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Review

Interaction of climate change and marine pollution in Southern India: Implications for coastal zone management practices and policies

Susana Lincoln [a,*], Piyali Chowdhury [a], Paulette E. Posen [a], R.S. Robin [b], Purvaja Ramachandran [b], Nithin Ajith [b], Olivia Harrod [a], Danja Hoehn [a], Richard Harrod [a], Bryony L. Townhill [a]

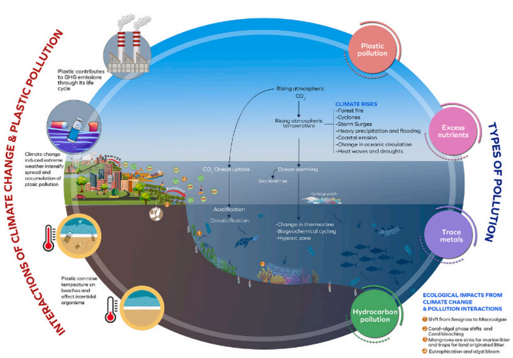
[a] *International Marine Climate Change Centre, The Centre for Environment, Fisheries and Aquaculture Science (Cefas), Cefas Laboratory, Pakefield Road, Lowestoft, Suffolk NR33 0HT, United Kingdom*

[b] *National Centre for Sustainable Coastal Management, Ministry of Environment, Forest and Climate Change, Chennai 600 025, India*

HIGHLIGHTS

- Assessment of climate change and marine litter interactions in Southern India
- Gulf of Mannar key issues: habitat decline, erosion, cyclones, and marine pollution
- Malabar Coast key issues: impacts on fisheries, monsoon changes, and microplastics
- Policy and framework tools are proposed to improve the management of cumulative impacts.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change and marine litter are inextricably linked, and their interaction manifests differently depending on the specific environmental and biological characteristics, and other human activities taking place. The negative impacts resulting from those synergistic interactions are threatening coastal and marine ecosystems and the many goods and services they provide. This is particularly pervasive in the coastal zone of the Indian subcontinent. India is already experiencing severe climate change impacts, which are projected to worsen in the future. At the same time, the country is gripped by a litter crisis that is overwhelming authorities and communities and hindering the country's sustainable development goals. The coastal environment and communities of the southern states of Kerala and Tamil Nadu are particularly vulnerable to the impacts of climate change. While these state governments and authorities are stepping up efforts to improve the management of their coastal zones, the scale and severity of these issues are mounting. Here we review the combined effects of climate change and marine litter pollution in Southern India, focusing on the Gulf of Mannar Reserve in Tamil Nadu and the Malabar Coast in Kerala. Finally, we discuss effective management options that could help improve resilience and sustainability.

* Corresponding author.
E-mail address: susana.lincoln@cefas.gov.uk (S. Lincoln).

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1. Introduction

The synergistic interactions between climate change and marine litter vary across oceanic regions, depending on local environmental and biological characteristics and other human activities taking place, and the resulting pervasive impacts threaten the functioning of coastal and marine ecosystems and the many goods and services they provide (Ford et al., 2022; Lincoln et al., 2022). Additionally, these interactions also threaten vital earth system processes, arguably at a planetary scale (Arp et al., 2021). While important knowledge gaps remain and research should continue, it is also timely and possible to take action using, for instance, climate resilience frameworks (Lincoln et al., 2022; Devlin et al., 2021; Yadav and Gjerde, 2020).

Increasingly, marine litter is being recognised as a threat multiplier that combines with other stressors such as climate change to cause far greater damage; for example, increased storminess as a result of climate change can lead to increased inputs of litter into the marine environment, and, in turn, greater accumulation of litter further undermines the climate resilience of habitats and species (Ford et al., 2022; Lincoln et al., 2022). Microplastics, classified as plastic particles ≤5 mm, are the focus of increasing attention due to their presence in the human food chain and their potential to act as vectors for chemical contaminants; however, most (59 %) published studies on the prevention and control of plastic waste appear to focus on microplastics already present in the aquatic environment (Schmaltz et al., 2020), rather than focusing on solutions at the source, and overlooking the role of climate change in modulating marine litter pathways.

The coastal zone is of great importance as it provides multiple and important ecosystem services (Lu et al., 2018), but the coastal boundary is particularly vulnerable to climate change due to its frontline exposure. In addition to sea-level rise and extreme weather impacts on the coastline, coastal waters are also exposed to increasing loads of nutrients, contaminants, and litter, from point and non-point sources (Gazeau et al., 2004). The combined impacts of pollution and climate change are driving some dramatic changes in the global coastal zones (Lu et al., 2018), and this issue is particularly acute in the Indian subcontinent. India is already experiencing severe climate change impacts, which are projected to worsen into the future unless present greenhouse gas emissions are curbed, and the country is also gripped by escalating issues of marine litter pollution, which is overwhelming authorities and communities and hindering the country's sustainable development goals.

India's coastline is home to about 170 million people, who live on the edge of a shifting climate experiencing damaging heavy rainfall, floods, erosion, droughts, heat waves, and devastating tropical storms and cyclones (Agarwal and Deb, 2023). Recent examples include the record-breaking floods in Mumbai, Maharashtra, in July 2005 (Prasad and Singh, 2005), Kerala in August 2018 (Hunt and Menon, 2020), Chennai, Tamil Nadu, in December 2015 (Ray et al., 2019), Odisha in May 2021 (Kundu and Santhanam, 2021), and again in Chennai in November 2021 (see Fig. 3). Droughts and heat waves are becoming more intense and frequent, driven by climate change (IPCC, 2022; Christensen et al., 2007), leading to large accumulations of litter in dry riverbeds, which can result in even more destructive flood-related debris flows when the rain arrives. Between 1901 and 2005, heavy monsoon precipitation trends indicate that extreme events have intensified and become more frequent, with an even clearer trend after 1950 (IPCC, 2012; Rajeevan et al., 2008; Sen Roy, 2009; Kshirsagar et al., 2006). Models suggest that monsoon rainfall will continue to increase in India as global mean temperatures rise (Katzenberger et al., 2021; IPCC, 2012).

The North Indian Ocean receives some of the highest influxes of plastic waste of all ocean basins, and the problem of marine litter is overwhelming the rim countries, including India (Van der Mheen et al., 2020). The Indian monsoon is a major pathway for marine litter, the vast majority of which (96 %) consists of plastics released from within the rim countries (Duhec et al., 2015). India itself is one of the world's main sources of plastic marine litter, generated principally from the ship-breaking industry (in addition to a variety of other scrap materials like metals and rubber), followed by fishing and coastal recreational activities, combined with inadequate waste disposal practices and littering behaviour (Mugilarasan et al., 2023; UNEP, 2022). India has been ranked the world's 12th largest supplier of mismanaged waste (Jambeck et al., 2015). It is estimated that over 150 thousand tonnes of solid waste are generated per day, of which less than half is recycled, and about a third is unaccounted for and likely discarded into the environment (CPCB, 2021). Scaled up, these estimates represent >9 million tonnes of plastic waste generated per year, of which almost 4 million tonnes remain uncollected (Daniel et al., 2020a; MoHUA, 2019). This problem is set to worsen, and by 2025, India is expected to become the 5th largest supplier of waste (CPCB, 2021; MoHUA, 2019). Once in the environment, much of the litter will be transferred to the sea via waterways, also aided by wind action (Daniel et al., 2020a; Lebreton et al., 2017; Jambeck et al., 2015). In India, uncollected waste is likely to find its way to the Arabian Sea and Bay of Bengal, either directly or via riverine systems, such as the Meghna-Brahmaputra-Ganges river system, which is estimated to discharge around 73,000 t of plastic waste per year into the Bay of Bengal in the North Indian Ocean, making it the 6th most polluted river system in the world (CPCB, 2021; MoHUA, 2019).

In India, the impact of litter is particularly severe in coastal communities (Daniel et al., 2020a; MoHUA, 2019). The population of Kerala state is projected to approach 35 million in 2023, a large percent of which live on or near the coastline, while the Tamil Nadu state is the 7th most populous in India, projected to surpass 83 million in 2023, and half of the population congregates in urban areas; the coastal capital mega-city of Chennai is set to reach over 11 million people by 2023. In addition to the challenges of dense and rapid population growth, coastal communities in both states are directly exposed to the impact of climate change and marine litter, which threatens their livelihoods and vital ecosystem services (DoECC, 2022; DoE, 2023a). State governments are stepping up their efforts to improve the management of their marine and coastal zones (DoECC, 2022; DoE, 2023b), but the severity and scale of these two threats combined are overwhelming, given the spatial extent and the population affected.

Here we present a review of published literature on the combined effects of climate change and marine litter in Southern India, focussing on the coastal states of Kerala and Tamil Nadu, and more specifically on the Malabar Coast and the Gulf of Mannar marine areas, because of the huge importance of their marine resources and ecological services. For instance, the Gulf of Mannar is designated as a biosphere reserve as part of the South and Central Asia Man and the Biosphere Network, while the continental shelf off the Malabar Coast encompasses internationally renowned fishing grounds and directly sustains the livelihood of over 222 coastal fishing villages. The aim of this review is to: i) better understand the specific effects on the southeastern and southwestern coasts; ii) determine implications for coastal management; and iii) propose recommendations for effective management practices to enhance the resilience of the coastal zone.

2. Material and methods

A literature review was carried out by adapting the rapid evidence assessment method following Smithers (2015). Further bibliographic references were obtained during secondary searches, and others were included as they were known to the authors. The geographical context of this review was the North Indian Ocean, with a focus on Southern India and the coastal states of Tamil Nadu and Kerala, and more specifically on the important marine areas of the Gulf of Mannar and the Malabar Coast, respectively (Fig. 1a).

3. Results

A total of 178 articles and reports were found during the literature searches, of which 150 focused on various aspects related to marine litter broadly grouped in the following categories: impacts on ecology and biodiversity, the role of oceanic processes, human and socio-economic implications, and information on policy and recommendations (Fig. 1b). Only 21 articles were found to relate to climate change, most of which dealt with extreme weather events, with some including a link or application in relation to marine litter issues, while only 7 articles were found that specifically addressed the interaction between these two global emergencies (Fig. 1b).

In the following sections, we summarize the main findings from the review. Firstly, we set the scene by introducing examples of typical global interactions between climate change and marine pollution, followed by a summary of the evidence of these synergistic interactions in the North Indian Ocean region. We then present a summary of the findings for Southeastern and Southwestern India specifically, focusing on the coastal states of Tamil Nadu and Kerala and the marine areas of the Gulf of Mannar and the Malabar Coast, respectively (Fig. 1a).

3.1. Global synergistic effects of marine climate change and pollution

Climate change and pollution are two of the most severe pressures currently affecting global coastal and ocean ecosystems, and their combined effects can, potentially, be more harmful than either stressor acting alone (Lu et al., 2018; Hatje et al., 2022). Synergistic interactions between marine pollution and climate change are also complex and vary depending on environmental characteristics, and the specific types of stressors and receptors involved (Cabral et al., 2019; Lu et al., 2018; Hatje et al., 2022). Some typical synergistic effects are represented in Fig. 2.

One example of how the interaction between climate change and marine pollution varies with the environmental conditions, is reflected by how warming ocean temperatures can increase the bioavailability of mercury, leading to negative impacts on the health and survival of marine organisms (Bates et al., 2021), while the toxicity of metals like copper and lead changes as a function of the pH, potentially increasing the cumulative risk of ocean acidification for some organisms (Wang et al., 2016). Another example is the role of ocean acidification in modulating the bioavailability of trace metals (Stockdale et al., 2016), as well as causing direct decalcification (Charrieau et al., 2018). Certain pollutants inhibit phytoplankton growth, leading to decreases in primary production and cascading effects through marine food webs (Hatje et al., 2022), with repercussions for fisheries (Lu et al., 2018). Pollution can also increase the susceptibility of organisms, populations, and habitats to disease (Cabral et al., 2019; Kibria et al., 2021). Variations in rainfall, extreme weather, and changes in land use driven by climate change, can increase runoff and nutrient fluxes into coastal areas, causing eutrophication and oxygen depletion (Lu et al., 2018).

3.1.1. Ocean circulation and litter pathways

Global ocean plastic waste enters the North Indian Ocean in significant quantities (Van der Mheen et al., 2020), but once adrift, the fate of buoyant plastic litter is still unclear (Connan et al., 2021). In the North Indian Ocean, the Bay of Bengal and the Arabian Sea are landlocked by the Asian continent, preventing the occurrence of subtropical gyres. There is limited evidence of the occurrence of garbage patches in the Indian Ocean basin, as they exist, for example, in the Pacific (Connan et al., 2021). In the North Indian Ocean, currents and winds transfer floating debris back and forth between the Arabian Sea and the Bay of Bengal as their direction reverses with the seasonal monsoons, and models suggest that most drifting litter is eventually deposited on rim countries' coastlines and beaches (Van der Mheen et al., 2020). During the southwest monsoon (August), litter is transported eastwards from the Arabian Gulf, passing along the Indian subcontinent and into the Bay of Bengal, and the route is reversed during the northeast monsoon (February) (Van der Mheen et al., 2020). This seasonal reversal, added to the continuous and increasing litter inputs from land, may explain why microplastic pollution in the Bay of Bengal is amongst the highest across the world's oceans, with an average of 0.34 ± 0.80 items per m^2 (Li et al., 2021). Coastlines bordering the Bay of Bengal are especially plagued by litter between September and November, as the influx of litter ashore peaks following the southwest monsoon (Ranjani et al., 2022). The longshore currents of the eastern coast strengthen during the southwest monsoon and flow from west to east, while currents are relatively weak during the northeast monsoon and spring inter-monsoon (March–May) (Sivadas et al., 2021). As a result of the weak currents and subsurface barrier effect of the Palk Strait, plastics are more likely to become trapped in this region, and their fate will depend upon their buoyancy, the coastal and tidal currents, and the type of coastal habitat they encounter (Sivadas et al., 2021). Heavier or less buoyant litter is likely to sink and accumulate on the seafloor, and potential accumulation zones include the Gulf of Kachchh (also known as the Gulf of Kutch, Cutch, or Kachh), the Gulf of Khambhat and the Lakshadweep Islands in the Arabian Sea, and the Gulf of Mannar and the Andaman and Nicobar Islands in the Bay of Bengal (Sivadas et al., 2021). Buoyant debris that escapes into the South Indian Ocean is likely to be transported by the winter monsoon current along the south of the Bay of Bengal, assisted by southeast trade winds, until it reaches as far as the Nicobar Islands, the Seychelles, and the coastlines and islands of East Africa (Kiruba-Sankar et al., 2023; Vogt-Vincent et al., 2023; Van der Mheen et al., 2020; Duhec et al., 2015).

Changes in large-scale oceanic and atmospheric patterns, particularly future changes to the El Niño-Southern Oscillation (ENSO), which drives El Niño and La Niña events, will influence current, wave, and wind regimes in the Indian Ocean basin over this century, but there is still considerable uncertainty around future simulations (Bindoff et al., 2019; IPCC, 2012). Significant long-term changes in the timing and duration of El Niño and La Niña phases, for instance, could alter the type and quantity of marine litter that enters the Indian Ocean, and its spatial distribution and fate once at sea (Bindoff et al., 2019).

3.1.2. Litter inputs through coastal wave action, inundation, and erosion

Positive sea-level trends have been confirmed for the North Indian Ocean based on tide gauge and satellite data (Chowdhury and Behera, 2015). Sea-level rise in the North Indian Ocean has been estimated at 1–2 mm per year, which is consistent with global estimates reported by the IPCC, albeit towards the lower end (Unnikrishnan and Shankar, 2007; Church et al., 2001). Wave height is also an important factor in sea-level rise. A detailed state-wise study indicates that significant wave height is rising for most of the Indian coastline (Chowdhury et al., 2020). Significant increases in extreme waves are projected for the wider Indian Ocean, versus decreases in significant wave height (IPCC, 2012). Another important parameter is wave period, which affects critical wave propagation processes such as shoaling, refraction, and diffraction, and therefore can modify sediment transport patterns or wave penetration into harbours (Chowdhury et al., 2020). Along the Indian coast, the wave period has increased by at least 20 %, suggesting a higher probability of swell waves and erosion, particularly under the effect of Southern Ocean swells (Chowdhury et al., 2020). The rate of sediment transport induced by longshore swell waves is an order of magnitude higher than by wind waves (see, for example, Chowdhury and Behera, 2017), and this is expected to be true for solid litter as well. Higher waves carry litter deposits further away from the shoreline (Fetisov and Chubarenko, 2021). Future climate change-related rising sea levels, increased rainfall, higher wind speeds, larger waves, and changes to oceanic currents are predicted to mobilise more debris from coastal regions into marine environments (Browne et al., 2015). There are indications that future wave action and coastal erosion are highly likely to be amplified in this region, which will increase the risk of pollution, for example, through further exposure of coastal landfills. Studies of European coastlines indicate direct links between coastal erosion and increased marine litter inputs; for example, Andriolo and Gonçalves (2022) reported how dunes act as litter reservoirs, both on urbanized as well as natural beach and dune systems, which are exhumed by storms

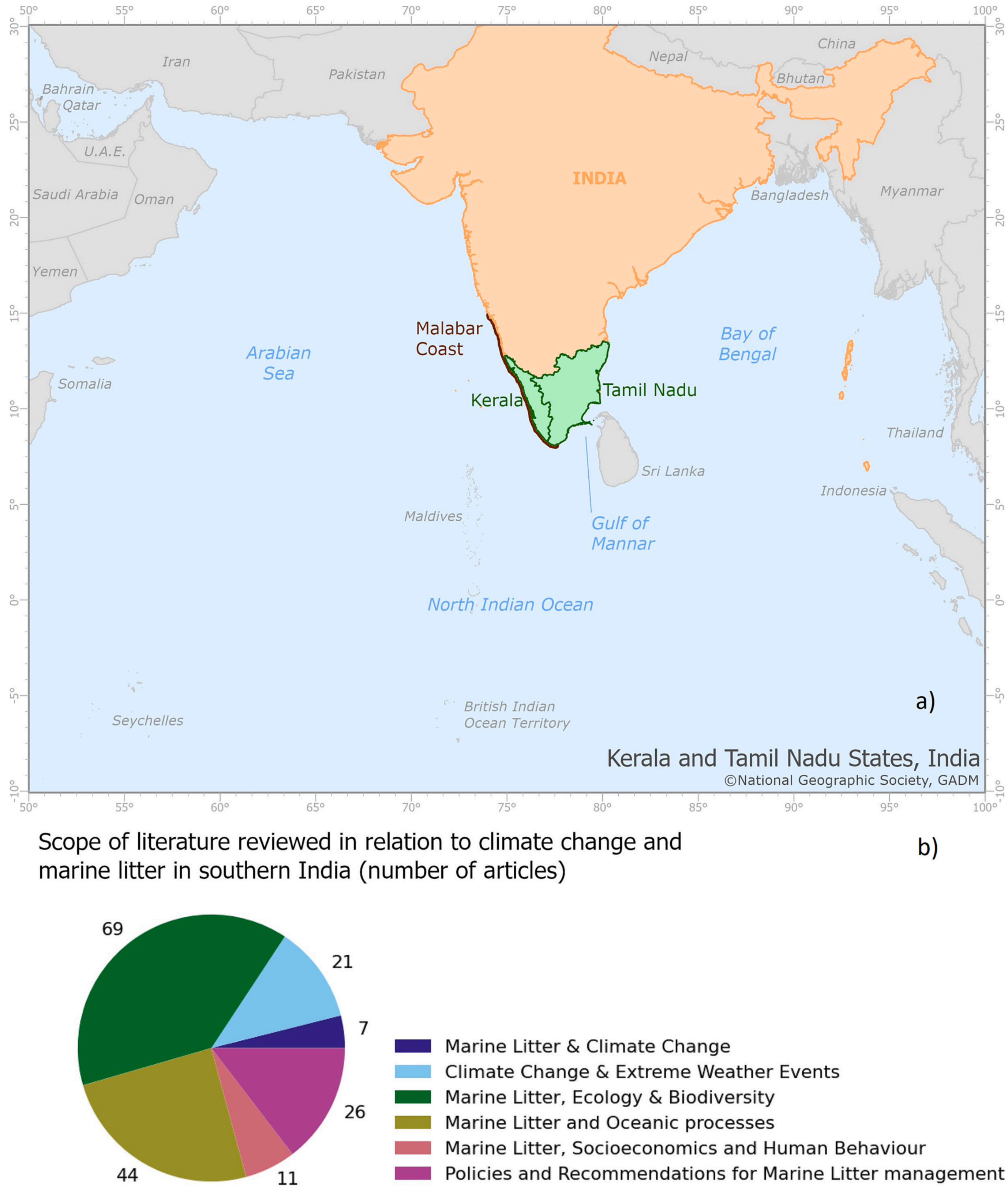

Fig. 1. Map of the Indian subcontinent (top panel, a) showing the southern coastal states of Kerala and Tamil Nadu, as well as the Gulf of Mannar and Malabar Coast, and the surrounding North Indian Ocean region. The chart (lower panel, b) represents the results of the bibliographic searches, and the number of articles found for each of the following broad topics: marine litter and climate change in general; climate change and extreme weather events; marine litter and impacts on ecology and biodiversity; marine litter in relation to oceanic processes; marine litter and links to socio-economic aspects and human behaviour; policies and recommendations for the management of marine litter.

