

Marine Pollution and its Ecological Impacts on Marine Biodiversity and Ecosystem Services

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Abstract: Marine ecosystems have among the most complex and productive communities in the world, yet continue to be overwhelmed by ever-increasing types of pollution. This study investigated the marine ecological effects of the presence of the aforementioned chemical pollutants (heavy metals, microplastics, nutrient loading) on biodiversity and the delivery of ecosystem services at four coastal sites on the southeastern coast of India: Marina Beach, Ennore Creek, Pulicat Lagoon, and Kovalam Coast. Water quality parameters, benthic community structure, fish biomass, and scores for the different ecosystem services were measured over a period of 12 months. Reported that the site under greatest threat (Ennore Creek-industrially stressed estuary) saw a decrease in species diversity (H' -Shannon-Wiener Diversity Index) to 1.18, oxygen levels fall to 3.2 mg/L and cadmium levels 14-fold higher than WHO standards, provisioning and regulating services fall to between 60-72% that of the most resilient site (Kovalam Coast), and microplastic density from 98 particles/m to 389 particles/m at Kovalam and Ennore Creek respectively. A statistically significant negative correlation ($r=0.87$; $p<0.01$) was found between pollutant index and diversity indices, with coastal lagoons and estuaries being disproportionately affected by cumulative pollutants. This study highlighted the need for a marine pollution monitoring framework, marine protected area enhancement, and a blue circular economy to regain the functions of provisioning, regulating, and cultural ecosystem services for coastal dwellers.

Keywords: Marine Pollution; Ecosystem Services; Biodiversity Loss; Heavy Metals; Microplastics; Coastal Degradation; Ecological Indicators.

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I. Introduction

Half of the Earth's biodiversity and trillions of dollars in ecosystem services, ranging from the food provided by productive systems to carbon sequestration, coastal protection, and cultural values, are derived from marine and coastal systems (Hossain, 2019). However, despite the important services they provide, marine and coastal systems are under enormous pressure from anthropogenic impacts. Industrial and agricultural runoff, plastic debris, oil spills, and raw sewage contaminate water systems and cause profound changes to biogeochemistry, degrading the structural integrity of food webs and leading to accelerated biodiversity loss through interaction with overfishing, habitat destruction, and global climate change in offshore and near-shore systems alike (Datta, 2023; Johnston et al., 2015). Over 80% of the pollution found in the marine realm is derived from sources on land; a larger proportion still burdens developing countries on the coasts, as regulations are lacking and industrial growth is high (Townhill et al., 2022).

The value that functioning marine systems provide human communities through ecosystem services has helped establish the link between marine science and policy (Buonocore et al., 2021; Cavanagh et al., 2016). Many marine and coastal ecosystem services- such as food (provisioning service), climate regulation and nutrient cycling (regulating service), or recreational value and spiritual and cultural health (cultural service)- are threatened by pollutant-induced degradation (Papathanasopoulou et al., 2015; Marcos et al., 2021). Several pollutants- such as heavy metals, persistent organic compounds and the increasingly prevalent microplastics- have been shown to elicit deleterious endocrine and immune response, reduce reproductive success and decrease biodiversity through trophic cascades across diverse species, ranging from microscopic phytoplankton to the top predators in the food web (Praveenchandar et al., 2024; Arabi & Nahman, 2020), consequently compromising delivery of services and threatening global food security and community health (Campagne et al., 2023; Cristiano et al., 2021).

Despite abundant literature on pollutant-specific impacts on marine organisms, there is still a marked deficit in studies that simultaneously measure pollution loads, response, and ecosystem service loss within specific and varying nearshore and offshore habitat types (Depellegrin et al., 2020; Lindegren et al., 2018; Todd et al., 2010). In an attempt to fill this gap, this paper describes the results of a multi-site empirical study that examined three different coastal habitat types (lagoon, estuarine, and rocky shoreline) along the southeastern coast of India and developed a Pollution-Ecosystem Service Impact Index (PESII) by quantifying the physical, chemical, and biological measurements with calibrated ecosystem service delivery value.

