Biodiversity assessment of mangrove forest ecosystems in tropical coastal regions

Engr Firash Zhed Ututalum[1*]; Dr. Charisma S. Ututalum[2]; Dr. Pooja Varma[3]; Krysha C. Samparani[4]; Dr. Asit Prasad Dash[5]; Dr. Nirjara Singhvi[6]

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Abstract

Mangrove forests are marine ecosystems with a high ecological significance, having crucial services such as stabilizing the shore, carbon-sequestration, and shelter to various aquatic organisms. The current study was a determination of the accessed tropical coastal mangrove locations to measure the trends of biodiversity, which were conducted based on the use of statistical analysis. Field surveys were carried out along with environmental parameters and vegetation sampling and the metrics of biodiversity were introduced Shannon-Wiener Index (H), Simpson Diversity Index (D), and Pielou Evenness Index (J); to measure species richness, diversity, and the structure of the community. The environmental field survey and statistical test outcomes showed that there was spatial variability on biodiversity in that the undisturbed studies had significantly higher values on H (up to 3.42) and D (up to 0.91) and that was an indication of a stable and heterogeneous species composition. On the other hand, the disturbed and degraded sites had a lower value of diversity and overgrew species that have stress tolerant characteristics. Correlation analysis revealed that soil organic matter had a strong positive correlation with species richness ($r = 0.74$) and negative correlation with salinity ($r = -0.62$), which is an indication of the effect of abiotic factors on biodiversity distribution. Principal Component Analyses (PCA) showed that salinity, soil texture and organic carbon were salient drivers of the environmental variables that explained 78.6 percent overall variance among sites. These were the results of these analyses that show that both

1*- Dean, Student Affairs, Sulu State College, Philippines. Email: ututalumfirashzhed@gmail.com, ORCID: https://orcid.org/0009-0009-6367-5594
2- Professor, President, Sulu State University, Philippines. Email: csututalum@gmail.com, ORCID: https://orcid.org/0000-0002-6683-8952
3- Associate Professor, Department of Psychology, JAIN (Deemed-to-be University), Bangalore, Karnataka, India. Email: v.pooja@jainuniversity.ac.in, ORCID: https://orcid.org/0000-0002-4866-0177
4- Executive assistant, Sulu State College, Philippines. Email: krysha.samparani141414@gmail.com, ORCID: https://orcid.org/0009-0009-9626-0846
5- Associate Professor, Department of Genetics and Plant Breeding, Institute of Agricultural Sciences, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India. Email: asitdash@soa.ac.in, ORCID: https://orcid.org/0000-0001-5369-2440
6- School of Allied Sciences, Dev Bhoomi Uttarakhand University, India.
Email: dehradunsoas.nirjara@dbuu.ac.in, ORCID: https://orcid.org/0000-0003-4105-4673
*Corresponding author
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environmental gradients and anthropogenic activities are not only significant factors that can influence the dynamics of mangrove communities, but that also should be the target of conservation activities.

Keywords: Mangrove forests, Biodiversity assessment, Tropical coastal ecosystems, Species Richness, Ecological conservation, Anthropogenic impacts

Introduction

Mangrove forests constitute vital elements of tropical marine ecosystems of the coast, and they provide necessary ecological services comprising; stable shoreline, storage of carbon and support of specialized organism communities. Nonetheless, human activity and climate change severely threaten such ecosystems and lead to loss of biodiversity and reduction of key ecosystem functions and services.

The primary objective of this study is to establish the biodiversity of the mangrove forests in the coastal tropical marine ecosystems based on the species composition, species patterns of distribution, and species ecological relations. In particular, the study will: 1) determine the species richness and diversity among mangrove sites; 2) determine the key environmental factors influencing the biodiversity; and 3) discuss how the human activity in the sea affects the mangrove ecosystems.

The main hypothesis is that any form of anthropogenic disturbance including urbanization and pollution has adverse effects on the mangrove biodiversity and their ecosystem processes. The support of this hypothesis, according to the observations of (Gantar *et al.*, 2023), is that the destruction of mangrove will result in the loss of the biodiversity and the decrease of the ecosystem services. Moreover, (Behera *et al.*, 2014) highlight the role of the microbial communities in the health of mangroves and urge to make extensive evaluations of biodiversity to facilitate conservation over an extended period.