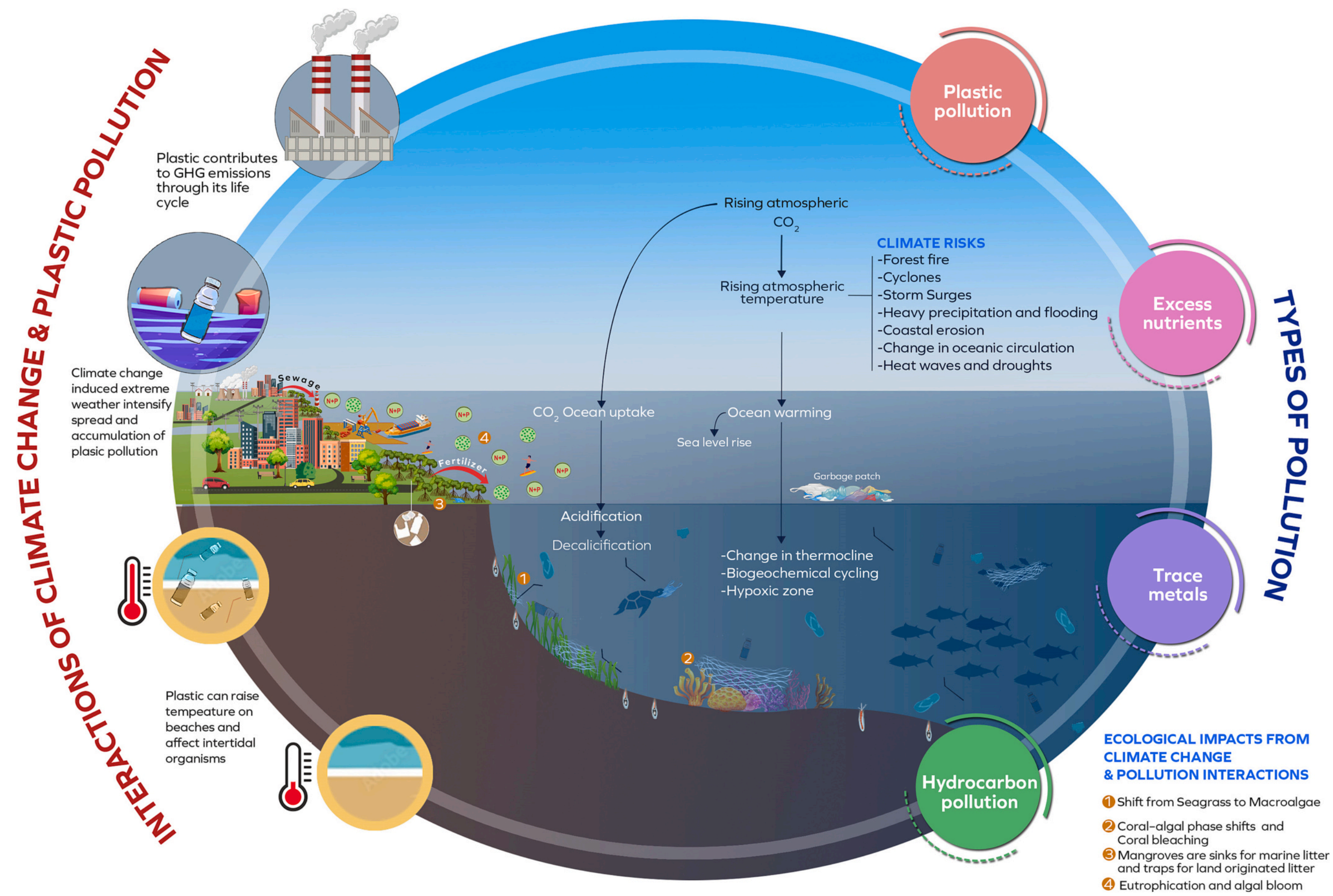

Fig. 2. Representation of typical interactions between climate change and marine pollution that can exacerbate adverse effects on coastal and marine ecosystems. The infographic depicts climate change forcings and risks, and the derived physical and chemical effects (central flow diagram), as well as different types of marine pollution (icons on the right). We also represent examples of interactions between climate change and plastic pollution (icons on the left), and the resulting ecological impacts (further explained in the legend, bottom right).
Image credited to ©NCSCM.

and erosional processes and introduced into the ocean. Other studies show that climate change-induced abrasion and mobilisation of large amounts of sedimentary deposits could be an important source of mercury into the marine environment (Bełdowska et al., 2016).

3.1.3. *Mobilisation of litter by extreme weather events*

A study of cyclonic activity over the North Indian Ocean found that, between 2001 and 2019, the frequency, duration, and intensity of tropical cyclones increased by 52 % over the Arabian Gulf, compared with an 8 % decrease over the Bay of Bengal (Deshpande et al., 2021). This intensification of cyclonic activity in the Arabian Gulf was most significant in May–June and October, correlating with changes in regional thermodynamics such as increases in sea surface temperature, heat potential, ocean to atmosphere heat flux, tropospheric humidity, and static energy (Deshpande et al., 2021). On the other hand, the decrease in cyclonic activity over the Bay of Bengal was linked to a drop in relative humidity (Deshpande et al., 2021). Cyclones are also more pronounced during La Niña regimes compared to El Niño regimes, with the number of extreme tropical cyclones over the Bay of Bengal increasing during the cold conditions imposed by La Niña (Mondal et al., 2022). Overall, however, long-term trends in cyclonic activity in this region are not yet fully clear, due to strong seasonal and inter-year variability combined with the influence of the ENSO forcing that significantly influences the frequency, position of genesis, and intensity of tropical cyclones during the primary cyclonic season in the Bay of Bengal (Mondal et al., 2022). In the Indian Ocean, storms ranging from low-pressure depressions to cyclones play a significant role in the mobilisation and accumulation of coastal debris (Gandhi et al., 2021; Lo et al., 2020). Cyclone-induced extreme weather such as flash floods can augment the transfer of plastic debris from land to the coast, while cyclonic overwash deposits larger-than-normal amounts of debris onto beaches (Sivadas et al., 2022; Gandhi et al., 2021; Veerasingam et al., 2016). However, this is modulated, not just through wind strength and direction, or storm wave and surge conditions, but also by the coastal topography, proximity to rivers and urban areas, and the role of local human activities during non-cyclonic conditions that could be an additional source of litter, such as fishing (Gandhi et al., 2021; Lo et al., 2020). To summarize, as cyclones and extreme winds and waves become more frequent and intense, debris deposits on beaches are anticipated to increase.

Increases in the magnitude of heavy rainfall events are projected globally as the atmospheric concentration of CO_2 continues to build up (IPCC, 2012; Turner and Slingo, 2009). Globally, heavy rainfall and extreme flooding events are likely to become more frequent with climate change (IPCC, 2012). Across Asia, the confidence in observed trends of heavy precipitation is low to medium for most regions, but at a subregional scale and particularly for India, statistically significant trends have been observed (IPCC, 2012; Krishnamurthy et al., 2009; Rajeevan et al., 2008), especially during the monsoon (Pattanaik and Rajeevan, 2010; Sen Roy, 2009). Extreme rain events during the Indian monsoon show a positive trend between 1901 and 2005, which appears to be stronger after 1950 (IPCC, 2012; Sen Roy, 2009; Rajeevan et al., 2008;

Kshirsagar et al., 2006). Increases in monsoon rainfall are also likely overall, although possibly more so in the northeast of the Bay of Bengal compared to the west coast of India (Katzenberger et al., 2021; IPCC, 2012). Intense rainfall events elevate the risk of flooding (Ali and Mishra, 2018). Floods may last from a few hours to days, depending on the terrain and drainage, but improper disposal and accumulation of waste in sewage systems causes blockages, resulting in longer-lasting floods and, potentially, greater socio-economic damage and health risks (Mujumdar et al., 2020). A study of mobilised plastic potential, combining global flood maps and data on mismanaged plastic waste, found that 10-year return-period flood events increase the plastic mobilisation potential tenfold compared with non-flood conditions (Roebroek et al., 2021). This global plastic mobilisation potential is elevated further in high flood-risk areas, which are almost exclusively located in coastal regions (Roebroek et al., 2021). India is amongst the 10 countries with the highest plastic mobilisation potential, with an estimated 0.12 million metric tonnes per year under non-flood conditions, which rises to 1.36 million metric tonnes per year under a 10-year return-period flood and therefore represents an increase factor of 11.45 (Roebroek et al., 2021).

3.2. Main review findings for Southern India

3.2.1. Description of the focus areas

We focussed this review on the coastal states of Tamil Nadu and Kerala in Southern India, and more specifically on the Gulf of Mannar and the Malabar Coast, because of the huge importance of their marine resources and ecological services. As shown in Fig. 1a, the Tamil Nadu state, along the Bay of Bengal, has a coastline that stretches for 1076 km (Karthik et al., 2018). There are several rivers, the largest being the Cauvery River, which forms the largest estuarine delta in Tamil Nadu, and the Vaigai, Tamiraparani, and Pennar Rivers, all of which empty into the Bay of Bengal (Karthik et al., 2022). These rivers are generally seasonal, so riverbeds have little flow and water is mostly stagnant, allowing litter to accumulate, except during the monsoon season, and their estuarine sections are mostly tidal (Karthik et al., 2022; Robin et al., 2021). Depending on the timing of the monsoons, the wet season occurs between October and December, and precipitation ranges from 630 to 1900 mm per year and falls mostly over the mountainous regions on the west of the state (Aiyappan, 2022). Tamil Nadu has 3 major seaports, 7 captive ports, and 16 smaller ports, fishing harbours, and coastal industries such as power plants, oil refineries, and fertilizer factories. The capital, Chennai, is a coastal megacity and a major financial and commercial hub (Robin et al., 2021; CMDA, 2008). The Adyar River that traverses Chennai is highly stressed by elevated inputs of untreated wastewater and sewage (Robin et al., 2021). The Gulf of Mannar off the coast of Tamil Nadu (Fig. 1a) is a biosphere reserve of global significance, designated in 2001 as part of the South and Central Asia Man and the Biosphere Network (UNESCO, 2019; ENVIS, 2015). It is endowed with extensive coral reefs, seagrass meadows, and mangroves and is considered one of the world's most biodiverse marine reserves (UNESCO, 2019; ENVIS, 2015). As well as hosting many charismatic marine species, the reserve is the last refuge for *Balanoglossus* sp., or acorn worm, a ‘living fossil’ that is the evolutionary link between vertebrates and invertebrates (Mondal and Lee, 2023; UNESCO, 2019). The Gulf of Mannar also supports 5500 km^2 of commercial fishing grounds, contributing to a quarter of the state's annual fish production and supporting the livelihood of thousands of fisherfolk scattered across >200 villages (Karthik et al., 2022; Raj et al., 2020). The reserve also has a prominent place in the cultural heritage and history of India and attracts more than one million tourists annually (Miththapala, 2012). The Gulf of Mannar Reserve is under pressure from overharvesting and land-based pollution (Keerthika et al., 2023, 2022). Pollution from point and non-point activities is causing eutrophication, dissolved oxygen depletion, and increased marine litter in Tamil Nadu's coastal environment (Ramesh et al., 2008). These pressures, together with a significant threat from climate change, threaten the degradation of important reef, seagrass, and mangrove habitats (Miththapala, 2012).

On the southwest, Kerala's coast stretches for 580 km along the Arabian Sea (DoF, 2021a; see also the map in Fig. 1a). The climate of Kerala is tropical monsoonal, with seasonally excessive rainfall ranging from 890 to 3940 mm annually (NABARD, 2020). Humidity is high, and temperature varies between 22 and 34 °C. It usually reaches its highest values during the summer months (March–May), leading to drought conditions, which are then followed by the southwest monsoon (June––October), the northeast monsoon (October–December), and a short winter (January–February) (DoECC, 2022). The Western Ghats mountain range traverses the state, but elsewhere it consists of extensive lowlands of <300 m elevation, and vast coastal plains (DoECC, 2022). Most of the Malabar Coast is formed of sandy dunes and ridges, barrier flats, alluvial plains, floodplains, river terraces, and marshes and lagoons, where much of the state's population and economic activity concentrates (ENVIS, 2022). Kerala has a population of about 33 million people and one of the highest population densities in India, at 860 persons per km^2 (DoECC, 2022). The predominant industries are fertilizer and chemicals manufacture, oil refineries, seafood, cashew, coir, minerals, and metals (Mugilarasan et al., 2023). The major port at Kochi (also known as Cochin) is a hub for shipping activity in the region (Mugilarasan et al., 2023). The state has abundant marine, brackish, and freshwater resources, and fisheries contribute substantially to the state's economy and directly support the livelihood of over 3 % of the population (DoF, 2023; NABARD, 2020). The continental shelf off the Malabar Coast has an area of about 39,000 km^2 and the exclusive economic zone extends for 218,536 km^2 and encompasses internationally renowned fishing grounds (DoF, 2021a; NABARD, 2020). There are over 200 coastal fishing villages and almost as many marine fish landing centres, with another 113 villages inland working on freshwater or brackish fisheries (DoF, 2021a, 2021b). Landings comprise over 300 species, and major commercial catches include penaeid prawn, lobster, seer fish, prawn, and ribbon fish, as well as mackerel and other pelagic species (Nair et al., 2015a; Harikumar and Rajendran, 2007; DoF, 2021a). Kerala's marine fishery production in the period 2020–21 was over 391,600 t, equivalent to about 77 billion rupees (DoF, 2021b). Kerala's coastal fishing communities have traditionally relied on marine ecosystems as their primary source of revenue, and the fisheries sector contributes around 1.6 % of the total gross added value of the state's economy (2020–21 data from DoF, 2021b). In addition to fishing, beach and backwater tourism also generate significant revenue for the state.

3.2.2. Interaction of climate change and marine pollution in the Gulf of Mannar, Southeast India

A coastal vulnerability study of the district of Thoothukudi in the Gulf of Mannar highlighted that sea-level rise is accelerating coastal erosion and loss of beach width and slope and increasing the risk of inundation from the sea (Parthasarathy and Natesan, 2015). Much of the coastline of Tamil Nadu is low-lying, consisting of sandy beaches and some stretches of muddy and rocky shoreline (Karthik et al., 2018). Beach erosion along the southeast coast is expected to continue at present high rates (Chowdhury et al., 2020), exacerbated by improper practices related to sand mining, urban development, and the industrialisation of the coastal zone (Parthasarathy and Natesan, 2015) all of which is aggravating the degradation of the coastal area. Across the Tamil Nadu state, weather-related disasters driven by climate change are escalating swiftly in terms of the affected area, frequency of events, and losses reported (UNISDR, 2009; IPCC, 2012).

The Tamil Nadu state generates about 13,500 t of solid waste per day, and of the collected waste, around 91 % is dumped in landfills, consisting mostly of plastics and electronic appliances, as well as municipal, biomedical and hazardous materials (CPCB, 2021; ENVIS, 2016). The state's capital, Chennai, alone generates approximately 4500 metric tonnes of solid waste per day, and litter often accumulates in yards and landfills in and around the megacity, from where it gets carried into waterways (Pradhan et al., 2018; ENVIS, 2016). Flooding and erosion during the seasonal monsoon, particularly during extreme rain or storm events, mobilise large quantities of solid litter and other contaminants (Sivadas et al., 2022), especially from landfill sites or areas affected by heavy littering. Previous assessments in the Gulf of Mannar have indicated levels of physicochemical parameters and microbial indicators that exceed permissible limits, suggesting pollution from unregulated urban and industrial discharges (Rajendran et al., 2018). In Chennai, Veerasingam et al. (2016) found that microplastic abundance tripled during post-flood periods compared to pre-flood periods, and included virgin (i.e., not yet bio-filmed) items, which suggests large quantities of plastics were mobilised and flushed out during the floods. This was corroborated by litter assessments on the nearby Marina Beach, the second-largest beach in the world, where the everyday abundance of plastic litter on the beach was significantly lower than post-flood litter (Kumar et al., 2016). Much of the litter found on the beaches around Chennai following the flood could be traced back to the nearby Cooum and Adayar Rivers (Pradhan et al., 2018), confirming that most of the litter entering the marine environment after flood events is from local land-based sources. Once in the marine environment, litter can be a vector for microbial dispersal, as observed following the 2015 Chennai floods, where a large amount of litter served as a substrate for microbial biofilms, including harmful faecal coliforms (Pradhan et al., 2018). The risk of severe flood and cyclone impacts on Chennai is high (Khanna, 2009). In November 2020, following the landfall of cyclone Nivar, a study of beach debris at Silver Beach in Cuddalore found that macroplastics were more abundant in pre-cyclonic sediments than in post-cyclonic sediments, while meso- and microplastics were more abundant in post-cyclonic sediments (Gandhi et al., 2021). The area receives significant quantities of debris from tourism and fishing, but most large-sized items discarded during these activities are washed away from the beach by wind and waves during cyclones (Gandhi et al., 2021). At popular coastal spots where visitors are numerous throughout the year, most of the litter is often found to be local, as opposed to washed up from the sea (Anand et al., 2018). Then, in November 2021, Chennai suffered destructive flooding following heavy rainfall of >1000 mm in one month, the second-most severe flood on record. Enormous amounts of litter were mobilised from urban and catchment areas, resulting in large accumulations of post-flood litter around river mouths and nearby public beaches (Fig. 3).