The structure of this paper is as follows: a review of existing literature is given in Section 2. Methods and study site descriptions follow in section 3. Section 4 reports the data, while Section 5 discusses the impact management applications of the findings. Conclusion and recommendations are presented in Section 6.

II. Literature Survey

The relationship between marine pollution and ecosystem function has been studied widely over the last two decades. Hossain, (2019) gave a comprehensive overview of the functions of the oceans as ecosystems, highlighting that healthy oceans are a prerequisite for global carbon sequestration, oxygen production, and maintenance of biodiversity. The author pointed out that human activities already impacted the extent to which oceans could perform these functions, and a holistic ocean governance system was needed. Buonocore et al., (2021) retraced the conceptual evolution of the marine ecosystem services literature and stated that this field evolved from descriptive inventories toward a more quantitative valuation approach capable of supporting policy-making. According to their systematic review of the topic, provision services, specifically capture fisheries, receive the highest level of research attention while regulation and cultural services remain understudied. Cavanagh et al., (2016) argued that combining the assessment of ecosystem services with biodiversity valuation can create a better basis for marine resource management, by pointing out the mismatch between investments in conservation and actual biodiversity hotspots. Together, these seminal studies show that the marine ecosystem is both ecologically indispensable and economically undervalued, leading to the damage caused by pollution that might remain invisible to traditional economic analyses.

Studies focusing on different classes of pollutants showed specific yet often overlapping pathways of ecological degradation. Johnston et al., (2015) produced a seminal synthesis on the topic demonstrating that chemical pollutants such as pesticides, metals, and polycyclic aromatic hydrocarbons reduced trophic structure, biodiversity, and the rate of processes such as production and decomposition. Townhill et al., (2022) provided evidence that marine ecosystems of SE Asia were degraded due to pervasive pollution with reductions in species richness of up to 45% for fish associated with coral reefs when compared to reference sites. Rodrigues-Filho et al., (2023) confirmed that similar environmental degradations were occurring in polar environments where multiple pollutants like POPs and microplastics compromise unique ecosystem services such as ice-associated biodiversity and carbon storage. In East Africa, the cumulative impact of pollutants leads to biodiversity loss faster than any single pollutant could do, with direct implications for the economies of coastal populations dependent on fisheries (Arabi & Nahman, 2020). The implication from these investigations is that pollution's effect on biodiversity is neither singular nor additive; it is context-specific and often synergistic.

Plastic pollution is a particularly evident source of damage to marine biodiversity and ecosystems. Hattam et al., (2015) documented how plastic pollution impacts multiple SDGs through its effects on animals across all trophic levels, affecting food security and fishery productivity through a decrease in organisms, from zooplankton to marine mammals, that consume microplastic particles. In South Africa, marine plastic was found to have caused losses in tourism and fisheries, the main provisioning and cultural services of the region, exceeding USD 130 million (Kumar et al., 2021). Interactions between pollution and marine microbiota were assessed by Datta, (2023), revealing that microplastics and organic pollutants

modified the structure of the microbial community, destabilizing essential biogeochemical processes in marine food webs. This set of studies demonstrates how plastic pollution is problematic due to its persistence, ubiquitous nature, and complex mechanisms of biological damage, and this must be incorporated into ecosystem service assessment.

