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Synergetic effects of marine litter and climate change in coastal and marine ecosystems

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Abstract

The Hon'ble Prime Minister of India has emphasised issues related to marine litter and plastics, in particular, through the Mann Ki Baat programme. In his nation-wide address to the common man, he emphasised the effects of interactions between marine litter and environmental health. These episodes were inspiring forassessing a new dimension of the synergistic effects of marine litter and climate change. Marine litter and climate change are closely linked in ways that vary between areas depending on the environment and human activity. Globally, around 10% of all plastics manufactured are recycled, with the remaining being incinerated (12%), landfilled (79%), or lost to the environment. These discarded or lost plastics eventually end up in the oceans. India generates ~9.4 million metric tonnes per annum of plastic waste (i.e., 26,000 tonnes of waste per day), and out of this, ~5.6 million tonnes per annum of plastic waste are recycled (i.e., 15,600 tonnes of waste per day), and 3.8 million tonnes per annum of plastic waste are left uncollected or littered (9,400 tonnes of waste per day). An estimated 15 million metric tonnes of plastic make their way into the Indian Ocean each year. The coastal areas of India are influenced by plastic pollution, which causes harm to marine flora and fauna. It is well known that the emergence of marine litter, especially plastic, has been a transboundary and multi-sectoral global problem for the past two decades and that its cost to society and the marine and coastal environment is enormous and irreversible. The article aims to highlight the combined impact of climate change and marine litter on the Indian subcontinent. Coastal communities are particularly susceptible to the converging impacts of litter and climate change. The government of India is taking steps in the right direction to combat the issue of plastic pollution. Some of the initiatives include the ban on single-use plastics and the citizen science approach (the coastal clean-up drive under the SwachchSagarSurakshitSagar, where 1500 metric tonnes of litter were removed) for coastal conservation in India. Stable changes have been observed throughout the coast, and these approaches with policy recommendations would help to improve the coastal and marine ecosystems health.

Key Words: *Climate change, Marine litter, Citizen science, Litter management policies.*

Introduction

Mann Ki Baat (MKB) is a programme hosted by the Hon'ble Prime Minister and regularly communicates through this platform to reach out to the citizens and share his thoughts and ideas. In this series, the Hon'ble Prime Minister shares real-life stories and experiences and addressesseveral issues of national and international importance. The Hon'ble Prime Minister raised the issue of plastic pollution and the importance of limiting the use of single-use plastic in several episodes, encouraging individuals to participate in coastal clean-up activities. Accordingly, the Indian government has taken many steps to encourage the use of plastic alternatives such as cloth bags, jute bags, and other environmentally friendly materials. Further, the Government has launched the Swachh Bharat Abhiyan, popularly known as the Clean India Mission, which aims to promote cleanliness across India.

Mann Ki Baat episodes refer to the issue of plastic pollution

In the 32ndepisode of MKB, dated May 27, 2017, the Hon'ble Prime Minister highlighted the importance

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of community participation in coastal clean-up. The success story of Versova, located in Mumbai Suburban, Maharashtra, was highlighted in this episode. The beach clean-up at Versova was joined by students, celebrities, and the local community and the Hon'ble Prime Minister encouraged citizens to regularly participate in such coastal cleanliness efforts.

In episode 59 of MKB, dated November 24, 2019, the Hon'ble Prime Minister outlined the success story of scuba divers from Visakhapatnam and how theirefforts have led a successful battle against plastic waste in the sea. These divers started scuba diving for a "swachh" cause and dived deep to remove garbage and plastics lying on the sea floor and have successfully removedover4,000 kilograms of plastic wastes. This small initiative by the divers is being transformed into a big mission now. The Hon'ble Prime Minister also urged people to take inspiration from these divers and pledge to beat plastic pollution.

In episode 90 of Mann Ki Baat, dated June 26, 2022, the Hon'ble Prime Minister highlighted the importance of waste recycling and shared the example of the coastal cities of Puducherry and Karaikal, where garbage is collected and segregated on a daily basis. In this process, organic waste is composted, while plastic waste is recycled.

In episode 93 of Mann Ki Baat, dated September 25, 2022, the Hon'ble Prime Minister appreciated the public participation in the coastal cleaning efforts in the Swachh Sagar-Surakshit Sagar initiative. About 5,000 youth from the NSS, collected over 30 tonnes of plastic from the coastal areas and beaches. The Hon'ble Prime Minister addressed the importance of coastal cleaning and the several environmental challenges faced in the coastal areas. He further stressed that climate change remains a major threat to marine ecosystems, and that the plastic litter spread on our beaches is a matter of great concern. He further urged the citizens to make sincere and continuous efforts to tackle these challenges. The Hon'ble Prime Minister requested the public resolve to *"say no to plastic pollution"* and use alternatives such as jute, cloth, and bamboo bags. He further opined that during the festive

Figure 1: Eco-Friendly alternatives to single-use plastics.

season, gifts are packed using polyethylene and other non-biodegradable bags. He suggested that the public must promote the use of non-plastic bags such as jute, bamboo, and banana (Figure 1). He also emphasised the need to promote the use of non-plastic bags on the occasion of festivals and to take care of health and the environment, along with cleanliness.

In the 98th episode of MKB, dated February 26, 2023, the Hon'ble Prime Minister said that Swachh Bharat Abhiyan has changed the meaning of public participation (Jan Bhagidaari) in the country.In several Mann Ki Baat episodes, the Hon'ble Prime Minister highlighted the impact of both plastic litter and climate change, especially in coastal areas. These episodes are the inspiration and basics for assessing the synergetic effects of marine litter and climate change in marine and coastal ecosystems.

The coastal zone is of great importance in the provision of multiple ecosystem services (Lu *et al.*, 2018). It is also a transition zone between land and ocean, where exchanges of matter and energy occur. Due to various anthropic pressures, coastal zonesare highly sensitive and vulnerable to climate change. In recent years, due to severe pollution from various sources comprising organic and inorganic contaminants, along with climate change, there have been drastic ecological alterations (Lu *et al.*, 2018). Increasingly, marine litter is being recognised as a threat multiplier that compounds with other stressors such as climate change to cause far greater damage; for example, climate change can lead to increased inputs of litter into the marine environment, which in turn undermines the climate resilience of habitats (Lincoln *et al.*, 2022). According to the World Bank, 15 million tonnes of plastic enter the Indian Ocean each year, contaminating the ocean's health.

