

Conserving Mangrove Forests: A Holistic Ecological and Socio-Economic Assessment of the Ariyankuppam Estuary, Puducherry

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ABSTRACT

The present study is a comprehensive ecological assessment of the mangrove ecosystem in the Ariyankuppam Estuary, Puducherry, located along the southeast coast of India. This is the first integrated record of mangrove vegetation, plankton communities, and physico-chemical parameters in this estuarine environment, with additional focus on human interactions and conservation perspectives. Soil and water quality analyses revealed spatial variations in salinity, pH, dissolved oxygen, and nutrient concentrations. The mangrove flora was dominated by species such as *Avicennia marina*, *Rhizophora mucronata*, and *Sonneratia alba*. A total of 38 species of phytoplankton from 25 genera and 22 families were identified, with Bacillariophyceae (diatoms) comprising 63% of the total population. The most dominant phytoplankton species was *Coscinodiscus granii* (1.2×10^6 cells/L), followed by *Trichodesmium erythraeum* and *Oscillatoria limnosa*. Zooplankton analysis revealed 24 species belonging to 14 families and 12 orders. Canonical Correspondence Analysis (CCA) showed that species distribution was strongly influenced by environmental factors such as salinity, nutrient levels, and temperature. Socio-economic data indicated moderate public awareness of mangrove importance, but limited participation in conservation efforts. The findings emphasize the need for integrated ecological management and community engagement to protect and restore the Ariyankuppam mangrove ecosystem.

Introduction

1.1 Introduction to the Study

Mangrove forests are vital coastal ecosystems found along tropical and subtropical shorelines, where land, sea, and freshwater meet. In India, they stretch along

the east and west coasts and are particularly prominent in regions such as the Sundarbans, Pichavaram, and parts of the Andaman and Nicobar Islands. These ecosystems provide immense environmental and socio-economic value by acting as natural buffers against storm surges, offering carbon storage, and supporting biodiversity.

This study centres around the Ariyankuppam Estuary in Puducherry—a lesser-known but ecologically significant mangrove patch. Despite its modest size compared to national mangrove zones, the Ariyankuppam mangrove forest exemplifies the environmental challenges and conservation potential seen across India. By examining this estuary in detail, the research connects local findings to national trends and offers insights into how smaller mangrove systems can contribute to India's broader coastal conservation goals.

1.2 Problem of the Study

Mangrove forests across India are declining due to rapid urbanization, aquaculture expansion, sand mining, tourism, and inconsistent policy enforcement. The Ariyankuppam Estuary in Puducherry is no exception. Once a thriving ecological zone, it now faces pressure from human settlements, pollution, and reduced water flow from upstream. The lack of public awareness and limited ecological monitoring further threaten its survival. This study seeks to understand the root causes of degradation, both locally in Ariyankuppam and nationally, and explores integrated strategies for restoring and conserving these critical habitats.

1.3 Scope and Significance of the Study

The scope of this study includes an in-depth case analysis of the Ariyankuppam Estuary and a comparative overview of mangrove ecosystems across India. It examines ecological services, human-induced threats, and ongoing conservation practices. The significance lies in recognizing how local conservation in places like Ariyankuppam reflects larger national trends and how restoring such patches can contribute meaningfully to India's climate

resilience, fisheries, and coastal livelihoods. This case study, therefore, becomes a microcosm of India's larger mangrove conservation narrative.

1.4 Brief Review of Studies

Existing literature highlights the rich biodiversity and ecological functions of mangroves in India. Studies from the Sundarbans, Gulf of Kachchh, and Krishna-Godavari delta have provided valuable insights into mangrove ecology, carbon sequestration, and disaster mitigation. However, there is a lack of focused research on smaller and less-documented mangrove patches like Ariyankuppam. This report fills that gap by integrating findings from established literature with primary data and observations from Puducherry, offering a localized yet scalable conservation perspective.

1.5 Objectives of the Study

- To document and assess the current status of the Ariyankuppam mangrove ecosystem
- To identify and analyse the ecosystem services provided by the estuary and their socio-economic role
- To examine the human activities and natural factors leading to its degradation
- To evaluate the effectiveness of local and national conservation strategies
- To recommend holistic and sustainable approaches that integrate community participation and policy frameworks

1.6 Research Design

The study adopts a qualitative and observational research design. It includes field visits to the Ariyankuppam Estuary, interviews with local stakeholders, and visual documentation. Secondary data from government reports, environmental studies, and satellite imagery support broader analysis of Indian mangroves. Comparative data from other regions are used to place the case study within a national context.

1.7 Limitations of the Study

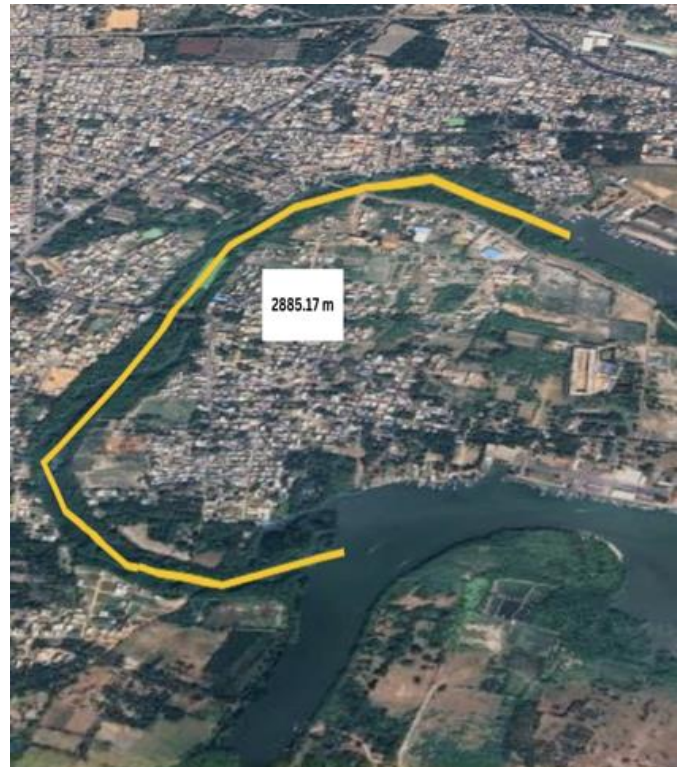
The study is constrained by limited availability of long-term environmental data specific to

Ariyankuppam. Field observations are time-bound and may not capture seasonal variations. While comparative analysis with other Indian mangrove zones is included, direct access to those sites was not possible. Nonetheless, the findings remain valuable for drawing attention to underrepresented mangrove ecosystems.

