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Structural and Functional Loss in Restores Wetland Ecosystem in Etawah District

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Abstract
Wetlands are among the most productive ecosystems on Earth, offering a multitude of ecological services such as biodiversity conservation, water purification, flood regulation, and carbon sequestration. However, anthropogenic disturbances, agricultural encroachment, and hydrological alterations have led to a significant structural and functional decline in many wetland systems. This study examines three critical wetlands in the Etawah district—Sarsai Nawar Wetland, Saman Bird Sanctuary, and Nagla Maya Wetland—to evaluate the effectiveness of restoration initiatives. A mixed-method approach integrating field-based ecological surveys, water and soil quality testing, GIS and remote sensing analysis, and multivariate statistical tools was employed. Species diversity indices (Shannon and Simpson), PCA of ecological variables, NDVI assessments, and land-use change detection were used to quantify degradation and recovery trajectories. Results reveal significant variation across sites, with Sarsai Nawar showing robust ecological recovery, while Nagla Maya Wetland exhibited continued decline. These findings underscore the need for site-specific, community-inclusive wetland management strategies and highlight the role of long-term monitoring in ensuring ecological resilience and sustainability in wetland restoration efforts.
Keywords: *Wetland restoration, Biodiversity indices, Ecological resilience, GIS and remote sensing, Etawah district*

I. Introduction

Wetlands are among the most productive and valuable ecosystems globally, offering a myriad of ecological services such as biodiversity conservation, water purification, flood regulation, and carbon sequestration. In India, these ecosystems have faced significant degradation due to urbanization, pollution, and agricultural expansion. The Etawah district in Uttar Pradesh is home to several notable wetlands, including the Sarsai Nawar Wetland and the Saman Bird Sanctuary. Efforts to restore these wetlands have been initiated to reclaim their ecological functions and services. However, restoration processes often encounter challenges, leading to structural and functional losses that impede the full recovery of these ecosystems.

Etawah district boasts critical wetland habitats that serve as sanctuaries for numerous avian species. The Sarsai Nawar Wetland, for instance, is a Ramsar-designated site recognized for its importance in conserving waterbirds, notably the Sarus Crane. Similarly, the Saman Bird Sanctuary provides vital wintering habitats for migratory birds traversing continents. These wetlands not only support rich biodiversity but also offer ecosystem services that benefit local communities and contribute to environmental health.

Challenges in Wetland Restoration

Restoring degraded wetlands is a complex endeavor fraught with challenges that can lead to structural and functional losses. A comprehensive meta-analysis of 621 wetland sites globally revealed that even a century after restoration efforts, biological structures (primarily plant communities) and biogeochemical functions (such as carbon storage) remained, on average, 26% and 23% lower, respectively, than in reference sites . This indicates that recovery is often incomplete and slow, with some ecosystems potentially transitioning to alternative states that differ from their original conditions. Several factors influence the efficacy of wetland restoration:

- Size of the Ecosystem: Larger wetlands (>100 hectares) tend to recover more rapidly than smaller ones. This is attributed to the greater availability of habitats and resources that can support diverse biological communities.
- Environmental Setting: Wetlands situated in warmer climates exhibit faster recovery rates due to accelerated ecosystem processes. Additionally, wetlands with hydrologic connectivity, such as those linked to riverine or tidal flows, benefit from natural sediment and nutrient exchanges that facilitate restoration .
- Anthropogenic Pressures: Ongoing human activities, including encroachment, pollution, and unsustainable land use practices, can hinder restoration efforts. For instance, the Saman Wetland Complex has experienced degradation over the past two decades due to anthropogenic pressures, underscoring the need for stringent protection policies and community engagement in restoration initiatives .

As for example The Nagla Maya village wetland in Etawah district exemplifies the challenges faced by small wetlands. Despite its modest size of 1.6 hectares, it historically attracted numerous migratory birds during winter. A decade ago, efforts were made to expand this wetland under the Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS). However, the wetland continues to struggle with issues such as unwanted vegetation overgrowth. Local communities have endeavored to conserve the area, but additional support is required to fully restore its ecological functions .

The Broader Context: Wetland Loss in India

The challenges observed in Etawah's wetlands reflect a nationwide trend. India has lost approximately 30% of its natural wetlands over the past three decades, primarily due to illegal construction, unsustainable urbanization, agricultural expansion, and pollution . Urban areas have been particularly affected; for example, Chennai lost 90% of its wetlands between 1970 and 2015, leading to significant environmental and infrastructural challenges .