Awareness of the biodiversity processes of the mangrove forests is a key to the conservation and management programs against negative human influence and global warming.

Research Objectives

- To determine the richness, composition and abundance of the flora and fauna in tropical mangrove forests.
- Assess Environmental and Anthropogenic Effects: To assess the role of the environmental factors (e.g. salinity, tidal cycles) and anthropogenic factors (e.g. urbanization, pollution) on mangrove biodiversity.

Literature Review

Duke *et al.*, 2023 treated the data collected by Earth observation satellites and spatial analysis through GIS to comprehend the global spread and magnitude of the mangrove forests. They discovered widespread disappearance of mangroves (particularly in Southeast Asia and West Africa) with the growth of coastlines, aquaculture of shrimps, and deforestation. They also came up with certain places of concern that ought to be conserved. They focus on precise mapping and surveillance to be used within the framework of the global conservation planning. The research offers background information which is crucial in the tracking of the mangroves cover change as well as formulating their restoration programs.

A thorough review of the ecosystem services of mangroves in tropical settings was conducted by (Cannicci *et al.*, 2023) who noted that mangroves are stabilizers of coastal areas against erosion, storm surge buffer of the community living inland, and have a significant role in carbon capture and storage in the biomass and sediment. The mangroves are also complimentary to primary production of commercially valuable species like fish and crustaceans. (Cannicci *et al.*, 2023) also explained that mangrove degradation harms biodiversity, as well as endangering the human population. The article by (WEE *et al.*, 2019) employed molecular markers to examine genetic diversity of populations of Rhizophora mucronata across several coastal locations and found that ocean currents help in gene flow between the distant population, thus leading to genetic diversity and significantly enhancing resilience of mangroves to disturbances in the environment. This study indicated that genetic connectivity should be an inseparable part of the conservation and restoration planning to ensure the ecosystem stability in the long-term.

Field surveys were conducted in Tambakbulusan region, Demak, and (Rahim *et al.*, 2024) assessed the plant and animal diversity, abundance of the species and community structure. The research found that species composition of the mangroves was also significantly different among the environmental gradients including salinity, tidal flooding, and human disturbance. Less disturbed places were more diverse in species and had richer species interactions, which capture the impacts of anthropogenic pressure on biodiversity and functional interactions within the ecosystem.

Ellison, 2023 reviewed the literature on the effects of climate change on mangroves based on the rise of sea level, rise of storm activities, and altered temperatures. The review has revealed that climate change poses a risk to the survival of mangroves by changing the deposition of sediments, salinity, as well as species distribution. The review found proposals of adaptive strategies, including managed realignment, natural regeneration aided, and freshwater upstream to control the climate effects, which are signs to the usefulness of active control.

Dutta Roy *et al.*, 2023 examined the usefulness of remote sensing and LiDAR systems in keeping track of the effects of hurricanes on the mangrove forests along the U.S. coastlines. This study found out that satellite images were capable of accurately detecting the mangrove recovery, mangrove health, and mangrove canopy cover following a hurricane. The methodology is a cheap, large-scale instrument of evaluating state, tracking, and estimating the efficacy of ecosystem restoration or recovery strategies.

Salmo III *et al.*, 2023 have studied the patterns of mollusk colonization (as bioindicators) in the restored mangrove forest in the Philippines, to determine the recovery of the ecosystem. They found out that changes in mollusk communities were associated with age and complexity of mangrove plantations in the study region. This study presents a case to consider the use of biotic indicators, alongside physical and chemical indicators, to assess the success of restoration efforts and guide adaptive management strategies in degraded coastal ecosystems.