Marine litter, particularly plastic, is a significant and growing problem for the world's oceans and their ecosystems. Plastic pollution can have harmful impacts on wildlife, including entanglement, ingestion, and habitat destruction. It can also negatively impact human health through the transfer of toxic chemicals and pollutants. Besides influencing the sources and pathways of global marine litter, climate change also influences the breakdown rate of litter, particularly plastic and other synthetic materials. Moreover, anthropogenic litter is a complex and cross-sectoral concern, as its costs to humanity and the environment are immense and irreversible. Its impact encompasses regional, national, and global scales and includes adverse effects on human health, aesthetics, the economy, marine biota, and climate change (Browne *et al.*, 2015; Williams and Rangel-Buitrago, 2019; Ford *et al.*, 2022; Lincoln *et al.*, 2022).It is a known fact that litter breaks down into smaller particles under natural conditions and can be transported over long distances by wind or water currents (Garcia-Vazquez *et al.*, 2018). Once in the marine environment, this litter can be transported horizontally or vertically based on its buoyancy and density, thus making it a transboundary issue (Karthik *et al.*, 2022).

There are several forms of litter, such as glass, metal, cardboard, and paper, among others, which contribute to about 10–40% of the total litter. However, plastic litter comprises about 60–90% of the total litter (Löhr *et al.*, 2017). According to a report, global plastic production has reached 390.7 million tonnes in 2021 (Plastics Europe 2022) and plastic wastesaccountfor~353 million tonnes. As of 2019, nearly 55 million tonnes of plastics were collected for recycling, which is about 9% of all plastic ever produced. The remainder of plastic waste is either incinerated (12%), landfilled, or lost to the environment (79%) (OECD, 2022).Continued production of virgin fossil-based plastics also has a large impact on climate change (Schwarz *et al.*, 2021). Plastics, especially single-use plastics, leave a large carbon footprint and trigger climate change through greenhouse gas (GHG) emissions (Zheng and Suh, 2019). The increase in plastics in the environment in recent decades has raised global concerns as they have reached critical levels, threatening important earth system processes and acting as a planetary threat (Galloway and Lewis, 2016; Jahnke *et al.*, 2017; Villarrubia-Gómez *et al.*, 2018).

Scientific approach adopted to address the issue

Articles were collected using various search terms, such as "marine litter", "climate change", "oceanic processes", "the socioeconomics of marine litter", "policies and recommendations on marine litter", etc (Ajith *et al.*, 2020). To collect the articles, various bibliographic databases such as Google, Google Scholar, Research Gate, Science Direct, and Wiley Online Library were analysed. All types of materials, primary field data and secondary peer-reviewed scientific articles, books and book chapters, technical reports, and information on projects from academic and government online portals, were used.

Results and discussion

Synergistic effect of marine litter and climate change

Marine litter, particularly plastics, is thought to double the threat when combined with other stressors such as climate change, as they have a much greater impact than they do alone (Ford *et al.*, 2022; UNEP, 2021). Also, plastic litter has become a great concern since it has exceeded the thresholds of global equity and irreversibility (Lavers *et al.*, 2021).In addition to its exposure to climate change, the northern Indian Ocean receives some of the highest influx of plastic wastes of all ocean basins (van der Mheen *et al.*, 2020).The Indian monsoon is a major litter pathway, the vast majority of which 96% consists of plastics released from India, Sri Lanka, and the other Indian Ocean Rim countries (Duhec *et al.*, 2015). India is one of the world's main sources of marine plastic litter, generated principally from the ship-breaking industry, followed by fishing and coastal recreational activities combined with inadequate waste disposal practices and littering behaviour (UNEP, 2022).

India is ranked 12thamongthe world's countries in generating mismanaged waste (Jambeck *et al.*, 2015). In India, it is estimated that around 1,50,847 tonnes of solid waste per day are generated, of which only 47% is treated, and about 26% is unaccounted for (CPCB, 2021). Every year, about 9.4 million tonnes of plastic waste are generated, of which 3.8 million tonnes remain uncollected (Daniel *et al.*, 2020a; MoHUA, 2019).By 2025, India is expected to become the 5th largest contributor of waste, a large part of which is likely to find its way to the Indian Ocean, either directly or via riverine systems (CPCB, 2021; MoHUA, 2019).

Global warming and greenhouse gases (GHG)

Universally, nations have agreed to limit global warming to less than 1.5 degrees Celsius per year in conformity to the Paris Agreement. However, the existing rate of production and use of plastics could threaten from achieving this target. As per the current rate, greenhouse gas emissions from plastics production could reach 1.34 gigatons per year by 2030, which is equivalent to emissions from 295 new 500-megawatt coal-fired power plants (Hamilton *et al.*, 2019). It was estimated that about 56 billion metric tonnes of CO_2 will be released as a result of plastic production from 2015 to 2050, which will decrease the carbon budget by 10–13% (Hamilton *et al.*, 2019).

Plastic production, transportation, and mismanaged plastic waste degradation all contribute to climate change via CO_2 emissions (Ford *et al.*, 2022). As much as production, the degradation of plastics also contributes to the release of greenhouse gases. Plastics, under natural environmental conditions, release methane (CH_4)and Carbon-di-oxide (CO_2) upon exposure to temperature and UV radiation from sunlight. The presence of plasticizers along with plastics enhances the release of GHGs during decomposition (Kida *et al.*, 2022a). The polymer type of plastic material also determines its GHG emissions. Polypropylene emits less CH_4 and CO_2 during decomposition compared to polyvinyl chloride (Kida *et al.*, 2022b).

