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Research Article

Reframing Indian Coastal Aquaculture and Fisheries: An IPCC Risk Assessment Framework Perspective

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ABSTRACT

The work examines the critical state of India's coastal aquaculture and fisheries, which are under pressure from climate change, overfishing, and unsustainable practices. Despite their economic and food security importance, these sectors are vulnerable to sea-level rise, ocean acidification, and extreme weather events. To enhance resilience, the paper suggests adopting a risk assessment framework inspired by the IPCC, focusing on climate-smart aquaculture, improved fisheries governance, and community adaptation. It also discusses the ecological impacts of fishing, such as "fishing down the food chain" and habitat destruction, and the potential of coastal aquaculture as a sustainable alternative. The Central Marine Fisheries Research Institute (CMFRI) is recognized for its role in developing sustainable aquaculture technologies. The interventions aim to protect marine biodiversity, ensure food security, and strengthen coastal economies, advocating for a holistic approach that integrates ecological and socio-economic considerations. It also provides detailed coastal demographics and fisher folk statistics, underscoring the need for tailored interventions and community involvement in coastal management. The work concludes by emphasizing the urgency of sustainable practices and global cooperation to secure a resilient future for India's coastal aquaculture and fisheries.

Key words: Climate change, Coastal aquaculture, Climate-smart aquaculture, Integrated multi-trophic aquaculture (IMTA), Mission LiFE, Overfishing

Introduction

India's coastal aquaculture and fisheries sectors find themselves at a critical stage, navigating a complex interaction of challenges that threaten their sustainability, resilience, and socio-economic contributions. As the world's third-largest producer of farmed seafood, with over 80% of aquaculture production stemming from coastal regions, India's reliance on these sectors for food security and economic stability is undisputable. However, the rising risks posed by climate change, overfishing, and unsustainable practices necessitate a comprehensive examination of the current state and a visionary framework for the future. In 2022, India's marine fisheries played a significant role globally, contributing 3.69 million tonnes (CMFRI, 2023a) of marine resources and simultaneously, the inland sector produced 12.12 million tonnes (Govt. of India, 2022a), securing India's position as a major player in the global fisheries landscape. The socio-economic implications are significant, with over 10 million people employed and a contribution of over 1.24 % to the country's Gross Value Added (GVA) (Govt. of India, 2022b). However, under these striking figures lies a vulnerable scenario. Climate change, marked by sea level rise, ocean acidification, and extreme weather events, pose impending threats. Sea

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level rise and coastal erosion threaten infrastructure, while ocean acidification hampers the growth of marine organisms. Changes in water temperature and salinity disrupt crucial life cycles, and the increased frequency of extreme weather events poses imminent danger to aquaculture farms and fishing activities. To address these challenges, this article proposes the adoption of a risk assessment framework inspired by the Intergovernmental Panel on Climate Change (IPCC) guidelines. This framework aims to reframe indian coastal aquaculture and fisheries for enhanced climate resilience. The strategies encompass implementing climate-smart aquaculture practices, enhancing fisheries management and governance, and building adaptive capacities within coastal communities. This approach acknowledges the interrelation of ecological and socio-economic systems, emphasizing the need for a holistic response to climate-induced stressors.

Beyond the realm of climate change, the article explores the enduring impacts of fishing on marine ecosystems. "Fishing down the food chain" disrupts predator-prey relationships, altering ecosystem productivity (EPA, 1999). Habitat disruption caused by fishing gear, such as bottom-trawling, leaves unseen problems on critical habitats like coral reefs and sea grass meadows. The persistent impact of "ghost fishing," where lost gear continues to entangle and kill marine life, further compounds the challenges faced by marine ecosystems (Kripa *et al*., 2013). Ocean warming, driven by increased greenhouse gas concentrations, is reshaping species distributions and migration patterns. Ocean acidification, resulting from the absorption of atmospheric carbon dioxide, poses a threat to calcifying organisms like corals and shellfish. Sea level rise, fuelled by global temperature increases, inundates coastal habitats, displacing marine life and increasing the risk of flooding and erosion. The article unveils the potential of coastal aquaculture as a sustainable alternative to traditional fisheries. Coastal aquaculture not only addresses global seafood demand but also minimizes the impact on wild fish populations and provides economic benefits, including employment opportunities and economic diversification for coastal communities. Central to the success of coastal aquaculture is the pioneering role played by the Central Marine Fisheries Research Institute (CMFRI). CMFRI's multifaceted contributions, ranging from species selection and culture techniques to disease prevention and management, underscore the institute's commitment to sustainable aquaculture development. The article highlights the success stories of CMFRI's cage culture projects, demonstrating innovative systems for different aquatic species and environments. As we navigate the crossroads of climate change, overfishing, and the pursuit of sustainable practices, this article concludes by emphasizing the urgent need for science-based interventions. Whether reframing indian coastal aquaculture and fisheries or advancing sustainable practices like cage culture, the main goal is to preserve marine biodiversity, ensure food security, and strengthen the economic resilience of coastal communities. Through collective efforts, informed policies, and global cooperation, we strive to secure a resilient and sustainable future for India's coastal aquaculture and fisheries.

The 2016 Marine Fisheries Census of India revealed that the coastal communities in India encompass 3,477 marine fishing villages, housing a total population of 37,74,577 marine fishermen along the Indian coast, spread among nine coastal states and the union territories of Puducherry, Daman & Diu, Lakshadweep, and Andaman & Nicobar. The total number of marine fish landing centres in the country is 1,363 with maximum number of 349 (25.6%) in Tamil Nadu followed by 234 (17.2%) in Andhra Pradesh and 174 (12.8%) in Kerala. There are 8,93,258 marine fishermen families residing in the maritime states and Union Territories, with 2,01,855 (22.6%) in Tamil Nadu, 1,55,062 (17.4%) in Andhra Pradesh and 1,21,637 (13.6%) in Kerala, topping the list. Nearly 91.6% of the families are traditional fishermen families. In the country 6, 00,890 marine fishermen families are below poverty line (BPL) which is 67.3% of the total number of families (Table 1).

Indian coastal regions are often been affected by frequent climate-induced natural disasters such as cyclones, floods, shoreline changes, sea level rise, marine heatwaves, and other related hazards in recent decades. In general, when we look into the entire coastline of India, we have a serious issue with respect to the risk the coast is facing.