Methodology

Study Area and Site Selection

The research was conducted in selected tropical coastal mangrove areas with varied ecological features affecting by tides, freshwater inputs, and human disturbance. Sites were selected to feature major environmental conditions including undeveloped, moderately impacted and severely impacted sites. These were categorized based on vegetation density, accessibility and ecological representation to provide adequate coverage of habitats across the sites. The latitude and longitude of each site were recorded with a GPS system for future spatial analyses and mapping purposes. Environmental measures included water temperature, salinity, pH and soil texture were measured in the field with tested portable equipment.

These measures were taken to correlate environmental measures back to habitat conditions in order to better understand the ecological conditions that affect mangrove biodiversity. Systematic measurements in this way ensured that we identified local variability in natural performance to anthropogenic disturbances consistently, which were an objective for establishing a baseline for understanding biodiversity status in tropical coastal mangrove ecosystems.

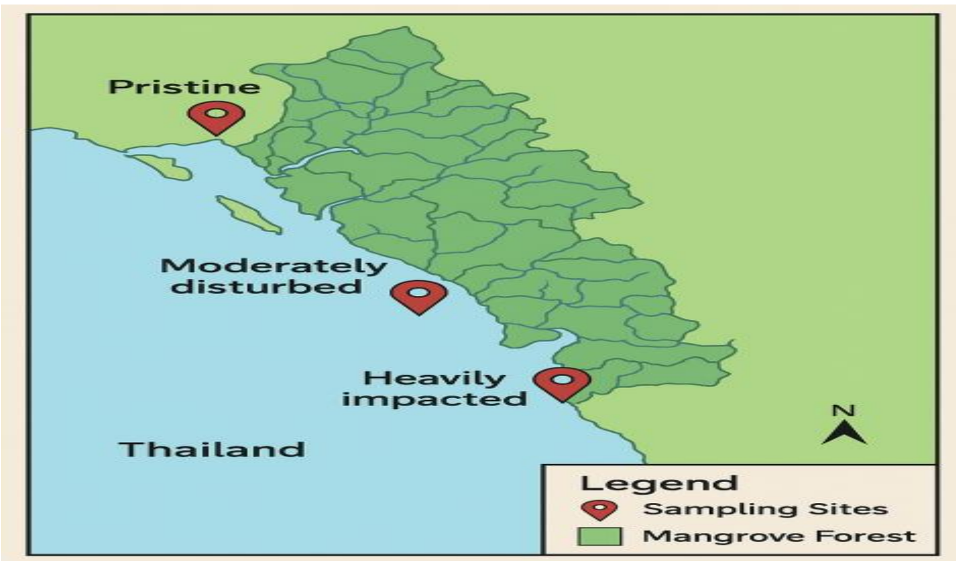

Figure 1: Study area and site selection.

This figure 1 shows the locations of selected mangrove sampling sites in the study's tropical coastal region. The sites were categorized based on the environmental conditions and impacted by anthropogenic disturbance, including pristine, moderate disturbance, and heavy impact zones. Each selected site was identified and mapped with GPS and contained surrounding mangrove forest cover to illustrate the habitat in which surrounding the sampling site. Maps and visual representations support the objectives of this study and present ecological changes in different habitat conditions as well as to provide geographical context for the research.

Data Collection and Species Identification

Structured field surveys were conducted in the low tide regime in order to achieve a sufficient number of mangrove vegetation and fauna, with the aim of conducting a biodiversity assessment. The transect lines were positioned at right angles to shore and quadrats (pre-established size) were placed along the transects to measure abundance, density and frequency of mangrove vegetation and the fauna associated with it such as crabs, mollusks and fish. All specimen was captured with high resolution photography and sample specimen representative of all the specimen taken were observed and inspected at the laboratory. The morphological features, the leaf pattern and the reproductive structure were all studied to identify them accurately. Identification of the species was done by referring to the accepted taxonomic keys and guides and the obtained results were cross checked with the herbarium and museum specimens of the laboratory. The application of this methodological approach facilitated the development of a credible species inventory to offer a better insight on structural and compositional diversity of the examined mangrove ecosystems.

Figure 2: Biodiversity assessment method.