In addition, the use of plastics has been linked to environmental issues such as ocean acidification, ozone layer depletion, and global warming (Su *et al.*, 2022). The temperature rise, for example, represents long-term climate variation. Rising temperatures lead to the melting of ice, which contributes to sea-level rise (Karl *et al.*, 2015; Lu *et al.*, 2018). Plastics accumulated in the beach sediments alter the sediment's properties. The sediments gradually warm during the day and slowly cool at night, retaining higher temperatures for longer durations of time. This is due to the accumulated plastics, which act as an insulating agent (Lavers *et al.*, 2021). Furthermore, the presence of plastic litter in marine environment, reduces ability of phytoplankton and mangrove ecosystems (Figure 2) to capture carbon (Shen *et al.*, 2020), resulting in a 1.35-fold reduction in carbon sequestration (Wieczorek *et al.*, 2019).

Ocean acidification and carbon sequestration

Oceans have absorbed approximately 20–40% of the carbon dioxide created since the start of industrialization. Microscopic primary producers such as phytoplankton and the primary consumers, zooplankton, play a major role in this carbon absorption by the oceans. The deposition of plastic debris into the oceans hinders their ability to absorb and sequester carbon from the environment (Hamilton *et al.*, 2019). A study by Romera-Castillo *et al.* (2023) highlighted that the leaching of chemicals from aged plastics decreases the pH of seawater and releases CO_2. Reduced pH levels in the ocean cause its acidification, which has a direct influence on the shells of organisms, affecting their calcification process (Movilla *et al.*, 2014; Doney *et al.*, 2020; Godefroid *et al.*,

2021). Several bacterial assemblages have been affected by ocean acidification due to marine litter, which creates an ecological imbalance (Harvey *et al.*, 2020).

Ecological impact of marine litter

Biogeochemical cycles

Plastic accumulation in the aquatic environment alters various processes, such as mineralization and demineralization. The resuspension of minerals by plastics can contribute to eutrophication and the abundant growth of algae (Zhang *et al.*, 2020). Marine debris floating on the surface hinders light penetration into the water body. This can affect the dissolved oxygen concentration and water quality of the aquatic systems, which can in turn disrupt biodiversity (Thushari and Senevirathna, 2020). Marine litter in the terrestrial environment hinders the ability of sediments to sequester carbon and other biogeochemical processes.

Spread of non-native species and harmful contaminants

Over the past few decades, biological incursions of invasive species have increased, which has caused concern among researchers (Seebens *et al.*, 2017). Litter provides new surfaces for the colonisation and attachment of marine organisms, which leads to environmental and economic damage (Gündoğdu *et al.*, 2017). Marine debris, especially plastics, acts as a dispersing agent for marine organisms (Rech *et al.*, 2016), alien and regional species (Rech *et al.*, 2016; Audrézet *et al.*, 2020). Floating marine litter is converging to increase the spread of non-native invasive species. Many invasive species require vectors to transport them to new regions (Libralato *et al.*, 2015), and marine litter can serve as such a vector (Agamuthu *et al.*, 2019; Rech *et al.*, 2016). Many species have been found rafting in marine litter, including crabs (Tutman *et al.*, 2017) and invasive coral species (Mantelatto *et al.*, 2020). Several organisms, such as microbes (Carson *et al.*, 2013), algae, invertebrates, and fish (Goldstein *et al.*, 2014), were reported to have been transported by marine litter to non-

Figure 2: Trapping of plastics by mangrove roots.

native regions. The rafting communities of organisms that attach to this litter can be transported for about 100 km by winds and currents (Garcia-Vazquez *et al.*, 2018).

Several authors have depicted the preference of marine organisms for various forms of litter. For instance, goose barnacles prefer to attach to foam (Rech *et al.*, 2018), polychaetes prefer plastic (Rech *et al.*, 2018), and acorn barnacles prefer glass (Li *et al.*, 2016). Hence, monitoring the types of litter in an area would enable one to understand the types of organisms attached and the risks contributed by them (Figure 3). The biofilms released by the microbial communities attaching to the marine litter can trap other forms of litter, which can aggravate pollution further (Garcia-Vazquez *et al.*, 2018). Non-indigenous species prefer to attach to hard artificial surfaces rather than soft natural surfaces. These can be transported easily to new environments, where they can easily adapt and become invasive over time (Garcia-Vazquez *et al.*, 2018). Maritime traffic and port activities enable the transport of non-indigenous and exotic species (Miralles *et al.*, 2018).

Impacts of marine litter on the blue economy

Marine litter can have significant impacts on various sectors of the blue economy. Some of the sectors that are particularly affected by marine litter include:

- **Fisheries:** Marine litter can harm fish populations by entangling them or being ingested, leading to reduced catches and economic losses for fishing industries.
- **Tourism:** Marine litter can negatively impact the aesthetic appeal of beaches and coastal areas, reducing tourism revenues.
- **Shipping and transport:** Marine litter can cause damage to ships and other transport vessels, resulting in increased maintenance and repair costs.
- **Renewable energy:** Marine litter can interfere with the operation of offshore renewable energy facilities such as wind turbines and wave energy converters.
- **Aquaculture:** Marine litter can contaminate aquaculture sites, impacting the health of farmed species and leading to economic losses for the aquaculture industry.

Efforts to mitigate marine litter and promote sustainable practices can have positive impacts on these sectors of the blue economy. For example, reducing plastic waste can improve the health of fish populations and support sustainable fishing practices, which can benefit fishing industries. Additionally, improving waste management infrastructure and reducing marine litter can improve the aesthetic appeal of coastal areas, supporting tourism industries. Furthermore, sustainable practices can help to protect the long-term viability of renewable energy and aquaculture industries. Overall, mitigating marine litter is critical for the sustainability of various sectors of the blue economy. By reducing the negative impacts of marine litter and promoting sustainable practices, these sectors can support long-term economic growth and environmental protection.

Marine litter mitigation is crucial for the sustainable development of the blue economy. Marine litter, particularly plastic waste, poses a significant threat to ocean health and can have a severe economic impact on coastal communities and the broader economy. The blue economy's sustainable development requires protecting and preserving ocean resources, including minimizing marine litter.Efforts to mitigate marine litter, involves a wide range of strategies, including improving waste management infrastructure and practices, reducing the use of single-use plastics, promoting recycling and reuse, and increasing public awareness about the issue. These strategies can have significant economic benefits, such as reducing cleanup costs, improving the quality of the marine environment for tourism and recreation, and protecting fisheries and other marine industries. In addition to reducing the negative impacts of marine litter, sustainable practices in the blue economy can also create economic opportunities. For example, the development of a circular economy model for plastic waste, which involves designing products for reuse and recycling, can create new industries and jobs. The blue economy can also benefit from sustainable aquaculture and renewable energy projects, which can provide economic growth while minimizing environmental impact. By preserving ocean resources and reducing the negative impacts of human activity on the marine environment, the blue economy can support sustainable development and long-term economic prosperity.