Table 1. Coastal Demographics and Fisherfolk Statistics: A State-wise Overview in India, based on Marine Fisheries Census (2016)

State	Coastal length	Landing centres	Fishing villages	Fishermen families	Traditional fishermen families	BPL families	Fisherfolk population
West Bengal*	158	49	111	81,067	56,447	55,301	3,68,816
Odisha	480	55	739	1,15,228	92,569	48,601	5,17,623
Andhra Pradesh	974	234	533	1,55,062	1,52,062	1,50,669	5,17,435
Tamil Nadu	1,076	349	575	2,01,855	1,96,784	1,83,683	7,95,708
Puducherry	45	22	39	14,347	14,328	12,968	50,270
Kerala	590	174	220	1,21,637	1,16,598	72,507	5,63,903
Karnataka	300	84	162	32,479	30,897	27,312	1,57,989
Goa	104	32	41	2,986	2,922	650	12,651
Maharashtra	720	155	526	87,717	80,906	27,400	3,64,899
Gujarat	1,600	107	280	67,610	64,395	19,123	3,54,992
Daman & Diu	21	8	12	3,163	3,094	20	15,836
Lakshadweep**	132	37	10	4,163	3,003	1,170	27,934
Andaman &Nicobar***	1,962	57	169	5,944	4,486	1,486	26,521
Total	8,162	1,363	3,477	8,93,258	8,18,491	6,00,890	37,74,577

*Subsequent reference to villages means Gram Panchayat in West Bengal. **Fishing islands. ***Landing centres/Landing points

Impact of cyclones

The impact of cyclones on coastal villages in India presents a complex challenge, encompassing severe consequences for communities residing along the shoreline. These cyclonic events result in extensive damage to infrastructure, disrupt livelihoods, particularly affecting fishing communities, trigger humanitarian crisis marked by displacement and loss of life, and contribute to environmental degradation through saltwater inundation and ecosystem destruction. Remarkably, the period from 2006 to 2020 the Indian coastline witnessed a total of 61 cyclonic disturbances, with Odisha experiencing the highest frequency (20), followed by West Bengal (14), Andhra Pradesh (11), and Tamil Nadu (11) (Kantamaneni *et al*., 2022) (Fig. 1a). The recent study depicting the spatial variability of cyclone hazards along Indian coast also indicates Odisha and West Bengal having high Cyclone Hazard Index values and Kerala the lowest among Indian states (Reshma *et al.*, 2024) (Fig. 1b). Specifically, the aftermath of cyclone Ockhi in the mechanized and outboard ring seines along the Kerala coast revealed a decline in the abundance of planktivorous fishes, such as oil sardines, lesser sardines, Indian mackerel, and *Stolephorus* spp. (Punya *et al*., 2023). Although there was an increase in their catch in the post-cyclone months, it failed to reach the levels comparable to the pre-cyclone period. Notably, the resource assemblage in trawl nets underwent a significant shift, with reduced occurrences of fish species such as scads, croakers, and penaeid shrimps during the cyclone, gradually recovering in the post-cyclone period. This underscores the far-reaching implications of cyclones on both socio-economic and ecological aspects of coastal regions, necessitating a comprehensive understanding for effective mitigation and adaptation strategies.

Flood proneness

Floods pose a critical and multifaceted challenge to coastal Indian states, impacting human settlements, infrastructure, and ecosystems. With a historical context marked by monsoon rains, cyclones, and storm surges, coastal regions in states like Kerala, Maharashtra, Goa, Karnataka, Gujarat, and West Bengal face recurrent inundation. Study by Reshma *et al*. (2024) indicating Kerala having the higher

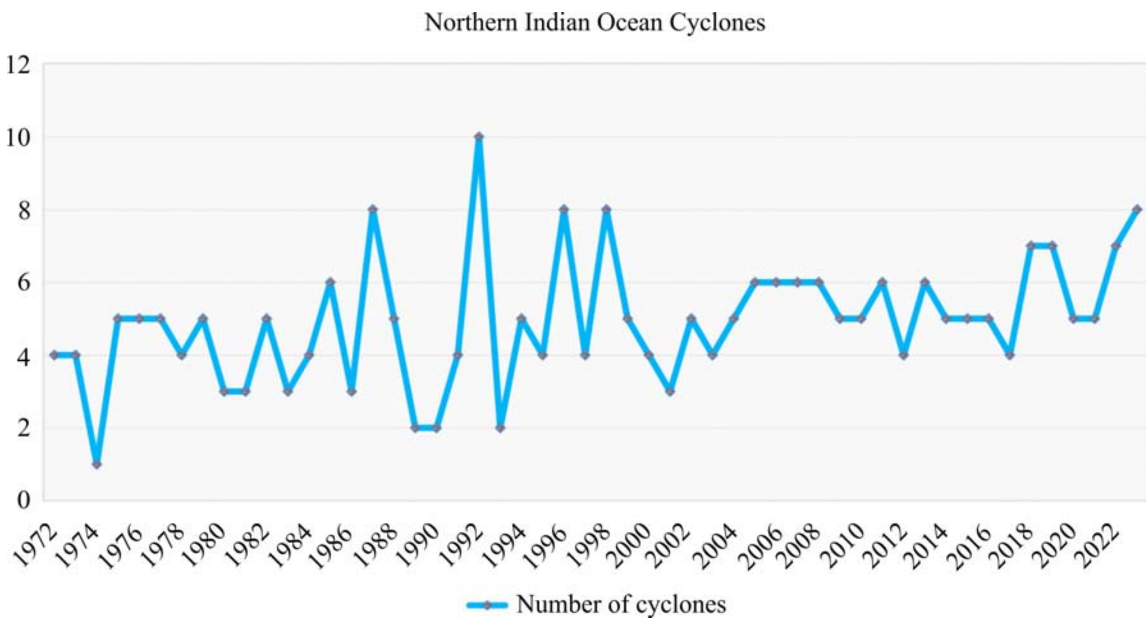

Fig. 1a. Number of cyclones in northern Indian Ocean from 1972 to 2022 - department of atmospheric science Colorado State University