Assessments of beach litter between 2013 and 2014 described 31 of the state's beaches in the “clean” (1–10 g of litter per m^2) category, 11 as “fair” (10–20 g/m^2), and 3 as “moderate” (20–50 g/m^2) (Kaladharan et al., 2017). In another survey of 6 beaches, Kaviarasan et al. (2022) found average beach litter to be composed of 0.24 ± 0.14 items/m^2 of macro (2.5 cm to 1 m) litter, 8.2 ± 5.6 items/m^2 of *meso* (5 mm to 2.5 cm) litter, and 505 ± 121 of micro ($\leq$5 mm) litter particles, per kg of dry sediment. Overall, litter abundance was higher on beaches closer to urban areas compared with more remote beaches, and macro litter was also more abundant (average 0.28 ± 0.34 items/m^2) at the backshore of

Fig. 3. Litter loadings near the Cooum River mouth and the public beaches of Chennai in December 2021, following the flash floods of the previous month. All images credited to ©NCSCM.

the beach compared to the intertidal area (average 0.20 ± 0.13 items/m^2) (Kaviarasan et al., 2022). High abundances of microplastics were also found between June and September at the Krishna River, followed by the Penna River and off Chilika Lake, indicating the influence of runoff during the southwest monsoon (Sambandam et al., 2022). Offshore, microplastic pollution appears to be more severe and widespread across the coral islands within the Gulf of Mannar, and this has been traced back to highly populated areas on the mainland where waste management is inadequate (Patterson et al., 2022). At Nallathanni Island, a small, inhabited island in the Gulf of Mannar, beach debris comprises fishing lines, floats, and nets; textiles; plastic bags; water bottles; wrapping and packaging materials; cosmetic materials; and resin pellets, deposited along the high tide mark by high-energy waves and landward winds, although some lighter items were dispersed further into the island, presumably carried by wind (Krishnakumar et al., 2018). Proximity to the mainland determines the distribution of microplastics on these coral islands, and abundance is consistently higher in sediment samples compared to water samples, suggesting that the sediments act as a sink for microplastics (Patterson et al., 2022). In the wider Bay of Bengal, microplastic pollution has been reported as 5.3×10^4 particles per km^2 in coastal waters, and 209 ± 99 particles per kg of dry weight in shelf sediments (Sambandam et al., 2022). Polyethylene and polypropylene appear as the most common polymer types, associated with packaging and single-use plastics, and are more abundant in surface water than in sediments. Microplastics can adsorb chemical pollutants such as metals or pharmaceuticals, and transfer them along the food chain, which represents an additional threat to marine life and requires consideration when assessing the risk of microplastic pollution (Patterson et al., 2022; Godoy et al., 2019).

The Gulf of Mannar is one of India's four major coral reef areas, where coral occurs mainly around a chain of twenty-one uninhabited islands between Thoothukudi and Rameswaram (Raj et al., 2020). These reefs are highly stressed and disturbed by climate change impacts and local anthropogenic pressures (Painter et al., 2023; Edward et al., 2018), with a significantly faster decline in the last decade, linked to thermal stress (Krishnan et al., 2018), and compounded by hypoxia die-offs (Raj et al., 2020), and outbreaks of disease and invasive species (Raj et al., 2019; Edward et al., 2018; Raj et al., 2016). Between 2005 and 2017, severe bleaching events resulted in coral mortality, particularly amongst fast growing corals such as *Acropora* spp. and *Pocillopora* spp., and also macroalgae proliferation under the influence of terrestrial runoff, which hinders the settlement of new coral polyps and undermines reef recovery (Raj et al., 2021; Raj et al., 2020; Edward et al., 2018; Purvaja et al., 2018). Coral communities in the Gulf of Mannar are shifting as a result and assemblages of sensitive species (typically structurally complex corals) are replaced by more thermally-tolerant species (typically simpler, massive corals) (Raj et al., 2021). In the future under an RCP8.5 high emissions scenario, the risk of annual severe coral bleaching in the Gulf of Mannar is expected to increase, with an earlier onset for the easternmost reefs (20 years sooner) compared to westernmost islands (Raj et al., 2021). On the other hand, although records of coral mortality due to hypoxia are rare worldwide (Raj et al., 2020; Gopakumar et al., 2009), over the past few decades there have been an increasing number of reports of mass coral mortality following non-toxic green tides of *Noctiluca scintillans* in the Indian Ocean and specifically in the Gulf of Mannar (Gomes et al., 2018; Gomes et al., 2014; D'Silva et al., 2012). In 2019, a massive *N. scintillans* green tide caused oxygen levels to drop below 2 mg/l following bloom decay, and the temporary hypoxia resulted in >70 % coral mortality amongst *Acropora* spp., *Montipora* spp., and *Pocillopora* spp. corals, as well as die-offs of fish and benthic crustaceans, molluscs, and echinoderms (Raj et al., 2020). Hypoxia affects coral respiration and productivity (Nelson and Altieri, 2019), and fast-growing species such as *Acropora* and *Pocillopora* are more susceptible, due to their higher metabolic requirements (Blakeway, 2018; Montoya-Maya, 2015; Haas et al., 2014). Hypoxia is also a risk multiplier for corals as it increases susceptibility to bleaching, disease, and algal proliferation (Alderdice et al., 2020; Raj et al., 2020; Nelson and Altieri, 2019), and therefore it is an issue of concern. Recurrent, massive algal blooms have been linked to climate change (Griffith and Gobler, 2020), but red and green tides of *Noctiluca* can also be a manifestation of water pollution and eutrophication (Harrison et al., 2011). Pollution, and specifically marine litter, is another concern for the structurally complex *Acropora* spp. corals that form the Gulf of Mannar reefs, which are more prone to entangle debris (Ballesteros et al., 2018; Edward et al., 2018). The reefs on the islands near Tuticorin are particularly at risk due to high levels of litter from fishing, shipping, and waste disposal, all of which is causing direct fragmentation of coral structures and aggravating the risk of disease and susceptibility to bleaching and invasive species (Lamb et al., 2018; Edward et al., 2018; Glas et al., 2012). In addition, all reefs in southern India corals are at risk from cyclone damage, as demonstrated by cyclone Ockhi, one of the strongest cyclones recorded in the region that hit the Lakshadweep Islands off the Malabar Coast in 2017, causing extensive mortality and lithification including dislodgment of massive structures in the deeper reef sections (Painter et al., 2023; Riyas et al., 2020).

Healthy coastal mangrove stands are an effective natural barrier against cyclone impact (Das and Vincent, 2009; IPCC, 2012). The dense system of above-ground roots of mangroves that helps the trees survive in waterlogged and tidal conditions also creates habitat for many species and contributes to stabilising sediments and mitigating erosion by buffering against waves, wind, and excess water during surges, flooding, or storms, thus protecting coastal communities and infrastructure (IPCC, 2012). But this architectural complexity also facilitates the entanglement and accumulation of debris (Sivadas et al., 2021). Mangrove forests along the Indian coast are a documented plastic sink (Sivadas et al., 2021), which is another risk factor to their survival. While mangroves are relatively resilient to partial burial by waste, but excessive accumulation of plastic material can create anoxic conditions, and the affected trees may suffer suffocation and leaf loss (van Bijsterveldt et al., 2021). In addition, in Tamil Nadu, the extent of coastal mangroves is rapidly shrinking due to urban expansion and deforestation; it is estimated that almost 4 km^2 of mangrove cover were lost between the forestry assessments of 2017 and 2019 (ISFR, 2019).

The North Indian Ocean is one of the busiest maritime traffic routes in the world. The risk of maritime incidents and hazardous spills is particularly high for sensitive marine areas such as Palk Bay and the Gulf of Mannar Reserve. The sinking of the *X-Press Pearl* container ship in May 2021, northwest of Colombo port, Sri Lanka, was the worst maritime disaster in the history of the Indian Ocean (UNEP and OCHA, 2021). It was estimated that 1600 t of plastic pellets were spilled, and other environmental concerns included an oil slick leaking from the ship, the potential spill of dangerous goods, the loss of cargo and debris from the vessel, and a large smoke plume (UNEP and OCHA, 2021). The disaster coincided with the southwest monsoon during heavy rain, intense winds, and a rough swelled sea, making rescue and clean-up operations difficult (UNEP and OCHA, 2021). The reversing monsoonal winds and currents determine the dispersion of any spills in this region. Following the *X-Press Pearl* disaster, models predicted that the prevailing strong monsoonal wind-driven currents would transport large quantities of the plastic nurdles towards the south of the Sri Lankan coast, away from India (Karthik et al., 2022). Along the Tamil Nadu coastline, southwest monsoon currents can reach velocities of 0.5–1.2 m/s and are largely directed eastward along Sri Lanka, until currents weaken, turn around the south-eastern Sri Lankan coast, and change direction towards the north (Karthik et al., 2022). However, as the post-monsoon wind and currents reverse, any pellets still afloat would drift towards India and the coastline of Tamil Nadu (Karthik et al., 2022). In 2017, the collision of two cargo ships near Chennai resulted in the spill of about 196 t of residual fuel oil, which led to morphological changes and declines of benthic foraminifera (Balachandar et al., 2023) and the proliferation of hydrocarbon-degrading bacteria (Neethu et al., 2019).

3.2.3. Interaction of climate change and marine pollution in the Malabar Coast, Southwest India

Riverine influx plays an important role in the biogeochemistry and high productivity of the Malabar Coast waters, along with the permanent upwelling (Anandavelu et al., 2020; Jyothibabu et al., 2018) and the seasonal inshore mudbanks (Samiksha et al., 2017). Of the 44 rivers that traverse Kerala, 3 flow eastward, and the rest flow westward into the Arabian Sea. The large volume of runoff from the Valapattanam, Chaliyar, Periyar, Kayamkulam, Kallada, and Perumathura Rivers during the summer monsoon rains enriches the inshore waters and flushes out rich plankton communities from the estuaries, which largely control the biological production along the entire west coast (Jyothibabu et al., 2010). At Kerala and since the 1960s, average air and sea surface temperature have both risen by over 0.5 °C (Valappil et al., 2022; Mazdiyasni et al., 2017). Sea surface warming, as well as changes in rainfall levels and in the timing and intensity of the upwelling, are likely affecting fish populations, as evidenced by declining catches of some pelagic fish like Indian oil sardines (*Sardinella longiceps*) and Indian mackerel (*Rastrelliger kanagurta*), along with an increasing trend in cephalopod landings (CMFRI, 2020). It has been suggested that the distribution and abundance of sardines in Indian waters are shifting, particularly along the Malabar Coast, while mackerel, typically associated with surface and subsurface waters, is moving deeper in search of cooler water (Vivekanandan et al., 2008). Increasing temperatures, changes in wind and wave circulation, extreme events, sea-level rise, and declining levels of oxygen in seawater can all severely impact on fisheries severely, and in multiple ways (Lehodey et al., 2006). However, it is likely that these shifts in fisheries species is not a simple response to climate change but are also the effect of other local pressures such as overfishing, habitat destruction, eutrophication, and pollution, and even the spread of non-native species (DoECC, 2022). A raise in the frequency and intensity of massive phytoplankton blooms and red tides along Kerala and inshore waters of India's west coast has been attributed to increasing eutrophication and pollution from changes in land use (Karthik et al., 2020; Robin et al., 2013a), but climate change is also a contributing factor through rising temperatures as well as heavy rain runoff (Ulloa et al., 2017). These mass blooms often result in red tides that cause fish kills through oxygen depletion or toxicity (Robin et al., 2013a; Madhu et al., 2011), and are reported to affect commercial fish species such as oil sardines (Shaju et al., 2018). These colliding effects affect not just the sustainability of the fisheries but also the lives of the people who most directly depend on them. On the Malabar Coast in particular, marine fisheries are the mainstay of many economically disadvantaged communities (DoECC, 2022). Pollution issues and unhygienic conditions are prevalent around fishing harbours, landing centres, and fish markets, and are compounded by the coastline's exposure to climate change impacts (DoECC, 2022). Mudbanks are another important seasonal feature along the Malabar Coast, known locally as *chakara* (Samiksha et al., 2017). These mudbanks form during the southwest monsoon (June–July) in the shallow coastal areas adjacent to estuaries (Samiksha et al., 2017) and dissipate during the northeast monsoon. The banks are usually semi-circular in shape and made of fine muddy sediments that create an important seasonal feeding ground for demersal and pelagic fisheries (Jyothibabu et al., 2018; Shyam et al., 2015). Near Kochi, the inshore mudbanks that accrete every year from the discharge of about 20 billion m^3 of backwater and suspended sediments are crucial for the local fisheries (Madhupratap et al., 2001; Rao et al., 2016). But these mudbanks also act as sinks for marine litter (Mugilarasan et al., 2023), resulting in trophic transfer and bioaccumulation of microplastics in benthic feeders and, crucially, in many commercial fish (James et al., 2022). The appearance and duration of the mudbanks are determined by wave conditions during the southwest monsoons, and intra-annual fluctuations have been observed over the past forty years (Saprykina et al., 2021). The threshold averaged monthly significant wave height for their formation is 2 m, but wave height on the Malabar Coast is determined by wave climate variability in the Arabian Sea, which in turns correlates with fluctuation of large-scale oceanic and atmospheric systems such as the Indian Ocean Dipole and ENSO (Saprykina et al., 2021). These interactions between climate change and pollution pose a considerable risk to these communities and by extention to Kerala, given the reliance of the state's economy on local coastal fisheries.

Prolonged hot and dry weather is having a detrimental effect on coastal mangroves, undermining their resilience to flooding and erosion while increasing pressure on the other ecosystems supported by these habitats (van Hespen et al., 2023; Soares et al., 2021). For example, mangroves are important for maintaining the health of nearshore coral reefs (Biju Kumar et al., 2017). Kerala receives about 70 % of its annual rainfall during the southwest monsoon (Nair et al., 2021). Analyses of historic rainfall over Kerala indicate cyclic trends in annual rainfall, but also a long-term trend of decreasing monsoon rainfall against increasing post-monsoon rainfall during the period 1871–2005 (Nair et al., 2014). The frequency of dry years has also increased since 1976 (Thomas and Prasannakumar, 2016). These changes in rainfall patterns, already under pressure from pollution and changes in land use, are accelerating the decline of coastal mangroves, resulting in instability in the sediments and the capacity of soils to hold onto water and organic matter, releasing further CO_2 into the atmosphere (Santos-Andrade et al., 2021). Indeed, mangroves play an important role in climate change mitigation through their ability to store carbon (Biju Kumar et al., 2017). Droughts and heat waves can also affect coastal water quality through the desiccation of vegetated coastal habitats (Lovelock and Reef, 2020; Choudhury et al., 2021). Heavy precipitation over deforested and desiccated wetlands that have lost their water-holding capacity can lead to widespread uncontrolled flooding and excess surface water runoff, carrying excess debris directly onto coastal regions. According to the IPCC (2022), sea-level rise in this region is anticipated to reach 0.3–0.5 m or higher by 2100, further increasing the risk of inundation for much of Kerala's low-lying coastline and the backwater plains beyond (DoECC, 2022). Sea-level rise and changes in rainfall resulting in varying inputs of freshwater and sediment loading from rivers and lakes are also of concern to coastal mangrove forests (Sreelekshmi et al., 2021). To keep pace with rising sea levels, mangrove forests need to either accrete enough fresh sediment loading from land runoff sources or be allowed to retreat landwards (Biju Kumar et al., 2017; Kintisch, 2013). Climate change will likely exacerbate the decline of mangroves, already under pressure from coastal squeeze, pollution, and deforestation (Sreelekshmi et al., 2021). In Kerala, there are concerns that rapid population growth is driving unregulated sand mining, land reclamation, and the construction of hard coastal defences, and resulting in the accelerating loss of mangroves and other coastal wetlands (Biju Kumar et al., 2017). The loss of coastal mangroves will further increase the risk of coastal erosion and inundation, increasing the risk to infrastructure assets and to vulnerable fishing communities (Biju Kumar et al., 2017). Degradation and loss of coastal mangroves will also have direct adverse cascading effects on fisheries stocks, as many invertebrates and fish species depend on mangrove habitats for their early life stages (Friess et al., 2016).

Droughts and heat waves can also have negative consequences for aquaculture production (Froehlich et al., 2022; Soares et al., 2021), and pose an inherent human health risk as those conditions encourage the prevalence of pathogens and foodborne diseases (Jennings et al., 2016; Morley and Lewis, 2014). Disease outbreaks are not confined to seafood production but also pose a serious risk to bathers using contaminated waters (Baker-Austin et al., 2017; Young et al., 2015). Extreme droughts and heat waves can also amplify the negative impact of extreme rainfall when it arrives, due to the sudden flushing of accumulated pollutants, solid litter, sediments, and pathogens, into watercourses (Mishra et al., 2021; Corbari et al., 2016; De Carlo et al., 2007; Bay et al., 2003). During the 2018 and 2019 floods in Kerala, particularly at Thottappally in the Alapuzha district, heavy rain accumulated in waterways clogged with litter, which resulted in extensive flooding into neighbouring areas (Robin et al., 2020). Incidentally, as heat waves become more pervasive, they may encourage higher demand for bottled water, potentially resulting in additional littering (Zapata, 2021).

In India, beach uses involving tourism and traditional activities can be sources of marine litter (Kaladharan et al., 2017). Most beaches in Kerala serve as landing and fishing centres, with varying degrees of activity depending on the season and the dominant vessel operation, from traditional, non-motorised single-day vessels to larger, multi-day powered fishing vessels, which then dictates the craft and gear (Daniel et al., 2020b). Generally, fishing-related debris is almost 4 times higher at the height of the pre-monsoon fishing season, compared to the low fishing season (Daniel et al., 2020b), while larger and heavier debris items are deposited as wrack on the shoreline by the higher-energy waves typical of the post-monsoon (Jayasiri et al., 2013; Daniel et al., 2020b). The accumulation of plastics on beaches can alter sediments properties, raising the internal temperature by 2.45 °C by day and retaining more heat at night, as plastics act as an insulating agent (Lavers et al., 2021). This can induce changes in the abundance and diversity of meiofauna such as crabs, and it has also been highlighted as a concern at turtle rookeries, as it can increase the risk of breeding failure and hatchling feminisation (Lavers et al., 2021). Other potential indirect effects include increased exposure to chemicals, microbes, and invasive species (Audrézet et al., 2021; Lavers et al., 2021).

The extent of microplastic pollution in the marine environment has not yet been fully quantified (Robin et al., 2020). Data from the North-East Atlantic supports that plastic items in the marine environment are identified as either oceanic transboundary litter, effluent waste, industrial waste, or vessel waste, and that microplastics near coasts and estuaries likely originate locally from the disintegration, abrasion, or weathering of larger items (Maes et al., 2017). In Southern India, the high abundance of microplastics is attributed to flood plumes transported by the dominant longshore southward current during the monsoon months (Robin et al., 2020; Faure et al., 2015; Nair et al., 2015b). A study of microplastics in Kerala indicated average values of 1.3 particles per m^3 in coastal waters and 41 particles per m^2 in beach sediments, with the abundance of microplastic in sediments increasing towards the south (Mugilarasan et al., 2023, 2021; Robin et al., 2020; Kaladharan et al., 2017). The values of microplastics in coastal water samples are similar to those reported from the Baltic Sea (Gewert et al., 2017), but higher than records from the Bohai Sea, China (Zhang et al., 2017). Similar values of 47 particles/m^2 have been reported for Tamil Nadu beaches (Karthik et al., 2018), which are in the same range as other values reported for the Gulf of Mexico (Wessel et al., 2016), but higher than Malta, the Central Mediterranean (Turner and Holmes, 2015), and the coast of Portugal (Martins and Sobral, 2011). Along the Malabar Coast, the abundance of microplastics correlated spatially with river runoff levels and proximity to urban areas (Robin et al., 2020). State figures estimate that over 3500 t of solid waste are produced daily, of which <1000 t per day are collected (CPCB, 2021). As most industry is located near the coastline and on riverbanks, backwaters and rivers act as conduits for industrial waste and sewage treatment effluents. Eventually, most of the waste reaches the coast, in addition to an estimated 300 million litres per day of untreated rural and municipal wastewater (Robin et al., 2020; Kaithery and Karunakaran, 2019). Out of the fragments of solid litter, fibres and lines are mostly derived from vessels and fishing (Andrady, 2011), although they also indicate possible sewage sources (Browne et al., 2011), particularly near shore (Cozar et al., 2014), while foam and film originate from packaging materials (Robin et al., 2020). Microplastics in beach sediments and coastal waters are likely washed ashore by surface residual currents and winds, because of their lower particle density (Robin et al., 2020; Isobe et al., 2014).