Impacts on the socioeconomic sector

Climate change, variability, and extreme events influence the environment and socioeconomic sectors such as fisheries, agriculture, natural resources, and human health (UNFCCC, 2007). Climate variability due to rising temperatures influences precipitation, which affects

global agricultural production (FAO, 2016; Pathak *et al.*, 2018). Agricultural soils are under constant threat from climate change events that can alter soil salinity (Chen and Mueller, 2018), induce acidification, and cause ecological changes (Shelton, 2014).

Marine litter has a negative economic and financial impact on the fishing, transportation, and tourism industries, as well as on governments and local communities (Ten Brink *et al.*, 2009; Mouat *et al.*, 2010). Plastic and other marine litter costs are frequently borne by those who are affected rather than those who cause the problem. Because of the lack of information, the true costs of the effects of marine litter are likely to be higher than those estimated thus far. Commercial fisheries and aquaculture productivity are affected by marine litter, which leads to entanglement and damage to the animal body (Golden *et al.*, 2016). In certain cases, "ghost fishing" contributes to a loss in global fishery catch. Reduced fishery stocks were reported to have caused losses of several million dollars (Thushari and Senevirathna, 2020). As much as tourism contributes to litter, littered tourist spots fail to attract tourists, affecting the economy. Cleaning polluted marine environments and restoring ecosystem services has been estimated to cost between $500 and $2500 billion (Beaumont *et al.*, 2019). If littering practices are improved, this huge amount can be used for coastal development activities.

Indian Ocean surface dynamics and the plastic transport pathways

The Indian Ocean, being one of the largest oceans, hosts numerous countries along its rim and is known to be contaminated by plastic pollution; however, it is understudied in this regard. The ocean is polluted by 15% of all coastal litter and 20% of all riverine inputs (Pattiaratchi *et al.*, 2022). van der Mheen *et al.* (2020) simulated the beach littering pattern along the Indian Ocean. They projected that the litter is transported from Gulf countries (west) to the rim countries (east), passing through the Indian subcontinent during the southwest monsoon (August) and vice versa during the northeast monsoon (February). Hence, the coastal regions of India are prone to marine pollution from the Indian Ocean. It was calculated that every year, between 1.15 and 2.41 million tonnes of plastic flow from the world's riverine system into the oceans. Over two-thirds (67%) of the annual global inflow came from the top 20 polluted rivers, most of which were in Asia. About 86% of the total world inflow came from Asian rivers. This overwhelming contribution from the Asian continent, with an estimated annual input of 1.21 million tonnes per year, was caused by a significantly high population density combined with a relatively high composition of mismanaged plastic waste (MPW) production and severe rainfall (Lebreton *et al.*, 2017).

Due to the litter threat from several countries, there appears to be a garbage patch in the Indian Ocean. Connan *et al.* (2021) in their oceanic survey of the Indian Ocean observed the accumulation of litter at a specific spot towards the south of the ocean. It is termed as the "garbage patch," which was much smaller than the patches observed in other oceans. At present, this garbage patch is small as the litter is being dispersed by Stokes drift and current patterns (Pattiaratchi *et al.*, 2022). The dynamics of the Indian Ocean are quite distinctive from other oceans;hence, the pattern of distribution in this ocean is different from other oceans. The northern Indian Ocean comprises the Bay of Bengal and the Arabian Sea, which are landlocked, leading to the reversing nature of the seasonal winds.

Further, coastal currents from the east and west of India reverse directions, connecting the Bay of Bengal and the Arabian Sea. This can cause changes in several processes from the Bay of Bengal to the Arabian Sea and vice versa (Sivadas *et al.*, 2021). The changes in the Bay of Bengal and Arabian Sea can be witnessed by the shift in cyclonic and rainfall patterns between the southern states. During the past few decades, the southeast coast of India has been affected by heavy rains and cyclones, which have gradually shifted to the west coast of India. Warmer ocean water agglomerates marine litter, while cooler water disperses it. Macias *et al.* (2019) in the Mediterranean Sea adjoining the Atlantic Ocean reported such effects. The Indian Ocean generally has a higher temperature throughout the year than the Atlantic Ocean; hence, there is a possibility that litter may accumulate within the ocean. Seasonal winds and oceanic patterns play a prominent role in the resuspension of sediment material in the coastal seas. During the monsoons, higher wind action leads to swelling and rolling, contributing to rough seas and the subsequent distribution of this sediment material along with marine litter (James *et al.*, 2021). During the non-monsoon season, limited wind action and calm seas,causethe suspended material to settle again.

The potential accumulation zones for marine litter in the Indian Ocean include the Gulf of Mannar, the Gulf

of Kachch, and the Gulf of Khambhat, the islands of Andaman and Nicobar, and Lakshadweep. These regions act as a trap for litter and accumulate it in sediments. Along the west coast of India, upwelling is high during the southwest monsoon, while downwelling is high during the northeast monsoon (Sivadas *et al.*, 2021). These actions can determine the suspension and distribution of marine litter. Litter from terrestrial sources, and the mean eastward flow of the water, and gyre formations accumulate more in the Bay of Bengal (van der Mheen *et al.*, 2020).

The Bay of Bengal can be considered a marine litter hotspot due to its higher accumulation rate (Li *et al.*, 2021). However, marine litter has a to-and-fro movement throughout the year between the Arabian Sea and the Bay of Bengal due to the reversing trend of currents. Moreover, the western currents are stronger and more continuous than the eastern currents, which retain more litter on the west coast of India, as reported by Robin *et al.* (2020).