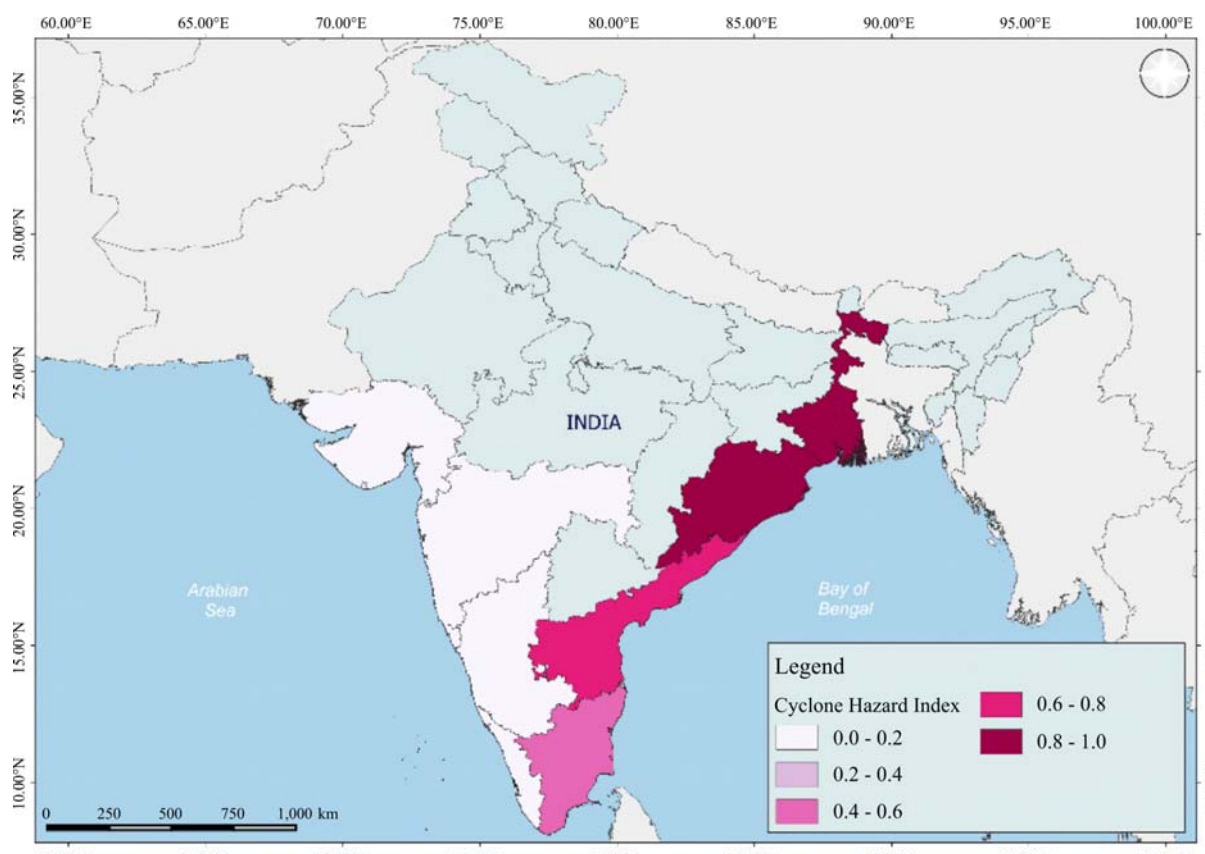

Fig. 1b. Cyclone Hazard Index of coastal states based on Reshma *et al*. (2024)

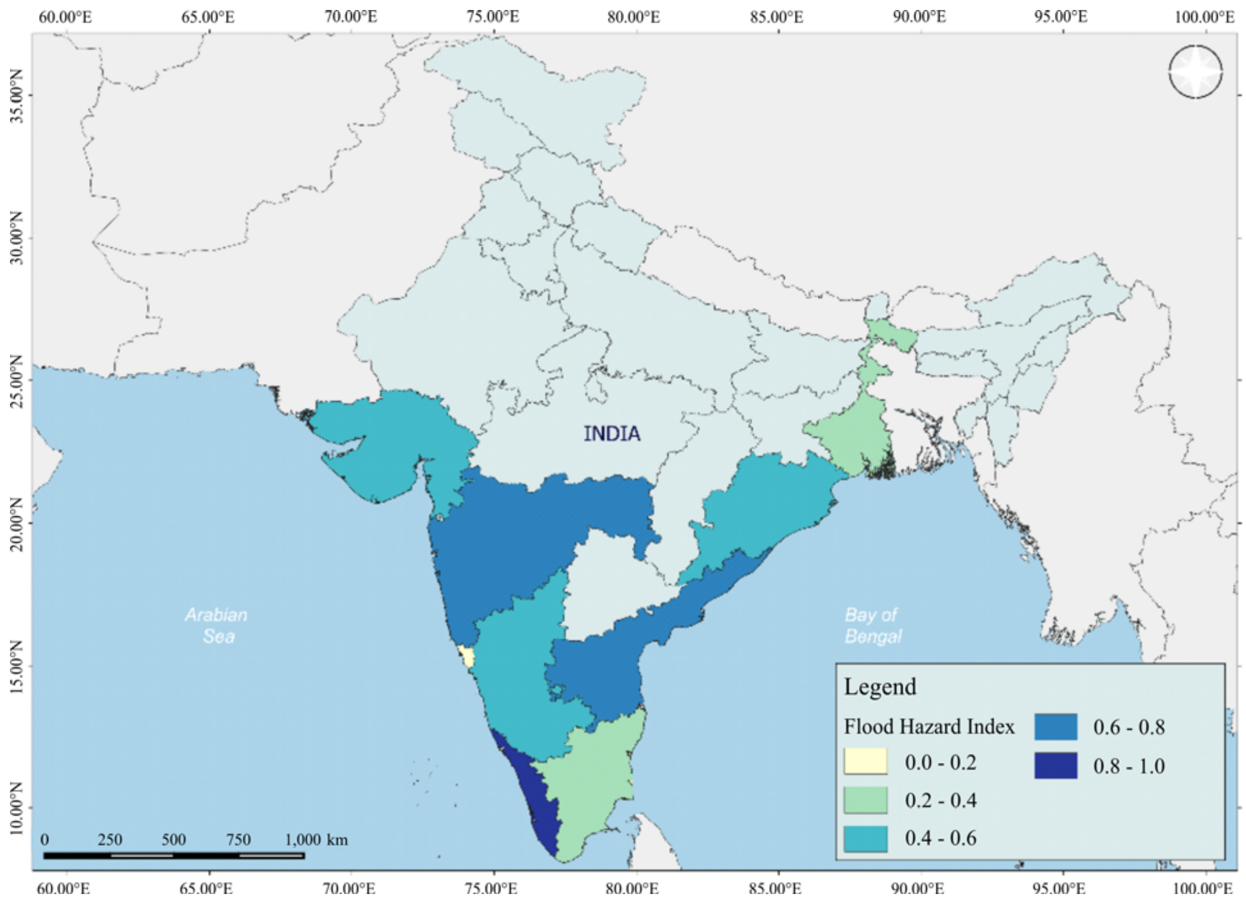

Fig. 2. Flood Hazard Index of coastal states based on Reshma *et al.* (2024)

Flood Hazard Index and Union territries of Goa and Pondicherry with the lowest among the coastal states affirms the threats imposed by flood (Fig. 2). The consequences are profound, leading to displacement, loss of life, damage to homes, and disruptions in the livelihoods of fishing communities, exacerbating economic challenges. Agriculture and tourism sectors also suffer as floodwaters damage crops, degrade soil, and deter visitors. Beyond the human and economic toll, floods contribute to environmental degradation, affecting coastal ecosystems and biodiversity. The 2018 flood event in Kerala, India, killed 433 people and displaced more than 1 million people from their homes (Young *et al*., 2022). In case of Odisha, floods emerge as a significant concern due to the presence of numerous perennial rivers traversing the state. The intensity of floods is more severe, especially during the cyclone period, causing more damage to the coastal districts in comparison to other districts of the state. Approximately 21% of Odisha's total area, equivalent to 3.34 million hectares, is classified as flood-prone, with 75% of this area concentrated across eight districts (Bahinipati, 2014). A notable increase was noticed in the frequency of floods and the number of affected districts during the last decade compared to the preceding periods.

Shoreline changes

Shoreline changes in india have become a critical area of study due to the dynamic nature of coastal environments, influenced by natural processes, anthropogenic activities, and global climate change. The vast indian coastline, extending over 8,118 kilometers, is home to diverse ecosystems, human settlements, and economic activities, making it imperative to understand the patterns, drivers, and implications of shoreline changes. Several factors contribute to shoreline changes, natural processes such as erosion, sedimentation, and sea-level variations, compounded by anthropogenic factors comprise coastal sand mining, river water conservations projects intercepting sediment, coastal engineering to enhance waterpower, beach vegetation damage (Baig *et al*., 2020). The impacts of climate change, including rising sea levels and changing storm patterns, further contribute to the complexity of shoreline dynamics. Shoreline changes exhibit regional disparities along the Indian coast. While erosion is pronounced in some areas, others experience accretion. The vulnerability of certain coastal stretches to erosion is exacerbated by factors such as subsidence, lack of sediment supply, and inappropriate land use practices. Accretion, on the other hand, may result from sediment deposition, riverine inputs, or coastal engineering interventions. The coast of Tiruvallur in Tamil Nadu is shrinking and changing as it becomes increasingly vulnerable to storms, flooding and other natural disasters, which cause coastal erosion and the retreating of shore line where in some locations, up to two meters has disappeared over the same period (Jayakumar, 2021). West Bengal characterised with highest shore line change hazard index also indicates the threats imposed by shore line changes (Reshma *et al*., 2024) (Fig. 3). It was suggested that mangrove loss is anticipated in the future due to shoreline changes and sea level rise, particularly with the formation of sand spits in the mouth region which reduce tidal water inflow, leading to a decrease in mangrove extent (Jayanthi *et al*., 2017).

