2019 with marine litter prevention and policies. Similar policies were introduced and implemented in many countries. For example, license holders have been required by Fisheries and Ocean Canada (DFO) terms since 2019 to report any ALDFG losses within 24 h, which helps to create a lost gear database. Later on, based on information provided by the fishermen, the NGOs or harbor authorities will retrieve the ALDFG. The present study data reveals that sea-based sources contributed 33.2% and 15.4% (Figs. 2c and 3b-3d) from on the ground and ground surveys, respectively. The sea-based sources (fishing-associated activities) are more compared to other studies from the Mumbai coast, India. De et al.[6]. and Kesavan et al.[7]. The present study shows that considerable ALDFG occurred in the Saudi Gulf mangrove

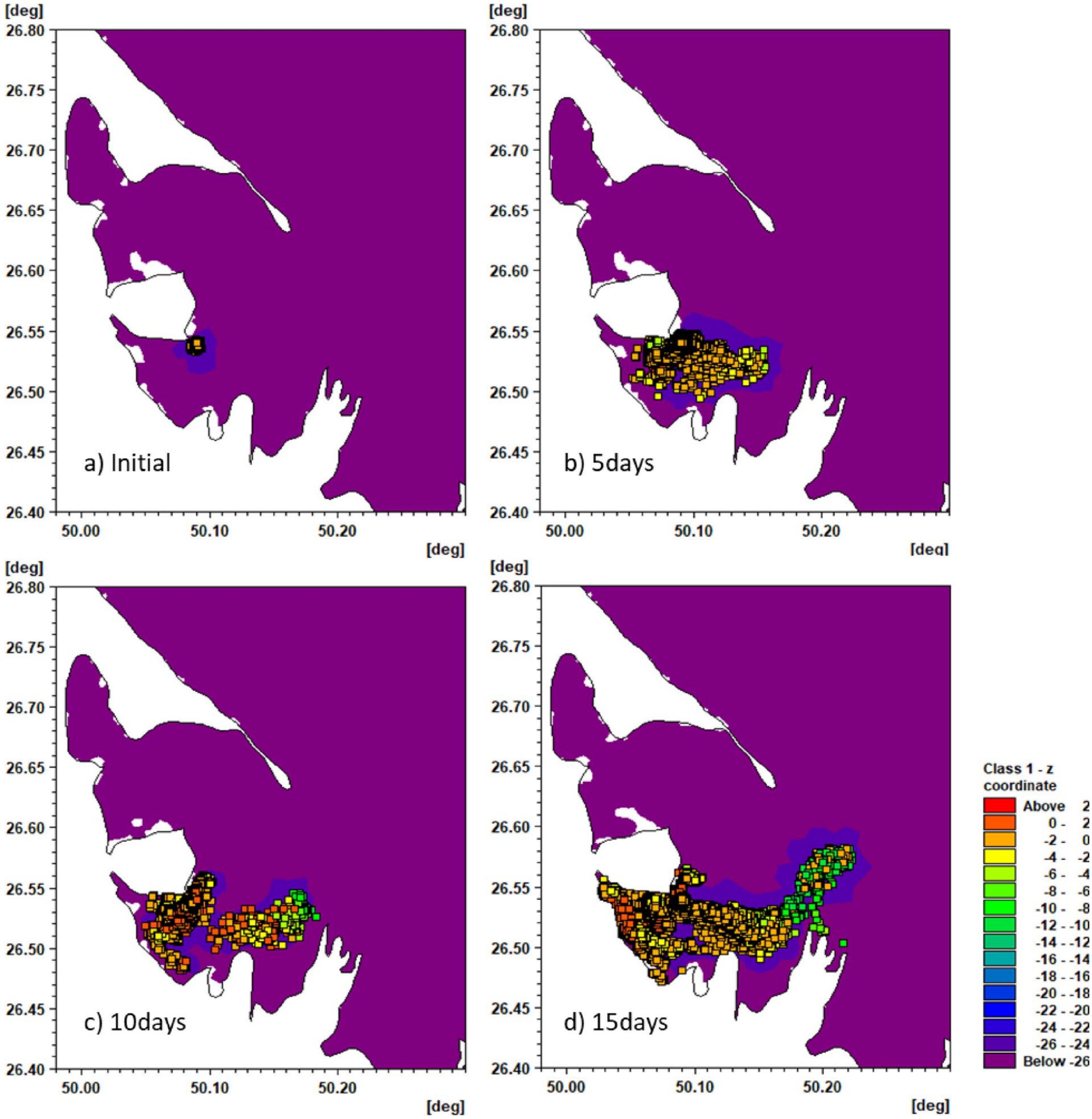


Fig. 9. Predicted trajectory and distribution of marine litter over 15 days period (**a**) Initial dispersion pattern released at Taruth Island's fishing harbor, (**b**) distribution on the fifth day, (**c**) distribution on the tenth day and (d) distribution of particles on fifteenth day. These plots are generated using Mike-21 plot composer.