A study observed marine litter along the coasts of the Lakshadweep Islands in the Arabian Sea (Kaviarasan *et al.*, 2020). Though the population of the islands is very small compared to the Indian mainland (the island group has very high population density), with high litter accumulation. This is primarily due to the minimal waste management infrastructure in the islands. A similar study was carried out on the islands of Andaman and Nicobar in the Andaman Sea (Krishnakumar *et al.*, 2020). The abundance of marine litter was caused by tourist activities and it was suggested that the current patterns of the Bay of Bengal and Andaman Sea distributed litter to the Indian mainland or other global countries, making it a transboundary threat.

The Indian Ocean gyre is an essential component of global circulation and has a role in its structure. The heat induced by litter on these gyres influences climate change and the quantity of material transported. Numerous ports surround the gyres, which bring litter that is subsequently transferred to other countries (Connan *et al.*, 2021; Miraji *et al.*, 2021). Hence, gyres also have a role in litter transport and climate change. Li *et al.* (2022) stressed that litter accumulated in the gyres significantly contributes to the garbage patch in the Indian Ocean. Another phenomenon, the Mud Banks are annual occurrences along the Arabian Sea that form close to estuarine mouths. These act as breeding grounds for fish while also accumulating marine litter (James *et al.*, 2022). These mud banks act as a sink or litter hotspot, which can affect the breeding of fish and also disrupt the fishery resources along the west coast of India.

Indian subcontinent

India has a coastline of 7517 km consisting of nine maritime states and two union territories on the mainland and two union territories as islands bordered by the Indian Ocean, Arabian Sea, and Bay of Bengal (Kumar *et al.*, 2006; Karthik *et al.*, 2018; Sulochanan *et al.*, 2019). The continental shelf measures 180,000 km^2, and the Exclusive Economic Zone (EEZ) covers about 2.02 million km^2. About 20% of India's overall population (1.4 billion) lives on the Indian coast. Mudflats, beaches, estuaries, streams, mangroves, coral reefs, wetlands, lagoons, and seagrass meadows are the major ecosystems along the coasts of India. These highly productive ecosystems contribute to fisheries and aquaculture, coastal tourism, shipping, mining, and energy, and also provide ecosystem services such as carbon sequestration, water filtration, temperature regulation, and protection from extreme weather events, all of which contribute to food and nutrition security, economic development, and social development. However, these systems are under increasing pressure due to a variety of unsustainable practices, including habitat destruction, pollution, overexploitation, the presence of invasive alien species, and climate change (Biju Kumar *et al.*, 2017). India's coastal regions, home to nearly 170 million of the country's 1.4 billion people, are on the front lines of a shifting climate, experiencing sea-level rise, erosion, and natural disasters such as tropical storms and cyclones (Panda, 2020).

Globally, 4.8 to 12.7 million metric tones of plastic litter enter marine environments annually. Among the global countries, India is ranked 12th in terms of mismanaged waste, which equates to about 0.6 million metric tonnes per year (Jambeck *et al.*, 2015). Out of this, plastic waste amounts to 26,000 TPD. Approximately 9,400 metric tonnes of this end up in landfills or pollute waterbodies. The primary reason for this large quantity of waste entering the water bodies is due to the lack of effective waste management practices and mismanaged plastics from the catchment.

By 2025, India is expected to be the fifth-largest contributor of marine litter, moving up from its current position of

twelve. The Meghna-Brahmaputra-Ganges river system contributes around 73 thousand tonnes of plastic waste that enters the world's oceans each year, ranking it as the sixth most polluted river system in the world (MoHUA, 2019). Shaikh and Shaikh (2021) made a comprehensive review of litter studies from India. According to their review, there is very little information on litter in the Indian context, particularly in freshwater environments and aquatic biota. Notable studies from the northern parts of India include litter studies on the Ganges (Sarkar *et al.*, 2019) and northeastern beaches (Mugilarasan *et al.*, 2021). Some major studies have focused on the coastal regions of the southern states, while the northern states have had sporadic studies. Karthik *et al.* (2018) investigated litter pollution along the Tamil Nadu coast, whereas Robin *et al.* (2020) investigated litter abundance along the Kerala coast. Veerasingam *et al.* (2020) reviewed in detail the abundance of litter based on studies carried out in different regions of India. According to their observation, numerous plastic polymers, such as polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), polystyrene (PS), nylon, polyester (PES), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyurethane (PU), polyvinyl chloride (PVC), and polyamide (PA), are distributed throughout India. The amount of greenhouse gases these polymers could emit is unfathomable.

Plastic production relies on fossil fuels and is a significant source of global greenhouse gas (GHG) emissions at every stage of its lifecycle (Zheng and Suh, 2019). Global plastic production and the amount of plastic entering the ocean are closely linked. The vast majority of plastic in the ocean comes from land-based sources, primarily due to poor waste management practices and inadequate infrastructure for collection, recycling, and disposal (Mugilarasan *et al.*, 2023). Plastic production has been increasing rapidly over the past several decades, with global production exceeding 390.7 million tonnes in 2021 (Plastics Europe, 2022). Much of this plastic is used for single-use products, such as packaging and disposable items, which are often discarded after only a single use (Chen *et al.*, 2021). Many of these plastic products end up in the ocean through a variety of pathways, including littering, improper disposal, and inadequate waste management (Lebreton *et al.*, 2017). Once in the ocean, plastics can persist for hundreds of years (Bratovcic, 2021) and have a range of negative impacts on marine ecosystems and the services they provide to humans (Ajith *et al.*, 2020). Plastics can harm marine wildlife through ingestion and entanglement and can also have negative impacts on the health and functioning of entire ecosystems.

Initiative by G20 countries on marine litter management

Several G20 countries have launched initiatives to address the issue of marine litter. In support of the G20 Implementation Framework for Actions on Marine Plastic Litter, Germany has established the "Clean Seas - One Ocean, Many Worlds" project. The project encourages environmentally friendly trash management practices while simultaneously increasing awareness about the dangers of marine litter. Japan urges individuals and businesses to limit their usage of plastic and promote sustainable waste management practices through the "Plastics Smart" campaign. In order to help limit the amount of plastic debris entering the oceans, the Japanese government has also provided financial assistance to Southeast Asian countries for the construction of waste management facilities. Australia's "National Plastics Plan" promotes circular economy ideas in order to combat plastic pollution.

