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Influence of Physicochemical Water Quality Variables on Ichthyofaunal Diversity in the Hasdeo River and Its Tributaries (Ahiran, Tan, and Chornai Rivers), District Korba, Chhattisgarh, India

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ABSTRACT

Freshwater fish communities are strongly influenced by spatial and seasonal variations in water quality, particularly in river basins exposed to anthropogenic pressures. This study evaluated the influence of physicochemical water-quality variables on ichthyofaunal diversity in the Hasdeo River and its tributaries - Ahiran, Tan, and Chornai in Korba District, Chhattisgarh, India. Sampling was conducted at 12 stations from May 2025 to April 2026 across pre-monsoon, monsoon, and post-monsoon seasons, generating 36 observations. Water temperature, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total dissolved solids (TDS) were assessed alongside species richness, Shannon diversity, Simpson dominance, and Pielou evenness. Data were analysed using one-way and two-way ANOVA, Tukey's HSD test, Pearson correlation, and heat-map visualization.

Hasdeo recorded the highest species richness (45.11 ± 3.22), Shannon diversity (3.61 ± 0.10), and Pielou evenness (0.95 ± 0.01), whereas Chornai showed the lowest richness (28.22 ± 2.28) and Shannon diversity (2.88 ± 0.10) and the highest Simpson dominance (0.14 ± 0.01). One-way ANOVA revealed significant river-wise differences in all fish-diversity indices, pH, BOD, COD, and TDS. Two-way ANOVA showed significant main effects of river and season on the biological and physicochemical variables, while River × Season interactions were non-significant for all fish-diversity indices and significant only for selected physicochemical variables. DO was positively correlated with species richness ($r = 0.487$), Shannon diversity ($r = 0.479$), and evenness ($r = 0.428$), whereas BOD and COD showed strong negative associations with richness and Shannon diversity.

Overall, fish-diversity patterns broadly followed Hasdeo > Ahiran > Tan > Chornai**,** emphasizing the importance of regular monitoring and pollution-control measures, particularly in the Tan and Chornai rivers.

Keywords: Ichthyofaunal diversity; water quality; seasonal variation; Hasdeo River; Pearson correlation.

INTRODUCTION

Freshwater ecosystems are among the most productive and biologically diverse ecosystems on Earth, supporting nearly one-third of all vertebrate species while occupying less than 1% of the Earth's surface (Dudgeon *et al*., 2006; Reid *et al*., 2019; Tickner *et al*., 2020). These ecosystems provide numerous ecological and socioeconomic services, including drinking water, fisheries, irrigation, nutrient cycling, flood regulation, and biodiversity conservation, thereby contributing substantially to human well-being and sustainable development (MEA, 2005; IPBES, 2019; United Nations Environment Programme [UNEP], 2023). However, freshwater ecosystems are currently experiencing unprecedented degradation due to rapid industrialization,

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urbanization, agricultural intensification, mining activities, hydrological alterations, and climate change, resulting in widespread deterioration of water quality and freshwater biodiversity (Albert *et al*., 2021; WWF, 2024; UNEP, 2023).

Fish constitute one of the most important biological components of freshwater ecosystems and are widely recognized as sensitive indicators of ecological health because they integrate the cumulative effects of environmental changes over time (Karr, 1981; Simon, 1999; Magurran, 2004). Alterations in fish-community composition often reflect changes in habitat quality, hydrological conditions, and physicochemical characteristics of water (Matthews, 1998; Dudgeon *et al*., 2006; Sarkar *et al*., 2021). Consequently, ichthyofaunal diversity has been extensively used for ecological assessment, environmental monitoring, and freshwater conservation planning in riverine ecosystems worldwide (Pont *et al*., 2006; Reid *et al*., 2019).

Among various environmental factors, physicochemical water-quality variables play a fundamental role in determining fish diversity and community structure (Wetzel, 2001; APHA, 2023). Dissolved Oxygen (DO) is considered one of the most critical factors influencing fish survival, metabolism, growth, and reproduction, whereas elevated biochemical oxygen demand (BOD) and chemical oxygen demand (COD) indicate organic pollution and reduced oxygen availability (Boyd, 2020; APHA, 2023). Similarly, water temperature regulates metabolic activity and oxygen solubility, while pH influences physiological processes and ionic balance in aquatic organisms (Wetzel, 2001; Boyd, 2020). Excessive total dissolved solids (TDS) may further alter water chemistry and habitat suitability, thereby influencing fish abundance and species composition (Chapman, 1996; UNEP, 2023).