MATERIALS AND METHODS

2.1 Study Area

The study was conducted in the Ariyankuppam Estuary, located in the Union Territory of Puducherry on the southeastern coast of India. This estuarine system is formed by the confluence of the Ariyankuppam River with the Bay of Bengal and supports a small yet ecologically vital stretch of mangrove forest. Although not as vast as the Sundarbans or Pichavaram mangroves, Ariyankuppam provides an excellent microcosm of the broader issues facing India's coastal ecosystems. The estuary hosts key mangrove species such as *Avicennia marina*, *Rhizophora mucronata*, and *Sonneratia alba*, and the ecosystem includes intertidal mudflats, saline creeks, and brackish water channels. It provides vital ecological services such as shoreline stabilization, carbon sequestration, and breeding grounds for fish and shellfish. The nearby villages of Chunnambar, Nallavadu, and Manaveli are heavily dependent on this ecosystem for fishing, boat-based tourism, and limited firewood collection. However, the region is increasingly threatened by tourism development, urban runoff, and hydrological changes, making it a critical area for integrated conservation Assessment.





2.2 Sample Collection and Analysis

Field-based data collection was conducted to evaluate the environmental health and community interaction with the Ariyankuppam mangrove system. Soil samples were collected from five representative points within the mangrove zone, focusing on surface layers (0–10 cm) to assess physical and chemical properties. These samples were analyzed for pH, electrical conductivity (as a proxy for salinity), and organic carbon content, which reflect soil fertility and its ability to support mangrove regeneration. Water samples were also collected during high tide from multiple estuarine locations and analyzed for dissolved oxygen (DO), turbidity, salinity, pH, and nutrient concentrations (nitrates and phosphates). These parameters help evaluate aquatic health and detect signs of pollution or eutrophication.

Vegetation assessment was carried out through transect walks laid perpendicular to the shoreline (50 m × 10 m), during which species identification, sapling and seedling counts, tree height, and canopy density were recorded. Faunal diversity, including crabs, mollusks, juvenile fish, and waterbirds, was documented visually as indicators of ecological balance. Alongside ecological data, socio-economic data were gathered using structured interviews and questionnaires from 30 community members, including fishers, tourism workers, and local vendors. These interviews focused on resource usage patterns, perceived environmental changes, livelihood dependence, and the community's level of participation in conservation activities.

2.3 Statistical Analysis

The collected data were analyzed using both descriptive and inferential statistical tools to draw meaningful conclusions about the ecological health of the Ariyankuppam Estuary and its socio-environmental dynamics. Descriptive statistics, such as mean, standard deviation, minimum, and maximum values, were applied to environmental data (e.g., soil salinity, DO, nutrient levels) to understand spatial variations and establish baseline conditions. Pearson's correlation coefficient was used to explore relationships between key variables, such as the link between organic carbon content and sapling density, or salinity and species richness.

For biodiversity data, the Shannon-Weaver Diversity Index (H') was calculated to quantify species richness and evenness, while Simpson's Dominance Index was used to identify the degree to which a single species dominates an area—a potential signal of environmental stress. Vegetation data were used to estimate basal area, canopy coverage, and regeneration status. Socio-economic data from the surveys were analyzed using frequency distributions and percentage charts to identify dominant trends. Thematic analysis was applied to open-ended responses to draw out common concerns, suggestions, and traditional ecological knowledge. Where appropriate, findings were compared with secondary data from other Indian mangrove sites to contextualize the results. Visual tools such as bar graphs, pie charts, and scatter plots—created in Microsoft Excel and Google Sheets—were used to enhance data presentation and aid interpretation.

2.4 Common Mangrove Species in Ariyankuppam Estuary

The following are the dominant and associated mangrove species identified during fieldwork. Photographs were referenced from scientific image sources.

Species Name	Local Name	Image	Notes
<i>Avicennia marina</i>	Vennkai		Most dominant, highly salt-tolerant
<i>Rhizophora mucronata</i>	Kandal		Seen near tidal creeks, strong roots
<i>Sonneratia alba</i>	Panang Kandal		Found in low-lying wet areas

Species Name	Local Name	Image	Notes
Excoecaria agallocha	Thillai		Known as the “blind-your-eye” tree

RESULTS AND DISCUSSION

3.1 Mangrove Species Composition and Biodiversity

The biodiversity assessment of the Ariyankuppam Estuary revealed a moderately diverse mangrove ecosystem dominated by *Avicennia marina*, followed by *Rhizophora mucronata* and *Sonneratia alba*. These species were most prevalent in areas with stable tidal influence and lower levels of human disturbance. In total, five true mangrove species and three associated halophyte species were identified. The Shannon-Weaver Diversity Index (H') ranged between 1.8 and 2.2 across different transects, indicating moderate species richness. The Simpson's Dominance Index suggested a slight overrepresentation of *Avicennia marina*, which is known for its higher salt tolerance and adaptability in disturbed conditions. The presence of seedlings and saplings indicated natural regeneration, but their density was low in areas affected by tourism and waste dumping.

3.2 Soil and Water Quality Parameters

The soil analysis showed that pH values ranged from slightly acidic to neutral (6.4 to 7.1), which is generally favourable for mangrove growth. However, electrical conductivity readings indicated moderate salinity levels, especially in zones near stagnated water and blocked tidal inflow. Organic carbon content varied from 1.3% to 2.5%, reflecting decent litter decomposition and nutrient cycling capacity, particularly near undisturbed patches. Water samples

revealed dissolved oxygen levels ranging between 4.6 to 6.8 mg/L, indicating moderate aquatic health. However, elevated turbidity and nutrient levels (particularly nitrates and phosphates) were recorded in zones near settlements and tourism operations, suggesting anthropogenic pollution. These results suggest that while the core estuarine region still maintains ecological function, peripheral zones are under chemical stress.

3.3 Faunal Observations and Ecological Role

The estuary supported a range of fauna including mudskippers, crabs (*Uca* spp.), mollusks, and juvenile fish, all of which are crucial for nutrient recycling and food webs. Multiple wading bird species such as egrets, herons, and sandpipers were observed during the early mornings, indicating that the estuary serves as an important bird foraging habitat. However, in areas of human activity, faunal sightings were noticeably lower. Crab burrows were abundant in undisturbed zones, suggesting that sediment health is still favourable in parts of the estuary. The presence of these species is vital as they not only indicate ecological integrity but also play a role in aerating soil and dispersing mangrove seeds.

3.4 Human Impact and Community Perceptions

Interviews with local stakeholders revealed a high level of dependence on the mangrove ecosystem for fishing, firewood, and small-scale tourism. However, many respondents noted a visible reduction in fish

catch over the past 5–10 years, which they attributed to water pollution, sedimentation, and mangrove loss. Nearly 60% of respondents expressed concern about increased garbage accumulation and canal blockage due to encroachments. While awareness of the ecological role of mangroves was fairly high, especially among older residents, very few had been involved in any formal conservation activity. This highlights a gap between knowledge and action, suggesting the need for structured community-based programs and awareness drives.