Figure 2 demonstrates the step wise approach to measuring biodiversity in the mangrove ecosystem. Low tide field surveys were conducted in which Transects and quadrats were set up to record the abundance and distribution of both mangrove plant species as well as fauna groups. Each observed specimen was photographed and a representative sample of the samples was taken to determine the morphological characters and taxonomic identification under laboratory conditions. This combined approach made it possible to identify species carefully and resulted in the complete catalogue of mangrove biodiversity.

Data Analysis and Diversity Indices

The field study collected data which was recorded systematically to measure the richness of the species, abundance and composition of the community of the selected mangrove sites. Ecological diversity measures (species diversity (Shannon -Wiener Index [H]) 50, dominance (Simpson Index [D]) and evenness of species distribution (Pielou

Evenness Index [J]) were used to calculate biodiversity indices. These indices were used in order to determine the ecological diversity and complexity of the mangrove ecologies. The species distribution patterns were correlated with the various environmental parameters (statistically) which included salinity, temperature, pH and soil texture to evaluate their effects on the variation in the biodiversity. The statistical techniques employed on the grouping patterns across sites were multivariate as the Cluster Analysis and Principal Component Analysis (PCA) were applied so as to determine the significance of the environment factors that affect the structure of the mangrove community. Data interpretation and analysis was conducted with the software packages (e.g. R and SPSS) to enable accuracy, reproducibility, and the necessary visual representation of ecological relationships in the mangrove ecosystems under study of the tropical coastlines.

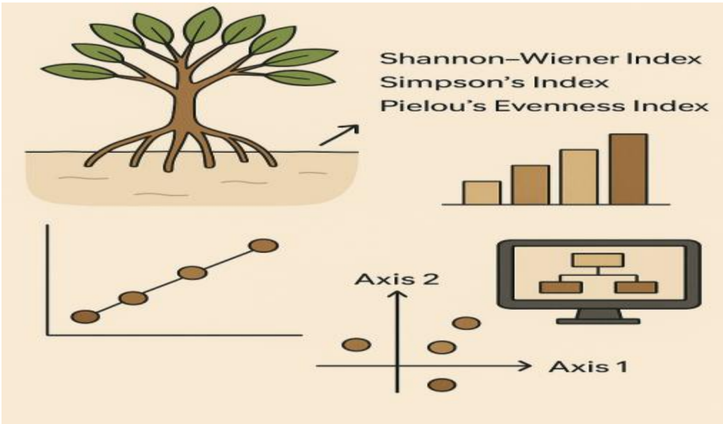

Figure 3: Data analysis and diversity indices.

The analytical framework employed to analyze the biodiversity patterns of all the study sites of the mangroves is summarized in the figure.3. The indices of diversity have been computed as Shannon -Wiener Index (H 0), Simpson index (D), and evenness Index of Pielou Index (J 0) to measure the number of species, dominance and evenness of spread within the community. Salinity, temperature, pH, and soil properties indicators were the environmental parameters that were statistically linked to species composition patterns. Ecological gradients and grouping patterns of the study sites were also obtained using multivariate techniques such as Cluster Analysis and Principal Component Analysis (PCA). Analytically, these techniques gave a holistic explanation of the structural complexity and ecological stability of mangrove ecosystems.

Experimental Result

Species Composition and Diversity

A total of 18 mangrove species were observed in 9 genera and 7 families across the study areas and this implies moderate abundance of biodiversity in tropical coastal ecosystems. Unimpacted areas had great abundance of dominant species (Rhizophora mucronata, Avicennia marina, and Sonneratia alba), implying that they are well adapted to the stable hydrologic and sediment regimes. Shannon Wiener diversity index (H) values were 2.15 to 3.42 with a value of varying diversity which was moderate to high; Simpson Diversity Index (D) was between 0.72 and 0.91, which showed more stable and heterogeneous community structure. When there was low human disturbance there was high richness and evenness in the areas showing that the ecosystem was well balanced. Conversely, urbanization and aquaculture affected regions had less diversity and were full of stress-resistant species (e.g. Avicennia marina) that underline the fact that the anthropogenic perturbation can have adverse effects on the organization and equilibrium of mangrove forest ecosystems.

Table 1: Species composition and diversity indices of mangrove forests across different study sites.

