



Ecological Modelling and Indicator Assessment of Seasonal Fish Diversity in Bhaluka Beel, West Bengal: Integrating GAM, RDA, and CCA Approaches

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Abstract: Understanding seasonal fish diversity in floodplain wetlands is crucial for effective conservation and management. This study assessed the fish assemblage structure of Bhaluka Beel, a monsoon-influenced floodplain wetland in Nadia District, West Bengal, India, using integrated ecological modelling approaches. Fish diversity was quantified across pre-monsoon, monsoon, and post-monsoon seasons alongside key physicochemical parameters, including temperature, dissolved oxygen, pH, free CO₂, alkalinity, and hardness. Generalized Additive Models (GAMs) revealed that temperature and free CO₂ negatively influenced Shannon-Weaver, Margalef's, and Pielou's indices, whereas pH exerted a positive effect. Species richness peaked post-monsoon, coinciding with stabilized water conditions after flood events. Multivariate ordination using Redundancy Analysis and Canonical Correspondence Analysis highlighted distinct seasonal community structures and identified dissolved oxygen and pH as key environmental drivers. Pre-monsoon indicator species included *Puntius ticto*, *Clarias batrachus*, and *Heteropneustes fossilis*. Functional guild analysis demonstrated a diverse assemblage of omnivores, carnivores, herbivores, and planktivores occupying pelagic, littoral, and benthic niches. The coexistence of tolerant and sensitive species reflects both ecological resilience and potential vulnerability to environmental stressors. This integrated modelling framework provides a robust tool for evaluating seasonal biodiversity patterns in tropical wetlands and offers practical insights for fishery management, biodiversity conservation, and water quality monitoring under monsoon-driven hydrological regimes.

Keywords: Multivariate ordination, Environmental gradients, Species assemblage, Wetland biodiversity, Trophic structure, Seasonal variation.

1. INTRODUCTION

Floodplain wetlands are among the most productive and biologically diverse ecosystems on Earth, offering critical habitats for a wide range of aquatic species, including fish, amphibians, birds, and invertebrates (Schofield et al., 2018). In tropical and subtropical regions, these wetlands are strongly influenced by monsoonal hydrology, resulting in seasonal pulses of inundation and drying that profoundly shape community dynamics and ecosystem functioning (Talbot et al., 2018). The periodic flooding not only enhances nutrient availability and habitat connectivity but also plays a key role in the life history strategies of many fish species, particularly those adapted to seasonal migration and spawning cycles (Van der Sleen and Rams, 2023). In India, floodplain wetlands such as beels, jheels, and chaus constitute essential ecological and economic resources. These water bodies support subsistence and small-scale fisheries, contribute to groundwater recharge, and buffer

against climate variability (Sarkar and Saha, 2021). However, anthropogenic pressures—such as land use change, overfishing, nutrient loading, and hydrological alteration—have severely impacted their ecological integrity. Understanding the patterns and drivers of fish diversity across seasonal cycles is thus critical for sustainable management and conservation planning (Zolfagharpour et al., 2022).

Traditional assessments of fish biodiversity in wetlands have relied on diversity indices and community composition analyses. While these provide valuable descriptive insights, they often fail to capture complex and nonlinear interactions between biotic communities and their environmental context (Rosenfeld, 2017; Stefani et al., 2024). To address this limitation, contemporary ecological research has increasingly adopted statistical modelling techniques, including Generalized Additive Models (GAMs), Redundancy Analysis (RDA), and Canonical Correspondence Analysis

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(CCA), to explore species-environment relationships with greater precision (Lubinski et al., 2008, Alam et al., 2024; Vavalidis et al., 2025; Zou et al., 2025).