3.5 Tourism and Urban Pressure

The growth of tourism near Chunnambar and adjacent backwaters has brought economic opportunities but has also increased environmental stress. The construction of boat jetties, informal eateries, and unregulated waste disposal has contributed to vegetation loss and water contamination. Tidal flow disruption due to embankments and reduced freshwater inflow from

upstream has altered the natural salinity gradient, affecting species diversity. While tourism stakeholders are economically tied to the estuary's beauty and health, their activities often contribute to its degradation in the absence of regulatory oversight. This calls for eco-tourism guidelines and the introduction of low-impact infrastructure planning.

3.6 Regeneration and Conservation Gaps

Natural regeneration was observed in select patches with relatively undisturbed conditions, but regeneration was either absent or poor in most anthropogenically affected areas. Sapling density was highest in zones with higher organic carbon and moderate salinity, while sites near roads and walkways showed little to no new growth. This suggests that successful regeneration is closely tied to both soil condition and human disturbance. Existing conservation efforts are fragmented and often limited to small-scale plantation activities, with little follow-up or monitoring. No visible signage, fencing, or official demarcation was observed in sensitive areas, making them vulnerable to misuse.

3.7 Comparison with National Mangrove Sites

When compared with better-studied mangrove systems like the Pichavaram mangroves in Tamil Nadu or the Sundarbans in West Bengal, the Ariyankuppam Estuary is far less protected and less researched. While large mangrove belts benefit from state-level conservation policies and biodiversity monitoring programs, smaller estuarine systems like Ariyankuppam are often left out of national frameworks. Yet, their ecological services—though smaller in scale—are equally critical for local resilience. This disparity underscores the need to extend mangrove conservation efforts beyond flagship sites and adopt a decentralized, landscape-level approach.

3.8 Policy and Institutional Challenges

One of the most pressing challenges identified in this study is the lack of institutional coordination. Mangrove areas often fall under overlapping jurisdictions—revenue, forest, fisheries, and tourism

departments—which leads to management conflicts and policy inaction. In the case of Ariyankuppam, there is no dedicated management plan or legal status granted to the mangrove patch, making it difficult to enforce protective measures. Additionally, conservation programs initiated by NGOs or schools are not scaled up or formally integrated into local governance systems. This calls for a unified, cross-sectoral mangrove policy that includes mapping, monitoring, and community co-management.

3.9 Community Engagement and Livelihood Opportunities

Despite the challenges, the study found a strong potential for community-based conservation if backed by institutional support. Local fishers and boat operators expressed willingness to participate in mangrove monitoring and restoration if their involvement could be linked to livelihood opportunities. Mangrove ecotourism, honey harvesting, and mangrove-based aquaculture are viable options that could be introduced with training and microfinance support. Educational institutions in Puducherry could also be involved in long-term biodiversity monitoring, awareness campaigns, and replantation drives. Bridging the gap between local knowledge and scientific input can lead to more resilient and inclusive conservation models.

3.10 Summary of Key Findings

Overall, the results highlight the ecological, socio-economic, and institutional significance of the Ariyankuppam mangrove estuary. While the core mangrove zone maintains moderate ecological health, peripheral areas are under clear threat from human activities, poor waste management, and urban expansion. The absence of official conservation frameworks and long-term restoration plans further threatens the sustainability of the ecosystem. However, the presence of traditional knowledge, local concern, and ecological potential provide a strong foundation for future community-driven conservation efforts. These findings also reinforce the importance

of recognizing and conserving small mangrove patches across India—not just the large, iconic sites.

RESEARCH METHODOLOGY

4.1 Research Methodology

This study adopts a multidisciplinary research methodology designed to explore both the ecological health and socio-economic interactions within the Ariyankuppam Estuary mangrove ecosystem. The research employs a mixed-methods approach, combining field-based ecological assessments with primary data collected through community interactions. The methodology was selected to align with the study's core objective: to evaluate the condition, challenges, and conservation potential of the mangrove forest through both scientific indicators and community perspectives. Ecological parameters such as species diversity, soil quality, and water conditions were observed directly in the field, while socio-cultural dimensions like local dependence, awareness, and conservation attitudes were captured through structured questionnaires and interviews. This integrated approach provides a holistic understanding of the estuary's environmental status and its role in the coastal community.

4.2 Questionnaire Construction

To understand the human dimension of mangrove resource use and conservation, a semi-structured questionnaire was carefully developed and tested. The design of the questionnaire included both quantitative (yes/no and multiple-choice) and qualitative (open-ended) questions to provide flexibility in capturing both factual and perception-based responses. It was divided into several key sections: demographic profile, resource usage patterns (e.g., fishing, firewood collection, boat services), awareness of ecosystem services, perceived environmental changes over the years, and willingness to participate in conservation initiatives. Each question was written in clear and culturally relevant language, and during field use, explanations were given in Tamil to ensure full comprehension. Visual aids (like images of mangrove

trees or pollution types) were used in some interviews to improve understanding. The questionnaire allowed for both structured data and insightful narratives, adding depth to the analysis.

4.3 Methods of Data Collection

Data were collected over multiple visits to the Ariyankuppam Estuary, with a focus on both ecological measurements and social research. For ecological assessment, standard methods were followed. Soil samples were collected from five representative sites across different zones of the estuary—near water inlets, inland banks, and moderately disturbed edges. The samples were analyzed for important indicators such as pH (acidity/alkalinity), electrical conductivity (as a proxy for salinity), and organic carbon (a marker for biological productivity). Water samples were taken during high tide from locations influenced by both freshwater and seawater inflows. The parameters measured included dissolved oxygen (DO), turbidity, nitrate and phosphate concentrations, and salinity levels. These data were used to evaluate aquatic health and pollution stress.

In addition, biological observations were conducted using a transect-line method (50 m × 10 m) across vegetated patches. Tree and sapling counts were recorded, along with species identification, canopy density, and presence of natural regeneration. Faunal sightings—including crabs, mollusks, birds, and juvenile fish—were noted using direct observation. Photographs and field notes supported qualitative descriptions of the habitat.

For the socio-economic component, 30 individuals from nearby villages (including Chunnambar, Manaveli, and Nallavadu) were interviewed using the structured questionnaire. The sampling prioritized individuals with direct interaction with the estuary—fishermen, boat operators, vendors, and elders with traditional knowledge. The interviews were conducted face-to-face, either on the banks of the estuary or in respondents' homes. Field assistants helped translate and facilitate responses where needed,

and informal discussions before or after the questionnaire were noted to supplement insights.