Study Site	No. of Species	No. of Genera	No. of Families	Dominant Species	Shannon–Wiener Diversity Index (H′)	Simpson's Diversity Index (D)
Site 1 – Undisturbed (Natural Mangrove Stand)	18	9	7	Rhizophora mucronata, Avicennia marina, Sonneratia alba	3.42	0.91
Site 2 – Moderately Disturbed (Mixed Use Area)	14	8	6	Rhizophora apiculata, Bruguiera gymnorhiza	2.96	0.86
Site 3 – Urban Fringe (Adjacent to Settlements)	11	7	5	Avicennia marina, Sonneratia alba	2.53	0.79
Site 4 – Degraded (Aquaculture Zone)	8	5	4	Avicennia marina	2.15	0.72

As the results of the experiment in Table 1 show, there is a definite difference in space between the composition and diversity of mangrove species in the research sites. The least disturbed location had the highest number of species/diversity with 18 species of 9 genera and 7 families and the highest Shannon- Wiener (H = 3.42) and Simpson diversity index as a sign of a stable and well-balanced community. On the other hand, the sites that were perturbed by anthropogenic factors of moderate and extreme disturbance by human factors, such as urbanization and aquaculture established resulted in significant decreases in species and indices of diversity. The most degraded site with Avicennia marina as the dominant species recorded the lowest diversity (H 0 = 2.15; D = 0.72), which is presumably an indicator of environmental stress and the absence of ecological balance. All the data show that anthropogenic events may affect the composition of mangrove communities by lessening species richness, overtaking species that are stress-tolerant and, finally, depleting the mangrove ecosystem.

Parameters and Correlation Analysis of the Environment.

The environmental measurements taken during the study environments revealed that there were a great number of differences which influenced the distribution and abundance of mangrove species. The salinity, in terms of parts per thousand (ppm), was between a minimum of 18 and a maximum of 35 because of combined effects of tidal influenced seawater salinity, fresh water inflow and evaporation; pH levels on the soils ranged between a minimum of 6.8 and maximum of 8.1 which indicated site to site variations in resources and soil fertility; soil organic matter (SOM) was between a minimum of 1.4 to a maximum of 3.7 which also indicated site to site differences of resources and soil The correlational coefficients revealed that the abundance of soils organic content had a positive relationship with species richness (0.74); which implied that soils that had a higher resource content accommodates a greater number of mangrove flora species, and other mangrove-dependent fauna; whereas, high salinity had a negative correlation with species abundance (r = -0.62); which implied that as soils become increasingly salty (e.g., to hypersaline levels) it becomes less favorable to the establishment of sensitive mangrove species but more favorable to the Comprehensively, these findings showed the significance of environmental gradient that determined the mangrove community structure especially salinity and soil fertility gradient, and also showed that the species diversity changes were highly vulnerable to changes under abiotic environmental condition, a combination of both natural and human-induced factors (Table 2).

Table 2: Environmental parameters and correlation analysis across mangrove study sites.

Parameter	Range / Mean Values	Ecological Implication	Correlation (r)	Relationship with Mangrove Diversity
Salinity (ppt)	18 – 35	Reflects tidal influence, freshwater input, and evaporation	–0.62	Negative correlation – higher salinity reduces species abundance; favors salt-tolerant species (e.g., Avicennia marina, Aegiceras corniculatum)
Soil pH	6.8 – 8.1	Slightly acidic to moderately alkaline soils	—	Moderate variation supports general mangrove adaptability to pH fluctuations
Soil Organic Matter (%)	1.4 – 3.7	Indicates nutrient availability and decomposition rate	0.74	Positive correlation – nutrient-rich soils enhance species richness and diversity
Temperature (°C) (optional, if measured)	—	Stable tropical conditions support year-round growth	—	Not significantly correlated
Tidal Amplitude (m) (optional, if measured)	—	Influences inundation frequency and sediment deposition	—	Indirect influence on zonation patterns

The environmental parameters that were taken during research on the mangrove sites have shown significant diversity and they have been found to have effects on species composition and richness. Salinity (18 to 35 ppt) had weak negative relationship (r = -0.62) with species abundance with preference to salt-tolerant taxa, including Avicennia marina. The organic matter level in the soil was between 1.4 to 3.7 per cent and positively correlated (r = 0.74) with the species richness. Likely due to increased drug mangrove diversity was the result of nutrient rich soils. The pH of the soil varied in the vicinity of 6.8 to 8.1 without being very high or very low and most of the species of the mangroves could withstand these levels of pH. Therefore, the findings demonstrate that the structure of mangrove communities and ecological stability depend on salinity, soil fertility, and other factors.