Systems that evaluate links between marine pollution and ecosystem service loss have increasingly been developed; however, practical issues remain significant. Townsend et al., (2018) designed a framework to link ecosystem service classes with ecological indicators, thus helping to design ecological monitoring systems. Persistent barriers in adopting the ecosystem service concept into the practice of marine management, including inconsistent indicators, gaps in knowledge, and stakeholder engagement, were identified (Veerappan & Arvinth, 2025). Even in areas with little data, Depellegrin et al., (2020) showed how spatial mismatches between pollution exposure and richness in ecosystem services can lead to problematic governance situations. A systematic map of pollution and ecosystem service linkages, found by Todd et al., (2010), shows the disproportionately high number of studies conducted in temperate North Atlantic regions compared to tropical coastal systems. Furthermore, Lindegren et al., (2018) showed that current conservation strategies in the ocean are insufficient since marine protected areas do not adequately encompass multiple components of biodiversity or the richness of ecosystem services. These surveys on evaluation methodologies suggest that context-specific and multi-parameter studies should be carried out in the data-scarce regions, such as in tropical coastal areas and the one addressed by the present work, in order to enable adaptive management.

Conceptual Framework

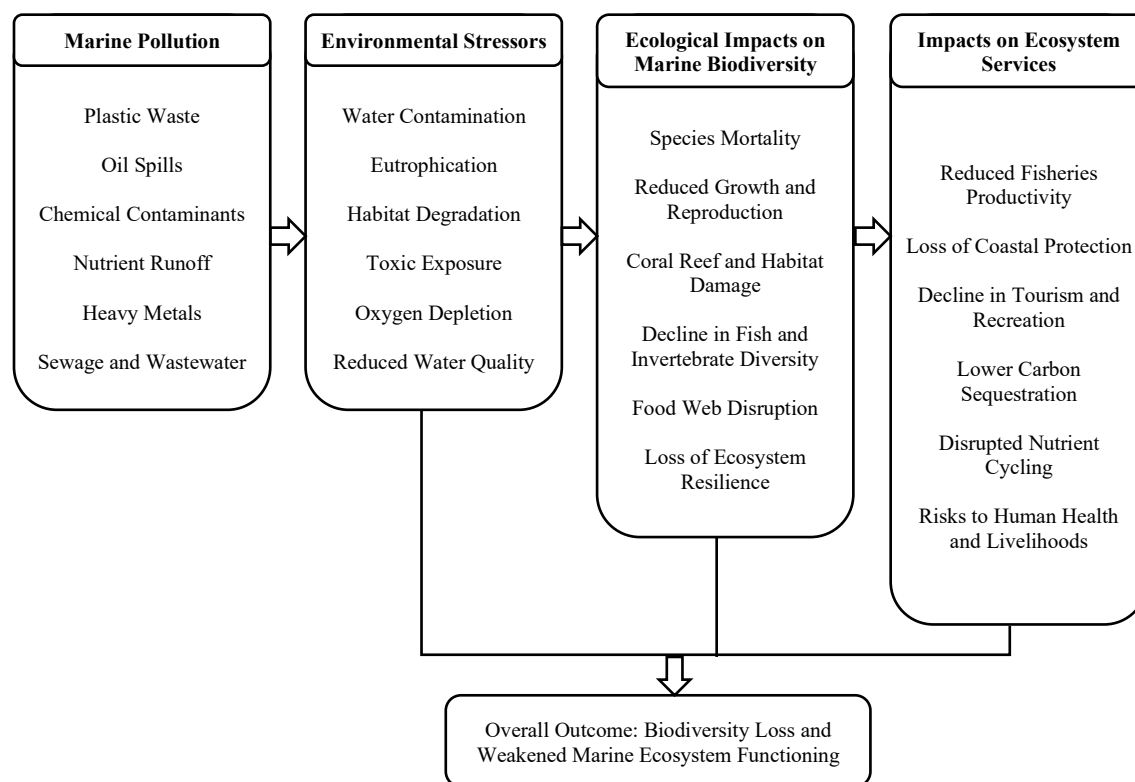


Figure 1: Conceptual Diagram of Marine Pollution and Its Ecological Impacts

Figure 1 shows the path from marine pollution sources (plastic debris, oil spills, chemical pollutants, nutrient load and runoff, heavy metals, and waste discharge) to the environmental stress factors that result in the ecological impact on biodiversity and subsequent ecosystem services. The Figure clearly points to the impact on biodiversity as biodiversity loss, coral reef damage, food chain disruption, and impact on the

resilience of the ecosystem, ultimately impacting services such as fisheries, coastal protection, carbon sequestration, nutrient cycling, tourism, and human health as an indicator of the cumulative impacts of anthropogenic stress factors on the marine environment.