Fish interact with and ingest microplastics due to their close resemblance to natural prey (Jovanovic, 2017). Over 21 % of the fish sampled from major landing centres in Kerala were shown to contain microplastics in their digestive tracts, with the highest occurrence of microplastic found on bottom-dwelling species that feed primarily on benthic organisms, which is attributed to the continuous supply of land-based plastic materials from rivers and backwaters to coastal waters, predominantly linked to fishing-derived debris (Robin et al., 2020). These values of microplastics in fish guts are higher than other reports from Southeast India (Karthik et al., 2018) and northeast Brazil (Possatto et al., 2011), although lower than values from the English Channel (Lusher et al., 2013). Kerala is India's second-largest marine fish-producing state, and the beaches both generate and receive high amounts of fishing-derived debris (Robin et al., 2020). The coastal areas surrounding the industrial belt at Kochi also receive heavy metals from untreated effluent discharges, and the presence of Cd, Cr, Hg, Fe, Sb, Ti, Zn, and Pb has been confirmed associated with polymer particles, highlighting the additional risk of chemical contamination and trophic transfer associated to microplastics (Robin et al., 2020). Analyses of samples of Indian white shrimp, *Fenneropenaeus indicus*, from Kochi have demonstrated content of microplastic fibres (83 %) that increased during and following the monsoon (Daniel et al., 2020a). Kochi is a densely populated city, an important touristic destination, and includes one of the five major fishing harbours in India as well as a major port, and an international container terminal on the bank of the estuary (Daniel et al., 2020a). The coastal area is highly susceptible to pollution from the large river plumes following heavy monsoon rains, compounded with inappropriate waste disposal systems and intense fishing (Naidu et al., 2018; Daniel et al., 2020a). The Kochi estuary discharges a large quantity of debris during the summer monsoon, including plastic particles (Seena et al., 2019). The high input of microplastics into the coastal waters makes them bioavailable to benthic organisms, including shrimp (Daniel et al., 2020a). *F. indicus* is a major commercial fishery associated with inshore muddy substrates (Daniel et al., 2020a). Seasonal differences in the microplastic concentration found in *shrimp* have been linked to physiological life-cycle changes such as spawning (Baechler et al., 2020; Devriese et al., 2015). Exposure to weathered polyethylene particles on another species commonly farmed in India, the whiteleg shrimp, *Penaeus vannamei*, has been shown to inhibit growth (Hariharan et al., 2022). Ingestion of polyethylene particles affected the oxidative and antioxidant systems, although no effects on survival have yet been confirmed (Hariharan et al., 2022). A similar study on edible green mussels, *Perna viridis*, showed significant accumulation in intestine tissue, suggesting that chronic exposure to weathered polyethylene particles can have damaging effects through oxidative injury and reduced filtering activity, ultimately leading to starvation (Hariharan et al., 2021). Ultimately, the exposure of commercial marine fish and invertebrates to microplastic pollution represents a human health risk (Daniel et al., 2020a).

3.3. Summary of key issues

The main findings regarding the interactions between climate change and marine pollution in the Gulf of Mannar are summarised in Table 1.

The main interactions between climate change and marine pollution on the Malabar Coast are summarised in Table 2.

4. Discussion

The synergistic impacts of climate change and marine litter are an increasing threat to the marine environment and the many goods and services on which societies and economies depend (Ford et al., 2022; Lincoln et al., 2022). These two global emergencies are ubiquitous, but their combined effects depend on characteristics of the physical environment, types of habitats and biological communities, and pressures from other human activities (Lincoln et al., 2022). Despite their significance and their pervasive effects, the linkages between climate change and marine litter remain understudied, and it is crucial that we improve our understanding in order to manage their combined impacts. The urgency of this issue is not unique to extensive and populated countries such as India, but it would also be vitally important to other regions, such as small oceanic islands for instance, where managing the

Table 1
Summary of fundamental climate change and marine litter issues in the Gulf of Mannar, Tamil Nadu.

Key issues	Description
Extreme sea levels, coastal erosion, and inundation	Ongoing coastal erosion is increasing the risk of coastal inundation from future sea-level rise. Coastal habitats are also subject to degradation from mining, deforestation, and the disposal of waste and untreated effluents.
Marine litter and extreme weather	Plastic pollution is severe and widespread across the coral islands in the Gulf of Mannar. Several hundred tonnes of waste generated daily are either uncollected or inappropriately disposed of. Rainfall and flooding flush large amounts of litter and other contaminants onto coastal areas, particularly following cyclones, although at tourist beaches most of the litter is local, deposited by visitors and other users.
Coral reefs	Coral reefs are significantly disturbed by climate change impacts and other local anthropogenic pressures, manifested as severe bleaching, coral disease, predation, and macroalgae growth. Depending on the emissions scenario, severe coral bleaching events will likely recur every year, changing reef composition and structure. The reefs are also exposed to mortality from hypoxia caused by algal blooms, cyclone damage, and high quantities of litter from fishing, waste disposal, and shipping, particularly around the islands.
Coastal mangroves	The mangroves in Tamil Nadu are in decline, exposing the coastline to extreme weather impacts. Mangroves accumulate debris, which in large quantities can cause suffocation and leaf loss.
Maritime spill risk	Shipping activity in the North Indian Ocean represents a risk of hazardous spills. Weather and sea conditions can make rescue and clean-up operations difficult during the monsoon season. The seasonal wind and current patterns would disperse the spill either towards the coast or away, towards Sri Lanka and into the Bay of Bengal.

Table 2
Summary of fundamental climate change and marine litter issues on the Malabar Coast, Kerala.

Key issues	Description
Fishing	Observed shifts in fish distribution are linked to changes in sea temperature, upwelling, and rainfall. Catches of some traditional commercial species are declining, although these changes are also likely linked to overfishing, habitat destruction, pollution, and the spread of invasive species. These issues put the sustainability of fisheries at risk, which are the mainstay for millions of people, particularly in exposed and disadvantaged coastal areas where poor conditions are prevalent. Fishing beaches are also a significant source of debris, depending on the fishing season and the predominant vessel type, craft, and gear.
River plumes and mudbanks	The productivity of the Malabar Coast depends on nutrient enrichment through monsoon runoff and upwelling. Mudbanks are also a major seasonal biologically productive feature that forms during the southwest monsoon in shallow areas, which are crucial for maintaining local fisheries, but also act as sinks for microplastics. Mudbank fluctuations have been linked to wave variability in the Arabian Sea.
Rainfall, droughts, and heat waves	The timing and rainfall levels of monsoons are changing with earlier onset and declining precipitation, while post-monsoon rainfall is increasing. Overall, dry years are becoming more common. Droughts and heat waves can accelerate deforestation and desiccation of wetlands and aggravate coastal water quality. They also increase the risk of pathogens and disease. Extreme droughts can also amplify the damaging impacts of heavy rainfall events when they arrive, leading to debris flows and flash floods. Incidentally, they also increase the consumption of bottled water and contribute to additional plastic littering.
Coastal mangroves	Sea-level rise, and varying rainfall and sediment loading driven by climate change are accelerating the decline of mangroves, already at risk from destruction and coastal squeeze, resulting in increased coastal erosion and inundation. In addition, the loss of mangroves results in additional negative effects on fisheries, and it leads to carbon dioxide emissions due to disturbance of the sediment layer and the loss of blue carbon storage capacity, an important climate change mitigation service.
Microplastic pollution	Microplastic pollution correlates spatially with major urban areas and with runoff levels from rivers. Sources of plastic pollution include untreated effluents, food packaging, tourism, shipping, and fishing activities. Microplastics have been found in fish and shrimp gut contents at landing centres in Kerala, along with traces of heavy metals associated with the plastic fragments. Plastic accumulation in sediments has a variety of negative effects on marine fauna and provides incidental habitat for invasive species.

combined risk of climate change and transboundary oceanic litter would be key to enabling long-lasting protection of highly sensitive and rare species and habitats (Kiruba-Sankar et al., 2023; Lincoln et al., 2022).

The coastal zone of the Indian subcontinent is experiencing severe impacts of climate change, which are projected to worsen and accelerate into the future, and at the same time, the country is gripped by a litter crisis that is overwhelming authorities and communities and hindering the country's sustainable development. We aimed to assess such linkages in Southern India by reviewing the evidence of the combined impacts of climate change and marine pollution in the Gulf of Mannar Reserve and the Malabar Coast.

Our findings highlight how climate change and marine pollution act as threat multipliers, for example through the interaction of litter and extreme weather, where land-based litter accumulates in waterways and is mobilised by heavy rain and flushed out into coastal areas together with other pollutants and runoff. In India, poor drainage systems often become blocked during heavy rainfall events due to the accumulation of litter and debris (IPCC, 2012; Ranger et al., 2011), and this can result in debris flows and worsen flood-associated damage (Honingh et al., 2020; Kundzewicz et al., 2014). Plastic materials gathered by debris flows lead to larger blockages in watersheds, further raising backwater flood levels and exacerbating the environmental and public health risks (Honingh et al., 2020; Kundzewicz et al., 2014). In Kerala and Tamil Nadu, coastal locations attract millions of visitors every year, and this mass tourism contributes to large-scale littering, as well as forest fires and soil erosion (Gandhi et al., 2021; Robin et al., 2020). Studies of extreme weather such as cyclones and cyclone-induced flash floods in these states suggest that most of the recognisable coastal debris is from local inputs or is mobilised through waterways from further inland, as opposed to long-distance transboundary litter (Gandhi et al., 2021; Veerasingam et al., 2016). Even cyclonic overwash deposits on beaches have been traced back to nearby rivers and urban areas and to local activities (Gandhi et al., 2021; Lo et al., 2020), which confirms that the majority of the coastal litter is of local origin and also offers an opportunity for implementing or improving control measures.

Once adrift in the ocean, litter becomes nearly impossible to eliminate or control. Plastics can persist at sea for hundreds of years (Bratovcic, 2021) and, depending on buoyancy, their transport is regulated by tides, currents, waves, and wind (UNEP, 2021). In coastal areas, tides also interact with shoreline topography to move litter onshore and offshore, as debris floats, sinks, or breaks up depending on density, size, and shape, as well as chemical composition (UNEP, 2021). Abrasion and fragmentation into smaller particles mostly occurs once debris is deposited onshore, and the smaller the particle size, the more likely the transfer across trophic levels unless they become trapped within marine sediments long-term (UNEP, 2021). Either pathway represents a range of potential negative impacts on marine organisms, ecosystems, and ecosystem services (Ajith et al., 2020), and even poses a risk to human health (Bhattacharya and Khare, 2022; Campanale et al., 2020; Robin et al., 2020).

4.1. Integrated Coastal Zone Management

It is widely recognised across the world's countries that climate change and marine pollution are serious threats to environment and people, and India is no exception. Relevant policies and plans are already in place, at the national and sub-national levels. At a national level, a Coastal Regulation Zone notification was issued in 1991 by the Ministry of Environment and Forests of the Government of India, to protect the livelihood of coastal communities, and conserve the coastal areas from hazards, including sea-level rise, and to restrict the expansion of industrial areas and the disposal of hazardous waste in the coastal zone (Parthasarathy and Natesan, 2015). But this notification is not fully operational, and coastal areas across India remain under severe stress from illegal mining, waste disposal, and the discharge of untreated effluents (Parthasarathy and Natesan, 2015). In Kerala, a State Action Plan on Climate Change (SAPCC) is built into policy to integrate programs at both state and national levels, such as the National Action Plan on Climate Change of India. Amongst other key adaptation and mitigation actions directly related to energy use, disaster response, etc., the SAPCC targets other compounding pressures, for example, through better waste management, pollution abatement, and enhancement and restoration of vegetated environments. Litter management practices include reduction at the source, mitigation, beach management, and behavioural change through education (Mugilarasan et al., 2021). In Tamil Nadu, a Coastal Zone Management Plan was developed in consultation with relevant authorities, stakeholders, local communities, and non-government organizations and entrusted to the National Centre for Sustainable Coastal Management (NCSCM) in Chennai in 2011 (DoE, 2023b). In 2014, the Tamil Nadu Climate Change Cell was also established, to focus on climate change-related initiatives and activities, build capacity, create awareness, and to collate and disseminate climate change information to enable effective governance and services. A National Adaptation Fund for Climate Change also manages and rehabilitates coastal habitats and biodiversity (DoE, 2023a). However, there is still a need to improve the enforcement of urban development regulations, waste management, forestry management, and extracting industries such as sand mining (DoECC, 2022), particularly where activities occur across the coastal boundary and involve connected catchment areas. For example, along the Malabar Coast, mangrove deforestation is exposing coastal villages to a higher risk of impact from extreme weather and is contributing to the depletion of Kerala's fisheries, which compounds with unsustainable inshore fishing practices that continue unchecked due to a lack of enforcement (DoE, 2009), while mass reclamation of land for agriculture and urbanization is also resulting in a widespread loss of backwaters and floodplains in the state (Robin et al., 2013b; DoE, 2009; Balachandran et al., 2008), worsening the effects of soil erosion and flooding.

When fully implemented, Integrated Coastal Zone Management (ICZM) approaches provide a decision-making framework that can be tailored to the unique characteristics and needs of a particular coastal environment. An ICZM pulls together all the complex functions and dynamic interactions that characterise the coastal environment, as well as the services and resources provided, and involves the participation of key stakeholders. Some of the geospatial tools that can be used to support decision-making, management, and planning of coastal zones include risk maps, built using data layers based on, for example, sensitive habitats and marine protected areas; climate change projections; litter source points (e.g., coastal landfill sites and open waste dumps); high flood-and erosion-risk areas; touristic spots; beaches; ports and harbours; and, fishing grounds. There are litter pollution control options that can be adapted for coastal communities, which typically include a suite of measures such as: bans of single-use plastic items and promotion of sustainable alternatives; circular economy approaches; improvements to waste management practices, including recycling drop-off locations, deposit-refund schemes, and processing of recyclable materials; active recovery of plastic materials from waterways; reviews of policies and regulations; and public awareness and engagement. These measures can effectively reduce marine litter inputs at the source, improve marine ecosystems' health, and create economic opportunities for coastal communities. For example, the Tamil Nadu government has installed debris barrier devices (also known as debris "booms") in urban rivers such as the Cooum and Adyar. Surf rakes and similar beach cleaning devices are also used to collect litter from Marina Beach. Similarly, the Kerala government initiated "*Suchithwa Sagaram*", a pilot effort to eliminate marine litter that encourages fishermen to return fishing litter, which can be upcycled and transformed into higher-value, usable items.

4.2. Other management approaches

In addition to ICZM, there are other recommended approaches to tackle the cumulative impacts of climate change and marine litter (or other local pressures) in large-scale coastal and marine areas.

Marine strategy directives are one example. A marine strategy directive, typically adopted by countries or administrations that share the same marine region, such as the European Union Marine Strategy Framework Directive, operates by mandate, by requiring the signatory member states to achieve a set environmental status in a cooperative manner and by using sets of agreed descriptors and indicators (MSFD, 2008). A marine strategy aims to tackle the intertwining pressures and impacts on the marine environment derived from human activities taking place at sea and on land, including those from climate change. Underpinning a marine strategy, climate resilience frameworks can be used to tackle specific climate change impacts on society, the economy, and the environment at a national level, by developing and implementing targeted measures to minimize the adverse effects of climate change "on the ground", as well as taking advantage of opportunities for adaptation and mitigation.

The IPCC defines risk as the potential for future negative impacts induced by the interaction of social and ecological systems, and the vulnerability to physical hazards and exposure variables (Cardona et al., 2012). Measures to mitigate or avoid any of the factors of risk – hazard, exposure, and vulnerability – may help to control these risks and build ecosystem resilience (Cardona et al., 2012). The control and mitigation of other synergistic stressors, such as pollution, are key components of a climate resilience framework (Fig. 4). Thus, climate resilience frameworks can be used to support communities and governments to better adapt and respond to the impacts of climate change and other co-stressors, while reducing vulnerability, and building resilience. Coordination and cooperation between the departments, sectors, and states that share a marine space are vital to ensuring sustainable management of resources and effective management of risks and impacts. In the case of Kerala and Tamil Nadu states, and indeed India, this could be achieved through an overarching marine strategy that facilitates the integration of policies at a high level and defines appropriate descriptors and indicators that can then be applied to, for example, assessments, monitoring, and interventions as part of a climate resilience framework.

A climate resilience framework typically includes the following elements:

- *Risk and vulnerability assessments*: This involves identifying climate change risks, as well as risks from other co-stressors such as pollution, and scoring and prioritising them by quantifying the magnitude and the urgency of their potential impacts on sectors, systems, and populations. It can also involve quantifying the overall confidence in those assessments depending on available evidence and expert agreement.
- *Adaptation and mitigation strategies*: This involves developing strategies and measures to minimize the impacts of climate change and other synergistic pressures, taking advantage of opportunities for adaptation and mitigation. Examples of adaptation strategies can include: improving building codes; sustainable management of marine fisheries; catchment area management; and enhancement of natural coastal buffer and protection habitats. Examples of

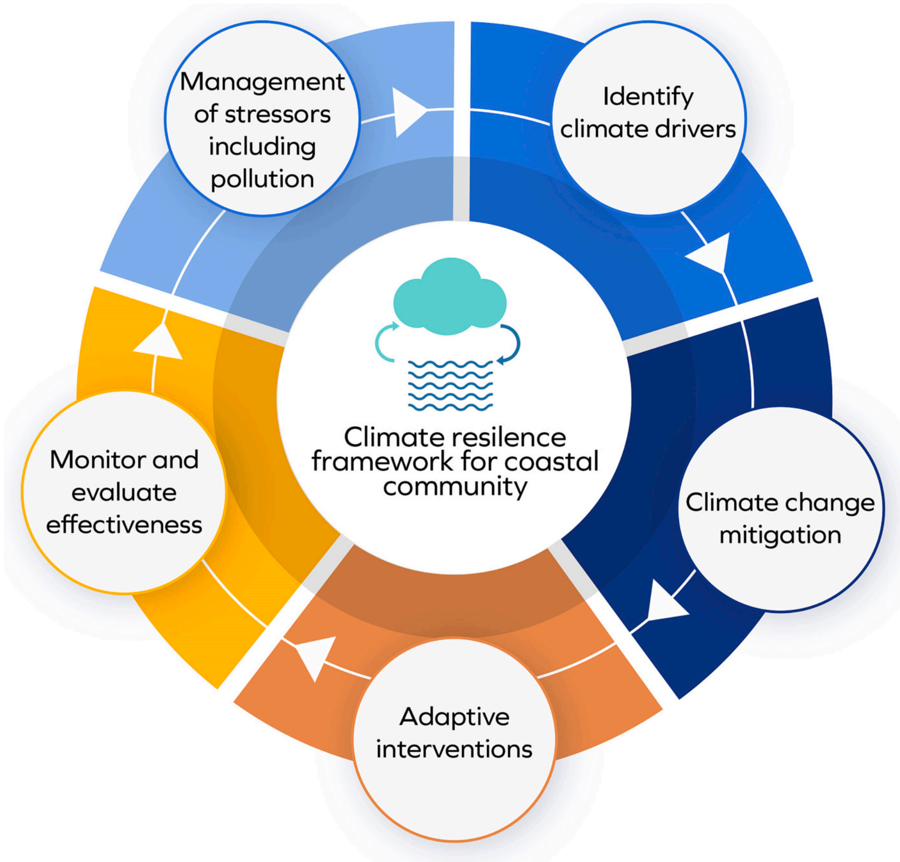

Fig. 4. Schematic representation of the key components of a climate resilience framework. Image credited to ©NCSCM.

mitigation strategies include de-carbonisation of sectors and activities, and protection of natural blue carbon habitats such as coastal mangrove forests.