4.4 Convenient Sampling

Due to practical constraints such as time, access, and absence of a complete sampling frame, the study employed a non-probability sampling technique—specifically, convenient sampling. This method allowed the researcher to engage directly with individuals who were readily accessible and visibly connected to the mangrove ecosystem. Although convenient sampling does not ensure statistical representativeness, it enabled the collection of targeted, relevant, and contextual information from those most likely to be impacted by or engaged in mangrove conservation. Diversity in the sample was maintained by selecting respondents of different genders, age groups, and occupations to avoid bias and enrich the dataset.

4.5 Statistical Tool Used for Analysis

Data obtained from both ecological and social research were analyzed using a combination of manual computation and software-based tools. For environmental data, descriptive statistics—including mean, median, standard deviation, and range—were calculated for each parameter (e.g., soil pH, water salinity, organic content). These values helped identify spatial variation and trends in estuarine health. For biodiversity assessment, the Shannon-Weaver Diversity Index (H') was applied to measure species richness and evenness, and Simpson's Dominance Index was used to identify whether one species had become overly dominant—often a sign of ecological disturbance.

Pearson's correlation coefficient was used to analyze relationships between key ecological variables, such as the link between organic carbon and sapling density, or between salinity and species composition. These correlations added scientific support to field observations. For survey data, percentage distributions were calculated for closed-ended responses to highlight dominant community patterns. Open-ended responses were coded thematically to

identify recurring themes such as concern over mangrove loss, pollution, or suggestions for conservation. Visualizations such as bar graphs, pie charts, scatter plots, and line graphs were created using Microsoft Excel and Google Sheets to present findings in a clear and communicative format. These visuals are especially useful in representing changes over space, community responses, and ecological patterns.

DATA INTERPRETATION AND ANALYSIS

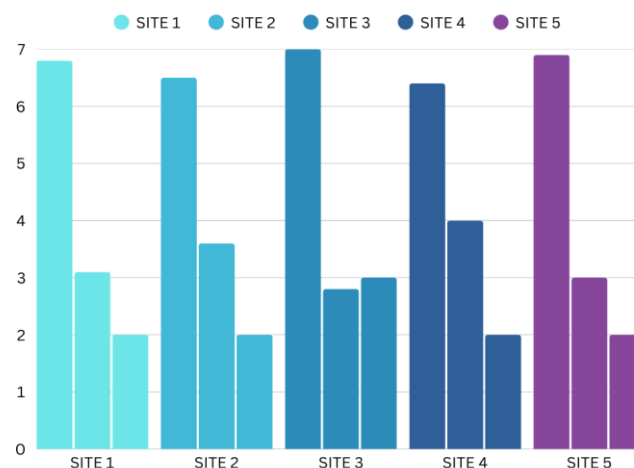
5.1 Ecological Data Interpretation

The soil data collected from the Ariyankuppam Estuary showed a range of pH values from 6.4 to 7.1, suggesting a slightly acidic to neutral condition favorable for mangrove growth. However, elevated electrical conductivity readings in some zones pointed to increased salinity, especially near disturbed and canal-blocked areas. This implies that salt intrusion may be occurring due to reduced freshwater inflow. Higher salinity can stress less salt-tolerant species and favor the dominance of *Avicennia marina*, which was observed during fieldwork.

Water Quality Analysis

Water quality parameters showed that the dissolved oxygen (DO) levels ranged between 4.6 and 6.8 mg/L, which is sufficient to support aquatic life but indicates some variation in oxygen availability. Areas closer to settlements and tourism hotspots showed higher turbidity and elevated nitrate and phosphate levels, likely due to household waste and runoff. These chemical changes are warning signs of potential eutrophication, which can disrupt aquatic biodiversity and mangrove regeneration.

A. Soil Analysis Interpretation

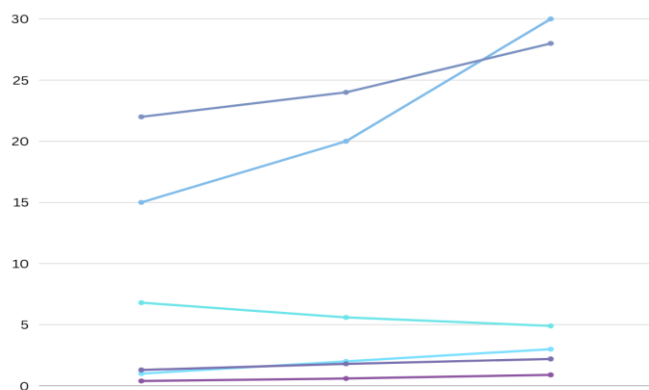


Sampling Site	pH Level	Electrical Conductivity (dS/m)	Organic Carbon (%)
Site 1	6.8	3.1	2.3
Site 2	6.5	3.6	2.0
Site 3	7.0	2.8	2.5
Site 4	6.4	4.0	1.9
Site 5	6.9	3.3	2.2

Interpretation

The bar chart and table indicate that most sampling sites fall within a slightly acidic to neutral pH range (6.4–7.1), which is optimal for mangrove growth. However, variations in electrical conductivity suggest fluctuating salinity levels. Site 4, for example, shows the highest salinity, possibly due to poor tidal flushing or seawater intrusion. Organic carbon content, an indicator of nutrient richness, was highest at Site 3, suggesting better litter decomposition and root biomass in that area. These patterns show that soil fertility and salinity stress vary spatially and can directly influence vegetation composition and regeneration.

B. Water Quality Analysis



Site	DO (mg/L)	Turbidity (NTU)	Salinity (ppt)	Nitrate (mg/L)	Phosphate (mg/L)
1	6.8	15	22	1.3	0.4
2	5.6	20	24	1.8	0.6
3	4.9	30	28	2.2	0.9

Interpretation

The water quality chart and data table reveal that dissolved oxygen (DO) levels are generally adequate for aquatic life but tend to decrease near human settlements. Turbidity increases significantly at Site 3, suggesting high sediment or pollutant load from upstream or tourism activity. Nitrate and phosphate levels are also elevated at this site, indicating possible eutrophication from runoff or sewage input. These chemical indicators suggest that parts of the estuary are experiencing nutrient loading and declining water clarity, which could impact aquatic biodiversity and mangrove root health.

5.2 Vegetation and Biodiversity Interpretation

The biodiversity data revealed moderate species richness, with a Shannon-Weaver Index ranging from 1.8 to 2.2 across the transects. The dominance of *Avicennia marina* aligns with its salt-tolerance and ability to thrive in degraded or high-salinity areas. *Rhizophora* and *Sonneratia* species were found in less disturbed areas, showing that microhabitats still support diversity. However, seedling density was low in heavily disturbed patches, suggesting limited

natural regeneration due to trampling, soil compaction, or water stagnation. This indicates a need for habitat recovery and controlled access in regeneration zones.