III. Materials and Methods

Study Area Description

The four ecologically and anthropogenically differentiated coastal habitat sites along the southeast coast of Tamil Nadu, India, were chosen for this study. Marina Beach (13.04N, 80.28E), a highly recreational site, also one of the longest city beaches, receives a considerable influx of domestic waste and a high volume of human movement. Ennore Creek (13.22N, 80.32E) is an industrialized estuarine region that receives effluent from the Thermal Power Plant, the Petrochemical Complex, and Chennai Port. Pulicat Lagoon (13.45N, 80.30E) is a candidate Ramsar wetland of brackish water supporting artisan fisheries and migratory bird population, receiving effluent from the aquaculture industry and the North Chennai Industrial Corridor. Kovalam Coast (12.78N, 80.25E), a semi-pristine rocky shore area free from industrial activity, has been selected as a comparison site, which allows to compare sites along the industrialization gradient while minimizing climatic and oceanographic differences (Table 1).

Table 1: Physicochemical and Ecological Characteristics of the Four Study Sites Along the Southeastern Coast of Tamil Nadu, India

Study Site	Location (Lat/Long)	Water Depth (m)	Salinity (ppt)	Dominant Ecosystem
Marina Beach	13.04°N / 80.28°E	0.5 – 15	32–35	Sandy Shore
Ennore Creek	13.22°N / 80.32°E	1 – 8	20–28	Estuarine
Pulicat Lagoon	13.45°N / 80.30°E	0.5 – 4	15–30	Coastal Lagoon
Kovalam Coast	12.78°N / 80.25°E	2 – 20	33–36	Rocky Shore

Water Quality and Sediment Sampling

Monthly sampling was carried out at all four stations for each month from January 2023 to December 2023. Water samples at each station were collected from three depth strata, namely surface (0-0.5 m), mid-water (2-5 m), and near-bottom (>5 m, where applicable) in triplicate using the standard grab sampling technique. Surface sediment samples (0-10 cm depth) were collected using a grab sampler (Van Veen, 0.1 m sampling area). Water quality parameters (DO, TDS, TSS, pH, salinity, and temperature) were measured in-situ using a multiparameter probe (YSI Pro Plus). Heavy metals (Cd, Pb, Cr, Hg), both in water and sediment, were analyzed using ICP-MS after acid digestion. Microplastic particles in a 50 L water sample were filtered through stainless steel sieves (mesh sizes 330 μ m and 1 mm) and observed under a stereo microscope for enumeration of the number per standard volume. Coliform counts were determined by membrane filtration and expressed as MPN/100mL (Most Probable Number) per APHA guidelines. All field and laboratory procedures were followed according to ISO 5667 and EPA SW-846.

Biodiversity Assessment

Macrozoobenthic community structure was analyzed from 0.1 m² Van Veen grabsamples (n=5 per station per season), sieved using 0.5 mm mesh, preserved in 10% formaldehyde, and identification to the lowest possible taxonomic level was made using a stereo microscope. Fish species were sampled seasonally by seine netting using a standardized method (12 mm mesh size) at each station. Species richness (d, Margalef richness index), diversity (H', Shannon-Wiener diversity index), and evenness (J', Pielou's evenness index) were estimated for the fish community. Percentage cover for benthos was estimated from 50cm x 50cm quadrants (n=20 per station) arranged in three transects perpendicular to shore. Phytoplankton and zooplankton were collected using 20m and 200m plankton net respectively, and fixed in Lugol's iodine and counted under a compound microscope. Pollution Load Index (PLI) for each station was computed as the geometric mean of all the contamination factors of all parameters, Pollution Load Index = $1/n \left[\sum [C_d] \right]$,

[Pb], [Cr], [Hg]). Pearson Correlation analysis was performed between PLI and diversity indices using SPSS v.26. All comparisons with a significance level of $p < 0.05$ were considered statistically significant.