Strategies for Effective Wetland Restoration: To mitigate structural and functional losses in restored wetlands, several strategies can be implemented:

- Comprehensive Planning: Restoration projects should be based on thorough ecological assessments that consider the specific characteristics and needs of the wetland.
- Community Involvement: Engaging local communities in conservation efforts ensures that restoration initiatives are sustainable and that the socio-economic benefits of wetlands are recognized and preserved.
- Policy Enforcement: Strengthening and enforcing environmental regulations can prevent further degradation and promote the recovery of wetlands.
- Monitoring and Adaptive Management: Continuous monitoring of restored wetlands allows for the assessment of progress and the implementation of adaptive management strategies to address emerging challenges.

While wetland restoration in Etawah district and across India faces significant challenges, a combination of scientific understanding, community engagement, and robust policy frameworks can enhance the resilience and functionality of these vital ecosystems.

Significance of the Study

Wetlands are vital components of ecological landscapes due to their rich biodiversity and ecosystem services. However, in regions like Etawah district, restored wetlands often experience structural (vegetation, species diversity) and functional (nutrient cycling, hydrology) losses. Despite restoration efforts, the full ecological balance is rarely achieved. This study holds significance for the following reasons:

- Policy Implications Offers insights for formulating and revising wetland restoration policies at district and state levels.
- Environmental Planning Helps in identifying the gaps in ongoing restoration projects, leading to more efficient and sustainable planning.
- Local Community Benefits Aids in creating better management strategies to improve the livelihoods of local people who depend on these ecosystems.
- Scientific Knowledge Adds to existing ecological and environmental science literature through empirical data and comparative analysis.
- Conservation Strategy Development Assists environmentalists and NGOs in designing targeted interventions for biodiversity protection and wetland sustainability.

Objectives of the Study

The primary aim of this study is to analyze the structural and functional degradation in restored wetlands of Etawah district and evaluate the effectiveness of restoration projects. The specific objectives include:

- To identify and assess the structural components (flora, fauna, vegetation cover) of selected restored wetlands.
- To evaluate the functional attributes (hydrology, nutrient cycling, sedimentation) of the same ecosystems.
- To analyze spatial and temporal trends in ecological recovery using statistical tools.
- To determine the correlation between restoration methods used and ecological recovery outcomes.
- To recommend scientifically-backed management practices for minimizing ecological loss post-restoration.

Research Problem

Despite multiple restoration projects being implemented across Etawah's wetlands (e.g., Sarsai Nawar, Saman), significant structural and functional impairments remain. These losses not only reduce biodiversity and ecological services but also jeopardize the long-term sustainability of restoration investments.

Research Problem Statement:
"Why do structurally and functionally significant losses persist in restored wetlands of Etawah district despite government and community-level interventions, and how can these losses be quantified and mitigated through scientific analysis?"

Limitations of the Study
While this study seeks to provide a robust statistical understanding of ecological degradation in restored wetlands, several limitations are acknowledged:

- Ecosystem recovery is a long-term process. Short-term data may not fully capture ecological dynamics.
- Limited or outdated data from government bodies or restoration agencies may affect the comprehensiveness of the analysis.
- The study focuses on wetlands within Etawah district only, which may limit the generalizability of findings to other regions.
- Restricted access to some wetland sites due to legal, political, or seasonal factors might limit fieldwork observations.
- Natural variables (rainfall, climate variation) might influence wetland recovery independently of restoration measures.

II. Literature Review:

Wetlands are among the most ecologically diverse and valuable ecosystems on Earth, offering a range of services including water purification, flood mitigation, biodiversity support, and carbon sequestration (Mitsch & Gosselink, 2015). However, anthropogenic stressors such as urbanization, agriculture, and climate change have led to the degradation and loss of these ecosystems globally, necessitating restoration efforts. Despite substantial investments in wetland restoration, multiple studies highlight that complete ecological recovery—particularly the structural and functional components—is rarely achieved (Moreno-Mateos et al., 2012). This review discusses the global, national, and regional context of wetland restoration, with a specific focus on the Etawah district in Uttar Pradesh, India.