Marine heat waves

Marine heat waves (MHWs) are phenomena characterized by prolonged periods of anomalously high sea surface temperatures, with potential far-reaching consequences for marine ecosystems and coastal environments. MHWs have profound effects on marine ecosystems, disrupting biodiversity, altering species distribution, and causing mass

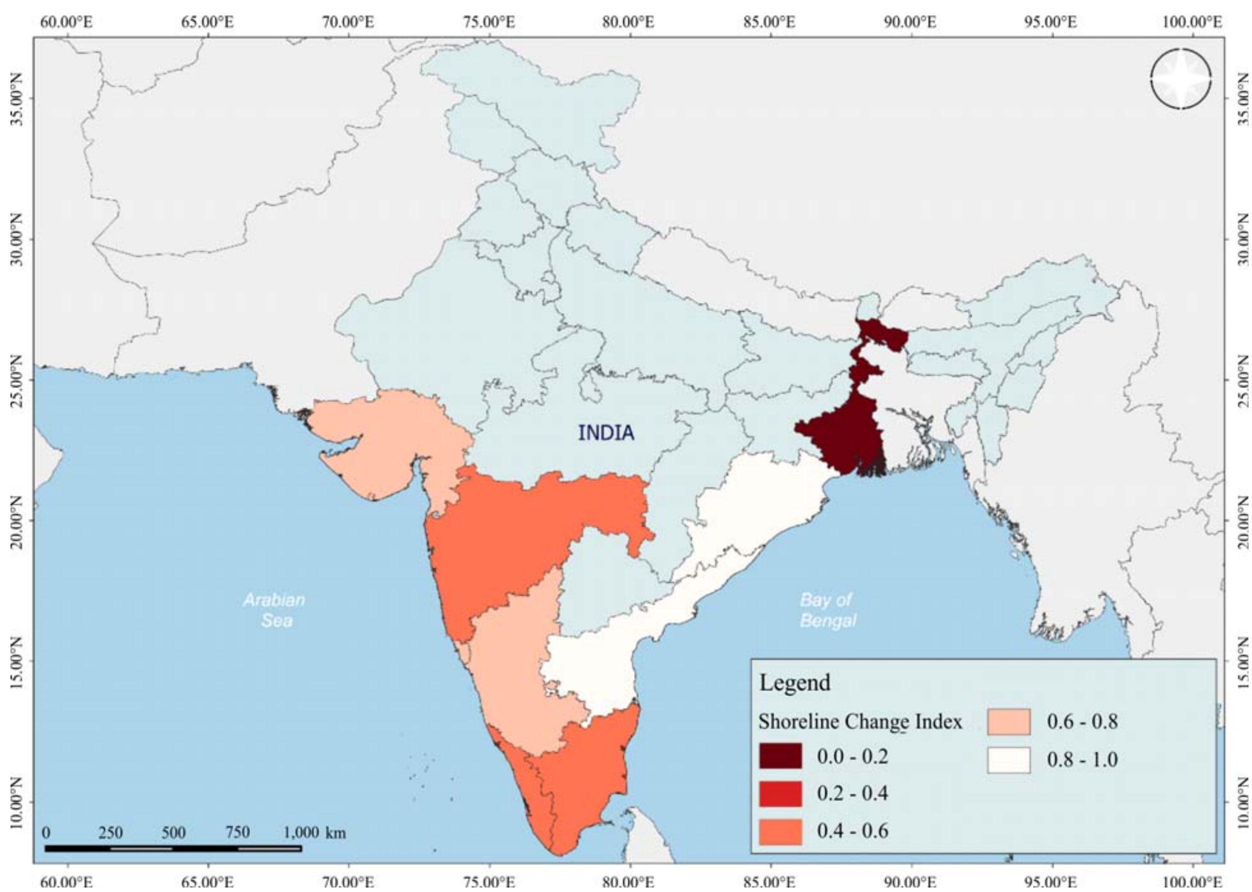

Fig. 3. ShoreLine change Hazard Index of coastal states based on Reshma *et al*. (2024)

bleaching events in coral reefs. They also impact the abundance and distribution of marine species, influencing fisheries and posing economic challenges for coastal communities dependent on marine resources. Coastal regions face socio-economic consequences due to MHWs. Fisheries are severely affected, leading to declines in catches and economic losses for fishing communities. Additionally, MHWs can result in the loss of tourism revenue, damage to coastal infrastructure, and increased vulnerability to extreme weather events. The northern and southeastern Arabian Sea demonstrate a significant and multi-fold increase in the duration (frequency) of MHW, with a rapidly rising trend of 20 days per decade since 1980s; notably, the years 2010 and 2016 stand out, exhibiting the highest number of 15 heatwave days, where over 75% of pre-monsoon and summer-monsoon season days are characterized by heatwaves (Chatterjee *et al*., 2022). Highest Heatwave Hazard Index for Andhrapradesh corroborates the threats faced by the coastal states of India (Reshma *et al*., 2024) (Fig. 4).This rapid increase in heatwave days in the northern and southeastern Arabian Sea is also likely to cause a severe impact on the physio-biogeochemical processes.

Sea level rise

Sea level rise indicates the sustained increase in the mean level of the earth's oceans over an extended period. This phenomenon is primarily associated with global climate change, a consequence of the earth's atmospheric warming and its subsequent influence on the melting of polar ice caps and glaciers. The key contributors to the increase in sea levels involve the melting of polar ice caps and glaciers, as well as the expansion of seawater as it absorbs additional heat. The processes leading to sea level rise are intensified by climate change-induced factors, particularly the escalating emissions of greenhouse gases. Sea level rise (SLR) will exhibit non-uniform