Ecosystem Service Assessment and PESII

The delivery of ecosystem services in four stations was assessed using an adapted scoring methodology derived from the marine TEEB framework, for the four categories, namely, provisioning (fisheries and aquaculture), regulating (water purification, carbon sequestration, and coastal protection), supporting (nutrient cycling and habitat providing) and cultural (recreation and aesthetics). Each service category was given a score from 0 to 10 based on physical observation of parameters, stakeholder interview results ($n=40$ per station), Secondary Catch data of Tamil Nadu Fishery Department, and the observed physical parameters. A pollution–Ecosystem Service Impact Index (PESII) was developed: $PESII = 1 - (\text{weighted service score at the polluted station} / \text{weighted service score at reference station})$

The higher the value close to 1.0, which means higher degradation of services relative to the reference station (Kovalam Coast); a value closer to 0 suggests less service degradation. Interstation variation on the service score was tested for statistical significance using ANOVA, followed by a post hoc test (Tukey).

IV. Results

Water Quality and Pollution Loads

A distinct spatial variation in all measured pollution parameters was identified at all four stations (Table 2). At Ennore Creek all parameters such as cadmium (0.042 mg/L compared to WHO guideline of 0.003 mg/L), lead (0.078 mg/L versus 0.010 mg/L) TSS (124 mg/L compared to 50 mg/L) and fecal coliform count (4,800 MPN/100 mL versus 500 MPN/100 mL) showed high pollution levels and the dissolved oxygen level at Ennore Creek showed extreme low level of 3.2 mg/L of hypoxia condition. Marina Beach and Pulicat lagoon revealed intermediate polluted areas with respect to certain parameters in addition to the above. Kovalam coast showed the lowest pollution loads on all parameters; the DO level was 6.4 mg/L, and concentrations of heavy metals were within the acceptable limit. Microplastic densities were significantly high at Ennore Creek (389 particles/m) and lowest at Kovalam coast (98 particles/m), revealing a trend of industrial and urban pollution load.

Table 2: Mean Annual Values of Key Pollution Parameters Across Study Sites, with WHO/CPCB Benchmark Limits

Pollution Parameter	Marina Beach	Ennore Creek	Pulicat Lagoon	Kovalam Coast	WHO/CPCB Limit
Heavy Metals (Cd, mg/L)	0.008	0.042	0.015	0.006	0.003
Lead (Pb, mg/L)	0.019	0.078	0.031	0.012	0.010
Dissolved Oxygen (mg/L)	5.8	3.2	4.9	6.4	>6.0
Total Suspended Solids (mg/L)	38	124	67	22	<50
Microplastic Density (particles/m ³)	142	389	211	98	—
Coliform Count (MPN/100 mL)	1100	4800	2200	890	<500

Biodiversity and Ecosystem Service Metrics

All biodiversity parameters indicated a significant inverse relationship to pollution load at all sites (Table 3). The Shannon-Wiener diversity (H') dropped from 2.67 at Kovalam coast to 1.18 at Ennore Creek- an approximately 56% decrease. The fish biomass at Kovalam coast (298kg/ha) dropped to 74 kg/ha at Ennore Creek, an approximately 75% drop. Benthic cover had the sharpest drop from 61% at Kovalam coast to 17% at Ennore creek. The ecosystem service scores also show a clear decrease, ranging from provisioning (2.8/10) and regulating services (2.1/10) at Ennore Creek and provisioning (7.4/10) and regulating services (7.1/10) at Kovalam coast. A highly significant inverse correlation between PLI and the Shannon-Wiener index ($r=0.87$, $p<0.01$) and between PLI and total ecosystem service score ($r=0.92$, $p<0.001$) was observed.