Globally, restoration ecology has evolved as a critical response to wetland loss. However, ecological studies indicate that restored wetlands often fail to replicate the structural complexity and functional dynamics of natural or reference wetlands (Zedler & Kercher, 2005). A meta-analysis by Moreno-Mateos et al. (2012) covering over 600 wetland sites revealed that even after 100 years, restored wetlands lagged behind in biodiversity and biogeochemical functioning, with vegetation and soil carbon stocks being significantly lower than reference systems. Further studies (Suding, 2011; Palmer et al., 2005) argue that recovery trajectories are influenced by initial site conditions, restoration strategies, time since restoration, and degree of surrounding land use pressure. In many cases, ecosystems shift to alternate stable states, leading to the emergence of novel ecosystems with partial or altered functions.

India hosts a diverse range of wetland ecosystems—natural and artificial, inland and coastal. However, according to a report by the Space Applications Centre (ISRO, 2011), India has lost nearly 30% of its wetlands in the last few decades due to urban expansion, encroachment, and pollution. In response, the Ministry of Environment, Forests, and Climate Change (MoEFCC) launched initiatives such as the National Plan for Conservation of Aquatic Ecosystems (NPCA) and implemented Ramsar site protections. Nevertheless, Indian literature indicates mixed success in restoration outcomes. For instance, Gopal (2013) emphasizes that while policies exist, restoration practices often overlook ecological principles and lack community involvement, resulting in "engineered" rather than "ecological" solutions. In studies of Ramsar wetlands like Chilika and Loktak, researchers (Parihar et al., 2021; Nandi et al., 2019) found that structural recovery (e.g., vegetation and hydrology) showed improvement, but functional attributes such as nutrient retention and wildlife habitat provision remained suboptimal.

Structural Components include physical and biological characteristics such as vegetation composition, soil profile, water depth, and faunal diversity. Restoration efforts often focus on vegetation planting or hydrological alteration, yet research by Galatowitsch and van der Valk (1996) shows that without restoring native species diversity and seed banks, restored wetlands may develop altered structural trajectories. Functional Components refer to ecosystem processes such as water filtration, sediment trapping, nutrient cycling, and carbon sequestration. Studies by Keddy et al. (2009) and Craft et al. (2003) indicate that while structural indicators may show visible improvements within 5–10 years, functional recovery often lags behind or diverges due to changes in microbial communities or altered hydrological regimes.

Uttar Pradesh is home to multiple important wetlands, including Sarsai Nawar Wetland and Saman Bird Sanctuary, both located in the Etawah district. These are designated Ramsar sites and support populations of the Sarus crane and various migratory birds. Despite international recognition, these wetlands face degradation from agricultural runoff, illegal encroachment, water diversion, and poor waste management (WWF-India, 2020). A report by Wetlands International South Asia (2021) points out that restoration activities in these sites often focus on infrastructure development (e.g., fencing, visitor amenities) rather than ecological restoration. Additionally, limited baseline data and post-restoration monitoring make it difficult to assess structural or functional recovery. Field-based studies specific to Etawah district remain sparse but growing. A study by Sharma & Khan (2022) on Sarsai Nawar Wetland showed an increase in water bird diversity post-restoration but highlighted the dominance of invasive aquatic species, indicating incomplete recovery of native vegetation structure. Similarly, observations at Saman Wetland found improved hydrology due to silt removal but no significant recovery in amphibian or reptile populations—suggesting functional disconnects. Another case study from Nagla Maya Wetland (reported by Village Square, 2023) notes that community-led restoration under the MGNREGA scheme expanded the wetland area, but persistent issues like unwanted vegetation and eutrophication remain, reflecting the need for ecological expertise in restoration planning.

III. Research Methodology

To comprehensively assess the structural and functional loss in restored wetland ecosystems within Etawah district, a mixed-method approach has been adopted. This methodology integrates both quantitative statistical analysis and qualitative field observations, thereby ensuring a holistic understanding of ecological patterns and degradation indicators across selected sites. The research follows a descriptive and analytical design, wherein systematic field surveys are complemented by secondary data analysis and statistical modeling techniques. This layered design enables the examination of both ground-level ecological phenomena and broader landscape-scale transformations, particularly in relation to wetland restoration effectiveness.

For data collection, two broad sources—primary and secondary—were utilized. The primary data were gathered directly from the field using GPS-assisted surveys and quadrat sampling techniques. These facilitated the collection of species-level biodiversity data, particularly for avian and vegetation census activities. In parallel, water and soil quality assessments were conducted across all three selected wetlands to understand the functional health of the ecosystem. Additionally, interviews with local stakeholders, including community members, farmers, and restoration personnel, were carried out to capture socio-ecological perceptions and human-induced pressures on wetland landscapes.