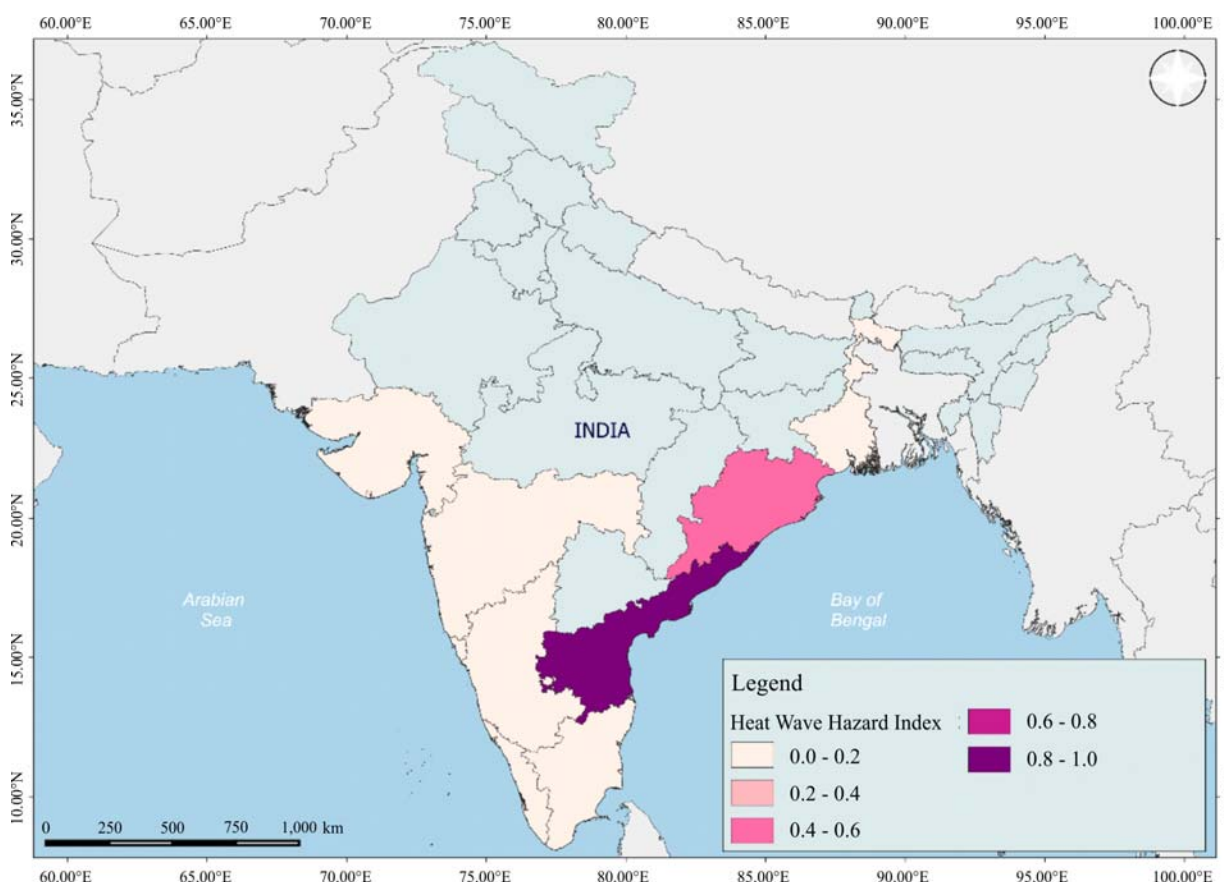

Fig. 4. Heatwave Hazard Index of coastal states based on Reshma *et al*. (2024)

spatial patterns, indicating that certain regions may undergo significantly faster and larger local SLRs than the global mean, while others may experience SLRs well below the global average or even negative, therefore each coastal community should formulate its unique strategy to address SLR based on its specific spatial variations (Yin *et al*., 2010). In Tamil Nadu, vulnerability of Kanyakumari's coastal areas to inundation was evaluated under projected sea level rise scenarios of 0.5 and 1 m, revealing that approximately 13 km² of land in Kanyakumari would face permanent submersion, resulting in land loss, changes to the coastal zone, and adverse effects on the coastal ecosystem (Natesan and Parthasarathy, 2010). Recent study conducted in West Bengal have pointed out that not only climate-related alterations but the direct human interventions of reservoir impoundment and groundwater depletion have individually contributed to sea level changes of at least several tenths of a millimeter per year (Church *et al*., 2013). High Sea Level Rise Hazard for Daman and Diu followed by Gujarat being the most prone states along the India coast as observed by Reshma *et al*. (2024) affirms the threats generated by Sea Level Rise (Figure 5).

Microbial impact due to climate change

In the current scenario, the impacts of climate change are evident in events such as drinking water shortages caused by the contamination of water with sewage, resulting in substantial losses and damages to both property and human lives. As per the Indian Council for Research on International Economic Relations (ICRIER) report, it is predicted that the working community in the area will lose 14% of their yearly working days (more than 51 days in a year) owing to water-associated illness, causing significant economic repercussions. The prevalence of such diseases is on the rise, further exacerbated by factors like sea level rise and water mixing. As temperature rises, the microbial load in water increases, promoting an environment favorable to the

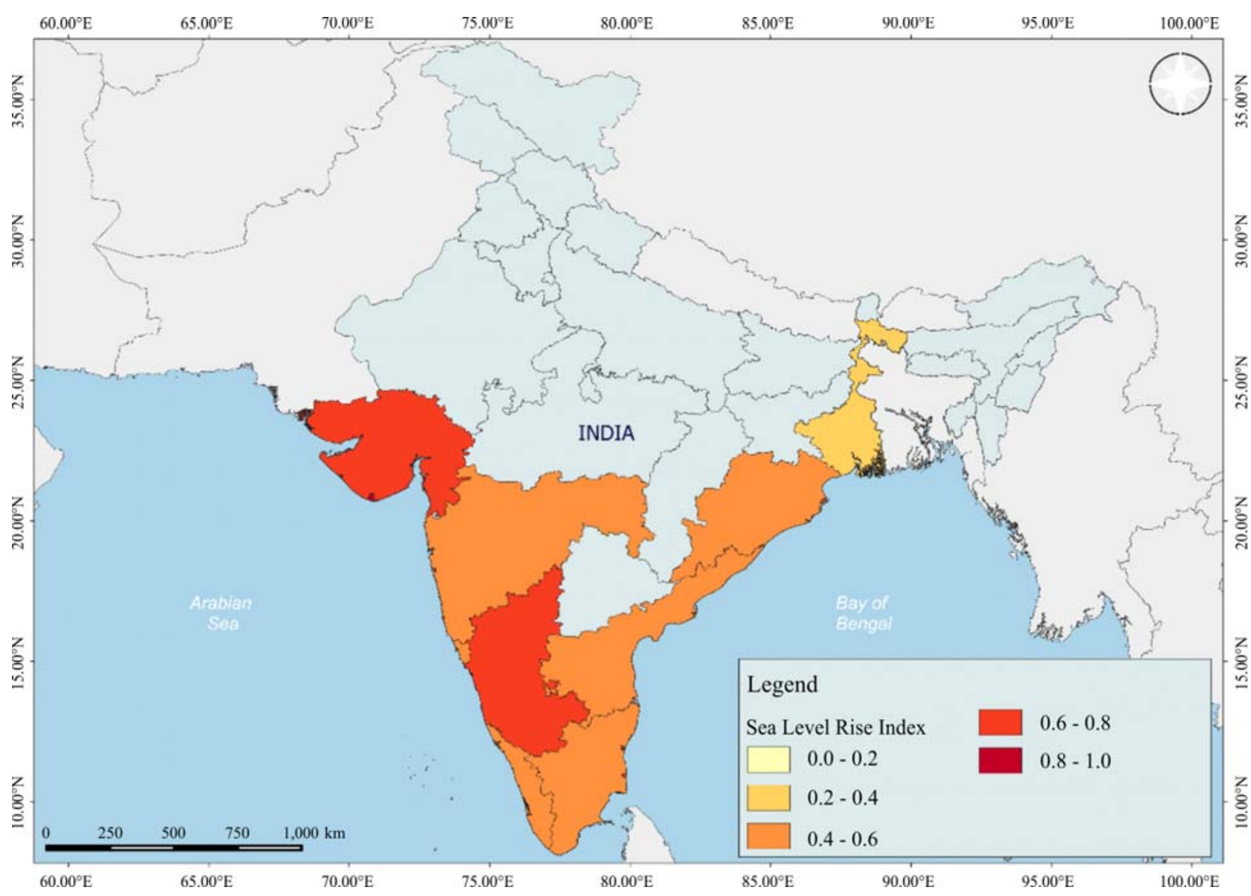

Fig. 5. Sea Level Rise Hazard Index of coastal states based on Reshma *et al.* (2024)