GAMs are particularly well-suited for modelling ecological data due to their flexibility in capturing nonlinear responses to environmental gradients (Clark and Wells, 2023). In aquatic systems, GAMs have been used to analyze temporal trends in species richness, detect thresholds of environmental tolerance, and predict the influence of physicochemical variables on biodiversity (Pilotto et al., 2023). Meanwhile, ordination techniques like RDA and CCA provide multivariate frameworks to assess how entire communities respond to environmental factors, making them valuable tools for habitat characterization and conservation prioritization (Shuai et al., 2018; Akhi et al., 2020).

This study focuses on Bhaluka Beel, a seasonally flooded wetland in the Nadia District of West Bengal, India. The beel represents a typical floodplain system with dynamic hydrology, varied physicochemical conditions, and diverse fish assemblages. Prior research in Bhaluka Beel has documented its ichthyofaunal richness and basic ecological parameters (Sarkar, 2023), but advanced modelling approaches to link environmental variability with fish community dynamics have not yet been applied. The present investigation was designed to develop a comprehensive ecological assessment framework for understanding seasonal fish diversity dynamics in Bhaluka Beel, West Bengal.

2. MATERIALS AND METHODS

2.1. Study Area: Bhaluka Beel is a perennial floodplain wetland situated in the Krishnagar-I Block of Nadia District, West Bengal, India (23.28°N, 88.32°E). This lentic water body is seasonally influenced by the adjacent Jalangi River system and experiences marked hydrological changes associated with the southwest monsoon. The wetland is shallow (average depth: 1.2-2.5 m), supports local fisheries, and is surrounded by agricultural land, which contributes to nutrient influx through runoff during rainy seasons. The study site was selected due to its ecological relevance, biodiversity richness, and previous documentation of ichthyofaunal diversity (Sarkar, 2023).

2.2. Sampling Design and Period: Stratified seasonal sampling with standardized multi-gear capture techniques was conducted seasonally during pre-monsoon (March-May), monsoon (June-September), and post-monsoon (October-January) periods from 2019 to 2022. Three representative stations within the beel were identified based on habitat characteristics, accessibility, and fishing pressure.

Although GPS tagging was not applied due to logistical constraints, sampling sites were fixed using permanent physical landmarks to ensure repeatability.

2.3. Fish Collection and Identification: Fish specimens were collected using a combination of gill nets, drag nets, and traditional cast nets operated by local fishers. Sampling effort was standardized across sites and seasons. Collected specimens were identified using standard taxonomic keys (Jayaram, 2010) and cross-verified with FishBase (Froese and Pauly, 2025). Relative abundance was assessed semi-quantitatively using field scoring methods (+, ++, +++) based on catch per effort and validated against community observations.

2.4. Water Quality Analysis: Key physicochemical parameters—temperature (°C), pH, dissolved oxygen (mg/L), free carbon dioxide (mg/L), total alkalinity (mg/L), and hardness (mg/L)—were measured in situ using portable probes and standard analytical kits (APHA, 2017). Sampling was performed between 7:00 and 9:00 AM to minimize diel variability. All measurements were averaged over three subsamples per station to improve accuracy.

2.5. Diversity Indices Calculation:

Seasonal fish diversity was quantified using three standard ecological indices: Shannon-Weaver diversity index (H'), Margalef's species richness index (D), and Pielou's evenness index (J').

The Shannon-Weaver diversity index (Shannon & Weaver, 1949) was calculated as:

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

where p_i represents the proportion of individuals belonging to the i th species. This index integrates both species richness and relative abundance.

Margalef's richness index (Margalef, 1958) was computed as:

$$D = (S-1) / \ln N$$

where S is the total number of species and N is the total number of individuals.

Pielou's evenness index (Pielou, 1966) was derived as:

$$J' = H' / \ln S$$

where H' is the Shannon diversity and S is species richness. This index measures the uniformity of species distribution within the community.

These indices provide complementary views of community structure by integrating species richness, abundance distribution, and compositional evenness (Sarkar, 2022; Dada et al., 2025; Bastola et al., 2025).