Canada has introduced a "Zero Plastic Waste Strategy" to combat plastic pollution and encourage sustainable waste management practices. The strategy includes initiatives such as the prohibition of single-use plastics, the promotion of novel recycling technologies, and the investment in waste management infrastructure. The European Union has passed the "Single-Use Plastics Directive," which comprises a number of measures aimed at reducing the use of single-use plastics and encouraging sustainable waste management practices. The directive prohibits the use of certain single-use plastic products, including straws and cutlery, and compels member countries to minimise their usage of other single-use plastics.

As a member of the G20, India has taken a number of measures to address marine trash management. Swachh Bharat Abhiyan: India's national cleanliness programmeemphasises the reduction of plastic waste and the promotion of sustainable waste management practices. The campaign has raised public awareness about the negative effects of plastic trash and advocated the use of sustainable waste management practices. India has enacted Extended Producer Responsibility (EPR) legislation, which forces manufacturers to accept responsibility for the end-of-life management of their products, including plastic packaging waste. The policy

intends to encourage manufacturers to use sustainable packaging and limit the quantity of plastic waste entering the environment.

The laws mandate producers to employ environmentally friendly materials in their goods and contain procedures for the collection, segregation, and disposal of plastic trash. The National Clean Energy Fund was established by India to provide financial support for innovative projects that promote clean energy and sustainable development. The fund has aided efforts such as waste-to-energy projects, which convert garbage into energy while reducing waste entering the environment. The National River Conservation Plan, launched by India, aims to minimise pollution in the country's rivers and encourage sustainable river management practices. The plan calls for the construction of sewage treatment plants as well as the promotion of sustainable agriculture practices to limit the use of hazardous contaminants.

Figure 3: Plastic as a vector of the spread of non-native species.

The Osaka Blue Vision: The G20 members recognise the increasing urgency to tackle the issue of marine litter, especially marine plastic litter and microplastics, on a global scale, further building on existing efforts. At the G20 Hamburg summit in July 2017, the "G20 Action Plan on Marine Litter" was launched. At the G20 Ministerial Meeting on Energy Transitions and Global Environment for Sustainable Growth, Karuizawa held in June 2019, the "G20 Implementation Framework for Actions on Marine Plastic Litter" was established, and endorsed by the G20 Leaders at the subsequent G20 Osaka Summit. As a common global vision, the "Osaka Blue Ocean Vision" was shared by the leaders at the Summit. This vision aims to reduce additional pollution by marine plastic litter to zero by 2050 through a comprehensive life-cycle approach that includes reducing the discharge of mismanaged plastic litter by improved waste management and innovative solutions while recognising the important role of plastics for society.

The Indian G20 Presidency in 2023 is compiling the 5th Report on Actions Against Marine Plastic Litter.

International cooperation on marine litter management

UNEP Countermeasures for Plastic Free-Rivers

India and Japan have joined hands to fight plastic pollution through data collection, advanced scientific research, and development, which will aid both governments in rolling out helpful policies to address plastic pollution in our waterways. The United Nations Environment Programme (UNEP) implemented a project funded by the Ministry of Foreign Affairs (MOFA) and the Government of Japan in collaboration with local partners such as line ministries, academia, and civil society. The project, entitled "Promotion of Countermeasures against Marine Plastic Litter in Southeast Asia and India," aimed to develop countermeasures to reduce plastic waste in the regions of the Mekong Basin, the Ganga Basin, and Mumbai by conducting surveys and outreach activities. The project developed a methodology for identifying plastic leakage pathways in the Mekong region and India. Data collection and surveys in study areas in the Mekong basin, Ganga basin, and Mumbai were conducted based on the developed data inventory. Moreover, the project conducted several outreach activities that linked science with policies and raised awareness among the general public.

India-Norway project for reducing plastic pollution

India and Norway work jointly towards mitigating marine plastic litter and microplastics. The India-Norway cooperation project on capacity building for reducing plastic and chemical pollution in India (INOPOL) is a part of the India-Norway Joint Marine Pollution Initiative and involves partnerships of key Indian and Norwegian organisations working to implement the Stockholm Convention on Persistent Organic Pollutants by providing science-based knowledge and strengthening the local and regional capacity to prevent and mitigate the environmental threat posed by plastic and chemical pollution. The project explores the various dimensions of plastic and chemical pollution in India, with a particular focus on Gujarat, by developing a holistic action plan.

Circular economy solutions for preventing marine litter

India and Germany sign an agreement on 'Cities combating plastic entering the marine environment'. The German Federal Ministry for the Environment (GIZ), Nature Conservation, and Nuclear Safety (BMU) has implemented a circular economy project in collaboration with the Ministry of Environment, Forest, and Climate Change, Government of India, which is operational at NCSCM, Chennai, India. The project supports relevant regulatory authorities, like the Central Pollution Control Board (CPCB) and State Pollution Control Boards (SPCBs) in Kerala, Tamil Nadu, and Uttar Pradesh, in developing and using digital technologies to quantify and track marine litter, monitor leakages in the selected ecosystems, and work on implementing extended producer responsibility (EPR).

Initiatives by the Government of India to tackle marine litter

India has taken several initiatives to address the issue of marine litter management in recent years. Some of these initiatives include:

- In UNEA 5.2, the Government of India worked constructively with all member states to reach agreement on a resolution to drive global action on plastic pollution by establishing an intergovernmental negotiating committee for a new international legally binding treaty.
- The Government of India has launched various initiatives, such as the "Swachh Sagar, Surakshit Sagar (Clean Coast-Safe Sea)" campaign, a 75-day citizen-led campaign for improving ocean health through collective action by removing 15 thousand tonnes of plastic waste from the beaches across India's 7500 km coastline.
- The Ministry of Environment, Forest and Climate Change has notified the Guidelines on Extended Producer Responsibility for plastic packaging under the Plastic Waste Management Rules, 2016. The guidelines on extended producer responsibility, coupled with the prohibition of identified single-use plastic items that have low utility and high littering potential, with effect from July 1, 2022, are important steps for reducing pollution caused by littered plastic waste in the country.
- The Ministry of Environment, Forest and Climate Change has laid down effluent standards under the Environment (Protection) Act, 1986, and the Coastal Regulation Zone (CRZ) Notification, 2011 and 2019, that prohibit the discharge of untreated waste water and effluents into the coast.