environment. Higher sea-based sources of marine litter on the mangrove are due to the highly traversed maritime routes present too close to the studied mangrove (Fig. 10) in the Gulf. The study from McIntyre et al.[72]. retrieved the ALDFG in Atlantic Canada, the result shows that 29,298 kg of ALDFG were recovered in total. There is no study in the Gulf about ALDFG retrieved, but this is the time we can think of retrieving them back to land for safe disposal or recycling, which can considerably mitigate the environmental damage and economic loss related to ghost fishing. This is an important step towards addressing ghost fishing gear and the environmental impact of marine litter, it is important to develop tailored strategies for ALDFG Management. The government must implement specific regulations and policies focused on ALDFG retrieval and management. This might include (i) requiring fishers to report lost gear, identifiable tags on fishing gear to tract ownership, and providing logistical or financial support for fishers and organizations involved in ALDFG retrieval; (ii) raise awareness among local fishing communities about the environmental and economic impact of ALDFG; (iii) develop facilities for the safe disposal and recycling of retrieved fishing gear; and (iv) establish a dedicated research program to study the level of ALDFG in the Gulf. Implementing these steps might significantly contribute to the preservation of marine biodiversity and the sustainability of the fishing industry in the Gulf.

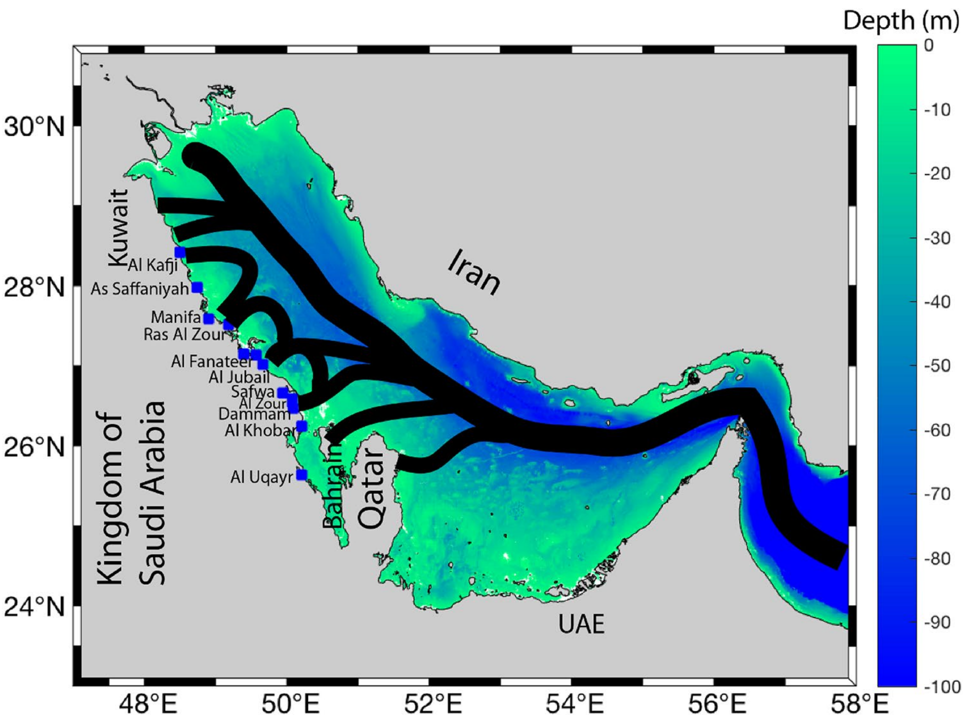


Fig. 10. Map of Gulf major maritime routes and harbors of western Saudi Arabian coast (based on marine live traffic website, https://www.marinetraffic.com/en/ais/home/centerx:−12.0/centery:25.0/zoom:4).

Microplastic and plastics pollution in Mangrove ecosystems

Mangrove ecosystems are essential sinks for plastic waste along the Saudi Coast of the Gulf[73]. A study by Martin et al.[73] noticed significant quantities of plastics were found in the sediment core from the mangrove ecosystem from the Saudi Coast of the Gulf, particularly in the top 2–5 cm of sediments. There were 84 ± 35 plastic items per kg in the top 2 cm and 83 ± 29 plastics per kg in the top 5 cm of mangrove sediments. Comparatively, the plastic concentration in the intertidal beach sediment in this region was lower (ranging from 8 to 15 items per kg[73]). Since the 1950 s, plastic deposition in the mangrove sediment has rapidly increased, paralleling the global rise in plastic production. Historical sediment core study indicated that an estimated 110 ± 80 metric tons of plastic have been buried in the mangrove sediments of the Gulf since 1930.