2.6. Ecological Modelling Approaches:

Generalized Additive Models (GAMs) were employed to

examine nonlinear relationships between diversity indices and environmental variables. GAMs extend generalized linear models by incorporating smooth functions of predictor variables (Wood, 2017). The general form of the GAM used in this study is (Eq.1):

$$g(\mu) = \beta_0 + s_1(X_1) + s_2(X_2) + \dots + s_k(X_k) \dots (1)$$

where $g(\mu)$ is the link function, β_0 is the intercept, and $s_k(X_k)$ represents smooth spline functions of environmental predictors such as temperature, dissolved oxygen, pH, free CO₂, alkalinity, and hardness. GAMs are particularly suitable for ecological datasets exhibiting nonlinear responses (Clark & Wells, 2023).

Multivariate ordination analyses were conducted using Redundancy Analysis (RDA) and Canonical Correspondence Analysis (CCA). RDA is a constrained

linear ordination technique that relates species composition to environmental gradients (Legendre & Legendre, 2012). CCA, in contrast, assumes unimodal species responses along environmental gradients (Legendre & Gallagher, 2001). Prior to analysis, environmental variables were standardized to reduce scale effects. The significance of canonical axes was assessed using permutation tests.

2.7. Indicator Species and Functional Guild Classification:

Species were assigned as seasonal indicators based on relative abundance differences across seasons. A species was considered an indicator if its occurrence score was highest in only one season. Functional guilds were categorized using ecological literature and FishBase data, assigning each species to trophic (herbivore, omnivore, carnivore, planktivore), habitat (benthic, pelagic, littoral),

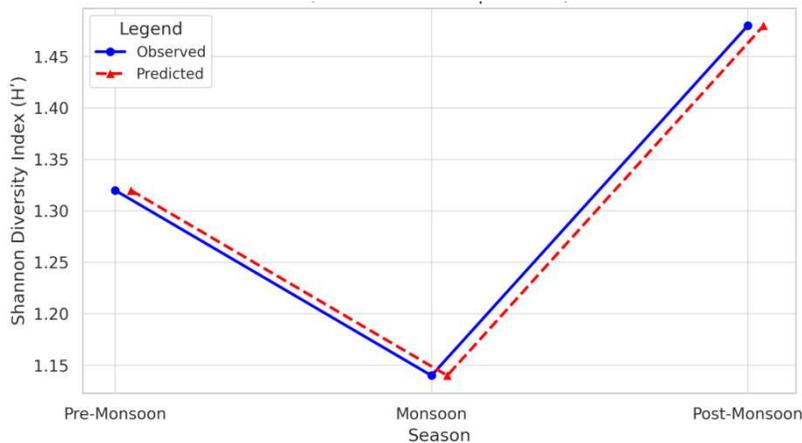


Figure 1. Observed vs. predicted Shannon–Weaver diversity index (H') for fish communities in Bhaluka Beel

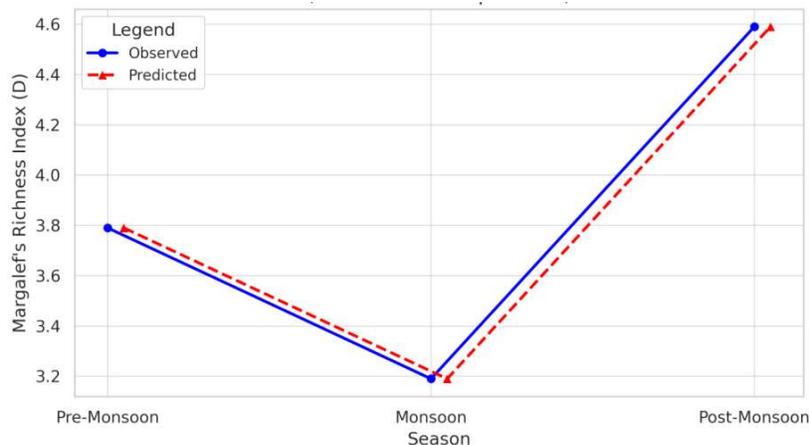


Figure 2. Observed vs. predicted Margalef’s Species Richness Index (D) for fish communities in Bhaluka Beel

and tolerance (sensitive, moderate, tolerant) groups (Froese and Pauly, 2025).