proliferation of disease-causing organisms. This phenomenon not only poses a direct threat to marine ecosystems but also has profound implications for human health. The direct correlation between temperature increase and microbial load in water has been well-established. As temperatures rise, microbial organisms thrive, creating conditions that contribute to the spread of waterborne diseases. Field studies conducted worldwide over the last 40 years have clearly showed the number of *Vibrio* in estuarine and coastal waters is strongly associated with seasonal temperature. In temperate regions of the world the abundance of *V. cholerae* and *V. parahaemolyticus* show a strong seasonal oscillation with higher abundances generally observed during the warmer season of the year (Vezzulli *et al*., 2013). The consequences of increased microbial load are multifaceted, encompassing the emergence of new diseases that pose threat to both aquatic life and human populations residing in coastal areas.

In addressing the complex challenge of microbial load escalation and its associated health risks, the One Health approach emerges as a comprehensive and holistic solution. The One Health concept recognizes the interconnectedness of environmental, animal, and human health, understanding that the health of one component is intricately linked to the health of the others. In the context of coastal regions, the One Health approach becomes particularly relevant. In the case of increased microbial load due to temperature variations, the One Health approach advocates for collaborative efforts between environmental scientists, veterinarians, and public health professionals. The application of the One Health approach involves not only understanding the dynamics of microbial organisms in coastal waters but also implementing measures to mitigate the impact on human health. This includes the development of sustainable water management practices, the monitoring of microbial indicators in water bodies, and the establishment of early warning systems for potential disease outbreaks.

Effect of invasive aquatic plants on the ecosystem

The invasion of new species in freshwater ecosystems is a harmful change, resulting in considerable damage and negatively affecting the functional and structural organization of ecosystem's. Aquatic weeds, particularly *Eichhornia*, are on the rise, leading to adverse effects on the normal flow of water. Typically thriving in saline water, these weeds trap rainwater during the rainy season, creating stagnant pools that serve as breeding grounds for mosquitoes contributing to the transmission of vector-borne diseases (Hassan and Nawchoo, 2020). The mosquito population is consequently increasing in the affected areas. To monitor and identify the growth of these aquatic weeds, advanced satellite and remote sensing studies prove to be valuable tools. When a surge in aquatic weed population is detected, prompt measures need to be taken to mitigate its impact. This could involve implementing strategies to reduce the proliferation of *Eichhornia* or disseminating early warning information to the local community. By adopting timely and effective measures, communities can proactively address the challenges posed by the increase in aquatic weeds and the associated rise in mosquito populations, promoting a healthier and more sustainable environment.

Adaptation strategies to mitigate climate change

Climate-resilient fisheries management

CMFRI's extensive database, encompassing information on more than 1200 marine fish species (CMFRI, 2018), plays a vital role in unravelling the richness and diversity of marine life in indian waters. CMFRI conducted assessments on 135 commercially significant marine fish stocks (Marine Fish Stock Status (MFSS) yielding surprising results shows a striking 91.1% of these stocks were deemed to be in good health (CMFRI, 2023b). While highlighting the immense potential within the indian Exclusive Economic Zone (EEZ), estimated at 5.31 million metric tons (DADF, 2018) annually, these assessments emphasize the sustainable nature of marine resources. Even if MFSS revealed that most of the fish stock is in good health, certain species exhibited lack of climate resilience. This underscores the necessity for a comprehensive approach to fisheries management that integrates climate considerations.

The impact of climate change on fish stocks has introduced a series of challenges that necessitate careful consideration. First and foremost, there has been a notable increase in recruitment failures among fish populations, disrupting their natural replenishment processes. Additionally, phenological issues have arisen, causing shifts in the timing of crucial biological events. These shifts, in turn, have led to changes in the distribution and abundance of marine species (Vivekanandan, 2010). Furthermore, despite an overall decrease in abundance, fishing efforts remain consistent, resulting in a range of associated problems. A largely concerning trend is the reduction in the abundance of preferred fish species, accompanied by the emergence of non-preferred alternatives. This shift not only poses practical challenges for fishermen but underscores the necessity for adaptive strategies. Amid these challenges lies a potential opportunity for strategic fisheries management.Underutilized resources like jellyfish and pufferfish, traditionally overlooked, present untapped potential. Utilizing these species for export, coupled with the dissemination of jellyfish bloom advisories to fishermen, could signify a transformative approach, mitigating climate change's adverse effects on traditional catches and promoting the development of a strong value chain around these alternative resources. However, incorporating these less-favored species into the traditional fishing framework presents its own set of challenges. Fishermen express legitimate concerns about potential damage to their gears and the subsequent impact on the harvest of preferred species. Addressing these complexities is pivotal in steering toward a sustainable and resilient future for Indian coastal aquaculture and fisheries. Achieving a delicate balance between exploiting alternative resources and preserving traditional catches demands nuanced strategies and collaborative efforts, marking a transformative phase in marine resource management.

IMTA-Integrated Multi-Trophic Aquaculture

As a diversified alternative livelihood option people are resorting to different activities, associated with water. Coastal aquaculture is coming as a big alternative, cage farming is taken up in different places, and refined technologies related to cage farming are taking form as part of the revolutionary activities. A typical example is that of Integrated Multi-Trophic Aquaculture (IMTA), a farming method that involves raising multiple aquatic species from different trophic levels together. In IMTA practiced in Palk Bay, cage culture of cobia is done along with sea weed, *Kappaphycus alvarezii* in floating rafts set around the cages. All the additional nutrients that come from these cages are taken by the seaweed in the raft so there is additional income for the farmers. At the same time sea weeds utilize atmospheric carbon dioxide, so this practice turns into a climate resilient greener technology. So additional profiting coming is good for the environment and beneficial for the farmers as there are more opportunities available for the rural youths in the coastal areas to come up with such technologies (Johnson *et al.*, 2019).

