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Environmental Stressors and Biodiversity Vulnerability in Mangrove Ecosystems of the Indian Sundarbans

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Abstract:

Mangrove ecosystems have been recognized as highly productive coastal environments that provide critical ecological services, including shoreline stabilization, carbon sequestration, and habitat support for diverse biotic communities. The Indian Sundarbans, forming the world's largest contiguous mangrove forest, have been exposed to a wide range of environmental stressors driven by natural processes and intensified anthropogenic pressures. The present review synthesized existing scientific literature to examine the major environmental stressors affecting the mangrove ecosystems of the Indian Sundarbans and to assess the resulting vulnerability of biodiversity across multiple trophic levels. Stressors such as salinity intrusion, climate change–induced sea-level rise, cyclonic disturbances, temperature anomalies, pollution, and land-use changes were reviewed in relation to their impacts on mangrove flora, faunal assemblages, and ecosystem functioning. Evidence from long-term ecological studies, remote sensing analyses, and field-based observations indicated that biodiversity loss and structural degradation had been strongly linked to the cumulative and interacting effects of these stressors. Mangrove species composition had been altered, faunal diversity had declined in sensitive zones, and ecosystem resilience had been reduced in several parts of the Sundarbans. The review highlighted critical research gaps, including limited long-term biodiversity datasets and inadequate integration of biotic and abiotic drivers. It was concluded that integrated conservation strategies incorporating climate adaptation, pollution control, and sustainable resource management were urgently required to reduce biodiversity vulnerability and ensure the long-term persistence of the Indian Sundarbans mangrove ecosystem.

Keywords: *Indian Sundarbans; Mangrove Ecosystems; Environmental Stressors; Biodiversity Vulnerability; Climate Change; Salinity Intrusion.*

1. Introduction

Mangrove ecosystems have been globally recognized as unique intertidal forests occurring at the interface between terrestrial and marine environments. These ecosystems have supported exceptionally high biological productivity and biodiversity despite being subjected to fluctuating and often extreme environmental conditions. Mangroves have been distributed primarily in tropical and subtropical regions and have provided a wide range of ecosystem services, including coastal protection, nutrient cycling, carbon sequestration, and nursery habitats for fisheries (Alongi, 2014).

The Indian Sundarbans, located at the mouth of the Ganga–Brahmaputra–Meghna delta, have represented the largest mangrove ecosystem in the world. This region has been characterized by a complex network of tidal creeks, estuaries, mudflats, and islands, supporting diverse mangrove flora and fauna (Chakraborty, 2011). The Sundarbans have also been designated as a UNESCO World Heritage Site and a Biosphere Reserve due to their ecological significance and biodiversity richness.

Despite their ecological importance, the mangrove ecosystems of the Indian Sundarbans have been increasingly threatened by a variety of environmental stressors. Both natural and anthropogenic drivers have been reported to exert pressure on ecosystem structure and function. Climate change–related factors such as sea-level rise, increasing frequency and intensity of cyclones, temperature anomalies, and altered precipitation patterns have been superimposed upon local stressors such as salinity intrusion, pollution, habitat fragmentation, and resource overexploitation (Ward et al., 2016; Samanta et al., 2021).

Biodiversity vulnerability in mangrove ecosystems has been defined as the susceptibility of species and communities to environmental changes that exceed their adaptive capacity. In the Indian Sundarbans, vulnerability has been manifested through shifts in species composition, reduced regeneration of key mangrove species, decline in faunal populations, and degradation of ecosystem services (Duke et al., 2007). Understanding the linkages between environmental stressors and biodiversity vulnerability has therefore been considered essential for effective conservation and management.

The present review aimed to synthesize available scientific knowledge on environmental stressors affecting the Indian Sundarbans and to critically examine their implications for biodiversity vulnerability. By integrating findings from ecological, climatological, and remote sensing studies, the review sought to provide a comprehensive understanding of stressor–biodiversity interactions and to identify research gaps and conservation priorities.

2. Overview of the Indian Sundarbans Mangrove Ecosystem

The Indian Sundarbans have been situated in the eastern part of India, covering approximately 4,200 km² of mangrove forest within West Bengal. The region has been influenced by semidiurnal tides, high sediment load from upstream rivers, and seasonal monsoonal rainfall. These factors have created strong environmental gradients, particularly in salinity and hydrology, which have governed mangrove zonation and species distribution (Chakraborty, 2013).

Mangrove vegetation in the Indian Sundarbans has been dominated by species such as *Heritierafomes*, *Excoecariaagallocha*, *Avicennia marina*, *Rhizophoramucronata*, *Ceriopsdecandra*, and *Sonneratiaapetala*. The ecosystem has supported diverse faunal groups, including fish, crustaceans, mollusks, reptiles, birds, and mammals, notably the Royal Bengal Tiger (*Pantheratigristigris*) (Ghosh et al., 2015).