3. RESULTS AND DISCUSSION

The ecological modelling framework applied in this study yielded comprehensive insights into the seasonal dynamics of fish diversity in Bhaluka Beel, a monsoon-influenced floodplain wetland. By integrating Generalized Additive Models (GAMs), Redundancy Analysis (RDA), Canonical Correspondence Analysis (CCA), indicator species analysis, and functional guild classification, the study elucidates both statistical patterns and ecological mechanisms shaping fish assemblages.

3.1. Seasonal Patterns in Diversity Indices

Seasonal analysis revealed consistent interannual patterns in fish diversity. Both Shannon-Weaver diversity (H') and Margalef's richness (D) peaked during the post-monsoon phase (Figure 1-2), reflecting ecological recovery and recolonization following monsoonal flooding. In contrast, the monsoon season exhibited comparatively lower diversity values, likely due to habitat disruption, dilution effects, and hydrological instability (Chea et al., 2020; Saha et al., 2022; Liu et al., 2023). Evenness (Pielou J') remained relatively stable across seasons (Figure 3), indicating consistent proportional distribution of individuals among species (Sarkar, 2023).

These seasonal patterns align with the flood-pulse concept, which posits that hydrological fluctuations regulate nutrient cycling, habitat connectivity, and biodiversity in floodplain systems (da Silva et al., 2013; Das et al., 2023). Post-monsoon stabilization of water levels likely enhances habitat heterogeneity and resource availability, supporting greater species richness and diversity.

3.2. Environmental Drivers and GAM Modelling

GAM results revealed significant environmental filtering effects (Table 1). Temperature and free CO_2 exerted consistent negative influences on diversity indices, whereas pH demonstrated strong positive associations. Dissolved oxygen exhibited non-linear responses, particularly during seasonal transitions, highlighting threshold effects.

The best model fit was observed for the Shannon index, which showed the highest explanatory power and lowest residual variance. Observed and predicted values closely matched across seasons (Figure 1), confirming model robustness. Margalef's richness also displayed strong

Table 1. Estimated coefficients from Generalized Additive Models (GAMs) predicting Shannon diversity (H'), Margalef's richness (D), and Pielou's evenness (J') based on environmental variables in Bhaluka Beel

Predictor	Shannon (H')	Margalef (D)	Evenness (J')
Intercept	0.0122	0.0432	0.0052
Spline (Temperature)[1]	-0.0041	-0.0153	-0.0009
Spline (Temperature)[2]	-0.0107	-0.0400	-0.0024
Spline (Temperature)[3]	-0.0281	-0.0998	-0.0118
Spline (DO)[1]	-0.0047	-0.0174	-0.0011
Spline (DO)[2]	-0.0109	-0.0407	-0.0025
Spline (DO)[3]	0.0472	0.1685	0.0186
pH	0.1061	0.3774	0.0436
Free CO_2	-0.0824	-0.3134	-0.0123
Alkalinity	-0.0534	-0.1868	-0.0274
Hardness	0.0706	0.2403	0.0385