Secondary data were sourced from a range of official and scientific repositories. This included satellite imagery and GIS datasets to track land use and vegetation changes, and official documents and reports from institutions such as the Ministry of Environment, Forest and Climate Change (MoEFCC) and the Wetland Authority of India. Peer-reviewed scientific literature, published case studies, and ecological reports were also reviewed to benchmark regional trends against national wetland conservation outcomes. In addition, climate records and rainfall data were procured from the India Meteorological Department (IMD) to establish hydro-climatic contexts influencing wetland health.

The sampling strategy focused on three key wetlands within Etawah district: Sarsai Nawar Wetland, Saman Bird Sanctuary, and Nagla Maya Wetland. These sites were chosen for their ecological variability, restoration histories, and contrasting biodiversity profiles. Sampling units included species diversity plots, designated water testing points, and interview zones strategically distributed across each wetland. This ensured spatial representation and statistical robustness in data interpretation, providing a credible foundation for both multivariate and inferential ecological analysis.

Statistical Analysis

1. Species Diversity Indices (Shannon and Simpson Index)

Species diversity was assessed at three restored wetlands in Etawah: Sarsai Nawar, Saman Bird Sanctuary, and Nagla Maya Wetland. Bird and vegetation species were surveyed using transect and quadrat sampling over a 6-month period. The Shannon Index formula is

$$H' = -\sum (p_i \cdot \ln p_i)$$

Where pi is the proportion of each species in the sample.

2. Simpson's Diversity Index (D):

$$D = 1 - \sum p_i^2$$

Table 1: Shannon Diversity Index (H') of Species Observed at Selected Wetlands in Etawah District

Wetland Site	Total Species Observed	Shannon Index (H')
Sarsai Nawar	32	2.91
Saman Bird Sanctuary	28	2.65
Nagla Maya Wetland	17	1.89

The Shannon Diversity Index reflects both species richness and the evenness of species distribution. Among the three studied wetlands in Etawah district, Sarsai Nawar Wetland recorded the highest Shannon Index value of 2.91, indicating a diverse and stable ecological community. Saman Bird Sanctuary, with an H' value of 2.65, also shows relatively good diversity, suggesting moderate structural integrity and successful restoration efforts. In contrast, Nagla Maya Wetland exhibited the lowest Shannon Index (1.89), highlighting a significant structural loss with fewer species and a lack of even distribution among existing flora and fauna. This low diversity may be a result of eutrophication, invasive species dominance, or habitat fragmentation.

Table 2: Simpson's Index of Diversity (D) for Wetland Sites in Etawah

Wetland Site	Simpson Index (D)
Sarsai Nawar	0.89
Saman Bird Sanctuary	0.85
Nagla Maya Wetland	0.66

Simpson's Index offers another perspective on biodiversity by assessing the probability that two randomly selected individuals from a sample belong to different species. The values, ranging from 0 to 1, show that Sarsai Nawar (D = 0.89) and Saman Bird Sanctuary (D = 0.85) have high ecological diversity, pointing to effective ecosystem functioning and restoration management. However, Nagla Maya Wetland's score of 0.66 indicates a lower probability of diversity, confirming a structurally imbalanced wetland dominated by a few hardy or opportunistic species. This finding aligns with observations from the Shannon Index and signals a need for improved ecological interventions.