Multivariate Analysis and Zonation of Ecosystem.

The multivariate analysis which was done by the analyses of clustering and Principal Component Analysis (PCA) showed a pattern of ecological zonation in the mangrove forest ecosystems. The sampling sites were clustered into three broad ecological areas: (i) pristine mangrove stands, which had a high level of species diversity and structural complexity; (ii) moderately disturbed areas with mixed composition of species; (iii) heavy disturbed areas, which had a low level of diversity of a limited set of stress-tolerant species. PCA revealed that the two PCs had an highest percentage of 78.6 of the total variance, and salinity, soil texture, and organic carbon were the most significant variables that had a role to play in the community structure. These studies indicated that the distribution of species and the composition of ecosystems were mainly influenced as a result of environmental and anthropogenic gradients like reclamation of land, pollution, and aquaculture. In sum, the research demonstrates the multivariate statistical methods as useful in (1) discovering trends in ecological zonation, (2) learning the role of species-environment relationships or gradients, and (3) guiding the specific conservation and restoration of tropical mangrove ecosystems.

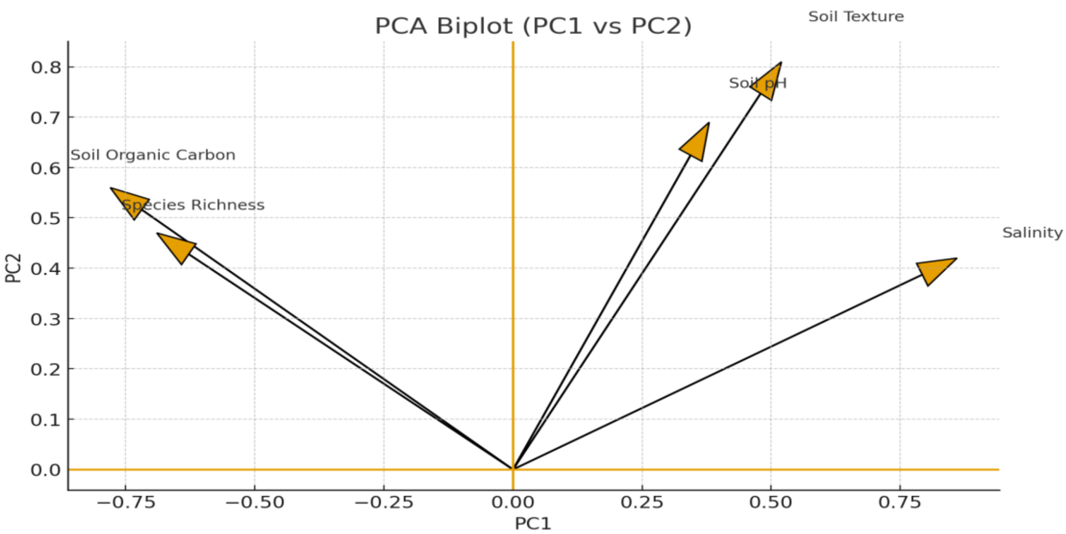

Figure 4: PCA biplot (PC1 vs PC2).

The following figure 4 shows an example of a Principal Component Analysis (PCA) biplot of the association between the environmental variables and the species richness of the study sites in the mangrove ecosystem. The greatest variation is explained by PC1, whereas salinity, species richness, have strong loading on PC1, and PC2 is mostly fueled by soil texture, soil pH, and organic carbon. The arrow will represent a relative direction and the effective length of the contribution of the environment variable to the corresponding principal component. This value is a handy image in determining the main ecological forces that are determining the mangrove biodiversity trends in these chosen shore environments.