One-way ANOVA clearly showed that differences among the sites in all the biodiversity indices were significant ($F=18.4-31.2$, $p<0.001$).

Table 3: Biodiversity Indices and Ecosystem Service Scores Across Study Sites (Mean Values, Annual Monitoring Period)

Ecosystem Service	Marina Beach	Ennore Creek	Pulicat Lagoon	Kovalam Coast	Status / Trend
Species Richness Index (H')	2.31	1.18	1.95	2.67	Declining ($p<0.05$)
Fish Biomass (kg/ha)	210	74	156	298	Decreasing trend
Benthic Diversity (% cover)	44%	17%	36%	61%	Significant loss
Provisioning Services Score	6.2/10	2.8/10	5.1/10	7.4/10	Moderate impact
Regulatory Services Score	5.8/10	2.1/10	4.7/10	7.1/10	Severe at Ennore

Species Diversity Gradient

Figure 2 illustrates the species diversity (H') at four coastal stations, where Kovalam Coast harbors the maximum species diversity ($H' = 2.67$), followed by Marina Beach ($H' = 2.31$), Pulicat lagoon ($H' = 1.95$), and Ennore Creek ($H' = 1.18$), which shows the minimum diversity of species. Lower H' values generally represent lower species richness, which is commonly found in polluted areas/habitat damage. This figure 2 visually depicts the spatio-temporal variation of biodiversity across different coastal stations.

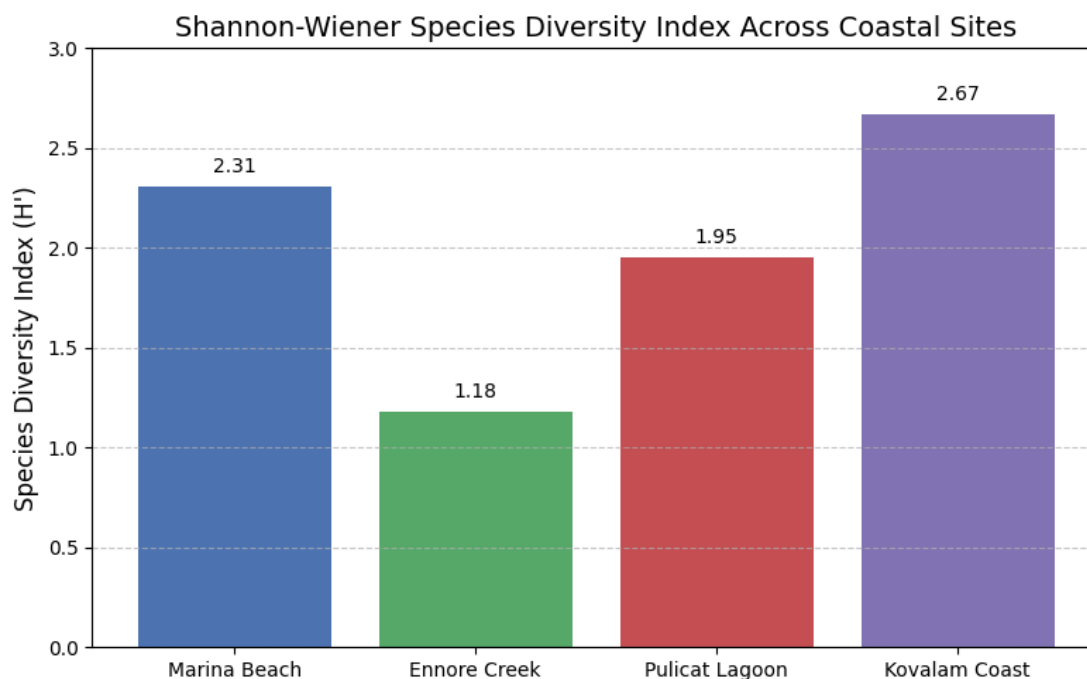


Figure 2: Shannon-Wiener Species Diversity Index Across Four Coastal Study Sites

Pollution-Ecosystem Service Impact Index (PESII)