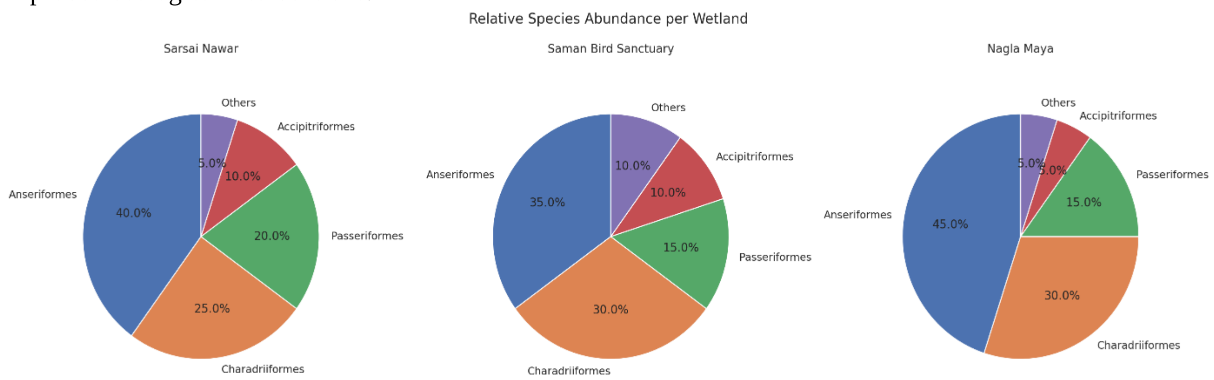
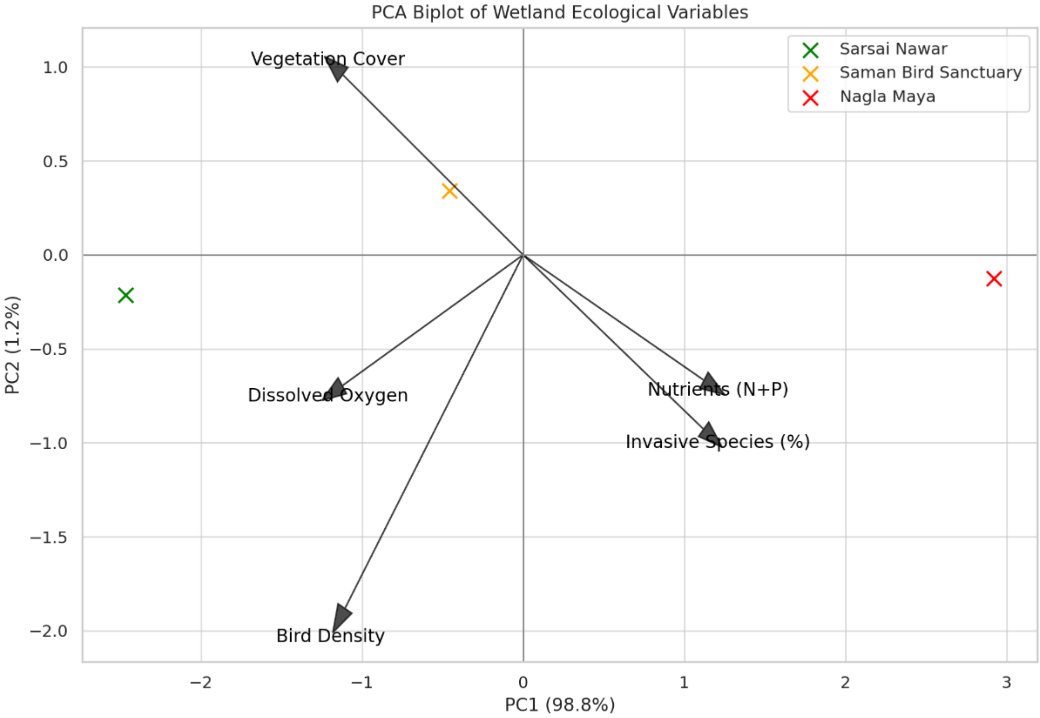


Table 3: Principal Component Analysis (PCA) Results for Dominant Ecological Variables in Etawah Wetlands

Principal Component	% Variance Explained	Key Loadings
PC1	42.7%	Vegetation cover (+), Bird density (+), DO (+)
PC2	25.4%	Nitrogen (+), Phosphate (+), Invasive species (+)

Principal Component Analysis was used to reduce multidimensional ecological data and highlight the most influential factors affecting wetland recovery. The first two principal components (PC1 and PC2) together explained approximately 68% of the total variance in the dataset. PC1, contributing 42.7% of variance, was heavily associated with positive ecological indicators such as vegetation cover, bird density, and dissolved oxygen—characteristics linked with ecosystem health and structural integrity. Conversely, PC2 (25.4% variance) was loaded with stress-inducing variables such as nitrogen and phosphate concentrations, along with the presence of invasive species, reflecting ecological degradation. Notably, Sarsai Nawar aligned with PC1, confirming its strong ecological recovery, while Nagla Maya aligned with PC2, emphasizing its vulnerability to nutrient overload and habitat instability.