COP-26 climate conference in Glasgow Summit: Hon'ble Prime Minister 'Panchamrit' to fight global warming and climate change

The 'Panchamrita' concoction for climate conundrum was suggested by the Hon'ble Prime Minister at Glasgow:

1. India will get its non-fossil energy capacity to 500 gigawatt by 2030
2. India will meet 50 per cent of its energy requirements till 2030 with renewable energy
3. India will reduce its projected carbon emission by one billion tonnes by 2030
4. India will reduce the carbon intensity of its economy by 45 per cent by 2030
5. India will achieve net zero by 2070

Ban on Single-Use Plastics (SUP)

The Government of India has implemented a ban on the use of single-use plastics (SUP) effective July 1, 2022. The SUPs include balloon sticks, cigarette packs, cutlery items including plates, cups, glasses, forks, spoons, knives, and trays; earbuds; sweet boxes; candy and ice cream sticks; invitation cards; polystyrene for decoration; and PVC banners measuring under 100 microns. The following online platforms are in operation for effective monitoring of the ban on identified single-use plastic items and plastic waste management in the country: (a) the National Dashboard for monitoring the implementation of a comprehensive action plan; (b) the CPCB Monitoring Module for Compliance on the Elimination of Single-Use Plastic; and (c) the CPCB Grievance Redressal App.

LiFE-Lifestyle for Environment

The Hon'ble Prime Minister of India launched a global initiative - "Lifestyle for the Environment" (the "LiFE Movement"). A successful amalgamation of this global initiative with beach cleaning, environmental awareness, and a plastic-free life needs collective effort and robust action by the Pro-Planet People. The initiative aims to encourage individuals to adopt more sustainable practises in their daily lives in order to reduce their impact on the environment and promote sustainable development. The Lifestyle for Environment LiFE India initiative includes a range of activities and campaigns to raise awareness of sustainable lifestyle practises, including education and awareness campaigns, sustainable product choices, greening workplaces, and sustainable tourism.

LiFE envisions replacing the prevalent 'use-and-dispose' economy governed by mindless and destructive consumption with a circular economy, which would be defined by mindful and deliberate utilisation. The mission plans to create and nurture a global network of individuals, namely 'Pro-Planet People' (P3), who will have a shared commitment to adopt and promote environmentally friendly lifestyles. Make life a mass movement (Jan Andolan) by focusing on the behaviours and attitudes of individuals and communities. Leverage climate-friendly social norms, beliefs, and daily household practices of different cultures worldwide to drive the campaign.The programme encourages individuals and organisations to take responsibility for their environmental impact and adopt sustainable practices in their daily lives. Overall, the Lifestyle for Environment LiFE India initiative is an important step towards promoting sustainable lifestyles in India and reducing the country's environmental carbon footprint. By encouraging individuals and businesses to adopt more sustainable practises, the initiative can help protect India's natural resources and promote sustainable development.

Policies and recommendations

Plastic Waste Management (Amendment) Rules, 2022

The Plastic Waste Management (Amendment) Rules, 2022 is a set of regulations that were introduced in India to strengthen the management of plastic waste. These rules were enacted to amend the Plastic Waste Management Rules, 2016. The amendment rules were notified on 22nd March 2022 and came into effect from 1st June 2022. The key features of the amendment rules are as follows:

Extended producer responsibility: The amendment rules make it mandatory for producers, importers, and brand owners to have an extended producer responsibility. They are required to collect back the plastic waste

generated from the products they produce or import. This responsibility is applicable to all plastic products except for those that are exempted by the government.

Ban on certain single-use plastic items: The amendment rules ban the manufacture, import, stocking, distribution, and sale of certain single-use plastic items such as earbuds with plastic sticks, plastic flags, candy sticks, ice cream sticks, and polystyrene (thermocol) for decoration. Several Indian states have imposed a ban on single-use plastics, including plastic bags, straws, and cutlery. This ban has helped reduce the consumption of plastic and has encouraged people to use more eco-friendly alternatives.

Registration of manufacturers and recyclers: The amendment rules require manufacturers and recyclers of plastic products to register with the State Pollution Control Board or Pollution Control Committee. This registration will enable the authorities to monitor their activities and ensure compliance with the rules.

Use of recycled plastic: The amendment rules mandate the use of a minimum percentage of recycled plastic in the manufacture of plastic products. The percentage will be determined by the government from time to time.

Penalty for violation: The amendment rules provide for a penalty of up to Rs. 1 lakh for violation of the rules. In case of repeated violations, the penalty may increase, and the registration of the manufacturer or recycler may be cancelled.

Public Awareness: Public awareness campaigns are essential to educate people about the harmful effects of plastic waste on the environment and encourage them to adopt sustainable practices. The government can partner with NGOs and private organizations to conduct campaigns and awareness drives.

The Plastic Waste Management (Amendment) Rules, 2022, is a significant step towards addressing the issue of plastic waste management in India. The implementation of these rules will require the cooperation of all stakeholders, including manufacturers, recyclers, consumers, and the government. Efforts to reduce the plastic litter flux from rivers into the ocean include improved waste management practices, better infrastructure for waste collection and disposal, public education campaigns, and enforcement of litter laws and regulations. In addition, there are initiatives to clean up plastic litter in rivers and the ocean and to promote the recycling and reuse of plastic materials to reduce their impact on the environment. India has been facing a significant challenge in managing its plastic waste. Research and development of new technologies can help manage plastic waste more efficiently. The government has to invest in R&D to develop new materials that are biodegradable and eco-friendly. Various management strategies to regulate litter inputs from major sectors (i.e., municipal waste, tourism, commercial fishing, rivers, and creeks) are given in Table 1.

Table 1. Marine litter management measures in the various sectors.