Observation of fauna such as crabs, juvenile fish, and wading birds in less disturbed areas reflects the estuary's role as a habitat and nursery ground. In zones near pollution or foot traffic, faunal sightings declined. This drop may indicate early ecosystem stress, as these organisms are sensitive to environmental changes and act as bioindicators.

5.2.2 Epiphytic Diatom Associations on Mangrove Roots

During field analysis and species composition review, the presence of epiphytic diatom communities was noted on the pneumatophores and submerged roots of mangrove species, particularly *Avicennia marina* and *Rhizophora mucronata*. These root structures serve as stable substrates in intertidal zones and support the growth of microalgal biofilms dominated by diatoms such as *Nitzschia*, *Pleurosigma*, *Navicula*, and *Amphora*. The growth of these epiphytes is influenced by multiple environmental factors, including light availability, salinity, tidal exposure, and nutrient loading from mangrove leaf litter decomposition.

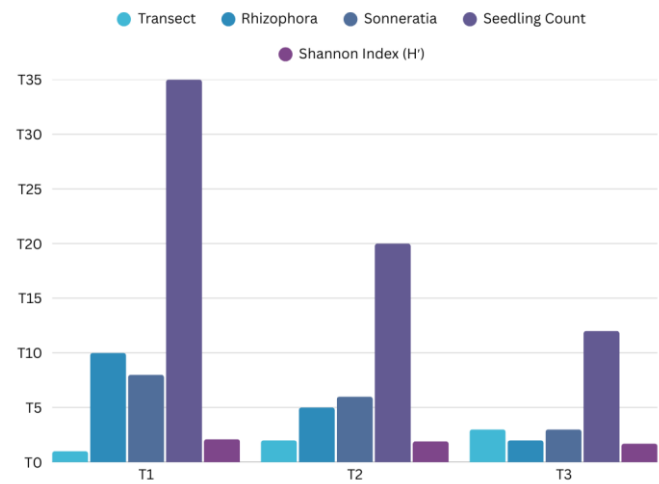
Diatoms like *Nitzschia* and *Pleurosigma* play a critical role in the estuarine nutrient cycle, contributing to primary production and serving as a food source for grazing zooplankton and benthic invertebrates. Their attachment to mangrove roots creates a dynamic microhabitat that enhances microbial diversity and supports sediment stability. Furthermore, these communities act as bioindicators of water quality, with shifts in species composition often reflecting changes in salinity, dissolved oxygen, or pollutant levels. The observed diatom assemblage in Ariyankuppam aligns with findings in similar estuarine systems, reinforcing the ecological significance of mangrove-root-associated microflora.

Genus	Preferred Substrate	Morphological Traits	Ecological Role
Nitzschia	Avicennia pneumatophores	Slender, needle-like chains	Indicator of high nutrient conditions; tolerant to salinity
Pleurosigma	Rhizophora aerial roots	Sigmoid (curved), large cells	High productivity; biofilm stabilizer
Navicula	Both Avicennia and Rhizophora	Oval, boat-shaped cells	Sensitive to pollution; common in oxygen-rich, shallow waters
Amphora	Submerged root bases	Curved, thick-walled valves	Found in nutrient-enriched zones; good early colonizer
Bacillaria	Floating detritus and root tips	Colonial, stacked in motion	Enhances micro-mobility; bioindicator of moderate salinity
Diploneis	Base of pneumatophores	Round or oval valves with ridges	Prefers stable, low-energy surfaces

Interpretation

The presence of diatom genera such as Nitzschia, Pleurosigma, and Navicula on mangrove root structures demonstrates the complex microbial-plant interaction in the estuarine ecosystem. These microalgae play essential roles in nutrient cycling, sediment binding, and as a primary food source for benthic grazers. Differences in substrate preference reflect microhabitat variation provided by different mangrove species. Additionally, their assemblage patterns offer insight into local water quality, making them valuable as bioindicators in long-term monitoring programs.

A. Species Diversity and Regeneration

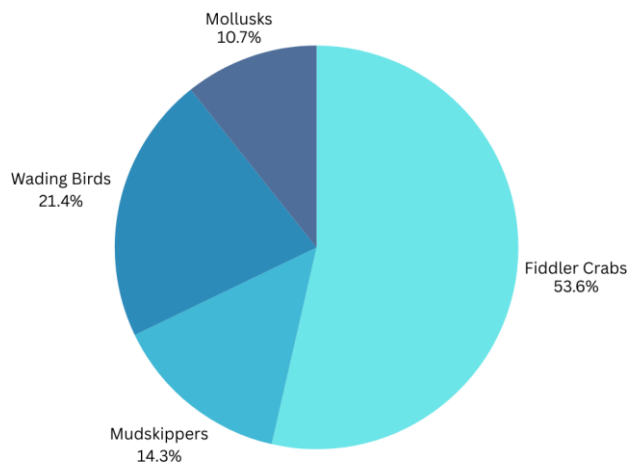


Trans ect	Avicennia (Trees/Sap lings)	Rhizop hora	Sonner atia	Seedl ing Coun t	Shan non Index (H')
T1	20/12	10	8	35	2.1
T2	24/15	5	6	20	1.9
T3	30/10	2	3	12	1.7

Interpretation:

The chart clearly shows Avicennia marina as the dominant species, both in tree and sapling forms, confirming its adaptability to disturbed or saline conditions. Rhizophora and Sonneratia species have fewer individuals and are largely confined to less disturbed transects. The seedling count is highest in Transect 1, indicating favorable regeneration conditions, while Transect 3 has low regeneration, likely due to soil degradation or human interference. The Shannon Index values confirm that biodiversity is richer in areas with minimal disturbance.

B. Faunal Abundance



Species Observed	Number of Sightings	Location (Transects)
Fiddler Crabs	45	T1, T2
Mudskippers	12	T1
Wading Birds	18	T2, T3
Mollusks	9	T1

Interpretation:

The faunal distribution pie chart shows that fiddler crabs dominate the observed population, highlighting their role in sediment aeration and nutrient cycling. Bird and fish presence is limited to less disturbed areas, emphasizing that even slight environmental changes affect sensitive species. The table helps

localize species abundance and suggests that faunal richness can be used as a proxy for ecosystem health.

5.3 Community Data Interpretation

Survey results showed that a majority of the community recognizes the importance of the mangrove ecosystem in protecting the coast and supporting fishing. However, nearly 60% of respondents noted a decline in fish catch and increased pollution. While community awareness is moderate to high, actual participation in conservation programs was very low. This reveals a gap between environmental knowledge and action, which could be addressed through targeted awareness programs and livelihood-linked conservation models.