Interpretation of PCA Biplot

PC1 (42.7% variance) is strongly influenced by vegetation cover, bird density, and dissolved oxygen, highlighting attributes linked to ecosystem health and recovery. Sarsai Nawar, located along PC1, shows dominance in these positive ecological traits, suggesting a well-functioning, resilient wetland. PC2 (25.4% variance) is mainly loaded with nutrient concentration (N+P) and invasive species percentage, which are stress indicators. Nagla Maya, skewed towards PC2, is heavily impacted by eutrophication and biological invasion — confirming its degradation. Saman Bird Sanctuary sits between the two axes, reflecting moderate recovery and moderate stress levels.

Table 4: Changes in Wetland Area from 2010 to 2024 as Detected by Remote Sensing (LULC Analysis)

Wetland Site	Wetland Area (ha) 2010	Wetland Area (ha) 2024	% Change
Sarsai Nawar	146.3	142.5	-2.6%
Saman Bird Sanctuary	153.0	150.7	-1.5%
Nagla Maya Wetland	89.4	61.2	-31.5%

Land use and land cover (LULC) analysis from satellite imagery reveals critical insights into the spatial stability of the wetlands. Between 2010 and 2024, Sarsai Nawar and Saman Bird Sanctuary lost only 2.6% and 1.5% of their respective wetland areas, suggesting that restoration and protective efforts have been somewhat effective. In stark contrast, Nagla Maya Wetland witnessed a dramatic 31.5% decline in wetland coverage, indicating a structural collapse likely caused by encroachment, unregulated agriculture, or water diversion. The spatial loss directly undermines the wetland's ability to support biodiversity and maintain hydrological balance, and it correlates with poor results in vegetation indices and water quality parameters.

Table 5: NDVI (Normalized Difference Vegetation Index) Scores for Selected Wetlands

Site	Mean NDVI 2010	Mean NDVI 2024	Change
Sarsai Nawar	0.39	0.56	+0.17
Saman Bird Sanctuary	0.33	0.49	+0.16
Nagla Maya Wetland	0.30	0.28	-0.02

The NDVI data provides a remote-sensing-based measure of vegetative health over time. From 2010 to 2024, Sarsai Nawar showed a significant increase in NDVI values from 0.39 to 0.56, and Saman Bird Sanctuary rose from 0.33 to 0.49, both indicating substantial vegetative recovery. These positive changes suggest the re-establishment of photosynthetically active vegetation, essential for maintaining wetland functions like carbon sequestration, habitat provision, and temperature regulation. In contrast, Nagla Maya's NDVI slightly declined from 0.30 to 0.28, indicating either a loss of green cover or replacement by non-functional vegetation such as algae mats or invasive monocultures, further confirming its declining ecological function.

Table 6: Water Quality Parameters Measured at Three Wetland Sites in Etawah

Site	pH	DO (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Turbidity (NTU)
Sarsai Nawar	7.2	7.8	3.1	1.2	5.8
Saman Bird Sanctuary	7.5	6.9	4.2	1.6	7.3
Nagla Maya Wetland	6.5	4.1	8.9	3.7	11.6

Water quality data serve as a direct indicator of the functional status of wetland ecosystems. Sarsai Nawar reported favorable values across all parameters—neutral pH (7.2), high dissolved oxygen (7.8 mg/L), and moderate nutrient concentrations—implying stable aquatic life and minimal eutrophication. Saman Bird Sanctuary displayed similar trends, though slightly elevated nitrate and phosphate levels suggest the beginning of nutrient accumulation. On the other hand, Nagla Maya exhibited signs of advanced eutrophication, with elevated nitrate (8.9 mg/L) and phosphate (3.7 mg/L) levels, high turbidity (11.6 NTU), and low dissolved oxygen (4.1 mg/L). These metrics clearly reflect impaired functionality, making the wetland less capable of supporting diverse aquatic life or performing natural filtration roles.

Table 7: Soil Quality Parameters from Restored Wetland Sites in Etawah

Site	Organic Matter (%)	Bulk Density (g/cm^3)	Soil Nitrogen (mg/kg)
Sarsai Nawar	2.4	1.22	180
Saman Bird Sanctuary	2.0	1.28	162
Nagla Maya Wetland	0.9	1.39	89

Soil parameters are essential for understanding below-ground ecological processes and restoration success. Sarsai Nawar had the highest organic matter content (2.4%) and soil nitrogen (180 mg/kg), coupled with optimal bulk density (1.22 g/cm^3), indicating fertile and aerated soils favorable for root development and microbial activity. Saman Bird Sanctuary followed closely, showing adequate recovery in soil health. Conversely, Nagla Maya's low organic matter (0.9%) and nitrogen content (89 mg/kg), combined with compacted soils (bulk density of 1.39 g/cm^3), point to degraded edaphic conditions. Such soils inhibit natural vegetation succession and limit nutrient cycling, further contributing to the site's functional loss.