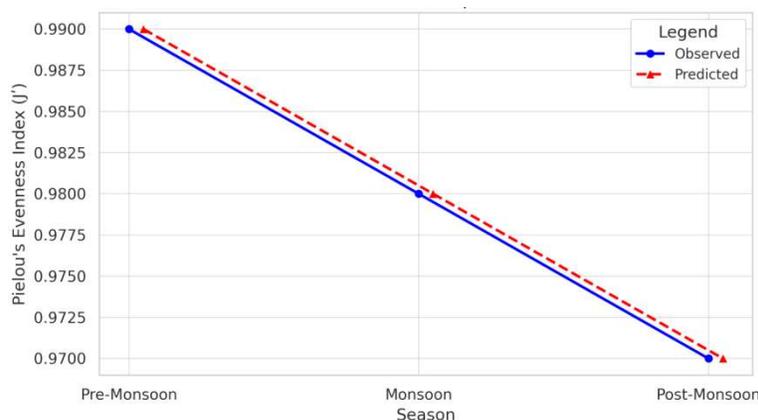


Figure 3. Observed vs predicted Pielou's Species Evenness Index (J') for fish communities in Bhaluka Bee

seasonal predictability (Figure 2), with post-monsoon peaks corresponding to improved water quality conditions. Evenness (Figure 3), however, exhibited comparatively subtle responses, suggesting that community equitability remains less sensitive to physicochemical variability.

Ecologically, elevated temperature during the pre-monsoon period likely induces thermal and oxygen stress, disproportionately affecting sensitive taxa (Lianthuamluaia et al., 2024). Increased free CO₂, often linked to organic decomposition and microbial respiration, may further reduce habitat suitability (Cupp et al., 2020). Conversely, slightly alkaline pH conditions appear to enhance physiological performance and diversity (Napit and Pillai, 2024).

The effectiveness of GAMs underscores the importance of flexible modelling approaches capable of capturing non-linear species-environment interactions, particularly in seasonally dynamic systems (Sun et al., 2024).

3.3. Multivariate Community Structuring (RDA and CCA)

Ordination analyses further clarified multivariate ecological responses. RDA indicated that pH and dissolved oxygen were dominant environmental axes structuring fish

assemblages, particularly in the post-monsoon season (Figure 4). In contrast, CCA effectively revealed unimodal species responses, with distinct clustering of pre-monsoon communities associated with elevated temperature and free CO₂ (Figure 5).

Pre-monsoon assemblages were dominated by air-breathing catfishes and tolerant omnivores, reflecting adaptive strategies under stress conditions. These findings corroborate earlier observations that ordination techniques effectively characterize niche differentiation and environmental filtering in floodplain ecosystems (Glińska-Lewczuk et al., 2016; Delong et al., 2019; Shields et al., 2021).

The separation of seasonal clusters confirms that physicochemical gradients strongly regulate compositional turnover and ecological niche partitioning.

3.4. Indicator Species and Seasonal Associations

Indicator species analysis identified *Puntius ticto*, *Clarias batrachus*, and *Heteropneustes fossilis* as strong pre-monsoon indicators (Table 2). These taxa are known for tolerance to low dissolved oxygen and elevated temperature, enabling persistence during water-stress periods (Alam et al., 2024).