Several investigations have demonstrated significant relationships between water quality and fish diversity across different freshwater ecosystems. Studies conducted in the Mahanadi River basin, Ganga tributaries, Yangtze River basin, and Neotropical rivers consistently reported that dissolved oxygen positively influences fish diversity, whereas increasing organic pollution, habitat degradation, and anthropogenic disturbances reduce species richness and alter community composition (Fu *et al*., 2003; Agostinho *et al*., 2008; Mishra *et al*., 2018; Singh *et al*., 2025). Similar findings have also been reported from recent global assessments emphasizing that deterioration of freshwater habitats remains one of the principal causes of biodiversity loss worldwide (Albert *et al*., 2021; Tickner *et al*., 2020).

The Hasdeo River is one of the major tributaries of the Mahanadi River and flows through Korba District, Chhattisgarh, which is recognized as one of India's largest coal-mining and thermal power generation regions. The basin is characterized by extensive mining operations, industrial establishments, agricultural activities, urban settlements, and forest ecosystems that collectively influence river water quality through industrial effluents, domestic sewage, agricultural runoff, mine drainage, and sediment transport (CPCB, 2023). Consequently, the Hasdeo River and its tributaries—Ahiran, Tan, and Chornai—provide an ideal river system for investigating the ecological relationships between physicochemical water-quality variables and ichthyofaunal diversity under varying degrees of anthropogenic disturbance.

Despite the ecological significance of the Hasdeo River basin, comprehensive studies integrating seasonal water-quality variation, fish-diversity indices, and advanced statistical analyses remain limited. Most previous investigations have evaluated either water quality or fish diversity independently, with relatively few studies assessing their combined ecological relationships using integrated statistical approaches such as one-way ANOVA, two-way ANOVA, Tukey's HSD post hoc test, Pearson correlation analysis, and heat-map visualization (Legendre & Legendre, 2012; Zar, 2010). This knowledge gap limits the understanding of the principal environmental drivers responsible for spatial and seasonal variation in fish-community structure within the basin.

Therefore, the present study was undertaken to evaluate the influence of physicochemical water-quality variables on ichthyofaunal diversity in the Hasdeo River and its tributaries (Ahiran, Tan, and Chornai Rivers), Korba District, Chhattisgarh, India. Using field observations collected from twelve sampling stations representing three seasons, the study integrates ecological diversity indices with statistical analyses to identify the major physicochemical factors governing fish-community composition and ecological health. The findings

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provide baseline scientific information for freshwater biodiversity conservation, pollution assessment, ecological monitoring, and sustainable river-basin management in central India.

Objectives

I. To assess the spatial and seasonal variations in physicochemical water-quality variables and ichthyofaunal diversity in the Hasdeo River and its tributaries (Ahiran, Tan, and Chornai Rivers) of Korba District; and
II. To determine the relationships between physicochemical water-quality variables and ichthyofaunal diversity indices and identify the major environmental factors influencing fish diversity in the Hasdeo River system.

MATERIALS AND METHODS

Study Area

The study was conducted in the Hasdeo River and its three major tributaries - Ahiran, Tan, and Chornai - located in Korba District, Chhattisgarh, India. The Hasdeo River is an important tributary of the Mahanadi River and flows through forested, agricultural, urban, mining, and industrial landscapes before entering the Korba region. The study area lies approximately between 22°01′–23°01′ N latitude and 82°07′–82°55′ E longitude.

Korba District experiences a tropical monsoon climate with marked seasonal variation in rainfall and temperature. The region receives most of its annual rainfall during the southwest monsoon, while summer temperatures may rise considerably. Coal mining, thermal power generation, agriculture, urban settlements, domestic discharge, and forest-based land use are major features of the basin. These activities may influence river water quality through industrial effluents, mine drainage, sewage discharge, agricultural runoff, and sediment transport. Therefore, the river system provides a suitable setting for examining the influence of physicochemical water-quality variables on ichthyofaunal diversity.