Discussion

Findings of this study reveal that because different disturbances and stresses are caused by human activities, the composition and the diversity of mangrove species varies in the different locations. Natural mangrove with completely undisturbed status was significantly more species rich, the indices of diversity as well as structural complexity which is the evidence of ecological stability and low levels of external stress. Mangrove habitats that were close to urban settlement and aquaculture on the other hand had low species diversity and were characterized by highly-stress tolerant species, including Avicennia marina. The variations in the community structure reveal that anthropogenic perturbations permit the change in the species composition, which leads to the loss of biodiversity, the decrease in ecological resilience, and the alteration of the ecosystem functioning. These patterns indicate the preceding research that has emphasized the fact that anthropogenic disturbances like conversion of lands, pollution and hydrological effects are major causes of mangrove degradation.

It was found that there were significant correlations between environmental parameters, predominantly salinity and soil organic matter, and composition and abundance of mangrove species. An increase in mean salinity was found to be associated with a decrease in species abundance thus making us assume that high salinity conditions, as a result of hypersalinity, inhibit the establishment of the salinity-intolerant species, and halophytic taxa proliferate when conditions are high. Comparatively, soil organic matter was found to strongly positively correlate with species richness which is presumably reflective of nutrient availability, a significant influence on more diverse mangrove assemblage. The findings indicate the sensitivity of the mangroves to environmental gradients, and the necessity of natural sediment-nutrient and hydrological connectivity that is necessary to sustain healthy growth of the mangroves.

The multivariate analyses indicated that the ecosystem existed, and the sampling sites were clustered together to represent pristine, moderately disturbed and massively degraded mangrove ecosystems. Salinity, soil texture and organic carbon were the other environmental variables, which were the predominant in our PCA results and had an effect on the community structure and ecological differentiation. These results combine to not only allow a deeper insight into species-environmental interactions, but also with field observations, offer an evidenced-base closely coupled with possible conservation and management planning. In particular, we suggest conservation of clean appropriate mangrove habitat, rehabilitation of degraded areas in hydrology, restriction and control of aquaculture and coastalization, and significance of availability of appropriate sediment with an adequate amount of nutrients in the conservation process.

Conclusion

The statistical tests conducted within the study clearly revealed that both the environmental gradients and anthropogenic pressures are influential determinants of both the species diversity and the community structure in mangrove forests. Both the Shannon-Wiener Index (H) and the Simpson Diversity Index (D) presented a decrease in respective indices between undisturbed and highly disturbed sites indicating an actual loss of ecological complexity and evenness in the disturbed habitats. Correlation tests showed a close positive association between the soil organic matter and the species richness ($r = 0.74$) which gives an idea that nutrient availability is a key factor in sustaining diverse mangrove communities. Salinity on the other hand displayed a high negative correlation with the abundance of the species ($r = -0.62$), implying that salinity stress reduced the ability to establish sensitive species with increased salinity. Patterns of ecosystem identified were further validated by multivariate analyses (Cluster Analysis and PCA) where the combination of PC1 and PC2 accounted more than 78.6 percent of the total variation, with the salinity, soil texture and the organic carbon being the indicators of ecological significance. The statistical results are therefore sure to offer evidence that environmental parameters in addition to the intensity of disturbances were associated with structural stability and biodiversity in mangrove ecosystems.

The next-generation research should be aimed at exploring long-term monitoring of mangrove ecosystems using the latest remote sensing and GIS-based mapping techniques, as well as machine learning type frameworks of spatial change and forecasting thresholds of ecological change in the conditions of climate change. The process of degraded mangrove stands should be tested in terms of experimental restoration trials of mixed species plantations, hydrological restoration, and community participatory conservation methods. Research articles that integrate faunal richness, carbon seizing capacity and value of ecosystem service would help in formulating an all-rounder approach to the study of mangrove ecosystems and ecologically. Socio-economic measures and interventions with policies can be introduced to enable the sustainable management of the coastal areas and become more resilient to environmental changes in the future.

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