Furthermore, microplastics smaller than 0.5 mm were found to dominate stocks in mangrove sediments, indicating that these habitats serve as final sinks for smaller particles that might float in the water column[73]. According to dated sediment cores, plastic particles were absent in layers older than 1907, which is consistent with the timeline of plastic production. Plastic rates increased after 1950, with recent estimates (2001–2020) indicating burial rates of 11 ± 7 metric tons. An estimated 70 metric tons of plastics are expected to be buried by 2050 if current trends continue in the mangrove sediment of the Gulf[73]. Microplastics, such as polypropylene and polyethylene, accumulate in mangrove sediments, possibly changing their physical and chemical properties[73]. Marine organisms inhabiting mangrove ecosystems, such as mollusks and crabs, have been discovered to ingest microplastics[74]. Higher trophic levels, mainly commercially important fish species, can be impacted by bioaccumulation caused by filter feeders and detritivores ingesting microplastics[75]. Persistent organic pollutants (POPs) may be transported through microplastics and released into the mangrove ecosystem over time[74].

Socio-economic implications of marine litter in Mangrove environments

Mangrove ecosystems in the Gulf play a crucial role in supporting fisheries, conserving biodiversity, and sequestering carbon, contributing significantly to the region's ecological and socioeconomic stability[76]. Marine litter accumulation in the Gulf coastal mangrove habitats may have socio-economic consequences, including fisheries, tourism, and public health. Even though mangroves act as organic barriers against marine litter, increasing litter load in these environments poses economic challenges for nearby people and businesses associated with mangrove resources. Mangrove ecosystems provide nursery habitats and livelihoods for many fishing families, particularly those engaged in small-scale fisheries[77]. Further, Gulf mangroves serve as important habitats for juvenile fish species of high commercial value, including *Lutjanus fulviflama*, *Liza macrolepis*, *Sparus sabra*, *Pseudorhombus javanicus*, and *Cynoglossus*sp[76]. The accumulation of Marine litter, microplastics, and ALDFG in mangroves negatively impacts fish stocks and nearby fisheries when litter becomes entangled in mangrove roots, reducing habitat availability for juvenile shrimp and fish, which causes population declines. Studies from other mangrove regions, including Philippines and Indonesia, shows that marine litter reduces fishery output by an estimated 20–30%, resulting in economic losses $2–5$million[74]. Another study from Penang Island in Malaysia on marine litter coastal pollution can reduce tourism revenue by up to 40%, underscoring the economic consequences of poorly managed waste in coastal ecosystems[74]. Similar economic impacts may be expected in the coastal fisheries of the Gulf region, where mangrove-associated fish species play an essential role in the seafood industry[74]. By integrating socioeconomic considerations into marine litter control plans, gulf countries can more effectively safeguard their fisheries, mangrove ecosystems, and coastal economies.

Future management strategies to control the marine litter on the Saudi Coast of the Gulf

The entire Gulf is home to a large number of islands, most of which are small and rich in diverse marine ecosystems. Breeding seabirds and sea turtle nesting can be found on these islands. The current study found that the eastern Saudi Arabia coast mangrove is a sink for marine litter and similar situations can be expected in other coastal beaches and also islands in the Gulf. Additionally, manmade structures and Marines also build physical barriers on the beaches and reduce the quantity of effort to lay sea turtles[78]. Marine litter also hinders nesting activity and the success of hatching emergence[79]. As a result, the diversity of invertebrates along the shore will decline and seabirds that nest along the coast will be more at risk of becoming entangled[80,81]. Many dead seabirds were observed during the coastal marine litter survey on the Uqair coast (Fig. 6I), particularly the Socotra cormorant (*Phalacrocorax nigrogularis*). Veerasingam et al.[37]. reported a similar observation at an uninhabited island, Qatar Beach. One of the least well studied regional endemic seabirds, *Phalacrocorax nigrogularis*is only found along the Oman coast and Gulf regions and is endangered by human activity[37]. Seabirds are top predators in the marine ecosystem and renowned ecosystem engineers, able to modify terrestrial ecosystems by transferring nutrients from the sea though the deposition of guano and other allochthonous inputs. Hence, even the most pristine setting will eventually become a plastic island when plastic deposition rises in such remote uninhabited regions[80].