The ecological stability of the Sundarbans has been maintained through a delicate balance between freshwater inflow and saline tidal water. However, this balance has been increasingly disrupted by upstream river regulation, climate variability, and human activities. Such disruptions have intensified environmental stressors, leading to heightened biodiversity vulnerability across the region.

3. Major Environmental Stressors in the Indian Sundarbans

3.1 Salinity Intrusion

Salinity has been identified as one of the most critical environmental variables influencing mangrove ecosystems. In the Indian Sundarbans, salinity levels have been reported to vary spatially and seasonally due to tidal dynamics, freshwater discharge, and rainfall patterns. Reduced freshwater inflow from upstream

rivers, particularly following the construction of dams and barrages, has resulted in increased salinity intrusion in several parts of the Sundarbans (Chakraborty, 2011).

Elevated salinity levels have been associated with physiological stress in mangrove plants, leading to reduced growth, impaired reproduction, and increased mortality. Freshwater-preferring species such as *Heritierafomes* and *Nypafruticans* have shown declining abundance in high-salinity zones, whereas salt-tolerant species such as *Avicennia marina* have expanded their distribution (Samanta et al., 2021).

Faunal communities have also been affected by salinity changes. Fish and crustacean diversity has been reported to decline in highly saline areas, altering food web structure and ecosystem functioning (Mitra et al., 2017).

3.2 Climate Change and Sea-Level Rise

Climate change has been recognized as a major driver of environmental stress in mangrove ecosystems worldwide. In the Indian Sundarbans, relative sea-level rise has been driven by global sea-level rise combined with local land subsidence. This phenomenon has increased the frequency of tidal inundation and shoreline erosion, leading to habitat loss and fragmentation (Ward et al., 2016).

Rising temperatures have been reported to influence mangrove phenology, productivity, and species interactions. Heat stress events have reduced seedling survival and increased vulnerability to pests and diseases. Additionally, altered precipitation patterns have affected freshwater availability, further exacerbating salinity stress (IPCC, 2021).

The cumulative impacts of climate change have reduced ecosystem resilience, making mangroves less capable of recovering from disturbances.

3.3 Cyclones and Extreme Weather Events

The Bay of Bengal has been identified as one of the most cyclone-prone regions in the world. The Indian Sundarbans have experienced frequent cyclonic storms, including recent high-intensity events such as Cyclone Aila (2009), Amphan (2020), and Yaas (2021). These events have caused large-scale destruction of mangrove vegetation through wind damage, storm surges, and saline water inundation (Ghosh et al., 2015).

Repeated cyclonic disturbances have been shown to reduce forest structure complexity, disrupt regeneration processes, and increase soil salinity. Faunal mortality and displacement have also been reported, particularly among birds and terrestrial mammals.

Table 1. Major Environmental Stressors Affecting Mangrove Ecosystems of the Indian Sundarbans

Environmental Stressor	Primary Source	Observed Ecological Effects	Key References
Salinity intrusion	Reduced freshwater inflow, tidal dominance	Decline of freshwater-preferring mangrove species; altered species zonation; reduced fish diversity	Chakraborty (2011); Samanta et al. (2021)
Sea-level rise	Climate change, land subsidence	Increased inundation, shoreline erosion, habitat loss, mangrove dieback	Ward et al. (2016); IPCC (2021)
Cyclonic disturbances	Extreme weather events	Physical damage to mangrove stands, increased soil salinity, faunal mortality	Ghosh et al. (2015)

Temperature rise	Global warming	Reduced seedling survival, altered phenology, physiological stress	Alongi (2014)
Pollution	Agricultural runoff, industrial effluents	Heavy metal accumulation, eutrophication, decline in water quality	Maiti & Chowdhury (2013)
Land-use change	Agriculture, aquaculture, settlements	Habitat fragmentation, biodiversity loss, ecosystem degradation	Mondal et al. (2021)

3.4 Pollution and Anthropogenic Stressors

Anthropogenic pollution has emerged as a significant environmental stressor in the Indian Sundarbans. Agricultural runoff, industrial effluents, plastic waste, and heavy metal contamination have been reported in several estuarine zones. Mangroves have acted as sinks for pollutants, but excessive accumulation has impaired ecosystem health (Maiti & Chowdhury, 2013).

Heavy metals such as mercury, lead, and cadmium have been detected in mangrove sediments and biota, posing risks to biodiversity and human health. Nutrient enrichment from agricultural runoff has contributed to eutrophication, affecting water quality and dissolved oxygen levels.

3.5 Land-Use Change and Resource Exploitation

Human population pressure in the Sundarbans region has driven land-use changes, including conversion of mangrove areas for agriculture, aquaculture, and settlements. Unsustainable extraction of timber, fuelwood, and non-timber forest products has further degraded habitat quality (Mondal et al., 2021).