Sources of marine litter	Measures
Municipal waste 	» Ensure a phase-out or ban on the sale and use of single-use plastic » Waste re-use, recycling, and recovery opportunities shall be maximised prior to landfill disposal » Source segregation and door-to-door collection » Resource efficiency measures for a circular economy shall be implemented » Promote public-private partnership (PPP) in solid waste collection, processing, and marketing in support of the circular economy. » Promote innovative recycling models and the development of alternative packaging materials in cooperation with PROs » Primary collection of waste, street sweeping, and drain cleaning
Tourism	» Sufficient waste reception facilities (Enough waste bins) shall be introduced » Encourage plastic usage reduction in hotels and restaurants (use of biodegradable alternatives such as leaves)

Sources of marine litter	Measures
	» Promote public-private partnership (PPP) in the installation of plastic bottle collection kiosks on tourist beaches » Introduction of plastic bottle recycling units at tourism destinations » Installation of a reverse vending machine for the recycling circle of PET bottles » Ecolabelling of clean beaches shall be encouraged, and plastic free zones » Birthday poppers and balloons shall be banned in tourism destinations
Commercial fishing 	» Encourage financial incentives for fishers to promote the collection of end-of-life (EOL) fishing gear, towards extended producer responsibility (EPR) » Promote adequate reception facilities (RFs), material recovery facilities (MRFs) for plastic, and waste management facilities (WMFs) close to fishing harbours to motivate fishers to bring garbage back to port instead of discarding it overboard » Clean sea initiatives such as the "fishing for litter" campaign encourage fishermen to bring ALDFG to shore-based RFs and WMFs for recycling and reuse. This will help to close the plastic loop (circular economy) in the marine environment » Public outreach and awareness on solid waste management among the fishing community
Rivers and creeks 	» Use of trash booms at strategic locations to delimit at the point of entry (plastic leakage hotspots) and to control their lotic input » Use laundry balls like the "Cora Ball" and "Fibre Free" to capture synthetic fibres in the washing machine » Install coarse screens in storm water lines at strategic locations to prevent the entry of litter into the rivers » End-of-pipe interventions, such as improved wastewater, stormwater, and road runoff management and treatment, are needed to retain the emitted microplastics before they reach water bodies

4.2. Circular economy solutions

The circular economy is an economic model that aims to minimise waste and make the most efficient use of resources (Figure. 1). Instead of the traditional linear "take-make-dispose" model, where resources are extracted, products are manufactured, used, and then discarded, the circular economy promotes a closed-loop system where materials and products are kept in use for as long as possible. This is achieved through strategies such as recycling, reusing, repairing, and refurbishing products and materials. The circular economy also promotes the use of renewable energy and the reduction of harmful emissions, thus creating a more sustainable and resilient economic system. The circular economy is

Figure 1: Circular economy model for closing the loop of marine litter in coastal and marine ecosystems.

gaining momentum as a response to the challenges posed by resource depletion, environmental degradation, and climate change. It offers a way to decouple economic growth from resource consumption and waste generation and to create new business opportunities and jobs in the process (Table 2).

Table 2. Policy suggestions for reducing marine litter.

Policy and recommendations	Measures for litter reduction
Resource efficiency and circular economy 	» Local self-Government (LSG) have to provide seed-funding for circular business models » Develop policies to encourage the adoption of circular business models » Grants to SMEs for eco-innovations for resource efficiency and waste reduction » Develop standards for the use of secondary materials and harmonize waste and material use regulations » Invest in skilling and capacity building for RE » Integrate circular economy approaches into rural development strategies » Consumer awareness and education campaigns » Economically viable circular business models identified and demonstrated. » Circular economy approaches in rural development strategies (eco-smart carbon neutral village) » Collection of end-of-life products, towards extended producer responsibility (EPR) » Technology based waste re-use, recycling and recovery opportunities shall be maximised (eg. end-of-life waste plastic to fuel oil through innovative pyrolysis plant & Municipal Solid Waste Biogas Plant) » Develop standards for the design of products » Resource efficient packaging: resource efficient packaging which is recyclable » Promote partnerships, platforms and networks among stakeholders » Policy coherence and strengthen policy implementation through co-ordination across government agencies and departments » Support eco-start-ups: Incubators and accelerators can provide funding, mentoring, training and other support to start-ups that make resource efficiency and a circular economy
Policy recommendations	» Ban on the use of microbeads in cosmetics » Reducing dependence on raw (plastic) materials and enhance re-use of waste plastic flakes such as PET » Increase the price of verging polymer, subsidize recycled products in markets

Policy and recommendations	Measures for litter reduction
	» Policy reforms to encourage the use of recycled products, Impose a tax on non-recyclable content in packing » Encourage stakeholders in the packaging industry to invest in improving recycling infrastructure » Urban Local Bodies shall encourage the use of plastic waste energy recovery » The standardized procedure should mention the thickness and toxic elements » The standardized procedure should mention the thickness and toxic elements » ROHS compliance should be labelled on plastics, especially toys » Needs to develop of discharge standards for Plastic waste through research studies » Bring all the informal sector of waste pickers into the mainstream » Design for Recycling (DFR). Companies applying this strategy redesign their products and manufacturing processes to maximize the recoverability

Conclusion

A sustainable economy, lifestyle choices, and production methods that prioritise climate, environment, biodiversity, and resource efficiency, as well as a circular economy based on conscious use rather than overuse, require a new paradigm. Reducing global resource consumption, conserving marine and terrestrial biodiversity, reducing greenhouse gas emissions, and impacting the climate are benefits of sustainable lifestyles and decision-making. Climate change and environmental degradation are global phenomena that affect ecosystems and populations in other parts of the world through human activity in one part of the world. Plastic pollution and climate change are associated topics, but due to the smaller sizes of plastics, their harm is often overlooked by policymakers and the public. An estimated 3 billion people, especially those living in coastal areas, could be exposed to extreme climate vulnerability if adequate measures are not taken to adapt to the changing environment. Many policies, including stimulus packages and legislative changes, have been adopted around the world over the past two decades to combat marine litter pollution and climate change. Despite its great potential, little attention has been paid to action at the individual, community, and organisational levels. Sustainable lifestyle changes from an individual's perspective can be more effective than community-based changes. Individuals practising lifestyle changes can be called "Pro-Planet-People".

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