Revitalizing essential fish habitats: Approach to sustainable fisheries

The essential fish habitats in oceans encompass critical ecosystems such as coral reefs, seagrass beds, seaweeds, mangroves, and salt marshes. These habitats play a pivotal role in supporting the complete life cycles of numerous marine species. The destruction of these habitats poses a significant threat to fish abundance, impacting the ecological balance of coastal and deep-sea resources alike (Simard *et al.*, 2016). Despite the vast expanse of deep-sea environments, many fish species, particularly those with critical life stages such as larvae and juveniles, depend on nearshore areas, emphasizing the indispensable nature of essential fish habitats. In addressing the challenges posed by climate change, the United Nations Framework Convention on Climate Change (UNFCCC) has recognized the importance of essential habitats and has incorporated mangrove reforestation as a major activity in binding treaties (Fuchs and Noebel, 2022). According to the Global Forest Resource Assessment, 2020 (FRA, 2020), Asia has the largest mangrove area, spanning 5.55 million hectares.The Forest Survey of India's 2021 (FSI, 2021) report reveals that the country's mangrove cover is 4,992 square kilometers, reflecting a net increase of 17 square kilometers compared to the 2019 assessment. This growth in mangrove cover is primarily attributed to natural regeneration and strategic plantation activities in suitable areas, such as along riverbanks near estuaries and on intertidal mud-flats that experience daily inundation by seawater. However, the situation is diverse for seaweed, seagrass, and corals. While mangroves show improvement, the restoration and conservation efforts for seaweed, seagrass, and corals are crucial. Seaweeds, despite their commercial importance, are yet to be developed into a robust industry with a strong value chain. A strategic focus on developing a production-to-end-user value chain could unlock the potential of seaweed as a viable farming species. The situation is different for seagrass, which, though not commercially important, serves as a crucial ecosystem for various species, including Dugong and sea turtles. The conservation of seagrass beds is integral to maintaining the populations of these species, emphasizing the broader importance of biodiversity and coastal environmental management. Therefore, a comprehensive approach to habitat restoration, coupled with effective monitoring and assessment, becomes paramount. In addressing the complexities of sustaining essential fish habitats, a holistic strategy that integrates environmental conservation, sustainable fisheries management, and the development of viable value chains is essential for navigating indian coastal aquaculture and fisheries towards a more resilient and sustainable future.

A critical aspect of the revival and restoration of ecosystems is the implementation of artificial reefs, reforestation initiatives, and coral transplantation efforts. The challenges associated with these approaches are met with innovative solutions aimed at enhancing the ecological balance and sustainability of marine resources. The Central Marine Fisheries Research Institute (CMFRI) plays a pivotal role in habitat restoration through the strategic deployment of artificial reefs (Kizhakudan *et al.*, 2023). This initiative extends across four states, encompassing 132 locations and incorporating a remarkable 26,575 reef units, covering a total area of 0.37 million square meters (37 hectares). The outcomes of these endeavors have been nothing short of impressive, manifesting in a notable 17 to 30% increase in fishery yields. This evident success underscores the positive impact of habitat restoration on marine ecosystems, emphasizing the potential of such initiatives to contribute significantly to the overall health and resilience of coastal aquaculture and fisheries. Furthermore, the expansion of these habitat restoration efforts not only showcases the efficacy of artificial reefs but also highlights the need for broader reforestation and coral transplantation programs. These endeavors, when strategically employed, have the potential to further enhance biodiversity, protect critical marine habitats, and secure the livelihoods of coastal communities dependent on fisheries.

Mitigating anthropogenic impact on marine fisheries: Circular economy approach

The challenges posed by anthropogenic activities in indian coastal aquaculture and fisheries demand a thorough examination of the sources of pollution and effective strategies to tackle them. A significant concern arises from the discharge of terrestrial pollutants into oceans, a situation historically believed to be alleviated by the natural buffering capacity occurring over extended periods. Despite the current perception of these discharges as relatively harmless, they contain potent pollutants that hold the potential for significant and lasting impacts in the future. Industrial waste, agricultural runoff, sewage discharge, plastic pollution, oil spills, and radioactive waste have severe consequences on marine ecosystems, impacting marine mammals, birds, and reptiles (Quayle, 1992; Sharma and Chatterjee, 2017). While industrialization contributes to economic development, it results in environmental disasters by contaminating surface water, groundwater, and soil (Ho *et al.*, 2012). Agricultural activities further contribute to pollution through the release of nutrients, pesticides, and chemicals (Ahuja, 1986). The discharge of radioactive waste into oceans raises concerns about long-term hazards (Ervin, 1971). Additionally, human activities introduce microplastics globally, affecting shorelines and freshwater bodies (Sharma and Chatterjee, 2017). The influence of human-induced CO_2 emissions leads to ocean acidification, highlighting the urgent need for sustainable practices (Laffoley and Baxter, 2019). Addressing these concerns requires a proactive strategy, including the removal of hazardous chemicals from coastal regions. Monitoring pollutants from upstream to lower stretches is crucial, necessitating the establishment of a citizen science network, as demonstrated in the successful pilot program in Vembanad Lake (George *et al.*, 2021). Expanding such solutions and comprehensive monitoring systems empower communities to actively participate in safeguarding their coastal environments. To prevent water eutrophication under climate change, governance measures controlling external sources of nutrients, such as waste discharges and non-point pollution, are crucial, as internal nutrient loading could still lead to eutrophication (Chakrabarti, 2018). A comprehensive approach is essential for mitigating pollution and protecting marine ecosystems for future generations.

Implementing circular economy principles in solid waste management, particularly in plastic management, emerges as a crucial strategy in addressing terrestrial waste concerns and positively impacting marine ecosystems. The focus on managing waste on land significantly reduces the prevalent practice of dumping waste into the sea, emphasizing recycling and reuse processes within terrestrial environments. To eliminate the adverse effects of plastic waste, proper recycling is essential, aiming to reduce waste and remake recycled material into useful plastic products (Sureshkumar *et al.*, 2020). Plastic manufacturers, waste managers, and the public play vital role in the development of the recycling sector, contributing to a more sustainable waste management system. Recent studies provide insights into plastic pyrolysis technology, showcasing trends and innovations worldwide and their alignment with circular economy objectives (Sakthipriya, 2021). The urgent challenge of plastic waste pollution in marine and terrestrial environments necessitates multilevel actions from various stakeholders, including oil and petrochemical producers, plastic manufacturers, consumer goods companies, retailers, consumers, waste managers, waste management authorities, and plastic recyclers (Wingfield and Lim, 2021). A proposed framework combines the source-to-sea approach and circular economy, offering a viable solution to eliminate plastic waste from the environment and the economy. This approach acknowledges that significant changes in consumer behavior and lifestyle are imperative to prevent marine plastic litter effectively (Francis and Herat, 2020). Investigating the potential of implementing a circular economy to reduce plastic waste in marine environments, studies like the one conducted by Sadeghi (2021) put forth effective measures and ideas, emphasizing the importance of aligning environmental goals with economic and political considerations. Together, these findings advocate for a holistic approach to plastic waste management, where circular economy principles play a pivotal role in mitigating the global challenge of plastic pollution.