Interestingly, no exclusive indicator species were

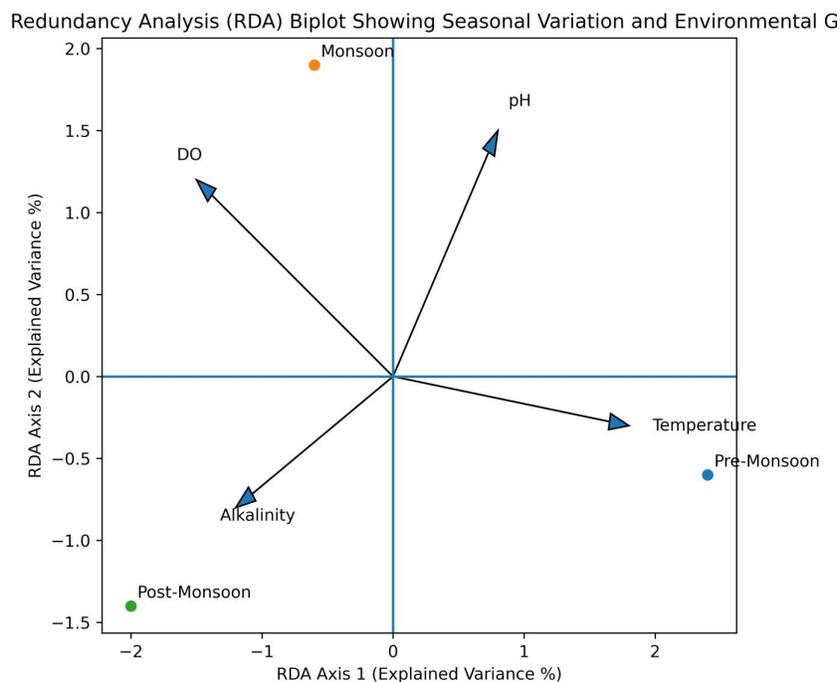


Figure 4. Redundancy Analysis (RDA) ordination plot showing the relationship between environmental variables and fish assemblage structure in Bhaluka Beel

detected for monsoon or post-monsoon seasons. This pattern likely reflects habitat homogenization during peak flooding, when increased connectivity facilitates dispersal and overlap among taxa (Espínola et al., 2017; Qiu et al., 2024). Thus, post-monsoon richness, although high, is broadly shared across species rather than dominated by season-specific specialists.

3.5. Functional Guild Composition and Ecological Implications

Functional guild classification revealed a diverse and ecologically versatile community (Table 3). Omnivores dominated the assemblage, followed by carnivores, herbivores, and planktivores. The coexistence of benthic and pelagic guilds highlights habitat heterogeneity within the wetland.

Table 2. Seasonal indicator fish species identified from Bhaluka Beel

Species	Pre-Monsoon	Monsoon	Post-Monsoon
<i>Puntius ticto</i>	3	0	1
<i>Aorichthys (Sperata) aor</i>	1	0	0
<i>Clarias batrachus</i>	3	2	2
<i>Heteropneustes fossilis</i>	3	2	2
<i>Channa striata</i>	3	2	2

3 (abundant); 2 (moderate); 1 (rare); 0 (absent)

Tolerance classification indicated the presence of both sensitive species (e.g., *Catla catla*, *Hypophthalmichthys molitrix*) and highly tolerant taxa (e.g., *Clarias batrachus*, *Cyprinus carpio*). While tolerant species enhance system stability under environmental stress, their increasing dominance may also signal ecological degradation, particularly under eutrophic or oxygen-limited conditions (Feng et al., 2023; Urbanski and Nogueira, 2024).

Projected increases in temperature and CO₂ under climate change scenarios may further shift community composition toward tolerant and air-breathing species, potentially reducing functional diversity (Dahms and Killen, 2023; Liu et al., 2025).

3.6. Integrated Ecological Interpretation

The integration of GAMs, ordination analyses, indicator species assessment, and trait-based classification provides a robust framework for understanding biodiversity dynamics in seasonally dynamic wetlands. The findings underscore the ecological importance of maintaining hydrological variability and water quality integrity to sustain diverse and functionally balanced fish assemblages.

This integrative modelling approach is transferable to other monsoon-driven wetlands across South Asia and can support adaptive conservation planning in regions facing accelerating climatic and anthropogenic pressures (Roy-Basu et al., 2020).