- *Policy and institutional frameworks*: These involve policies and institutional schemes that support climate-smart regulations, incentives, and financial mechanisms. It may also involve building partnerships and collaborations between governments, non-governmental organizations, and other stakeholders.
- *Adaptive frameworks*: To be effective and resource-efficient, it is advisable that frameworks have built-in monitoring, self-evaluation, self-learnt, and evidence gathering processes.

Climate resilience frameworks require a collaborative and interdisciplinary approach with the active participation of governments and local authorities, industry and the private sector, communities, researchers, and individuals. Following prioritisation, actions and interventions can then be implemented for climate adaptation and mitigation, and to effectively regulate human activities, and to reduce stress on the environment such as marine pollution (Maynard et al., 2017). Examples of actions and interventions range from improvements of waste management processes and facilities, tax incentives, and habitat restoration, to outreach and education encouraging positive behavioural and lifestyle changes (Mugilarasan et al., 2023). In a related issue, during the COVID-19 pandemic in India, as in many other countries, there was a sharp increase in biomedical waste and personal protective equipment items made of polymeric material (Robin et al., 2021; Schnurr et al., 2018; Fadare and Okoffo, 2020). In Tamil Nadu's state capital, Chennai, the pandemic is estimated to have generated 47 t of biomedical waste daily (The Hindu, 2020). The surge in plastic waste was amongst the worst environmental consequences of the pandemic, and it has been recommended that India should develop plastic pollution management strategies that consider both climate change and pandemics (Sivadas et al., 2022). In addition, restrictions imposed on activities such as fishing and tourism in Tamil Nadu were perceived to have a “positive” environmental effect and emphasize the importance of applying ecosystem-based approaches to enhance and safeguard the sustainability of ecosystem services and the wellbeing of communities against risks such as pollution and natural disasters (Robin et al., 2021). Further research and monitoring can continue to address knowledge gaps, which can progress in parallel, while effective actions and interventions are implemented.

Despite the high profile of the environmental emergency of marine litter, including microplastics, a sharper focus in global frameworks such as the Sustainable Development Goals (SDGs) (Walker, 2021) is still required. The UN proposed 17 SDGs and 169 targets to be achieved by 2030, and amongst those, the issue of marine (micro)plastics has been recognised under Goal 14, which is to: *Conserve and sustainably use the oceans, seas and marine resources for sustainable development* (Walker, 2021). Specifically, target 14.1 says: *By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution*, which is to be measured by indicator 14.1.1: *Index of coastal eutrophication and floating plastic debris density* (Walker, 2021). Governments and corporations have widely adopted the SDGs to improve their sustainability, and the international community understands that reducing floating plastic debris is central to the sustainable use of the oceans (Walker, 2021). However, currently there is no internationally accepted index of floating plastics debris density, which presents challenges for governments and organizations, exacerbated by the pervasive nature of (micro)plastic pollution as long as it is not properly monitored (Walker, 2021).

The critical issues of climate change and marine litter highlighted by this review could be explored in more detail, for instance, using a regional participatory approach that involves risk scoring and ranking, such as that used for the United Kingdom Climate Change Risk Assessment and subsequent applications (CCRA, 2012; Garrett et al., 2015; Maltby et al., 2022). Such an approach accounts for receptors of climate change risk that may also be threatened by other anthropogenic pressures, including marine litter, and helps to identify areas of low confidence due to a lack of evidence or expert agreement, so that critical knowledge gaps can then be addressed through targeted monitoring and research (Maltby et al., 2022).

Globally, the principles and approaches for the conservation and sustainable use of marine biodiversity can be used to help improve our understanding as well as our ability to manage the cumulative impacts of marine litter and climate change, and to improve the resilience of marine ecosystems and services (Lincoln et al., 2022; Devlin et al., 2021; Yadav and Gjerde, 2020). However, it is up to countries to ultimately develop and implement plans and actions for climate change mitigation and adaptation and marine litter reduction, that can effectively tackle these two emergencies. But even at the national and sub-national levels, this requires integration between sectors and across regions to address infrastructural roadblocks, and other factors hindering action such as lack of awareness and low community participation (Lincoln et al., 2022; Lyons et al., 2020). The designation of marine protected areas, and the protection of vulnerable habitats and species, are effective measures that help build resilience against climate change and other anthropogenic pressures, as demonstrated by remote oceanic coral atolls in a relatively "pristine" condition, but a lack of data often hinders the assessment of that resilience (Lincoln et al., 2022; de Oliveira Soares, 2018; Aswani et al., 2015; Standish et al., 2014). One option is to combine monitoring, research, and marine planning activities as part of marine protection practices (Lincoln et al., 2022; de Oliveira Soares, 2018), which is precisely the latest advice from UNEP on the issue of marine litter: to apply ecosystem-based and holistic ocean governance approaches, measurable targets, and blue economy principles (UNEP, 2021). To be effective, ocean and coastal management measures must consider observed and future stressors from climate change and other human activities and apply marine spatial prioritisation approaches that acknowledge the ecological connectivity of terrestrial, coastal, and marine systems (Ford et al., 2022; Lincoln et al., 2022; de Oliveira Soares, 2018).

5. Conclusions

The interaction between climate change and plastics calls for stronger attention and action given the pervasive interaction of these two global emergencies, which has an uneven effect worldwide by causing a much greater impact on disadvantaged coastal communities. In the case of India, while the efforts made by coastal states are important and commendable, the combined climate change and marine litter crisis is overwhelming authorities and communities and hindering their potential for sustainable development. To our knowledge, 18 Indian states have banned single-use plastic, but enforcement remains a problem. This study adds clear evidence to the importance and urgency of the issue, specifically in Southern coastal states. The combined negative effects of litter and climate change on the marine environment and the communities and economies that depend on it can potentially obstruct efforts to achieve the SDGs. To tackle the problem, it is important to consider the regional and national context to guide targeted monitoring, and research, and practical policy and management actions. The Malabar Coast and the Gulf of Mannar are globally important marine areas; however, they are increasingly at risk from climate change, litter pollution, and other pressures derived from the rapid economic development that the country is experiencing. The scale of these issues requires coordinated and innovative approaches guided by evidence-based, measurable indicators and achievable outcomes.

Coastal management should prioritise protecting and restoring coastal habitats and promoting sustainable fishing and responsible tourism practices. These practices can be developed in collaboration with local communities and stakeholders to ensure they are culturally appropriate, socially acceptable, and economically viable, while balancing the needs, health, and wellbeing of the people and the environment. Local communities often hold valuable knowledge and experience regarding their local area and should be best placed to become custodians and researchers of their coasts and seas, with the appropriate training and resources, to detect and document evidence of changes in the ecosystem. In addition, when devising coastal management frameworks and plans, it is desirable to include representation of environmental groups, authorities, industries, and communities.

Finally, specifically for Kerala and Tamil Nadu but also generally for other Indian coastal states, we would recommend the undertaking of a critical review of current policies, frameworks, plans, and actions related to the coastal zone management, to understand and highlight existing gaps and barriers that prevent their effectiveness, as well as enablers and opportunities for improvement, at the district, state, or national levels as appropriate. Such a review would help identify areas where policies could benefit from a more robust evidence base, where whole-ecosystem approaches are feasible, where there are opportunities for enhancing integration and coordination across relevant departments and sectors, and where a stronger community and stakeholder involvement is required. The expected outcome of these interventions would be effective, long-term climate change adaptation and resilience while tackling marine litter with a higher probability of success.

CRediT authorship contribution statement

Susana Lincoln: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Piyali Chowdhury:** Writing – original draft, Writing – review & editing. **Paulette E. Posen:** Writing – review & editing. **R.S. Robin:** Methodology, Writing – original draft, Writing – review & editing. **Purvaja Ramachandran:** Writing – original draft, Writing – review & editing. **Nithin Ajith:** Writing – review & editing. **Olivia Harrod:** Writing – review & editing. **Danja Hoehn:** Writing – review & editing. **Richard Harrod:** Visualization. **Bryony L. Townhill:** Conceptualization.

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.

Data availability

No data was used for the research described in the article.

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References

Agarwal, S., Deb, T., 2023. Climate change induced migration with special emphasis on the coastal zones in India. In: Global Climate Change and Environmental Refugees: Nature, Framework and Legality. Springer International Publishing, Cham, pp. 105–119. https://doi.org/10.1007/978-3-031-24833-7_7.

Aiyappan, A., 2022. Tamil Nadu. Encyclopaedia Britannica. Available online from. https://www.britannica.com/place/Tamil-Nadu (accessed November 2022).

Ajith, N., Arumugam, S., Parthasarathy, S., Manupoori, S., Janakiraman, S., 2020. Global distribution of microplastics and its impact on marine environment—a review. Environ. Sci. Pollut. Res. 27, 25970–25986. https://doi.org/10.1007/s11356-020-09015-5.

Alderdice, R., Suggett, D.J., Cárdenas, A., Hughes, D.J., Kühl, M., Pernice, M., Voolstra, C.R., 2020. Divergent expression of hypoxia response systems under deoxygenation in reef-forming corals aligns with bleaching susceptibility. Glob. Chang. Biol. 27 (2), 312–326. https://doi.org/10.1111/gcb.15436.

Ali, H., Mishra, V., 2018. Contributions of dynamic and thermodynamic scaling in subdaily precipitation extremes in India. Geophys. Res. Lett. 45 (5), 2352–2361. https://doi.org/10.1002/2018GL077065.

Anand, M., Rangesh, K., Rajeswari, B., Maruthupandy, M., Jayakumar, K., Ravikumar, S., 2018. A Comprehensive Assessment of Marine Debris in the Seeniappa Dargha Beach, Gulf of Mannar, Ramanathapuram District. National Conference on Marine Debris (COMAD 2018), Book of Abstracts and Success Stories. Marine Biological Association of India, Kochi. https://doi.org/10.13140/RG.2.2.35085.36321 (April 11–12, 2018).

Anandavelu, I., Robin, R.S., Purvaja, R., Ganguly, D., Hariharan, G., Raghuraman, R., Prasad, M.H.K., Ramesh, R., 2020. Spatial heterogeneity of mesozooplankton along the tropical coastal waters. Cont. Shelf Res. 206, 104193 https://doi.org/10.1016/j.csr.2020.104193.

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62 (8), 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030.

Andriolo, U., Gonçalves, G., 2022. Is coastal erosion a source of marine litter pollution? Evidence of coastal dunes being a reservoir of plastics. Mar. Pollut. Bull. 174, 113307 https://doi.org/10.1016/j.marpolbul.2021.113307.

Arp, H.P.H., Kühnel, D., Rummel, C., MacLeod, M., Potthoff, A., Reichelt, S., Rojo-Nieto, E., Schmitt-Jansen, M., Sonnenberg, J., Toorman, E., Jahnke, A., 2021. Weathering plastics as a planetary boundary threat: exposure, fate, and hazards. Environ. Sci. Technol. 55 (11), 7246–7255. https://doi.org/10.1021/acs.est.1c01512.

Aswani, S., Vaccaro, I., Abernethy, K., Albert, S., de Pablo, J.F.L., 2015. Can perceptions of environmental and climate change in island communities assist in adaptation planning locally? Environ. Manag. 56, 1487–1501. https://doi.org/10.1007/s00267-015-0572-3.

Audrézet, F., Zaiko, A., Lear, G., Wood, S.A., Tremblay, L.A., Pochon, X., 2021. Biosecurity implications of drifting marine plastic debris: current knowledge and future research. Mar. Pollut. Bull. 162, 111835 https://doi.org/10.1016/j.marpolbul.2020.111835.

Baechler, B.R., Granek, E.F., Hunter, M.V., Conn, K.E., 2020. Microplastic concentrations in two Oregon bivalve species: spatial, temporal, and species variability. Limnol. Oceanogr. Lett. 5 (1), 54–65. https://doi.org/10.1002/lol2.10124.

Baker-Austin, C., Trinanes, J., Gonzalez-Escalona, N., Martinez-Urtaza, J., 2017. Non-cholera vibrios: the microbial barometer of climate change. Trends Microbiol. 25 (1), 76–84. https://doi.org/10.1016/j.tim.2016.09.008.

Balachandar, K., Viswanathan, C., Robin, R.S., Abhilash, K.R., Sankar, R., Samuel, V.D., Purvaja, R., Ramesh, R., 2023. Benthic foraminifera as an environmental proxy for pollutants along the coast of Chennai, India. Chemosphere 310, 136824. https://doi.org/10.1016/j.chemosphere.2022.136824.

Balachandran, K.K., Reddy, G.S., Revichandran, C., Srinivas, K., Vijayan, P.R., Thottam, T.J., 2008. Modelling of tidal hydrodynamics for a tropical ecosystem with implications for pollutant dispersion (Cohin Estuary, Southwest India). Ocean Dyn. 58, 259–273. https://doi.org/10.1007/s10236-008-0153-6.

Ballesteros, L.V., Matthews, J.L., Hoeksema, B.W., 2018. Pollution and coral damage caused by derelict fishing gear on coral reefs around Koh Tao, Gulf of Thailand. Mar. Pollut. Bull. 135, 1107–1116. https://doi.org/10.1016/j.marpolbul.2018.08.033.

Bates, E.H., Alma, L., Ugrai, T., Gagnon, A., Maher, M., McElhany, P., Padilla-Gamino, J. L., 2021. Evaluation of the effect of local water chemistry on trace metal accumulation in puget sound shellfish shows that concentration varies with species, size, and location. Front. Mar. Sci. 8, 636170 https://doi.org/10.3389/fmars.2021.636170.

Bay, S., Jones, B.H., Schiff, K., Washburn, L., 2003. Water quality impacts of stormwater discharges to Santa Monica Bay. Mar. Environ. Res. 56 (1–2), 205–223. https://doi.org/10.1016/S0141-1136(02)00331-8.

Bełdowska, M., Jędruch, A., Łęczyński, L., Saniewska, D., Kwasigroch, U., 2016. Coastal erosion as a source of mercury into the marine environment along the Polish Baltic shore. Environ. Sci. Pollut. Res. 23, 16372–16382. https://doi.org/10.1007/s11356-016-6753-7.

Bhattacharya, A., Khare, S.K., 2022. Ecological and toxicological manifestations of microplastics: current scenario, research gaps, and possible alleviation measures. J. Environ. Sci. Health C 38 (1), 1–20. https://doi.org/10.1080/10590501.2019.1699379.

Biju Kumar, A., Bhagyalekshmi, V., Riyas, A., 2017. Climate change, fisheries and coastal ecosystems in India. J. Aquat. Biol. Fish. 5, 7–17.

Bindoff, N.L., Cheung, W.W.L., Kairo, J.G., Arístegui, J., Guinder, V.A., Hallberg, R., Hilmi, N., Jiao, N., Karim, M.S., Levin, L., O'Donoghue, S., Purca Cuicapusa, S.R., Rinkevich, B., Suga, T., Tagliabue, A., Williamson, P., 2019. Changing ocean, marine ecosystems, and dependent communities. In: Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., Weyer, N.M. (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 447–587. https://doi.org/10.1017/9781009157964.007.

Blakeway, D., 2018. Hypoxia shapes coral reefs. PeerJ 6, e26794v1. https://doi.org/10.7287/peerj.preprints.26794v1.

Bratovcic, A., 2021. Available recycling solutions for increased personal protective equipment in the environment due to the COVID-19 pandemic. Aswan Univ. J. Environ. Stud. 2 (1), 1–10. https://doi.org/10.21608/aujes.2021.149155.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R., 2011. Accumulation of microplastic on shorelines worldwide: sources and sinks. Environ. Sci. Technol. 45, 9175–9179. https://doi.org/10.1021/es201811s.

Browne, M.A., Chapman, M.G., Thompson, R.C., Amaral Zettler, L.A., Jambeck, J., Mallos, N.J., 2015. Spatial and temporal patterns of stranded intertidal marine debris: is there a picture of global change? Environ. Sci. Technol. 49 (12), 7082–7094. https://doi.org/10.1021/es5060572.

Cabral, H., Fonseca, V., Sousa, T., Costa Leal, M., 2019. Synergistic effects of climate change and marine pollution: an overlooked interaction in coastal and estuarine areas. Int. J. Environ. Res. Public Health 16 (15), 2737. https://doi.org/10.3390/ijerph16152737.

Campanale, C., Massarelli, C., Savino, I., Locaputo, V., Uricchio, V.F., 2020. A detailed review study on potential effects of microplastics and additives of concern on human health. Int. J. Environ. Res. Public Health 17 (4), 1212. https://doi.org/10.3390/ijerph17041212.

Cardona, O.D., van Aalst, M.K., Birkmann, J., Fordham, M., McGregor, G., Perez, R., Pulwarty, R.S., Schipper, E.L.F., Sinh, B.T., 2012. Determinants of risk: exposure and vulnerability. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 65–108 (https://www.ipcc.ch/site/assets/uploads/2018/03/SREX_Full_Report-1.pdf).

CCRA, 2012. The UK Climate Change Risk Assessment (CCRA) 2012 evidence report. https://randd.defra.gov.uk/ProjectDetails?ProjectId=15747.

Charrieau, L.M., Filipsson, H.L., Nagai, Y., Kawada, S., Ljung, K., Kritzberg, E., Toyofuku, T., 2018. Decalcification and survival of benthic foraminifera under the combined impacts of varying pH and salinity. Mar. Environ. Res. 138, 36–45. https://doi.org/10.1016/j.marenvres.2018.03.015.

Choudhury, M., Sharma, A., Singh, P., Kumar, D., 2021. Impact of climate change on wetlands, concerning Son Beel, the largest wetland of Northeast, India. Glob. Clim. Chang. 393–414. https://doi.org/10.1016/B978-0-12-822928-6.00006-X.

Chowdhury, P., Behera, M.R., 2015. A study on regional sea level variation along the Indian coast. Procedia Eng. 116, 1078–1084. https://doi.org/10.1016/j.proeng.2015.08.348.

Chowdhury, P., Behera, M.R., 2017. Effect of long-term wave climate variability on longshore sediment transport along regional coastlines. Prog. Oceanogr. 156, 145–153. https://doi.org/10.1016/j.pocean.2017.06.001.

Chowdhury, P., Behera, M.R., Reeve, D.E., 2020. Future wave-climate driven longshore sediment transport along the Indian coast. Clim. Chang. 162 (2), 405–424. https://doi.org/10.1007/s10584-020-02693-7.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A., Whetton, P., 2007. Regional climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 847–940 (https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter11-1.pdf).