Adapting Indian fisheries to climate challenges under SSP and RCP scenarios

In the context of reframing Indian coastal aquaculture and fisheries with consideration given to Representative Concentration Pathway (RCP) and Shared Socioeconomic Pathway (SSP) scenarios, the challenges posed by these projections serve as crucial indicators of the increasing concentration of various factors in the future, thereby posing challenges to the sustainability of marine ecosystems. Mitigation strategies, facing limitations due to the projected trajectories, prompt a shift in emphasis towards the promotion and implementation of adaptation strategies. This necessitates a comprehensive and forward-thinking approach that addresses not only current vulnerabilities but also anticipates and prepares for future changes.The complexity of challenges presented by RCP and SSP scenarios calls for the development of comprehensive assessment solutions encompassing a multifaceted understanding of the complex interactions between environmental, social, and economic factors influencing coastal aquaculture and fisheries. From understanding changing climate patterns to evaluating the socio-economic impacts on fishing communities, a robust assessment framework becomes the cornerstone for informed decision-making. In light of the limited scope for mitigating the anticipated changes, adaptation strategies emerge as pivotal components of a resilient and sustainable future for Indian coastal aquaculture and fisheries. This involves fostering adaptive capacity within communities, integrating technology and innovation into fishing practices, and implementing policies that align with the evolving dynamics of marine ecosystems. The reframing process, guided by an IPCC risk assessment frame-work, should actively engage with the challenges presented by RCP and SSP scenarios, fostering adaptive strategies to ensure the resilience and longevity of India's coastal aquaculture and fisheries in the face of future uncertainties.

Additionally, considering the regional and species-level variations in the impact of climate change, research needs to focus on exploring the region-wise influence of oceanographic variations on key marine species. Study conducted by (Hussain *et al.*, 2021) examining the annual and decadal fluctuations in Indian mackerel fishery along the Kerala coast of the southeastern Arabian Sea over a 31-year period (1985–2016) reveals its relationship with four major oceanographic variables Sea Surface Temperature (SST) Precipitation (Pr), Sea Surface Salinity(SSS), and Sea Surface Chlorophyll (SSC) and future predictions under two Representative Concentration Pathways (RCPs). The projected Catch Per Unit Effort (CPUE) and effort of Indian mackerel exhibit varying trends under the RCP 4.5 and RCP 6.0 scenarios, with the future catch potential predicted to show a reduction under both RCP scenarios for the period 2020–2100, with the latter exhibiting a more drastic reduction. The study suggests that for sustainable long-term fishery and to mitigate the impact of climate change on Indian mackerel, fishing pressure must be maintained at a low and healthy level. Pinnegar (2021) stressed the critical importance for the climate science community to adopt a scenarios framework centered around Shared Socioeconomic Pathways (SSPs), emphasizing the need to harmonize communication regarding potential bioeconomic impacts of climate change. He reported the crafting of four socio-political-economic futures, inspired by both the IPCC SRES (Special Report on Emissions Scenarios) framework and the newer system of SSPs. Furthermore, he underscored the equal importance of short, medium, and long-term developments in socio-political drivers and physical drivers like long-term climate change in shaping the economic landscape of the aquaculture and fisheries industries.

Mission LiFE and practical guidelines for fisheries management

The pressing challenges of climate change prompting an urgent shift from the existing 'take-make-use-dispose' economic model to a circular economy. At the heart of this transformative shift lies Mission LiFE, or Lifestyle for Environment, a visionary initiative advocating for resilient and sustainable lifestyles that not only combat the climate crisis but also prepare for unforeseen future challenges. Mission LiFE aspires to transform into a global mass movement, propelling the P-3 'Pro Planet People' public participation campaign. This initiative aligns seamlessly with India's commitment to environmentally conscious lifestyles, as seen in campaigns like "Prakruti". Recognizing the inherently sustainable nature of Indian culture and living traditions, Mission LiFE aims to tap into ancient wisdom that emphasizes the importance of conserving precious natural resources and living in harmony with nature, disseminating this message widely.

The mission seeks to channel individual and community efforts into a global mass movement fostering positive behavioral change. In parallel, energy efficiency emerges as a cornerstone in India's strategy for low carbon development, with a targeted focus on achieving 100% market penetration of energy-efficient appliances MoEFCC (2022). This endeavor is reinforced by initiatives such as the Standards and Labelling program, electrification promotion, encouragement of non-fossil fuel-based electricity, digitization of processes, and the establishment of a carbon pricing program to incentivize energy efficiency (BEE, 2022). Collaborative efforts across sub-sectors further reflect India's commitment to nurturing sustainable practices.Through such initiatives, India endeavors to inspire individuals to contribute to worldwide endeavors aimed at constructing a sustainable and resilient future.

The strength of India lies in its large population, underscoring the collective responsibility of each individual to contribute to positive environmental change.

Practical guidelines to advocate for adopting environmentally friendly changes:

1. *Plastic Management:* Choose reusable items, opt for products with minimal packaging, and actively participate in community clean-up drives to address plastic pollution.

2. *Lifestyle Choices for the Environment:* Embrace the LiFE approach, which involves reducing energy consumption through renewable sources like solar panels, advocating for energy-efficient appliances, and using eco-friendly transportation options.
3. *Community Engagement:* Empower local communities in decision-making processes related to Integrated Coastal Zone Management (ICZM) plans. Integrate traditional knowledge and community needs into coastal management initiatives.
4. *Alternative Livelihoods:* Promote alternative livelihoods for coastal communities to reduce dependence on activities that harm Marine Protected Areas (MPAs).
5. *Education and Awareness:* Implement education and awareness initiatives that underscore the importance of MPAs and encourage eco-friendly tourism practices.
6. *Enforcement and Monitoring:* Strengthen enforcement and monitoring mechanisms within ecologically sensitive zones to deter illegal activities and ensure compliance with sustainable practices.
7. *Scientific Data Collection:* Continuously collect scientific data to inform the adaptive management of coastal ecosystems, allowing for evidence-based decision-making.
8. *Capacity-Building Programs:* Implement capacity-building programs for local communities and authorities to enable effective management and derive benefits from both MPAs and ICZM initiatives.

By adopting these practical guidelines and inspired by Mission LiFE, individuals can actively contribute to resolving conflicts and promoting sustainable coastal management, ultimately conserving marine and coastal ecosystems for future generations.

Conclusion

The complex web of challenges faced by India's coastal aquaculture and fisheries demands a holistic and forward-looking approach. The significance of these sectors in global seafood production, food security, and economic stability underscores the urgency for strategic interventions. The proposed IPCC-inspired risk assessment framework serves as a beacon for navigating the complexities arising from climate change, overfishing, and environmental degradation. The pivotal role of institutions like the Central Marine Fisheries Research Institute (CMFRI) in pioneering sustainable practices, demonstrated through successful cage culture projects, showcases the transformative potential of science-based interventions. Coastal communities, facing a numerous challenges, necessitate tailored strategies and community-based solutions. The escalating threats posed by marine heat waves and sea level rise require not only adaptive measures but also proactive, community-centric initiatives. The pervasive impact of anthropogenic activities reinforces the need for circular economy principles, especially in waste management, to mitigate pollution and protect marine ecosystems. Adapting to climate challenges under Representative Concentration Pathway (RCP) and Shared Socio-economic Pathway (SSP) scenarios demands nuanced, region-specific approaches and underscores the importance of sustainable long-term fishery management. Mission LiFE, alongside practical guidelines, provides a roadmap for cultivating sustainable living practices and fostering a global mass movement towards environmental consciousness. The collective responsibility of individuals, communities, and institutions is paramount in ensuring the resilience and sustainability of India's coastal ecosystems and the livelihoods they sustain. Through collaborative efforts and a commitment to science-based, environmentally conscious practices, a resilient and sustainable future for coastal aquaculture and fisheries can be realized.

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