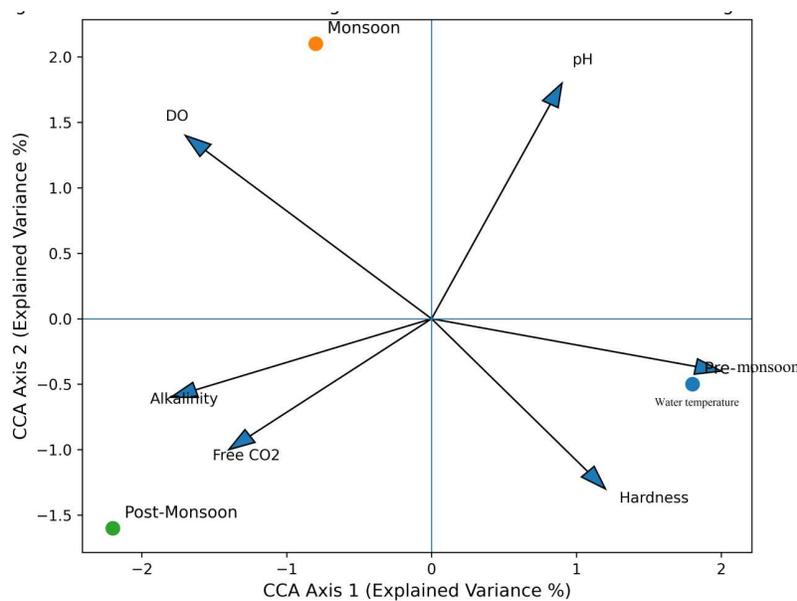


Figure 5. Canonical Correspondence Analysis (CCA) ordination plot showing the influence of environmental variables on fish assemblage structure in Bhaluka Beel across seasons

Table 3. Functional guild classification of selected fish species

Species	Trophic guild	Habitat guild	Tolerance level
<i>Labeo rohita</i>	Herbivore	Pelagic	Moderate
<i>Labeo bata</i>	Omnivore	Pelagic	Moderate
<i>Labeo calbasu</i>	Omnivore	Benthic	Moderate
<i>Gibelion (Labeo) catla</i>	Omnivore	Pelagic	Sensitive
<i>Cirrhinus mrigala</i>	Detritivore	Benthic	Moderate
<i>Puntius sarana</i>	Omnivore	Littoral	Sensitive
<i>Puntius ticto</i>	Omnivore	Littoral	Tolerant
<i>Hypophthalmichthys molitrix</i>	Planktivore	Pelagic	Sensitive
<i>Cyprinus carpio</i>	Omnivore	Benthic	Tolerant
<i>Ctenopharyngodon idella</i>	Herbivore	Pelagic	Moderate
<i>Notopterus notopterus</i>	Unknown	Unknown	Unknown
<i>Notopterus chitala</i>	Unknown	Unknown	Unknown
<i>Mystus vittatus</i>	Unknown	Unknown	Unknown
<i>Aorichthys (Sperata) aor</i>	Unknown	Unknown	Unknown
<i>Wallago attu</i>	Carnivore	Benthic	Moderate

4. CONCLUSION

This study provides an integrated ecological assessment of fish diversity in Bhaluka Beel, a monsoon-driven floodplain wetland in West Bengal, India. Seasonal surveys combined with statistical modelling and trait-based analyses revealed that temperature and free CO₂ act as stressors, whereas pH and dissolved oxygen promote richer, balanced communities. Generalized Additive Models highlighted nonlinear species-environment relationships, while RDA and CCA captured community structuring and niche differentiation across seasonal phases, particularly the ecological recovery in post-monsoon and stress-adapted pre-monsoon assemblages. Functional guild analysis demonstrated a diverse community dominated by omnivores alongside carnivores, herbivores, and planktivores, reflecting both resilience and vulnerability. Indicator taxa such as *Clarias batrachus* and *Puntius ticto* underline the monitoring potential. The findings advocate adaptive wetland management that safeguards hydrological variability and sustains biodiversity.

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Authors' Contributions

Chandan Sarkar: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software,

Visualization, Writing - original draft, Writing - review & editing.

The author has read and approved the final manuscript.

Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript.

Data Availability

The datasets analyzed during the current study are available from the author upon reasonable request.

Declaration about use of AI tools

The author declares that artificial intelligence (AI) tools were used only for language refinement, formatting assistance, and improvement of clarity. All research design, data collection, analysis, interpretation, and scientific conclusions were independently developed by the author. The author takes full responsibility for the accuracy, integrity, and originality of the manuscript.

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