Church, J.A., Gregory, J.M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M.T., Qin, D., Woodworth, P.L., Anisimov, O.A., Bryan, F.O., Cazenave, A., Dixon, K.W., Fitzharris, B.B., Flato, G.M., Ganopolski, A., Gornitz, V., Lowe, J.A., Noda, A., Oberhuber, J.M., O'Farrell, S.P., Ohmura, A., Oppenheimer, M., Peltier, W.R., Raper, S.C.B., Ritz, C., Russell, G.L., Schlosser, E., Shum, C.K., Stocker, T.F., Stouffer, R.J., van de Wal, R.S.W., Voss, R., Wiebe, E.C., Wild, M., Wingham, D.J., Zwally, H.J., 2001. Changes in sea level. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 639–693 (https://www.ipcc.ch/site/assets/uploads/2018/03/WGI_TAR_full_report.pdf).

CMDA, 2008. Second master plan for Chennai metropolitan area, 2026. In: Volume I: Vision, Strategies and Action Plans. Chennai Metropolitan Development Authority, Government of Tamil Nadu, p. 18 (http://www.cmdachennai.gov.in/Volume1_English_PDF/Vol1_Chapter00_Introduction.pdf).

CMFRI, 2020. Annual Report 2019. Indian Council of Agricultural Research Central Marine Fisheries Research Institute (ICAR-CMFRI), Kochi, p. 284 (http://eprints.cmfri.org.in/15458/7/CMFRI%20Annual%20Report_2020.pdf).

Connan, M., Perold, V., Dilley, B.J., Barbraud, C., Cherel, Y., Ryan, P.G., 2021. The Indian Ocean 'garbage patch': empirical evidence from floating macro-litter. Mar. Pollut. Bull. 169, 112559 https://doi.org/10.1016/j.marpolbul.2021.112559.

Corbari, C., Lassini, F., Mancini, M., 2016. Effect of intense short rainfall events on coastal water quality parameters from remote sensing data. Cont. Shelf Res. 123, 18–28. https://doi.org/10.1016/j.csr.2016.04.009.

Cozar, A., Echevarría, F., González-Gordillo, J.I., Irigoien, X., Úbeda, B., Hernández-León, S., Palma, Á.T., Navarro, S., García-de-Lomas, J., Ruiz, A., Fernández-de-Puelles, M.L., Duarte, C.M., 2014. Plastic debris in the open ocean. PNAS 111 (28), 10239–10244. https://doi.org/10.1073/pnas.1314705111.

CPCB, 2021. Annual Report on Solid Waste Management (2020−21), Central Pollution Control Board, Delhi, India, 156 pp. Available online from. https://cpcb.nic.in/uploads/MSW/MSW_AnnualReport_2020-21.pdf.

Daniel, D.B., Ashraf, M.P., Thomas, S.N., 2020a. Abundance, characteristics and seasonal variation of microplastics in Indian white shrimps (*Fenneropenaeus indicus*) from coastal waters off Kochi, Kerala, India. Sci. Total Environ. 737, 139839 https://doi.org/10.1016/j.scitotenv.2020.139839.

Daniel, D.B., Thomas, S.N., Thomson, K.T., 2020b. Assessment of fishing-related plastic debris along the beaches in Kerala Coast, India. Mar. Pollut. Bull. 150, 110696 https://doi.org/10.1016/j.marpolbul.2019.110696.

Das, S., Vincent, J.R., 2009. Mangroves protected villages and reduced death tolls during Indian super cyclone. PNAS 106 (18), 7357–7360. https://doi.org/10.1073/pnas.081044010.

De Carlo, E.H., Hoover, D.J., Young, C.W., Hoover, R.S., Mackenzie, F.T., 2007. Impact of storm runoff from tropical watersheds on coastal water quality and productivity. Appl. Geochem. 22 (8), 1777–1797. https://doi.org/10.1016/j.apgeochem.2007.03.034.

de Oliveira Soares, M., 2018. Climate change and regional human pressures as challenges for management in oceanic islands, South Atlantic. Mar. Pollut. Bull. 131 (Part A), 347–355. https://doi.org/10.1016/j.marpolbul.2018.04.008.

Deshpande, M., Singh, V.K., Ganadhi, M.K., Roxy, M.K., Emmanuel, R., 2021. Changing status of tropical cyclones over the north Indian Ocean. Clim. Dyn. 57, 3545–3567. https://doi.org/10.1007/s00382-021-05880-z.

Devlin, M.J., Lyons, B.P., Johnson, J.E., Hills, J.M., 2021. The tropical Pacific Oceanscape: current issues, solutions and future possibilities. Mar. Pollut. Bull. 166, 112181 https://doi.org/10.1016/j.marpolbul.2021.112181.

Devriese, L.I., van der Meulen, M.D., Maes, T., Bekaert, K., Paul-Pont, I., Frère, L., Vethaak, A.D., 2015. Microplastic contamination in brown shrimp (*Crangon crangon*, Linnaeus 1758) from coastal waters of the Southern North Sea and Channel area. Mar. Pollut. Bull. 98 (1–2), 179–187.

DoE, 2009. Kerala State Environment Policy 2009 Department of Environment Government of Kerala. http://www.indiaenvironmentportal.org.in/files/Environment%20Policy-%20English.pdf (pp 33. accessed January 2023).

DoE, 2023a. Draft Tamil Nadu State Action Plan on Climate Change - 2.0 Department of Environment (DoE), Government of Tamilnadu. https://www.environment.tn.gov.in/tnsapcc-draft (accessed February 2023).

DoE, 2023b. Coastal zone management, Department of Environment, Government of Tamil Nadu. https://www.environment.tn.gov.in/crz (accessed February 2023).

DoECC, 2022. Kerala State Action Plan on Climate Change 2.0 (2023−2030), Directorate of Environment and Climate Change (DoECC), Department of Environment, Government of Kerala. https://envt.kerala.gov.in/wp-content/uploads/2022/12/Kerala-State-Action-Plan-on-Climate-Change-2.0.pdf.

DoF, 2021a. Integrated fisheries development plan for coastal zone management plan 2019, Kerala, Department of Fisheries (DoF), Government of Kerala. https://fisheries.kerala.gov.in/sites/default/files/2022-05/CZMP%20report.pdf (July 2021. pp 291. accessed February 2023).

DoF, 2021b. Kerala fisheries statistics at a glance 2021, Directorate of Fisheries (DoF), Government of Kerala. https://fisheries.kerala.gov.in/sites/default/files/2022-05/Fisheries%20statistics%20At%20a%20Glance%202021.pdf (accessed February 2023).

DoF, 2023. Department of Fisheries (DoF), Government of Kerala. https://fisheries.kerala.gov.in/marine-fisheries#:~:text=which%20contribute%20a%20rich%20resource%20fish%20production%20is%20around%2013%25 (accessed February 2023).

D'Silva, M.S., Anil, A.C., Naik, R.K., D'Costa, P.M., 2012. Algal blooms: a perspective from the coasts of India. Nat. Hazards 63, 1225–1253. https://doi.org/10.1007/s11069-012-0190-9.

Duhec, A.V., Jeanne, R.F., Maximenko, N., Hafner, J., 2015. Composition and potential origin of marine debris stranded in the Western Indian Ocean on remote Alphonse Island, Seychelles. Mar. Pollut. Bull. 96 (1–2), 76–86. https://doi.org/10.1016/j.marpolbul.2015.05.042.

Edward, J.K.P., Mathews, G., Raj, K.D., Laju, R.L., Bharath, M.S., Aarasamuthu, A., Kumar, P.D., Bilgi, D.S., Malleshappa, H., 2018. Coral mortality in Gulf of Mannar, Southeastern India, due to bleaching caused by elevated sea temperature in 2016. Curr. Sci. 114 (9), 1967–1972 (http://www.jstor.org/stable/26495348).

ENVIS, 2015. Information Booklet on Gulf of Mannar Biosphere Reserve, Environmental Information System Centre, Department of Environment, Government of Tamil Nadu. http://www.tnenvis.nic.in/WriteReadData/UserFiles/file/gulfofmanner.pdf (accessed January 2023).

ENVIS, 2016. Database on solid waste management in Tamil Nadu, ENVIS Centre, Environmental Information System, Department of Environment, Government of Tamil Nadu. http://www.tnenvis.nic.in/WriteReadData/UserFiles/file/swm.pdf (accessed January 2023).

ENVIS, 2022. ENVIS Hub: Kerala State of environment and related issues. http://www.kerenvis.nic.in/Database/Areas_2254.aspx (accessed February 2023).

Fadare, O.O., Okoffo, E.D., 2020. COVID-19 face masks: a potential source of microplastic fibers in the environment. Sci. Total Environ. 737, 140279 https://doi.org/10.1016/j.scitotenv.2020.140279.

Faure, F., Saini, C., Potter, G., Galgani, F., de Alencastro, L.F., Hagmann, P., 2015. An evaluation of surface micro- and mesoplastic pollution in pelagic ecosystems of the Western Mediterranean Sea. Environ. Sci. Pollut. Res. 22, 12190–12197. https://doi.org/10.1007/s11356-015-4453-3.

Fetisov, S., Chubarenko, I., 2021. Marine litter stormy wash-outs: developing the neural network to predict them. Pollutants 1, 156–168. https://doi.org/10.3390/pollutants1030013.

Ford, H.V., Jones, N.H., Davies, A.J., Godley, B.J., Jambeck, J.R., Napper, I.E., Suckling, C.C., Williams, G.J., Woodall, L.C., Koldewey, H.J., 2022. The fundamental links between climate change and marine plastic pollution. Sci. Total Environ. 806 (Part 1), 150392 https://doi.org/10.1016/j.scitotenv.2021.150392.

Friess, D.A., Thompson, B.S., Brown, B., Amir, A.A., Cameron, C., Koldewey, H.J., Sasmito, S.D., Sidik, F., 2016. Policy challenges and approaches for the conservation of mangrove forests in Southeast Asia. Conserv. Biol. 30 (5), 933–949. https://doi.org/10.1111/cobi.12784.

Froehlich, H.E., Koehn, J.Z., Holsman, K.K., Halpern, B.S., 2022. Emerging trends in science and news of climate change threats to and adaptation of aquaculture. Aquacul. 549, 737812 https://doi.org/10.1016/j.aquaculture.2021.737812.

Gandhi, K.S., Pradhap, D., Prabaharan, G., Singh, S.H., Krishnakumar, S., 2021. Distribution of plastic litter in beach sediments of Silver beach, Cuddalore, during Nivar Cyclone – a first report. Mar. Pollut. Bull. 172, 112904 https://doi.org/10.1016/j.marpolbul.2021.112904.

Garrett, A., Buckley, P., Brown, S., 2015. Understanding and responding to climate change in the UK seafood industry: Climate change risk adaptation for wild capture seafood. A Seafish report to the UK Government under the Climate Change Adaptation Reporting Power. Available online from. https://www.seafish.org/document/?id=ea8b8232-22da-4da5-b063-f2903648c476 (Accessed December 2022).

Gazeau, F., Smith, S.V., Gentili, B., Frankignoulle, M., Gattuso, J.P., 2004. The European coastal zone: characterization and first assessment of ecosystem metabolism. Estuar. Coast. Shelf Sci. 60 (4), 673–694. https://doi.org/10.1016/j.ecss.2004.03.007.

Gewert, B., Ogonowski, M., Barth, A., MacLeod, M., 2017. Abundance and composition of near surface microplastics and plastic debris in the Stockholm archipelago, Baltic Sea. Mar. Pollut. Bull. 120, 292–302. https://doi.org/10.1016/j.marpolbul.2017.04.062.

Glas, M.S., Sato, Y., Ulstrup, K.E., Bourne, D.G., 2012. Biogeochemical conditions determine virulence of black band disease in corals. ISME J. 6, 1526–1534. https://doi.org/10.1038/ismej.2012.2.

Godoy, V., Blázquez, G., Calero, M., Quesada, L., Martín-Lara, M.A., 2019. The potential of microplastics as carriers of metals. Environ. Pollut. 255 (Part 3), 113363 https://doi.org/10.1016/j.envpol.2019.113363.

Gomes, H. do R., Goes, J.I., Matondkar, S.G.P., Buskey, E.J., Basu, S., Parab, S.G., Thoppil, P.G., 2014. Massive outbreaks of *Noctiluca scintillans* blooms in the Arabian Sea due to spread of hypoxia. Nat. Commun. 5, 4862. https://doi.org/10.1038/ncomms5862.

Gomes, H. do R., McKee, K., Mile, A., Thandapu, S., Al-Hashmi, K., Jiang, X., Goes, J.I., 2018. Influence of light availability and prey type on the growth and photo-physiological rates of the mixotroph *Noctiluca scintillans*. Front. Mar. Sci. 5, 374. https://doi.org/10.3389/fmars.2018.00374.

Gopakumar, G., Sulochanan, B., Venkatesan, V., 2009. Bloom of *Noctiluca scintillans* (Macartney) in Gulf of Mannar, southeast coast of India. J. Mar. Biol. Assoc. India 51 (1), 75–80 (http://eprints.cmfri.org.in/2207/1/Gopakumar_75-80.pdf).

Griffith, A.W., Gobler, C.J., 2020. Harmful algal blooms: a climate change co-stressor in marine and freshwater ecosystems. Harmful Algae 91, 101590. https://doi.org/10.1016/j.hal.2019.03.008.

Haas, A.F., Smith, J.E., Thompson, M., Deheyn, D.D., 2014. Effects of reduced dissolved oxygen concentrations on physiology and fluorescence of hermatypic corals and benthic algae. PeerJ 2, e235. https://doi.org/10.7717/peerj.235.

Hariharan, G., Ramachandran, P., Anandavelu, I., Robin, R.S., Ramesh, R., 2021. Accumulation and ecotoxicological risk of weathered polyethylene (wPE) microplastics on green mussel (*Perna viridis*). Ecotoxicol. Environ. Saf. 208, 111765 (ISSN 0147-6513). https://doi.org/10.1016/j.ecoenv.2020.111765.

Hariharan, G., Ramachandran, P., Anandavelu, I., Robin, R.S., Ramesh, R., 2022. Ingestion and toxic impacts of weathered polyethylene (wPE) microplastics and stress defensive responses in whiteleg shrimp (*Penaeus vannamei*). Chemosphere 300, 134487 (https://www.sciencedirect.com/science/article/pii/S0045653522009808).

Harikumar, G., Rajendran, G., 2007. An Overview of Kerala Fisheries With Particular Emphasis on Aquaculture. Souvenir. Integrated Fisheries Project (IFP), Kochi, India, pp. 1–19 (https://www.slideshare.net/dona363/an-over-view-of-kerala-fisheries).

Harrison, P., Furuya, K., Glibert, P., Xu, J., Liu, H., Yin, K.D., Lee, J.H.W., Anderson, D., Gowen, R., Al-Azri, A., Ho, A., 2011. Geographical distribution of red and green *Noctiluca scintillans*. Chin. J. Oceanol. Limnol. 29, 807–831. https://doi.org/10.1007/s00343-011-0510-z.

Hatje, V., Sarin, M., Sander, S.G., Omanović, D., Ramachandran, P., Völker, C., Barra, R. O., Tagliabue, A., 2022. Emergent interactive effects of climate change and contaminants in coastal and ocean ecosystems. Front. Mar. Sci. 9, 936109 https://doi.org/10.3389/fmars.2022.936109.

Honingh, D., van Emmerik, T., Uijttewaal, W., Kardhana, H., Hoes, O., van de Giesen, N., 2020. Urban river water level increase through plastic waste accumulation at a rack structure. Front. Earth Sci. 8, 28. https://doi.org/10.3389/feart.2020.00028.

Hunt, K.M., Menon, A., 2020. The 2018 Kerala floods: a climate change perspective. Clim. Dyn. 54 (3), 2433–2446. https://doi.org/10.1007/s00382-020-05123-7.

IPCC, 2012. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA (582 pp. https://www.ipcc.ch/site/assets/uploads/2018/03/SREX_Full_Report-1.pdf).

IPCC, 2022. In: Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B. (Eds.), Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA (3056 pp. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryVolume.pdf).

ISFR, 2019. Forest Survey of India. Ministry of Environment, Forest Climate Change, State of India Forest Report, Government of India, , 16th editionVol. I. Forest Survey of India, Uttarakhand, India (ISBN 978-81-941018-0-2 https://ruralindiaonline.org/en/library/resource/india-state-of-forest-report-2019-volume-i/).

Isobe, A., Kubo, K., Tamura, Y., Nakashima, E., Fujii, N., 2014. Selective transport of microplastics and mesoplastics by drifting in coastal waters. Mar. Pollut. Bull. 89 (1–2), 324–330. https://doi.org/10.1016/j.marpolbul.2014.09.041.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347 (6223), 768–771. https://doi.org/10.1126/science.1260352.

James, K., Kripa, V., Vineetha, G., Padua, S., Prema, D., Babu, A., John, S., John, S., Lavanya, R., Joseph, R.V., 2022. Microplastics in the environment and in commercially significant fishes of mud banks, an ephemeral ecosystem formed along the southwest coast of India. Environ. Res. 204, 112351 https://doi.org/10.1016/j.envres.2021.112351.

Jayasiri, H.B., Purushothaman, C.S., Vennila, A., 2013. Quantitative analysis of plastic debris on recreational beaches in Mumbai, India. Mar. Pollut. Bull. 77 (1–2), 107–112. https://doi.org/10.1016/j.marpolbul.2013.10.024.

Jennings, S., Stentiford, G.D., Leocadio, A.M., Jeffery, K.R., Metcalfe, J.D., Katsiadaki, I., Auchterlonie, N.A., Mangi, S.C., Pinnegar, J.K., Ellis, T., Peeler, E.J., 2016. Aquatic food security: insights into challenges and solutions from an analysis of interactions between fisheries, aquaculture, food safety, human health, fish and human welfare, economy and environment. Fish Fish. 17 (4), 893–938. https://doi.org/10.1111/faf.12152.

Jovanovic, B., 2017. Ingestion of microplastics by fish and its potential consequences from a physical perspective. Integr. Environ. Assess. Manag. 13 (3), 510–515. https://doi.org/10.1002/ieam.1913.

Jyothibabu, R., Madhu, N.V., Habeebrehman, H., Jayalakshmy, K.V., Nair, K.K.C., Achuthankutty, C.T., 2010. Re-evaluation of 'paradox of mesozooplankton' in the eastern Arabian Sea based on ship and satellite observations. J. Mar. Syst. 81 (3), 235–251. https://doi.org/10.1016/j.jmarsys.2009.12.019.

Jyothibabu, R., Balachandran, K.K., Jagadeesan, L., Karnan, C., Arunpandi, N., Naqvi, S.W.A., Pandiyarajan, R.S., 2018. Mudbanks along the southwest coast of India are not too muddy for plankton. Sci. Rep. 8 (1), 1–13. https://doi.org/10.1038/s41598-018-20667-9.

Kaithery, N.N., Karunakaran, U., 2019. Study on attitude of household waste management in a rural area of Northern Kerala. Int. J. Community Med. Public Health 6 (5), 2095–2102.

Kaladharan, P., Vijayakumaran, K., Singh, V., Prema, D.P.S., Asha, Sulochanan, B., Hemasankari, P., Edward, L., Padua, S., Shettigar, V., Anasukoya, A., Bhint, H., 2017. Prevalence of marine litter along the Indian beaches: a preliminary account on its status and composition. J. Mar. Biol. Assoc. India 59 (1), 19–24. https://doi.org/10.6024/jmbai.2017.59.1.1953-03.