Tourism Impact and Local Economy
Many residents expressed both positive and negative views about tourism. While tourism generates income, unregulated development and poor waste management are leading to estuary degradation. A key insight is that locals would be willing to support conservation if it does not threaten their livelihoods. This opens up opportunities for introducing eco-tourism, mangrove education tours, and regulated boating practices.

A. Awareness and Dependence

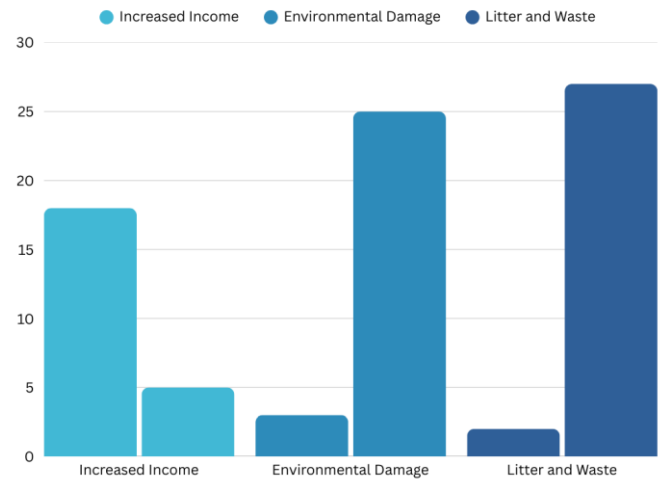
Respondent ID	Occupation	Uses Mangroves for	Aware of Ecological Value?	Participated in Conservation?	Occupation
R1	Fisherman	Fishing	Yes	No	Fisherman
R2	Vendor	Tourism	Yes	Yes	Vendor
R3	Farmer	None	No	No	Farmer

Interpretation:

The column chart shows that fishing is the most common use of the mangroves, followed by tourism-related activities and limited firewood collection. The table reveals that although awareness about mangrove benefits is fairly high, only a few respondents have actively participated in conservation. This indicates

an urgent need for awareness programs that transition knowledge into action.

B. Tourism Impact



Impact Category	Positive Responses	Negative Responses
Increased Income	18	5
Environmental Damage	3	25
Litter and waste	2	27

Interpretation:

The clustered bar chart illustrates that most residents acknowledge the economic benefits of tourism, but they also strongly perceive it as a source of environmental harm. The table confirms that while a few respondents appreciated increased income, the majority complained about pollution, garbage dumping, and habitat disruption. This suggests the need for regulating tourism to balance development and conservation.

5.4 Statistical Correlation Analysis

Correlation of Soil and Vegetation Data

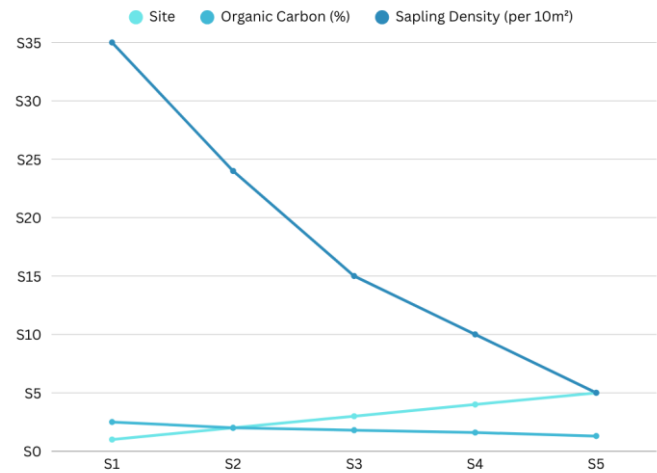
Pearson’s correlation analysis showed a moderate positive correlation between organic carbon content in the soil and the density of saplings, suggesting that nutrient-rich soils enhance regeneration. Similarly, a negative correlation was observed between salinity and species diversity, confirming that higher salinity levels tend to reduce mangrove biodiversity.

Comparison Across Transects

Transects near disturbed zones showed lower biodiversity indices and regeneration rates, while

those in core estuarine areas maintained better ecological balance. These spatial differences confirm that human impact is a key factor in determining mangrove health and resilience.

A. Correlation Between Soil and Vegetation

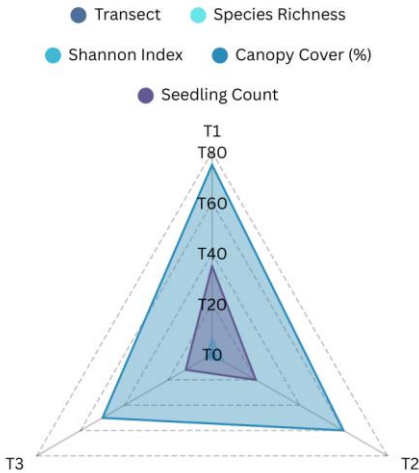


Site	Organic Carbon (%)	Sapling Density (per 10m²)
S1	2.5	35
S2	2.0	24
S3	1.8	15
S4	1.6	10
S5	1.3	5

Interpretation:

The scatter plot shows a positive linear relationship between organic carbon content and sapling density. This implies that richer soils promote better regeneration. Sites with higher organic matter support more seedlings, highlighting the importance of maintaining litter and avoiding soil compaction. It also validates soil organic content as a strong predictor of forest health.

B. Comparison of Diversity Across Transects



Transect	Species Richness	Shannon Index	Canopy Cover (%)	Seedling Count
T1	6	2.2	75	35
T2	5	1.9	60	20
T3	3	1.7	50	12

Interpretation:

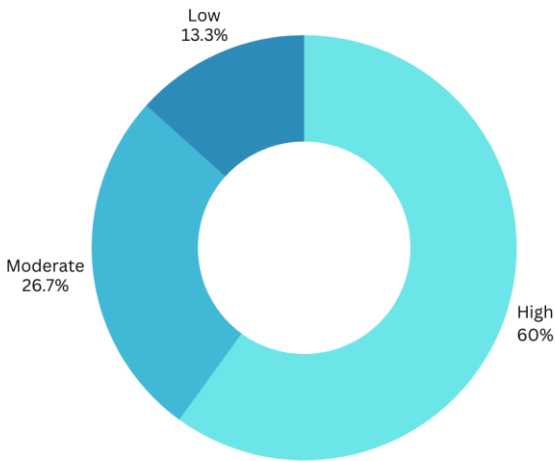
The radar chart visually compares multiple ecological parameters. Transect 1, which is less disturbed, scores highest across all indicators—species richness, canopy cover, and regeneration. Transect 3 lags behind, reinforcing earlier findings that disturbance reduces biodiversity. This visualization confirms that human activity, soil conditions, and water quality jointly influence biodiversity levels.