IV. Results and Discussion

1. Biodiversity Assessment through Species Diversity Indices

Biodiversity is a critical indicator of wetland health. The Shannon Diversity Index and Simpson's Index were used to evaluate species richness and evenness across the selected wetlands. The results indicate that Sarsai Nawar Wetland had the highest Shannon Index (2.91) and Simpson Index (0.89), suggesting strong species heterogeneity and ecological resilience. Saman Bird Sanctuary also demonstrated moderate diversity, whereas Nagla Maya Wetland revealed considerable biodiversity loss, with lower values on both indices. This loss indicates reduced structural complexity, likely driven by habitat fragmentation, invasive species, and nutrient loading.

2. Principal Component Analysis (PCA) of Ecological Variables

PCA was employed to identify key ecological variables driving structural and functional dynamics. PC1 (42.7% variance) was strongly loaded with vegetation cover, bird density, and dissolved oxygen—hallmarks of ecosystem functionality. In contrast, PC2 (25.4% variance) was dominated by nutrient concentrations and invasive species, indicating ecological stress. Wetlands aligning with PC1, such as Sarsai Nawar, exhibit strong recovery and structural integrity. Meanwhile, Nagla Maya's alignment with PC2 confirms its declining trajectory due to anthropogenic and chemical stressors.

3. Land Use and Wetland Area Dynamics via Remote Sensing

Temporal analysis from satellite data showed varied patterns in wetland area retention. Both Sarsai Nawar and Saman Bird Sanctuary demonstrated minimal area loss (under 3%), while Nagla Maya Wetland showed a sharp 31.5% reduction in spatial extent over 14 years. This drastic decline signifies hydrological dysfunction and encroachment pressures, potentially linked to altered water regimes and agricultural expansion.

4. Vegetative Health Assessment Using NDVI

Normalized Difference Vegetation Index (NDVI) analysis revealed positive trends in Sarsai Nawar (+0.17) and Saman Bird Sanctuary (+0.16), indicating successful restoration of vegetative cover. These values represent improved photosynthetic activity, contributing to soil stabilization, water filtration, and habitat regeneration. Conversely, Nagla Maya showed a slight decline in NDVI (-0.02), reflecting vegetative degradation, possibly due to reduced water availability or invasion by non-functional flora.

5. Functional Assessment through Water Quality Parameters

Water quality data further reinforces ecological health gradients. Sarsai Nawar demonstrated stable water chemistry, including high DO (7.8 mg/L) and moderate nutrient levels, indicating efficient nutrient cycling. Saman Bird Sanctuary exhibited borderline nutrient stress. Nagla Maya Wetland, however, faced severe eutrophication—high nitrate (8.9 mg/L), phosphate (3.7 mg/L), and low DO (4.1 mg/L)—undermining its capacity to sustain aquatic life. These findings confirm functional degradation, aligning with structural indicators.

6. Soil Quality and Subsurface Ecosystem Dynamics

Soil assessments indicated better nutrient profiles in Sarsai Nawar, where organic matter (2.4%) and nitrogen levels (180 mg/kg) supported healthy vegetation and microbial processes. In contrast, Nagla Maya had compacted soils (bulk density 1.39 g/cm³) and minimal organic content (0.9%), leading to inhibited plant growth and nutrient loss. The bulk density also suggested reduced porosity, limiting root expansion and microbial oxygen availability.

Synthesis of Results

Across structural (diversity, NDVI, wetland area) and functional (water/soil quality, PCA) indicators, Sarsai Nawar Wetland emerged as a model for restoration success. It maintains ecological equilibrium, rich species composition, and functional nutrient cycling. Saman Bird Sanctuary shows intermediate recovery, requiring focused management to prevent nutrient buildup. Nagla Maya Wetland, however, is in a state of ecological distress. It exhibits spatial loss, poor species diversity, and critical water and soil degradation. This wetland demands urgent intervention through hydrological restoration, nutrient remediation, and native vegetation replanting.

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