Karthik, R., Robin, R.S., Anandavelu, I., Purvaja, R., Singh, G., Mugilarasan, M., Jayalakshmi, T., Samuel, V.D., Ramesh, R., 2020. Diatom bloom in the Amba River, west coast of India: a nutrient-enriched tropical river-fed estuary. Reg. Stud. Mar. Sci. 35, 101244 https://doi.org/10.1016/j.rsma.2020.101244.

Karthik, R., Robin, R.S., Ramachandran, P., Ganguly, D., Anandavelu, I., Raghuraman, R., Hariharan, G., Ramakrishna, A., Ramesh, R., 2018. Microplastics along the beaches of southeast coast of India. Sci. Total Environ. 645, 1388–1399. https://doi.org/10.1016/j.scitotenv.2018.07.242.

Karthik, R., Robin, R.S., Ramachandran, P., Karthikeyan, V., Subbareddy, B., Balachandar, K., Hariharan, G., Ganguly, D., Samuel, V.D., Jinoj, T.P.S., Ramesh, R., 2022. Microplastic pollution in fragile coastal ecosystems with special reference to the X-Press Pearl maritime disaster, southeast coast of India. Environ. Pollut. 305, 119297 (ISSN 0269-7491). https://doi.org/10.1016/j.envpol.2022.119297.

Katzenberger, A., Schewe, J., Pongratz, J., Levermann, A., 2021. Robust increase of Indian monsoon rainfall and its variability under future warming in CMIP6 models. Earth Syst. Dynam. 12, 367–386. https://doi.org/10.5194/esd-12-367-2021.

Kaviarasan, T., Dhineka, K., Sambandam, M., Sivadas, S.K., Sivyer, D., Hoehn, D., Pradhan, U., Mishra, P., Ramana Murthy, M.V., 2022. Impact of multiple beach activities on litter and microplastic composition, distribution, and characterization along the southeast coast of India. Ocean Coast. Manag. 223, 106177 https://doi.org/10.1016/j.ocecoaman.2022.106177.

Keerthika, K., Padmavathy, P., Rani, V., Jeyashakila, R., Aanand, S., 2022. Contamination of microplastics, surface morphology and risk assessment in beaches along the Thoothukudi coast, Gulf of Mannar region. Environ. Sci. Pollut. Res. 29, 75525–75538. https://doi.org/10.1007/s11356-022-21054-8.

Keerthika, K., Padmavathy, P., Rani, V., Jeyashakila, R., Aanand, S., Kutty, R., Tamilselvan, R., Subash, P., 2023. Microplastics accumulation in pelagic and benthic species along the Thoothukudi coast, South Tamil Nadu, India. Mar. Pollut. Bull. 189, 114735 https://doi.org/10.1016/j.marpolbul.2023.114735.

Khanna, B.B., 2009. Culture of preparedness for management of disasters in India - an initiative by national disaster management authority. Rev. Manage. Avenir 27 (7), 174–181. https://doi.org/10.3917/MAV.027.0174.

Kibria, G., Nugegoda, D., Rose, G., Haroon, A.K.Y., 2021. Climate change impacts on pollutants mobilization and interactive effects of climate change and pollutants on toxicity and bioaccumulation of pollutants in estuarine and marine biota and linkage to seafood security. Mar. Pollut. Bull. 167, 112364 https://doi.org/10.1016/j.marpolbul.2021.112364.

Kintisch, E., 2013. Can coastal marshes rise above it all? Science 341 (645), 480–481. https://doi.org/10.1016/j.marpolbul.2021.112364.

Kiruba-Sankar, R., Saravanan, K., Adamala, S., Selvam, K., Lohith Kumar, K., Praveenraj, J., 2023. First report of marine debris in Car Nicobar, a remote oceanic Island in the Nicobar archipelago, Bay of Bengal. Reg. Stud. Mar. Sci. 102845 https://doi.org/10.1016/j.rsma.2023.102845.

Krishnakumar, S., Srinivasalu, S., Saravanan, P., Vidyasakar, A., Magesh, N.S., 2018. A preliminary study on coastal debris in Nallathanni Island, Gulf of Mannar Biosphere Reserve, Southeast coast of India. Mar. Pollut. Bull. 131 (Part A), 547–551. https://doi.org/10.1016/j.marpolbul.2018.04.026.

Krishnamurthy, C.K.B., Lall, U., Kwon, H.H., 2009. Changing frequency and intensity of rainfall extremes over India from 1951 to 2003. J. Clim. 22 (18), 4737–4746. https://doi.org/10.1175/2009JCLI2896.1.

Krishnan, P., Purvaja, R., Sreeraj, C.R., Raghuraman, R., Robin, R.S., Abhilash, K.R., Mahendra, R.S., Anand, A., Gopi, M., Mohanty, P.C., Venkataraman, K., 2018. Differential bleaching patterns in corals of Palk Bay and the Gulf of Mannar. Curr. Sci. 679–685 (http://www.jstor.org/stable/26495124).

Kshirsagar, N., Shinde, R., Mehta, S., 2006. Floods in Mumbai: impact of public health service by hospital staff and medical students. J. Postgrad. Med. 52 (4), 312 (PMID: 17102558).

Kumar, A., Kumar, A., Sivakumar, R., Yellasiri, S.R.R., Raja, M.V., Nishanth, T., Revanth, V., 2016. Preliminary study on marine debris pollution along Marina Beach, Chennai, India. Reg. Stud. Mar. Sci. 5, 35–40. https://doi.org/10.1016/j.rsma.2016.01.002.

Kundu, S.K., Santhanam, H., 2021. A report on the impacts of cyclone Yaas over a fish landing centre vulnerable to cyclonic storms and natural hazards–Talsari, Northern Odisha. Local Environ. 26 (9), 1043–1050. https://doi.org/10.1080/13549839.2021.1964457.

Kundzewicz, Z.W., Kanae, S., Seneviratne, S.I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L.M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G.R., Kron, W., Benito, G., Honda, Y., Takahashi, K., Sherstyukov, B., 2014. Flood risk and climate change: global and regional perspectives. Hydrol. Sci. J. 59 (1), 1–28. https://doi.org/10.1080/02626667.2013.857411.

Lamb, J.B., Willis, B.L., Fiorenza, E.A., Couch, C.S., Howard, R., Rader, D.N., True, J.D., Kelly, L.A., Ahmad, A., Jompa, J., Harvell, C.D., 2018. Plastic waste associated with disease on coral reefs. Science 359 (6374), 460–462. https://doi.org/10.1126/science.aar3320.

Lavers, J.L., Rivers-Auty, J., Bond, A.L., 2021. Plastic debris increases circadian temperature extremes in beach sediments. J. Hazard. Mater. 416, 126140 https://doi.org/10.1016/j.jhazmat.2021.126140.

Lebreton, L., Van Der Zwet, J., Damsteeg, J.W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nat. Commun. 8 (1), 1–10. https://doi.org/10.1038/ncomms15611.

Lehodey, P., Alheit, J., Barange, M., Baumgartner, T., Beaugrand, G., Drinkwater, K., Fromentin, J.-M., Hare, S.R., Ottersen, G., Perry, R.I., Roy, C., van der Lingen, C.D., Werner, F., 2006. Climate variability, fish, and fisheries. J. Clim. 19 (20), 5009–5030. https://doi.org/10.1175/JCLI3898.1.

Li, C., Wang, X., Liu, K., Zhu, L., Wei, N., Zong, C., Li, D., 2021. Pelagic microplastics in surface water of the Eastern Indian Ocean during monsoon transition period: abundance, distribution, and characteristics. Sci. Total Environ. 755 (Part 2), 142629 https://doi.org/10.1016/j.scitotenv.2020.142629.

Lincoln, S., Andrews, B., Birchenough, S.N.R., Chowdhury, P., Engelhard, G.H., Harrod, O., Pinnegar, J.K., Townhill, B.L., 2022. Marine litter and climate change: inextricably connected threats to the world's oceans. Sci. Total Environ. 837, 155709 https://doi.org/10.1016/j.scitotenv.2022.155709.

Lo, H.S., Lee, Y.K., Po, B.H.K., Wong, L.C., Xu, X., Wong, C.F., Wong, C.Y., Tam, N.F., Cheung, S.G., 2020. Impacts of typhoon Mangkhut in 2018 on the deposition of marine debris and microplastics on beaches in Hong Kong. Sci. Total Environ. 716, 137172 https://doi.org/10.1016/j.scitotenv.2020.137172.

Lovelock, C.E., Reef, R., 2020. Variable impacts of climate change on blue carbon. One Earth 3 (2), 195–211. https://doi.org/10.1016/j.oneear.2020.07.010 (Review).

Lu, Y., Yuan, J., Lu, X., Su, C., Zhang, Y., Wang, C., Cao, X., Li, Q., Su, J., Ittekkot, V., Garbutt, R.A., Bush, S., Fletcher, S., Wagey, T., Kachur, A., Sweijd, N., 2018. Major threats of pollution and climate change to global coastal ecosystems and enhanced management for sustainability. Environ. Pollut. 239, 670–680. https://doi.org/10.1016/j.envpol.2018.04.016.

Lusher, A.L., McHugh, M., Thompson, R.C., 2013. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. Mar. Pollut. Bull. 67 (1–2), 94–99. https://doi.org/10.1016/j.marpolbul.2012.11.028.

Lyons, B.P., Cowie, W.J., Maes, T., Le Quesne, W.J.F., 2020. Marine plastic litter in the ROPME Sea Area: current knowledge and recommendations. Ecotoxicol. Environ. Saf. 187, 109839 https://doi.org/10.1016/j.ecoenv.2019.109839.

Madhu, N.V., Reny, P.D., Paul, M., Ullas, N., Resmi, P., 2011. Occurrence of red tide caused by *Karenia mikimotoi* (toxic dinoflagellate) in the Southwest coast of India. IJMS 40 (6), 821–825 (http://drs.nio.org/drs/handle/2264/3993).

Madhupratap, M., Gopalakrishnan, T.C., Haridas, P., Nair, K.K.C., 2001. Mesozooplankton biomass, composition and distribution in the Arabian Sea during the fall intermonsoon: implications of oxygen gradients. Deep-Sea Res. II Top. Stud. Oceanogr. 48 (6–7), 1345–1368. https://doi.org/10.1016/S0967-0645(00)00142-9.

Maes, T., Jessop, R., Wellner, N., Haupt, K., Mayes, A.G., 2017. A rapid-screening approach to detect and quantify microplastics based on fluorescent tagging with Nile Red. Sci. Rep. 7, 44501. https://doi.org/10.1038/srep44501.

Maltby, K.M., Howes, E.L., Lincoln, S., Pinnegar, J.K., Buckley, P., Ali, T.S., Al Balushi, B., Al Ragum, A., Al Shukail, H.S.A., Balmes, C.O., Ben-Hamadou, R., 2022.

Marine climate change risks to biodiversity and society in the ROPME Sea Area. Clim. Risk Manag. 35, 100411 https://doi.org/10.1016/j.crm.2022.100411.
Martins, J., Sobral, P., 2011. Plastic marine debris on the Portuguese coastline: a matter of size? Mar. Pollut. Bull. 62 (12), 2649–2653. https://doi.org/10.1016/j.marpolbul.2011.09.028.
Maynard, J., Byrne, J., Kerrigan, K., Tracey, D., Bohnsack, K., Pagan, F., Walczak, J., Williams, G.J., Waddell, J., 2017. Coral reef resilience to climate change in the Florida Reef Tract. In: Florida Department of Environmental Protection Technical Report, p. 23 (https://repository.library.noaa.gov/view/noaa/16973).
Mazdiyasni, O., AghaKouchak, A., Davis, S.J., Madadgar, S., Mehran, A., Ragno, E., Sadegh, M., Sengupta, A., Ghosh, S., Dhanya, C.T., Niknejad, M., 2017. Increasing probability of mortality during Indian heat waves. Sci. Adv. 3 (6), 1700066 https://doi.org/10.1126/sciadv.1700066.
Mishra, A., Alnahit, A., Campbell, B., 2021. Impact of land uses, drought, flood, wildfire, and cascading events on water quality and microbial communities: a review and analysis. J. Hydrol. 596, 125707 https://doi.org/10.1016/j.jhydrol.2020.125707.
Miththapala, S., 2012. The Gulf of Mannar and Its Surroundings: A Resource Book for Teachers in the Mannar District. IUCN Sri Lanka Office, Colombo, p. 64 (https://portals.iucn.org/library/sites/library/files/documents/2012-094.pdf. accessed December 2022).
MoHUA, 2019. Plastic waste management - issues, solutions and case studies. Available online from, Ministry of Housing and Urban Affairs (MoHUA), Government of India. https://www.readkong.com/page/plastic-waste-management-8118213 (accessed July 2022).
Mondal, M., Biswas, A., Haldar, S., Mandal, S., Bhattacharya, S., Paul, S., 2022. Spatio-temporal behaviours of tropical cyclones over the Bay of Bengal Basin in last five decades. Trop. Cyclone Res. Rev. 11 (1), 1–15. https://doi.org/10.1016/j.tcrr.2021.11.004.
Mondal, S., Lee, M.A., 2023. Long-term observations of sea surface temperature variability in the Gulf of Mannar. J. Mar. Sci. Eng. 11 (1), 102. https://doi.org/10.3390/jmse11010102.
Montoya-Maya, P.H., 2015. Algal bloom: transplanted corals fight back, Nature Seychelles Reef Rescuers Project. http://www.seychellesweekly.com/November%2026%202015/environ1_algal_bloom_reefs.html.
Morley, N.J., Lewis, J.W., 2014. Temperature stress and parasitism of endothermic hosts under climate change. Trends Parasitol. 30 (5), 221–227. https://doi.org/10.1016/j.pt.2014.01.007.
MSFD, 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy. Off. J. Eur. Union 164, 19–40 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0056&from=EN (accessed April 2023).
Mugilarasan, M., Karthik, R., Purvaja, R., Robin, R.S., Subbareddy, B., Hariharan, G., Rohan, S., Jinoj, T.P.S., Anandavelu, I., Pugalenthi, P., Ramesh, R., 2021. Spatiotemporal variations in anthropogenic marine litter pollution along the northeast beaches of India. Environ. Pollut. 280, 116954 https://doi.org/10.1016/j.envpol.2021.116954.
Mugilarasan, M., Karthik, R.R.S., Subbareddy, B., Hariharan, G., Anandavelu, I., Jinoj, T.P.S., Purvaja, R., Ramesh, R., 2023. Anthropogenic marine litter: an approach to environmental quality for India's southeastern Arabian Sea coast. Sci. Total Environ. 866, 161363 https://doi.org/10.1016/j.scitotenv.2022.161363.
Mujumdar, M., Bhaskar, P., Ramarao, M.V.S., Uppara, U., Goswami, M., Borgaonkar, H., Chakraborty, S., Ram, S., Mishra, V., Rajeevan, M., Niyogi, D., 2020. Droughts and floods. In: Krishnan, R., Sanjay, J., Gnanaseelan, C. (Eds.), Assessment of Climate Change Over the Indian Region: A Report of the Ministry of Earth Sciences (MoES), Government of India. Springer, Singapore, Singapore, pp. 117–141. https://doi.org/10.1007/978-981-15-4327-2.
NABARD, 2020. State Focus Paper. National Bank for Agriculture and Rural Development (NABARD), State: Kerala, p. 132 (https://www.nabard.org/auth/writereaddata/tender/1202195910SFP%202019-20_Kerala-min.pdf).
Naidu, S.A., Ranga Rao, V., Ramu, K., 2018. Microplastics in the benthic invertebrates from the coastal waters of Kochi, Southeastern Arabian Sea. Environ. Geochem. Health 40, 1377–1383. https://doi.org/10.1007/s10653-017-0062-z.
Nair, A., Joseph, K.A., Nair, K.S., 2014. Spatio-temporal analysis of rainfall trends over a maritime state (Kerala) of India during the last 100 years. Atmos. Environ. 88, 123–132. https://doi.org/10.1016/j.atmosenv.2014.01.061.
Nair, A., Nair, V.G., Nair, K.S., 2021. The role of North West Equatorial Indian Ocean in modulating the variability of southwest monsoon rainfall over Kerala in a climate change perspective. Theor. Appl. Climatol. 146, 39–154. https://doi.org/10.1007/s00704-021-03716-8.
Nair, L.S., Sundar, V., Kurian, N.P., 2015b. Longshore sediment transport along the coast of Kerala in southwest India. Procedia Eng. 116, 40–46. https://doi.org/10.1016/j.proeng.2015.08.262.
Nair, R.J., Manojkumar, P.P., Zacharia, P.U., Mohamed, K.S., Sathianandan, T.V., Kuriakose, S., Asokan, P.K., Venkatesan, V., Koya, K.P., Abdussamad, E.M., Pillai, S. L., 2015a. Status of marine fisheries of Kerala. Mar. Fish. Inf. Serv. Tech. Ext. Ser. 226, 22–26 (http://eprints.cmfri.org.in/10979/1/226-11.pdf).
Neethu, C.S., Saravanakumar, C., Purvaja, R., Robin, R.S., Ramesh, R., 2019. Oil-spill triggered shift in indigenous microbial structure and functional dynamics in different marine environmental matrices. Sci. Rep. 9 (1), 1354. https://doi.org/10.1038/s41598-018-37903-x.
Nelson, H.R., Altieri, A.H., 2019. Oxygen: the universal currency on coral reefs. Coral Reefs 38, 177–198. https://doi.org/10.1007/s00338-019-01765-0.
Painter, S.C., Artioli, Y., Amir, F.H., Arnull, J., Ganeshram, R.S., Ibrahim, N., Samuel, V. D., Robin, R.S., Raghuraman, R., Purvaja, R., Ramesh, R., 2023. Anthropogenic nitrogen pollution threats and challenges to the health of South Asian coral reefs. Front. Mar. Sci. 10, 1187804 https://doi.org/10.3389/fmars.2023.1187804.
Parthasarathy, A., Natesan, U., 2015. Coastal vulnerability assessment: a case study on erosion and coastal change along Tuticorin, Gulf of Mannar. Nat. Hazards 75, 1713–1729. https://doi.org/10.1007/s11069-014-1394-y.
Pattanaik, D.R., Rajeevan, M., 2010. Variability of extreme rainfall events over India during southwest monsoon season. Meteorol. Appl. 17 (1), 88–104. https://doi.org/10.1002/met.164.
Patterson, J., Jeyasanta, K.I., Laju, R.L., Booth, A.M., Sathish, N., Edward, J.K.P., 2022. Microplastic in the coral reef environments of the Gulf of Mannar, India - characteristics, distributions, sources and ecological risks. Environ. Pollut. 298, 118848 https://doi.org/10.1016/j.envpol.2022.118848.
Possatto, P., Barletta, M., Costa, M., Ivar do Sul, J., Dantas, D., 2011. Plastic debris ingestion by marine catfish: an unexpected fisheries impact. Mar. Pollut. Bull. 62 (5), 1098–1102. https://doi.org/10.1016/j.marpolbul.2011.01.036.
Pradhan, U., Naik, S., Begum, M., Kumar, S.S., Panda, U.S., Mishra, P., Murthy, M.V.R., 2018. Marine litter: post-flood nuisance for Chennai beaches. Curr. Sci. 115 (8), 1454–1455 (https://www.currentscience.ac.in/Volumes/115/08/1454.pdf).
Prasad, A.K., Singh, R.P., 2005. Extreme rainfall event of July 25–27, 2005 over Mumbai, west coast, India. J. Indian Soc. Remote Sens. 33, 365–370. https://doi.org/10.1007/BF02990007.
Purvaja, R., Robin, R.S., Ganguly, D., Hariharan, G., Singh, G., Raghuraman, R., Ramesh, R., 2018. Seagrass meadows as proxy for assessment of ecosystem health. Ocean Coast. Manag. 159, 34–45. https://doi.org/10.1016/j.ocecoaman.2017.11.026.
Raj, K.D., Mathews, G., Bharath, M.S., Edward, J.K.P., 2016. Mass mortality of *Montipora digitata* (Scleractinia) in Vaan Island, Gulf of Mannar, Southeast India. Curr. Sci. 110 (8), 1407–1408.
Raj, K.D., Mathews, G., Kumar, P.D., 2019. Tiger cowrie *Cypraea tigris* feeds on coral-competing sponge *Rhabdastrella globostellata* in an *Acropora* dominated reef of Gulf of Mannar, India. Mar. Freshw. Behav. Physiol. 52 (2), 101–105. https://doi.org/10.1080/10236244.2019.1637701.
Raj, K.D., Mathews, G., Obura, D.O., Laju, R.L., Bharath, M.S., Kumar, P.D., Arasamuthu, A., Kumar, T.K.A., Edward, J.K.P., 2020. Low oxygen levels caused by *Noctiluca scintillans* bloom kills corals in Gulf of Mannar, India. Sci. Rep. 10, 22133. https://doi.org/10.1038/s41598-020-79152-x.
Raj, K.D., Aeby, G.S., Mathews, G., Williams, G.J., Caldwell, J.M., Laju, R.L., Bharath, M. S., Kumar, P.D., Arasamuthu, A., Asir, N.G.G., Wedding, L.M., Davies, A.J., Moritsch, M.M., Patterson Edward, J.K., 2021. Coral reef resilience differs among islands within the Gulf of Mannar, southeast India, following successive coral bleaching events. Coral Reefs 40, 1029–1044. https://doi.org/10.1007/s00338-021-02102-0.
Rajeevan, M., Bhate, J., Jaswal, A.K., 2008. Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data. Geophys. Res. Lett. 35 (18), L18707 https://doi.org/10.1029/2008GL035143.
Rajendran, V., Nirmaladevi, S.D., Srinivasan, B., Rengaraj, C., Mariyaselvam, S., 2018. Quality assessment of pollution indicators in marine water at critical locations of the Gulf of Mannar Biosphere Reserve, Tuticorin. Mar. Pollut. Bull. 126, 236–240. https://doi.org/10.1016/j.marpolbul.2017.10.091.
Ramesh, R., Nammalwar, P., Gowri, V.S., 2008. Database on coastal information of Tamilnadu, Institute for Ocean Management, Anna University, Chennai. Report submitted to Environmental Information System (ENVIS), Department of Environment, Government of Tamilnadu, Chennai. http://tnenvis.nic.in/tnenvis_old/coastal%20data.pdf (pp 133pp. accessed January 2023).
Ranger, N., Hallegatte, S., Bhattacharya, S., Bachu, M., Priya, S., Dhore, K., Rafique, F., Mathur, P., Naville, N., Henriet, F., Herweijer, C., Pohit, S., Corfee-Morlot, J., 2011. An assessment of the potential impact of climate change on flood risk in Mumbai. Clim. Chang. 104, 139–167. https://doi.org/10.1007/s10584-010-9979-2.
Ranjani, M., Veerasingam, S., Venkatachalapathy, R., Jinoj, T.P.S., Guganathan, L., Mugilarasan, M., Vethamony, P., 2022. Seasonal variation, polymer hazard risk and controlling factors of microplastics in beach sediments along the southeast coast of India. Environ. Pollut. 305, 119315 https://doi.org/10.1016/j.envpol.2022.119315.
Rao, G.S., Sathianandan, T.V., Kuriakose, S., Mini, K.G., Najmudeen, T.M., Jayasankar, J., Mathew, W.T., 2016. Demographic and socio-economic changes in the coastal fishing community of India. Indian J. Fish. 63 (4), 1–9 (http://eprints.cmfri.org.in/id/eprint/11406).
Ray, K., Pandey, P., Pandey, C., Dimri, A.P., Kishore, K., 2019. On the recent floods in India. Curr. Sci. 117 (2), 204–218 (https://www.jstor.org/stable/27138236).
Riyas, C.A., Idreesbabu, K.K., Marimuthu, N., Sureshkumar, S., 2020. Impact of the tropical cyclone Ockhi on ecological and geomorphological structures of the small low-lying islands in the Central Indian Ocean. Reg. Stud. Mar. Sci. 33, 100963 https://doi.org/10.1016/j.rsma.2019.100963.
Robin, R.S., Kanuri, V.V., Muduli, P.R., Mishra, R.K., Jaikumar, M., Karthikeyan, P., Suresh Kumar, C., Saravana Kumar, C., 2013a. Dinoflagellate bloom of *Karenia mikimotoi* along the southeast Arabian Sea, bordering western India. J. Ecosyst. 1–11. https://doi.org/10.1155/2013/463720.
Robin, R.S., Kanuri, V.V., Muduli, P.R., Jaikumar, M., Karthikeyan, P., Suresh Kumar, C., Saravana Kumar, C., 2013b. Influence of coastal and backwaters coupling on sustenance of high nutrients and organic production along the Southeast Arabian Sea. Mar. Sci. 3 (3), 79–90. https://doi.org/10.5923/j.ms.20130303.03.
Robin, R.S., Karthik, R., Purvaja, R., Ganguly, D., Anandavelu, I., Mugilarasan, M., Ramesh, R., 2020. Holistic assessment of microplastics in various coastal environmental matrices, southwest coast of India. Sci. Total Environ. 703, 134947 https://doi.org/10.1016/j.scitotenv.2019.134947.
Robin, R.S., Ramachandran, P., Ganguly, D., Hariharan, G., Paneerselvam, A., Sundari, R. T., Karthik, R., Neethu, C.S., Saravanakumar, C., Semanti, P., Prasad, M.H.K., Mugilarasan, M., Rohan, S., Arumugam, K., Samuel, V.D., Ramesh, R., 2021. COVID-19 restrictions and their influences on ambient air, surface water and plastic waste in