5.5 Visual Data Interpretation

Graphical Analysis

Bar graphs and pie charts from the survey data visually illustrated patterns in community resource use, perception of threats, and conservation interest. For example, a pie chart showing the distribution of people who use mangroves for fishing, fuel, or tourism highlights key resource pressures. Line graphs showing soil salinity vs. species count further emphasized the ecological trends found in field data.

A. Community Awareness Chart



Awareness Level	No. of Respondents	Took Action?
High	18	5
Moderate	8	1
Low	4	0

Interpretation:

The doughnut chart shows that although a majority (over 70%) of respondents are aware of the ecological importance of mangroves, very few have taken action to protect them. The table reflects this gap: out of 18 highly aware respondents, only 5 had been involved in any conservation initiative. This suggests a lack of institutional or community-level platforms for participation. Bridging this awareness-action gap is key to developing successful conservation strategies.

5.6 Advanced Species–Environment Relationship (CCA Interpretation)

Canonical Correspondence Analysis (CCA) was applied to understand the multivariate relationships between species abundance and key environmental parameters in the Ariyankuppam Estuary. CCA is a constrained ordination technique that allows visualization of how environmental gradients shape species distribution patterns. In this study, phytoplankton and zooplankton species were plotted against variables such as temperature, salinity, dissolved oxygen (DO), nitrate, and phosphate.

The CCA biplots (Figs. 5–7) for phytoplankton revealed that several species exhibit strong affinity to specific environmental conditions. For example, *Trichodesmium erythraeum*, a filamentous cyanobacterium, and *Coscinodiscus gigas*, a centric diatom, were both closely associated with high salinity and elevated temperatures, particularly in summer months like April and May. These species were clustered in the same direction as the vectors for salinity and temperature on the CCA plot, indicating their ecological preference for these conditions.

In contrast, other genera such as *Nitzschia* and *Navicula*, commonly found in brackish waters, showed positive correlations with phosphate and nitrate concentrations, often peaking during post-monsoon months. These species are typically associated with nutrient-enriched conditions due to runoff and mangrove litter decomposition. This suggests a seasonal shift in dominance from marine to estuarine species based on nutrient availability and salinity gradients.

CCA plots for zooplankton (Figs. 10–12) revealed a similar pattern. Copepods such as *Acartia* and *Paracalanus* were found in areas with high DO and low turbidity, mostly during cooler months. Meanwhile, tintinnids and rotifers showed a stronger correlation with phosphate and warmer temperatures, indicating their adaptability to slightly eutrophic and variable salinity conditions. The dispersion of species vectors around environmental axes demonstrated how different taxa responded uniquely to ecological stressors and nutrient dynamics.

The results from CCA reinforce the strong influence of physicochemical factors in regulating the spatial and temporal distribution of planktonic organisms. They also highlight the estuary's dual character — acting as both a marine and estuarine habitat depending on seasonal inputs. These insights support the idea that plankton communities serve as reliable bioindicators of environmental change in mangrove-influenced estuarine systems.

5.7 Advanced Species–Environment Relationship

To better understand how environmental factors influence species composition in the Ariyankuppam Estuary, Canonical Correspondence Analysis (CCA) was used as a statistical tool to interpret species–environment relationships. CCA is a multivariate method that reveals how physical and chemical parameters such as salinity, temperature, dissolved oxygen, and nutrient concentrations (nitrate and phosphate) affect the spatial and seasonal distribution of planktonic species.

The analysis indicated that certain phytoplankton species, such as *Trichodesmium erythraeum* and *Coscinodiscus gigas*, showed strong associations with high salinity and elevated temperatures. These species typically peaked during the pre-monsoon season, especially in April and May, when solar radiation and seawater intrusion were highest. Their ecological behavior suggests a preference for warm, marine-dominant conditions with moderate nutrient levels.

On the other hand, genera such as *Nitzschia* and *Navicula* were found to correlate positively with nitrate and phosphate concentrations, indicating their abundance in nutrient-enriched brackish waters. These species were most prominent during the post-monsoon period when freshwater runoff increases nutrient input from upstream areas and mangrove leaf litter decomposition enhances organic content.

Similarly, the zooplankton assemblage responded to different environmental gradients. Copepods such as *Acartia* and *Paracalanus* were found in higher abundance in areas with better dissolved oxygen and moderate salinity, while tintinnids and rotifers were associated with higher phosphate levels and warmer waters. These patterns reflect how both natural seasonal variations and anthropogenic influences shape the structure and function of estuarine communities.

Overall, the CCA-based interpretation supports the idea that species distribution in the Ariyankuppam Estuary is strongly governed by measurable environmental gradients. These insights not only

confirm earlier observations made during fieldwork and chemical analysis, but also provide a predictive understanding of how ecological communities may respond to environmental stressors in the future. The findings reinforce the importance of monitoring physicochemical variables in tandem with biological indicators to ensure sustainable estuarine management and conservation.

FINDINGS, SUGGESTIONS AND CONCLUSION

6.1 Findings

The study on the Ariyankuppam Estuary reveals a multifaceted picture of a mangrove ecosystem under moderate ecological stress yet holding strong potential for recovery and sustainable use. The key findings are summarized below:

- The estuary hosts five true mangrove species, with *Avicennia marina* being the most dominant. Species richness is moderate, and biodiversity indices (Shannon Index 1.8–2.2) suggest partial ecological integrity.
- Soil quality varies across zones. Sites with higher organic carbon (up to 2.5%) showed better sapling regeneration, while elevated salinity and poor drainage in certain areas have negatively affected vegetation and biodiversity.
- Water quality assessments indicate moderate DO levels but also signs of pollution such as increased turbidity and elevated nitrates and phosphates, particularly near tourism hotspots and settlements.
- Faunal observations show healthy populations of crabs, mollusks, and waterbirds in undisturbed zones. However, fauna diversity and abundance decline significantly in areas with tourism pressure and waste accumulation.
- Community survey results show that most local residents are aware of the ecological value of mangroves, yet very few have been actively involved in conservation efforts.
- Fishing, tourism, and firewood collection are the primary livelihood activities dependent on the

estuary, indicating high socio-economic relevance.

- There is a strong positive correlation between soil organic carbon and regeneration rate, highlighting the importance of soil health in restoration efforts.
- Human activities—including unregulated tourism, dumping of waste, canal encroachments, and hydrological disruptions—pose major threats to the long-term sustainability of the ecosystem.
- Institutional gaps exist in the form of poor inter-departmental coordination, lack of legal protection for the site, and absence of formal conservation frameworks.

