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Coupled Effects of Salinity on Mangrove Flora in the Indian Sundarbans: Resilience, Functional Diversity, and Systematic Shifts

Sanjay Kumar Samanta

Research Scholar, Department of Environmental Educational Study, RKDF University, Ranchi

Abstract:

The Indian Sundarbans, a UNESCO World Heritage site and the largest contiguous mangrove ecosystem globally, faces an existential threat from escalating surface water and soil salinity. This study investigates the coupled effects of salinity on the physiological and structural dynamics of dominant mangrove flora between January 2023 and December 2025. Utilizing a multi-sectoral monitoring approach across the western, central, and eastern sectors, we assessed changes in Above Ground Biomass (AGB), species zonation, and foliar traits. Our findings reveal a significant decline in AGB for salinity-sensitive species like Heritierafomes and Sonneratia apetala, alongside a landward migration and proliferation of salt-tolerant taxa such as Avicennia marina and Excoecariaagallocha. Physiological data indicate a reduction in leaf area index (LAI) and chlorophyll content, coupled with increased leaf succulence, as conservative resource-use strategies under osmotic stress. These results underscore a narrowing of ecological resilience and suggest that without urgent freshwater restoration and transboundary management, the structural integrity of the Sundarbans will continue to deteriorate.

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1. Introduction:

Mangrove ecosystems are vital for global carbon storage and coastal protection, yet they are increasingly threatened by salinity intrusion resulting from sea-level rise and altered hydrological regimes (Karim et al., 2025). The Indian Sundarbans, a megadeltaic system, presents a unique case where biodiversity co-occurs with steep salinity gradients. Since 2023, research has intensified on how these gradients impose selective pressures that favour stress-tolerant species with traits suited to prevailing osmotic conditions (Wang et al., 2024). The Indian Sundarbans, located at the apex of the Bay of Bengal, is a fragile ecosystem characterized by a complex network of tidal waterways and mudflats. While mangroves are facultative halophytes, their growth and distribution are strictly governed by a delicate balance between freshwater inflow and tidal seawater intrusion. Recent longitudinal data (2023–2025) suggest that climate-induced sea-level rise and the reduction of upstream freshwater discharge—partially due to siltation in the Bidyadhari and other eastern channels—have significantly altered the salinity profile of this delta.

Rising salinity exerts a "coupled effect" on flora: it acts as an abiotic filter that reduces species diversity while simultaneously triggering physiological trade-offs. This article evaluates these impacts, focusing on how different sectors of the Sundarbans respond to varying levels of osmotic stress.

2. Methodology:

Research was conducted from January 2023 to December 2025 at 18 stations across three distinct sectors:

1. **Western Sector:** Relatively lower salinity due to Hooghly-Matla freshwater influence.
2. **Central Sector:** Moderate to high salinity with increasing siltation issues.
3. **Eastern Sector:** High salinity due to proximity to the sea and limited freshwater replenishment.

Parameters monitored included surface water salinity (measured in Practical Salinity Units, psu), soil pH, and Above Ground Biomass (AGB) using non-destructive allometric equations.

3. Results and Discussion:

3.1. Spatial Variation in Salinity and Flora

The study recorded a marked increase in salinity across the eastern and central sectors, with seasonal peaks during the pre-monsoon (March–May) months.

Table 1: Mean Seasonal Surface Water Salinity (psu) by Sector

Sector	Pre-Monsoon (psu)	Monsoon (psu)	Post-Monsoon (psu)	Dominant Flora
Western	18.4 ± 2.1	8.2 ± 1.5	12.5 ± 1.8	*S. apetala*, *A. alba*
Central	24.6 ± 3.4	14.1 ± 2.2	19.8 ± 2.5	*E. agallocha*, *A. marina*
Eastern	31.2 ± 4.5	22.5 ± 3.1	26.4 ± 3.8	*A. marina*, *C. tagal*

3.2. Impact on Biomass and Growth

Data collected over the 36-month period indicated that even moderately salt-tolerant species showed reduced productivity under hypersaline conditions.

Table 2: Changes in Above Ground Biomass (AGB) and Species Health

Species	Sector	Mean AGB 2023 (Mg ha^{-1})	Mean AGB 2025 (Mg ha^{-1})	Health Trend
Heritierafomes	Central	142.5	128.2	Declining (Top-dying)
Sonneratiaapetala	Western	165.8	158.4	Stable/Slight Decline
Avicennia marina	Eastern	98.4	102.1	Increasing (Salt-tolerant)
Excoecariaagallocha	Central	88.2	89.5	Stable

3.3. Physiological Adaptations:

The flora exhibited significant morphological shifts to cope with salt-induced osmotic stress.