a coastal megacity, Chennai, India. Mar. Pollut. Bull. 171, 112739 https://doi.org/10.1016/j.marpolbul.2021.112739.
Roebroek, C.T.J., Harrigan, S., van Emmerik, T.H.M., Baugh, C., Eilander, D., Prudhomme, C., Pappenberger, F., 2021. Plastic in global rivers: are floods making it worse? Environ. Res. Lett. 16, 025003 https://doi.org/10.1088/1748-9326/abd5df.
Sambandam, M., Dhineka, K., Sivadas, S.K., Kaviarasan, T., Begum, M., Hoehn, D., Sivyer, D., Mishra, P., Ramana Murthy, M.V., 2022. Occurrence, characterization, and source delineation of microplastics in the coastal waters and shelf sediments of the central east coast of India, Bay of Bengal. Chemosphere 303 (2), 135135. https://doi.org/10.1016/j.chemosphere.2022.135135.
Samiksha, S.V., Vethamony, P., Rogers, W.E., Pednekar, P.S., Babu, M.T., Dineshkumar, P.K., 2017. Wave energy dissipation due to mudbanks formed off southwest coast of India. Estuar. Coast. Shelf Sci. 196, 387–398. https://doi.org/10.1016/j.ecss.2017.07.018.
Santos-Andrade, M., Hatje, V., Arias-Ortiz, A., Patire, V.F., da Silva, L.A., 2021. Human disturbance drives loss of soil organic matter and changes its stability and sources in mangroves. Environ. Res. 202, 111663 https://doi.org/10.1016/j.envres.2021.111663.
Saprykina, Y.V., Samiksha, S.V., Kuznetsov, S.Y., 2021. Wave climate variability and occurrence of mudbanks along the southwest coast of India. Front. Mar. Sci. 8, 671379 https://doi.org/10.3389/fmars.2021.671379.
Schmaltz, E., Melvin, E.C., Diana, Z., Gunady, E., Rittschof, D., Somarelli, J., Virdin, J., Dunphy-Daly, M.M., 2020. Plastic pollution solutions: emerging technologies to prevent and collect marine plastic pollution. Environ. Int. 144, 106067 https://doi.org/10.1016/j.envint.2020.106067.
Schnurr, R.E., Alboiu, V., Chaudhary, M., Corbett, R.A., Quanz, M.E., Sankar, K., Srain, H.S., Thavarajah, V., Xanthos, D., Walker, T.R., 2018. Reducing marine pollution from single-use plastics (SUPs): a review. Mar. Pollut. Bull. 137, 157–171. https://doi.org/10.1016/j.marpolbul.2018.10.001.
Seena, G., Muraleedharan, K.R., Revichandran, C., Azeez, S.A., John, S., 2019. Seasonal spreading and transport of buoyant plumes in the shelf off Kochi, southwest coast of India-a modeling approach. Sci. Rep. 9 (1), 19956. https://doi.org/10.1038/s41598-019-56103-9.
Sen Roy, S., 2009. A spatial analysis of extreme hourly precipitation patterns in India. Int. J. Climatol. 29 (3), 345–355. https://doi.org/10.1002/joc.1763.
Shaju, S.S., Akula, R.R., Jabir, T., 2018. Characterization of light absorption coefficient of red *Noctiluca scintillans* bloom in the South Eastern Arabian Sea. Oceanologia 60 (3), 419–425. https://doi.org/10.1016/j.oceano.2017.12.002.
Shyam, S.S., Rahman, M.R., Antony, B., 2015. Sardine economy of Kerala: paradigms and perspectives. Int. J. Fish. Aquat. Stud. 2 (6), 351–356 (http://eprints.cmfri.org.in/id/eprint/10481).
Sivadas, S.K., Ramu, K., Mishra, P., Ramana Murhty, M.V., 2021. Potential plastic accumulation zones in the Indian coastal seas. Front. Mar. Sci. 8, 1801. https://doi.org/10.3389/fmars.2021.768001.
Sivadas, S.K., Mishra, P., Kaviarasan, T., Sambandam, M., Dhineka, K., Ramana Murthy, M.V., Nayak, S., Sivyer, D., Hoehn, D., 2022. Litter and plastic monitoring in the Indian marine environment: a review of current research, policies, waste management, and a roadmap for multidisciplinary action. Mar. Pollut. Bull. 176, 113424 https://doi.org/10.1016/j.marpolbul.2022.113424.
Smithers, R., 2015. SPLICE Phase 1. A Methodology for Rapid Evidence Assessments. Report for Defra. Ricardo-AEA, p. 36. https://doi.org/10.13140/RG.2.2.20787.22567.
Soares, M.O., Campos, C.C., Carneiro, P.B.M., Barroso, H.S., Marins, R.V., Teixeira, C.E.P., Menezes, M.O.B., Pinheiro, L.S., Viana, M.B., Feitosa, C.V., Sánchez-Botero, J.I., Bezerra, L.E.A., Rocha-Barreira, C.A., Matthews-Cascon, H., Matos, F.O., Gorayeb, A., Cavalcante, M.S., Moro, M.F., Rossi, S., Belmonte, G., Melo, V.M.M., Rosado, A.S., Ramires, G., Tavares, T.C.L., Garcia, T.M., 2021. Challenges and perspectives for the Brazilian semi-arid coast under global environmental changes. Perspect. Ecol. Conserv. 19 (3), 267–278. https://doi.org/10.1016/j.pecon.2021.06.001.
Sreelekshmi, S., Veettil, B.K., Nandan, S.B., Harikrishnan, M., 2021. Mangrove forests along the coastline of Kerala, southern India: current status and future prospects. Reg. Stud. Mar. Sci. 41, 101573 https://doi.org/10.1016/j.rsma.2020.101573.
Standish, R.J., Hobbs, R.J., Mayfield, M.M., Bestelmeyer, B.T., Suding, K.N., Battaglia, L.L., Eviner, V., Hawkes, C.V., Temperton, V.M., Cramer, V.A., Harris, J.A., 2014. Resilience in ecology: abstraction, distraction, or where the action is? Biol. Conserv. 177, 43–51. https://doi.org/10.1016/j.biocon.2014.06.008.
Stockdale, A., Tipping, E., Lofts, S., Mortimer, R.J.G., 2016. The effect of ocean acidification on organic and inorganic speciation of trace metals. Environ. Sci. Technol. 50 (4), 1906–1913. https://doi.org/10.1021/acs.est.5b05624.
The Hindu, 2020. Chennai-based environmental group seeks more norms for disposal of COVID-19 medical waste in Tamil Nadu. https://www.thehindu.com/news/national/tamil-nadu/chennai-based-environmental-group-seeks-more-norms-for-disposal-of-covid-19-medical-waste-in-tamil-nadu/article31739355.ece.
Thomas, J., Prasannakumar, V., 2016. Temporal analysis of rainfall (1871–2012) and drought characteristics over a tropical monsoon-dominated state (Kerala) of India. J. Hydrol. 534, 266–280. https://doi.org/10.1016/j.jhydrol.2016.01.013.
Turner, A., Holmes, L.A., 2015. Adsorption of trace metals by microplastic pellets in fresh water. Environ. Chem. 12 (5), 600–610. https://doi.org/10.1071/EN14143.
Turner, A.G., Slingo, J.M., 2009. Subseasonal extremes of precipitation and active break cycles of the Indian summer monsoon in a climate-change scenario. Q. J. R. Meteorol. Soc. 135 (640), 549–567. https://doi.org/10.1002/qj.401.
Ulloa, M.J., Álvarez-Torres, P., Horak-Romo, K.P., Ortega-Izaguirre, R., 2017. Harmful algal blooms and eutrophication along the Mexican coast of the Gulf of Mexico large marine ecosystem. Environ. Dev. 22, 120–128. https://doi.org/10.1016/j.envdev.2016.10.007.
UNEP, 2021. From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution. United Nations Environment Programme, Nairobi, p. 146 (Available online from https://www.unep.org/resources/pollution-solution-global-assessment-marine-litter-and-plastic-pollution (accessed December 2022)).
UNEP, 2022. Review of Current Knowledge and Data on Marine Litter in Asia. United Nations Environment Programme, Bangkok, p. 146 (Available online from https://wedocs.unep.org/handle/20.500.11822/40132 (accessed December 2022)).
UNEP and OCHA, 2021. X-Press Pearl Maritime Disaster: Sri Lanka - Report of the UN Environmental Advisory Mission, pp 70. Available online from. https://wedocs.unep.org/20.500.11822/36608 (accessed February 2023).
UNESCO, 2019. Gulf of Mannar Biosphere Reserve, India. Available online from. https://en.unesco.org/biosphere/aspac/gulf-mannar (accessed September 2022).
UNISDR, 2009. Global Assessment Report on Disaster Risk Reduction - Risk and Poverty in a Changing Climate: Invest Today for a Safer Tomorrow. United Nations International Strategy for Disaster Reduction, Geneva, Switzerland, p. 207 (https://digitallibrary.un.org/record/762672/files/GAR2009_EN.pdf).
Unnikrishnan, A.S., Shankar, D., 2007. Are sea-level-rise trends along the coasts of the north Indian Ocean consistent with global estimates? Glob. Planet. Chang. 57 (3–4), 301–307. https://doi.org/10.1016/j.gloplacha.2006.11.029.
Valappil, N.K.M., Hamza, V., de Oliveira Júnior, J.F., 2022. Evaluation of daily average temperature trends in Kerala, India, using MERRA-2 reanalysis data: a climate change perspective. Environ. Sci. Pollut. Res. 1–24. https://doi.org/10.1007/s11356-022-23895-9.
van Bijsterveldt, C.E.J., van Wesenbeck, B.K., Ramadhani, S., Raven, O.V., van Gool, F.E., Pribadi, R., Bouma, T.J., 2021. Does plastic waste kill mangroves? A field experiment to assess the impact of macro plastics on mangrove growth, stress response and survival. Sci. Total Environ. 756, 143826 https://doi.org/10.1016/j.scitotenv.2020.143826.
van der Mheen, M., Sebille, E., Pattiaratchi, C., 2020. Beaching patterns of plastic debris along the Indian Ocean rim. Ocean Sci. 16, 1317–1336. https://doi.org/10.5194/os-16-1317-2020.
van Hespen, R., Hu, Z., Borsje, B., De Dominicis, M., Friess, D.A., Jevrejeva, S., Kleinhans, M.G., Maza, M., van Bijsterveldt, C.E.J., Van der Stocken, T., van Wesenbeeck, B., Xie, D., Bouma, T.J., 2023. Mangrove forests as a nature-based solution for coastal flood protection: biophysical and ecological considerations. Water Sci. Eng. 16 (1), 1–13 (https://www.sciencedirect.com/science/article/pii/S1674237022000874).
Veerasingam, S., Mugilarasan, M., Venkatachalapathy, R., Vethamony, P., 2016. Influence of 2015 flood on the distribution and occurrence of microplastic pellets along the Chennai coast, India. Mar. Pollut. Bull. 109 (1), 196–204. https://doi.org/10.1016/j.marpolbul.2016.05.082.
Vivekanandan, E., Pillai, N.G.K., Rajagopalan, M., 2008. Adaptation of the oil sardine *Sardinella longiceps* to seawater warming along the Indian coast. In: Glimpses of Aquatic Biodiversity-Rajiv Gandhi Chair Special Publication 7, pp. 111–119 (http://eprints.cmfri.org.in/id/eprint/4681).
Vogt-Vincent, N.S., Burt, A.J., Kaplan, D.M., Mitarai, S., Turnbull, L.A., Johnson, H.L., 2023. Sources of marine debris for Seychelles and other remote islands in the western Indian Ocean. Mar. Pollut. Bull. 187, 114497 https://doi.org/10.1016/j.marpolbul.2022.114497.
Walker, T.R., 2021. (Micro)plastics and the UN sustainable development goals. Curr. Opin. Green Sustain. Chem. 30, 100497 https://doi.org/10.1016/j.cogsc.2021.100497.
Wang, Z., Meador, J.P., Leung, K.M., 2016. Metal toxicity to freshwater organisms as a function of pH: a meta-analysis. Chemosphere 144, 1544–1552. https://doi.org/10.1016/j.chemosphere.2015.10.032.
Wessel, C.C., Lockridge, G.R., Battiste, D., Cebrian, J., 2016. Abundance and characteristics of microplastics in beach sediments: insights into microplastic accumulation in northern Gulf of Mexico estuaries. Mar. Pollut. Bull. 109, 178–183. https://doi.org/10.1016/j.marpolbul.2016.06.002.
Yadav, S.S., Gjerde, K.M., 2020. The ocean, climate change and resilience: making ocean areas beyond national jurisdiction more resilient to climate change and other anthropogenic activities. Mar. Policy 122, 104184. https://doi.org/10.1016/j.marpol.2020.104184.
Young, I., Gropp, K., Fazil, A., Smith, B.A., 2015. Knowledge synthesis to support risk assessment of climate change impacts on food and water safety: A case study of the effects of water temperature and salinity on *Vibrio parahaemolyticus* in raw oysters and harvest waters. Food Res. Int. 68, 86–93. https://doi.org/10.1016/j.foodres.2014.06.035.
Zapata, O., 2021. The relationship between climate conditions and consumption of bottled water: a potential link between climate change and plastic pollution. Ecol. Econ. 187, 107090 https://doi.org/10.1016/j.ecolecon.2021.107090.
Zhang, W., Zhang, S., Wang, J., Wang, Y., Mu, J., Wang, P., Lin, X., Ma, D., 2017. Microplastic pollution in the surface waters of the Bohai Sea, China. Environ. Pollut. 231, 541–548.