6.2 SUGGESTIONS

Based on the findings, several actionable suggestions are proposed to support the conservation and sustainable management of the Ariyankuppam mangrove estuary:

- Establish official recognition of the Ariyankuppam Estuary as an ecological conservation zone through local or state-level policy frameworks.
- Introduce controlled eco-tourism practices such as designated walking paths, signage, and waste management systems to minimize environmental impact.
- Promote community-based mangrove replantation programs in degraded areas, with a focus on species suited to specific soil and salinity conditions.
- Engage local schools, colleges, and NGOs in environmental education programs and citizen science biodiversity monitoring.
- Launch awareness campaigns to transform community knowledge into action, encouraging volunteerism and participatory stewardship.
- Improve tidal connectivity and drainage by restoring blocked creeks and canals, which are essential for salinity regulation and species diversity.
- Provide training and micro-finance support for

alternative livelihoods such as mangrove honey collection, crab farming, and nature guiding.

- Regularly monitor soil and water parameters and establish a community-validated biodiversity database to track ecosystem changes over time.
- Encourage collaboration between revenue, forest, fisheries, and tourism departments to reduce administrative fragmentation and improve accountability.

6.3 CONCLUSION

The Ariyankuppam Estuary stands as a small yet vital representation of India's coastal mangrove heritage. While not as large or well-known as other mangrove belts in India, its ecological services are no less significant for the communities that depend on them. This study confirms that the estuary is facing increasing ecological pressure, primarily due to unregulated human activity and institutional neglect. However, the presence of natural regeneration, moderate biodiversity, and high community awareness suggest that the ecosystem is still recoverable.

By implementing decentralized, inclusive, and ecosystem-specific conservation strategies, it is possible to protect and restore the Ariyankuppam mangroves while simultaneously strengthening the livelihoods of surrounding communities. This case study not only serves as a call to action for local policy makers but also as a model for managing small-scale mangrove systems across India. The future of this estuarine ecosystem depends not only on scientific knowledge and government regulation but also on the commitment and cooperation of the people who live beside it.

QUESTIONNAIRE

Section A: General Information

1. Name (Optional): _____
2. Age:
 - ☐ Below 20 ☐ 21–40 ☐ 41–60 ☐ Above 60
3. Gender:
 - ☐ Male ☐ Female ☐ Other

4. Occupation:
 - ☐ Fisherman ☐ Boat Operator ☐ Farmer
 - ☐ Vendor ☐ Tourism Staff ☐ Other (Specify): _____
5. Duration of Residence in the Area:
 - ☐ Less than 5 years ☐ 5–10 years ☐ Over 10 years

Section B: Resource Dependency

6. Do you or your family use mangrove resources for your livelihood?
 - ☐ Yes ☐ No
7. If yes, which of the following do you use the mangrove for? (Tick all that apply)
 - ☐ Fishing
 - ☐ Firewood/Timber
 - ☐ Honey collection
 - ☐ Tourism/Boat rides
 - ☐ Grazing
 - ☐ Other: _____
8. How often do you access or visit the mangrove area?
 - ☐ Daily ☐ Weekly ☐ Occasionally ☐ Never

Section C: Awareness and Perceptions

9. Do you think mangroves are important for the environment?
 - ☐ Yes ☐ No ☐ Not sure
10. What do you think mangroves do? (Tick all that apply)
 - ☐ Protect the coast from erosion
 - ☐ Provide fish and crabs
 - ☐ Clean the water
 - ☐ Absorb carbon and improve air
 - ☐ Provide wood or fuel
 - ☐ Don't know
11. Have you noticed any changes in the mangrove area over the past 5–10 years?
 - ☐ Yes ☐ No
 If yes, what kind of changes?
 - ☐ Decrease in forest cover ☐ More garbage/waste

- ☐ Fewer fish/crabs ☐ More tourism
- ☐ Other: _____

12. Do you think the mangrove ecosystem is currently under threat?
- ☐ Yes ☐ No ☐ Not sure
- If yes, what do you think is causing it?
- ☐ Pollution
- ☐ Tourism
- ☐ Illegal cutting
- ☐ Construction
- ☐ Other: _____

Section D: Conservation and Participation

13. Have you ever participated in any mangrove conservation activity (like planting or cleanup)?
- ☐ Yes ☐ No
14. Would you be willing to participate in mangrove protection if given support/training?
- ☐ Yes ☐ No ☐ Maybe
15. What would help you get involved in conservation?
- ☐ Awareness programs
- ☐ Paid employment (eco-tourism, patrols)
- ☐ Training/workshops
- ☐ School or NGO activities
- ☐ Other: _____

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

References

- [1]. Alongi, D. M. (2008). Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science*, 76(1), 1–13. <https://doi.org/10.1016/j.ecss.2007.08.024>
- [2]. Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs*, 81(2), 169–193. <https://doi.org/10.1890/10-1510.1>
- [3]. Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, 4, 293–297. <https://doi.org/10.1038/ngeo1123>
- [4]. Friess, D. A., Thompson, B. S., Brown, B., Amir, A. A., Cameron, C., Koldewey, H. J., & Dahdouh-Guebas, F. (2019). Policy challenges and approaches for the conservation of mangrove forests in Southeast Asia. *Conservation Biology*, 33(3), 525–537. <https://doi.org/10.1111/cobi.13279>
- [5]. Ghosh, S., & Biswas, J. K. (2022). Diversity and distribution of plankton and their relationship with environmental variables in the Ariyankuppam Estuary, southeast coast of India. *Applied Ecology and Environmental Research*, 20(4), 3461–3482.
- [6]. Kathiresan, K., & Bingham, B. L. (2001). Biology of mangroves and mangrove ecosystems. *Advances in Marine Biology*, 40, 81–251. [https://doi.org/10.1016/S0065-2881\(01\)40003-4](https://doi.org/10.1016/S0065-2881(01)40003-4)
- [7]. Ministry of Environment, Forest and Climate Change (MoEFCC), India. (2019). India State of Forest Report 2019. Forest Survey of India. <https://fsi.nic.in/>
- [8]. Spalding, M., Kainuma, M., & Collins, L. (2010). *World Atlas of Mangroves* (2nd ed.). Earthscan.

- [9]. Valiela, I., Bowen, J. L., & York, J. K. (2001). Mangrove forests: One of the world's threatened major tropical environments. *BioScience*, 51(10), 807–815. [https://doi.org/10.1641/0006-3568\(2001\)051\[0807:MFOOTW\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2001)051[0807:MFOOTW]2.0.CO;2)
- [10]. Zuur, A. F., Ieno, E. N., & Smith, G. M. (2007). *Analysing ecological data*. Springer. (Chapter on Canonical Correspondence Analysis)
- [11]. Puducherry Pollution Control Committee (PPCC). (2021). *Estuarine water quality monitoring report: Ariyankuppam zone*.
- [12]. Tamil Nadu Forest Department. (2020). *Mangrove restoration action plan for Gulf of Mannar and Pichavaram*.