The environmental health of the nation, its economy, and the Sustainable Development Goals (SDGs) established by the United Nations may encounter significant challenges as a result of the concerning forecasts regarding the production and accumulation of plastics in the forthcoming years. Plastics were included on the agenda of the 26 th conference of the parties to the United National Climate Change (COP26), which happened in 2021, with a waste reduction. Therefore, environmental managers must ask for long-term solutions to the plastic issues immediately. For example, India showed its early understanding of the problem by being the first country to outlaw single-use plastic in 2019. The use of single-use plastics was to be outlawed nationwide in India by 2022. The current analysis shows that land-based sources and related activities are the primary source of most marine litter. Recently, the Government of India cleared over 90,000 tons of plastics from Mumbai mangroves through periodic cleanup programs[6]. A global meta-analysis found that, because of the huge amount of plastic emission in the ecosystem, litter cleanup efforts have little influence on long-term litter pollution even though they can temporarily reduce the concentration of litter in the coastal environment. Therefore, source control, preventing litter from entering water channels and increased seabed collection must be the top priorities.

Sustainable Development Goal (SDG) 14, which aims to conserve and exploit the ocean and marine resources responsibly for sustainable development is highlighted by the United Nations Department of Economic and Social Affairs (UNDESA). Plastic pollution is one of the most urgent issues under this objective since it seriously endangers ecosystems, marine biodiversity, and human livelihoods. International agreements and policy measures have been established to prevent plastic pollution, including. The United National Environmental Programme (UNEP) has developed the global plastics treaty which is a binding measure to curb plastic waste[82]. Regional action plans (RAPs) implemented by the Regional Organization for Protection of Marine Environment (ROPME) in the Gulf regions to reduce and monitor marine litter.

A multifaceted strategy is needed to address plastic pollution in a sustainable manner in Gulf regions. Improving waste management plays an important role by strengthening recycling infrastructure, enforcing a ban on single use plastics, and encouraging circular economy model. Further, innovative cleanup technologies, such as autonomous cleanup systems. Community involvement and awareness campaigns as well as beach cleanups and citizen science programs. Furthermore, in order to reduce their environmental impact industries need to use sustainable fishing gear, ecofriendly packaging and biodegradable materials. The awareness programs should start with educational initiatives targeting key stakeholders such as coastal communities, fisheries and industries directly involved in marine activities.

The fishing communities in the Gulf region play a crucial role in marine resource management. However, most of the fishermen have an education level below high secondary, which can make it challenging to implement best practices for handling plastic waste at sea. As a result, they are unable to understand the effects of plastics and the extent of the harm they inflict on our environment. Without proper knowledge, they may unintentionally contribute to plastics pollution, including ALDFG, which is a major threat to marine life. Dedicated training and awareness initiatives must be carried out for all fishermen in the Gulf region of Saudi Arabia in order to address this issue. Training programs might use storytelling techniques, visual demonstrations, and hands-on workshops to highlight the risks of plastic pollution and the benefits of responsible waste disposal. Further, environmental groups and government officials must work together to introduce incentive-based programs, including paying fishermen for retrieving ALDFG or plastic waste from the sea. By combining education, community engagement, and policy, we can empower fishermen to play a crucial role in marine conservation and assure a cleaner and more sustainable future for the region.

Conclusions

In this research endeavor, an assessment was conducted on the status of marine litter across eight distinct mangrove forests situated along the western Gulf, specifically along the coast of Saudi Arabia. Among the various forms of marine litter, single-use plastics emerged as the predominant category present within the studied environments. The mangrove ecosystem plays a vital role in the interception of litter, thereby inhibiting its dispersal between terrestrial and marine domains. Nevertheless, heightened interactions between litter and mangrove habitats may pose detrimental effects on pneumatophores and overall tree health, consequently influencing the ecological integrity of this essential coastal ecosystem. The degradation of mangrove forests, attributable to litter pollution, may directly undermine the health of mangroves and the associated ecosystem services, which include safeguarding coastal areas from erosion and mitigating the impacts of extreme weather phenomena such as rising sea levels, tsunamis, and cyclones. The considerable accumulation of litter within mangrove environments may result from inadequate solid waste management practices, public littering behaviors, fishing activities, tourism influence, and local oceanographic conditions such as tidal movements, currents, and wind patterns. Therefore, safeguarding the mangrove forests along urbanized coastal regions and implementing both preventive and remedial measures to mitigate exposure to litter pollution could significantly enhance the livelihoods, economic stability, and overall well-being of millions of individuals.

Data availability
Data provided in the manuscript and supplementary file. Further details, the corresponding author can provide the datasets used and analyzed in this study upon request.

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Declarations

Competing interests
The authors declare no competing interests.

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