These activities have fragmented mangrove habitats, reduced connectivity, and increased exposure to environmental stressors, thereby amplifying biodiversity vulnerability.

4. Biodiversity Vulnerability in the Indian Sundarbans

4.1 Mangrove Flora

Mangrove plant diversity has been particularly sensitive to environmental stressors. Long-term studies have indicated a decline in species richness and a shift toward dominance by salt-tolerant species. Reduced regeneration of key species such as *Heritierafomes* has been linked to salinity stress and altered hydrology (Chakraborty, 2013).

Loss of structural diversity has also been observed, with implications for habitat complexity and associated fauna.

Table 2. Responses of Mangrove Flora to Environmental Stressors in the Indian Sundarbans

Mangrove Species	Stress Sensitivity	Observed Response	Ecological Implication
Heritierafomes	High sensitivity to salinity	Reduced regeneration and population decline	Loss of structural dominance and biodiversity
Excoecariaagallocha	Moderate salinity tolerance	Restricted distribution in high-salinity zones	Altered community composition

Avicennia marina	High salinity tolerance	Expansion into degraded and saline areas	Increased monospecific stands
Nypafruticans	Freshwater-dependent	Sharp decline in saline regions	Reduced habitat complexity
Sonneratiaapetala	Moderate tolerance	Variable survival depending on hydrology	Changes in forest zonation

4.2 Faunal Communities

Faunal biodiversity, including fish, crustaceans, birds, and mammals, has been affected by habitat degradation and water quality changes. Declines in fish diversity and abundance have been reported in areas with high salinity and pollution levels. Bird populations have shown sensitivity to habitat loss and cyclonic disturbances (Mitra et al., 2017).

The Royal Bengal Tiger population, although relatively stable, has been exposed to increasing risks due to habitat fragmentation and human–wildlife conflict.

Table 3. Impact of Environmental Stressors on Faunal Biodiversity in the Sundarbans

Faunal Group	Major Stressors	Observed Impacts	Ecological Consequences
Fish	Salinity increase, pollution	Decline in species richness and abundance	Disrupted food webs and fisheries
Crustaceans	Water quality degradation	Reduced recruitment and growth	Decline in estuarine productivity
Birds	Habitat loss, cyclones	Nest destruction and population decline	Reduced avian diversity
Reptiles	Salinity and habitat fragmentation	Restricted distribution	Loss of trophic balance
Mammals	Habitat fragmentation, human pressure	Increased human–wildlife conflict	Threatened ecosystem stability

4.3 Ecosystem Functioning and Services

Biodiversity loss has been associated with reduced ecosystem functioning, including lower primary productivity, disrupted nutrient cycling, and diminished carbon sequestration capacity. Degradation of mangrove ecosystems has also reduced their ability to provide coastal protection against storms and erosion (Alongi, 2014).

Table 4. Biodiversity Vulnerability Indicators in the Indian Sundarbans Mangrove Ecosystem

Indicator	Observed Trend	Implication for Ecosystem Health
Species richness	Declining	Reduced ecosystem resilience
Species composition	Shift toward salt-tolerant taxa	Loss of ecological balance
Regeneration rate	Reduced in sensitive zones	Long-term forest degradation
Habitat connectivity	Fragmented	Increased vulnerability to disturbances
Ecosystem services	Declining	Reduced coastal protection and carbon storage

5. Synthesis and Research Gaps

The review revealed that biodiversity vulnerability in the Indian Sundarbans has been driven by interacting environmental stressors rather than single factors. However, several research gaps have remained, including limited long-term biodiversity monitoring, insufficient integration of microbial communities, and inadequate assessment of cumulative impacts.

6. Conservation and Management Implications

Effective conservation of the Indian Sundarbans has required integrated management approaches that address both climate-related and local stressors. Restoration of freshwater flow, pollution control, community-based resource management, and climate-adaptive conservation strategies have been identified as critical priorities.

Table 5. Conservation Challenges and Management Strategies for the Indian Sundarbans

Key Challenge	Identified Cause	Suggested Management Strategy
Increasing salinity	Reduced freshwater inflow	Restoration of river connectivity
Cyclone damage	Climate change	Climate-adaptive mangrove restoration
Pollution accumulation	Agricultural and industrial discharge	Strengthened pollution regulation
Habitat loss	Land-use conversion	Strict enforcement of protected zones
Biodiversity decline	Multiple interacting stressors	Integrated ecosystem-based management

7. Conclusion

The present review demonstrated that environmental stressors have significantly increased biodiversity vulnerability in the mangrove ecosystems of the Indian Sundarbans. Salinity intrusion, climate change, cyclonic disturbances, pollution, and land-use changes have collectively altered ecosystem structure and function. Without urgent and integrated conservation interventions, continued biodiversity loss and ecosystem degradation have been projected. Strengthening scientific research, policy integration, and community participation has been essential for safeguarding the ecological integrity of the Indian Sundarbans.

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