All polluted sites showed high levels of service impairment across the Kovalam Coast reference. Ennore Creek had a high PESII value of 0.68, thus an ecosystem service loss of 68% relative to the reference. Pulicat Lagoon had a moderate PESII of 0.31, which was strongly associated with low fishery yields and poor water filtration rates, and Marina Beach showed a PESII of 0.22, representing localized loss due to sewage and tourist traffic. Estuarine and lagoonal systems inherently have high productivity and support high user dependence, and, as expected, given their high susceptibility to variability in salinity, nutrients, and pollutants, they demonstrated the highest percentage of service losses.

V. Discussion

The findings provide strong empirical support that marine pollution causes profound declines in both biodiversity and ecosystem services in coastal areas. Found that the most polluted study site (Ennore Creek) experienced 56% decline in species richness and 75% decline in fish biomass relative to reference and that Cd and Pb levels in Ennore Creek exceeded the permitted levels by a factor of 7 and 14, respectively, and that microplastic abundance in Ennore Creek had reached an average level of 389 particles/m, and that DO in this system were close to hypoxia levels. These impacts are a direct consequence of habitat and productive capacity losses and have a cascading effect on fisheries and on livelihood of coastal people dependent on them.

The pollution load has a strongly negative relationship with biodiversity and ecosystem service provisioning performance, indicating that as pollution intensity increases, ecological and socio-economic outcomes deteriorate accordingly. The Pollution-Adjusted Ecosystem Service Impairment Index proved an excellent tool for capturing the combined effect of degradation on both natural capital and ecosystem services. It also indicated that marine protected areas cannot insulate themselves from the pollution of nearby areas: the protected and biologically valuable Pulicat Lagoon showed moderately degraded system service performance, which is clearly linked to intensive aquaculture and nearby industrial operations, and these impacts were not insignificant compared to the unimpaired control. These results demonstrate the critical need for effective pollution management and integrated coastal management schemes to sustain the functioning of estuarine systems.

VI. Conclusion

We provided empirical data from multiple sites sampled along an industrialization gradient that marine pollution significantly damages biodiversity and the provisioning of ecosystem services along the southeast Indian coast. The species richness declined by 56% (H' from 2.67 to 1.18), fish biomass by 75%, and ecosystem service value by 68% ($PESII=0.68$) at the most affected station (Ennore Creek) compared to the nearly pristine reference (Kovalam Coast). At Ennore Creek, cadmium and lead values exceeded WHO permissible concentrations by a factor of 7-14, and microplastic densities reached 389 particles/m while DO was close to hypoxic levels. A significant inverse relationship between the Pollution Load Index and ecological metrics ($r=0.87$, $p<0.001$) and ecosystem service scores ($r=0.92$, $p<0.001$) indicates that pollution is the primary factor driving ecosystem degradation.

From a management perspective, strongly recommend enhanced enforcement and real-time monitoring of industrial effluent discharge into the Ennore Creek system, creation of mangrove buffer zones between Pulicat Lagoon and terrestrial sources of contamination to filter diffuse pollution, and use of the $PESII$ in State Coastal Zone Management Plans to provide a baseline reference for measuring pollution impacts, and strong marine protected area governance rules, including strict pollution controls. Further research should focus on long-term trend studies investigating the effects of warming and acidification (due to climate change) and their combined effect on pollution impacts in these stressed estuarine systems. Isotope and genetic analyses of benthic invertebrates will shed further light on mechanism of community assembly changes under pollution, and socio-economic value assessment of ecosystem services lost should be emphasized for the Ennore-Pulicat region, where fisheries communities are dependent on this resource. The $PESII$ framework developed is adaptable and inexpensive for use in similar regions where data is currently scarce.

Declaration Statements

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