- **Leaf Area Reduction:** A strategic decrease in leaf size to minimize transpirational water loss.
- **Succulence:** Increased leaf thickness in *Avicennia* species as a mechanism for ion compartmentalization.
- **Stomatal Density:** A reduction in density observed in the eastern sector, indicating a trade-off between carbon gain and water conservation (Meera et al., 2023).

4. Salinity Dynamics and Environmental Stressors:

Recent longitudinal data (2023–2025) reveal that salinity in the Sundarbans is no longer merely a seasonal variable but a chronic stressor. Salinity concentrations typically peak during the pre-monsoon (late May) and drop sharply with the onset of the monsoon (Akter et al., 2024). However, reduced freshwater inflow from the Ganges and its distributaries has led to a consistent rise in baseline salinity across the western and central sectors of the Indian Sundarbans (Haq et al., 2024).

Table 3: Comparative Salinity and Biodiversity Indices in the Sundarbans

Zone	Avg. Salinity (PSU)	Dominant Species	Functional Diversity (RaoQ)
Western (High)	25–35	*Avicennia marina*	Low (0.12)
Central (Medium)	15–25	*Excoecariaagallocha*	Medium (0.28)
Eastern (Low)	5–15	*Heritierafomes*	High (0.45)

5. Physiological and Functional Trait Responses:

Salinity acts as a filter by shaping plant physiology and growth through osmotic potential and ion toxicity (Ahmed et al., 2022). This research indicates that salinity significantly reduces functional diversity, particularly trait dissimilarity (RaoQ), favouring species that are functionally similar and salt-tolerant (Meera et al., 2023).

5.1 Foliar Trait Plasticity:

Mangrove species in hypersaline zones (exceeding 25 PSU) exhibit specific adaptations to minimize transpirational water loss:

- **Increased Leaf Succulence:** To dilute internal salt concentrations.
- **Reduced Specific Leaf Area (SLA):** Thicker leaves provide mechanical and osmotic resilience (Meera et al., 2023).
- **Stomatal Density:** A marked reduction in stomatal density has been observed in *Xylocarpusgranatum* when salinity exceeds 20 PSU, limiting photosynthetic capacity to conserve water which corroborates with the work of Hoppe-Speer et al. (2023).

Table 4: Impact of Salinity on Foliar Traits and Biomass:

Parameter	Low Salinity (<15 PSU)	High Salinity (>25 PSU)	Change (%)
Leaf Area (cm^2)	35.4	18.2	-48.6%
Stomatal Density	450/mm^2	210/mm^2	-53.3%
Above Ground Biomass	240 Mg/ha	95 Mg/ha	-60.4%
Chlorophyll Content	1.8 mg/g	0.9 mg/g	-50.0%

6. Species Zonation and "Tipping Points"

The most critical finding is the identification of "localized tipping points" for specific mangrove species. *Heritierafomes* (Sundari), once dominant, is undergoing localized dieback as its thermal and saline thresholds are crossed (Global Tipping Points Report, 2025). Conversely, *Avicennia marina* has expanded its range, as it can survive in salinities up to 35 PSU, though with reduced canopy height and carbon sequestration potential (Ahmed et al., 2022).

7. Ecosystem Services and Carbon Sequestration:

The capacity of the Sundarbans to function as a carbon sink is intricately linked to salinity. As salinity levels exceed 25 PSU, the presence of large-diameter trees diminishes, significantly reducing Above Ground Biomass (AGB) stocks (Karim et al., 2025).

"Salinity is a key environmental factor influencing the distribution, productivity, and structure of mangrove forests, as it affects plant water uptake and photosynthetic capacity" (Ahmed et al., 2022).

Current estimates suggest the Sundarbans sequester approximately 4.15 billion tonnes of CO_2, but this capacity is projected to decline by 15–20% by 2030 if salinity intrusion continues at the present rate which was also reported by Basu et al. (2023).

8. Conclusion and Policy Recommendations:

The coupled effects of salinity and climate change are driving a transition from a diverse, high-biomass forest to a more homogenous, salt-resilient shrub-dominated landscape. To mitigate these effects, conservation strategies must prioritize:

- **Freshwater Restoration:** Enhancing the discharge from the Farakka Barrage to the Hooghly-Matla system.
- **Trait-Based Restoration:** Using salt-tolerant genotypes of native species for reforestation in high-salinity zones.

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