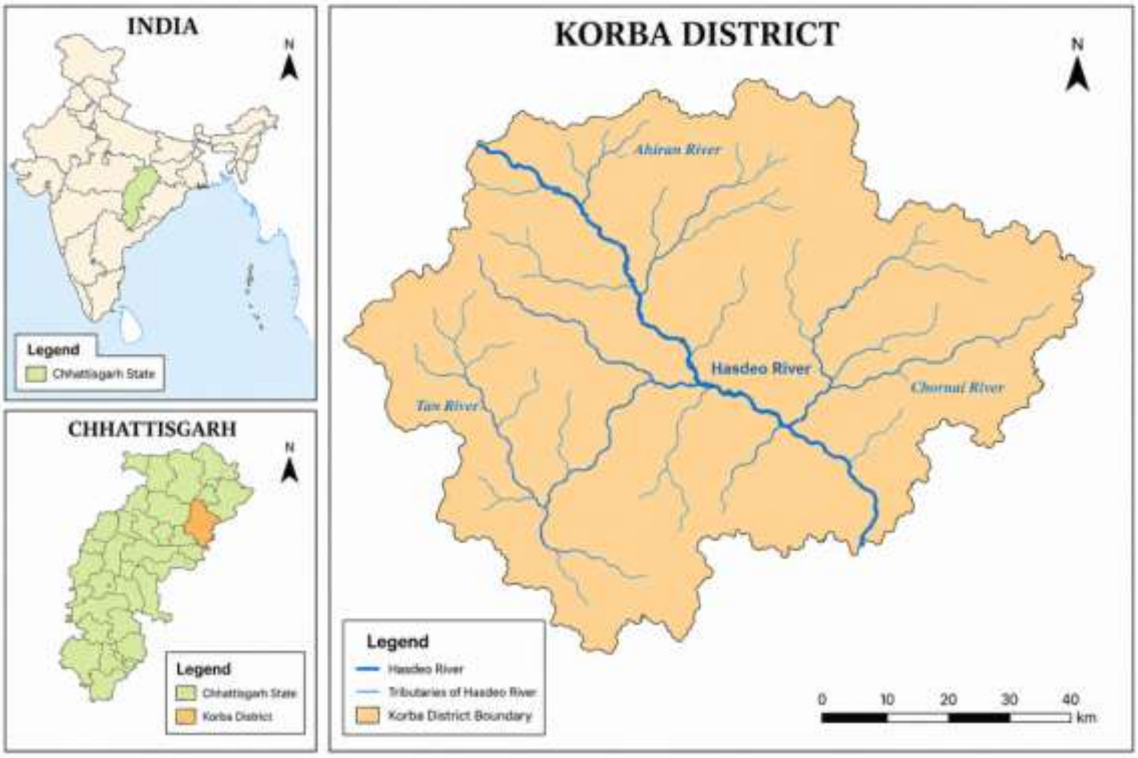

Figure 1. Map showing the Hasdeo River and selected tributaries in Korba District, Chhattisgarh, India.

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Selection of Sampling Stations

A total of 12 sampling stations were selected across the Hasdeo River and its tributaries (Ahiran, Tan, and Chornai), with three stations in each river representing upstream, midstream, and downstream reaches under varying ecological conditions and anthropogenic influences, including industrial, agricultural, urban, and relatively undisturbed forest areas. Sampling was conducted during the pre-monsoon, monsoon, and post-monsoon seasons, generating a total of 36 observations. Water-quality parameters and ichthyofaunal diversity were assessed simultaneously during each field visit to enable direct evaluation of the relationships between physicochemical variables and fish-community characteristics.

Table 1. Sampling stations across four rivers

S. No.	River	Site Code	Stretch	Geographical Location	Brief Habitat Characteristics
1	Hasdeo River	HS-1	Upstream	22.610318° N, 82.595326° E	Riverine habitat with relatively low anthropogenic disturbance and comparatively natural riparian conditions.
		HS-2	Midstream	22.438434° N, 82.686050° E	Moderately disturbed river stretch influenced by human settlements and associated anthropogenic activities.
		HS-3	Downstream	22.340362° N, 82.694059° E	Downstream riverine habitat exposed to comparatively greater anthropogenic pressure and altered habitat conditions.
2	Tan River	TS-1	Upstream	22.708028° N, 82.400943° E	Upstream riverine habitat with relatively low human disturbance and comparatively natural riverbank conditions.
		TS-2	Midstream	22.643210° N, 82.523833° E	Moderately disturbed river stretch with local human influence and modified riparian conditions.
		TS-3	Downstream	22.604102° N, 82.560125° E	Downstream riverine habitat with comparatively greater human influence and disturbance of the surrounding riverbank.
3	Ahiran River	AS-1	Upstream	22.586498° N, 82.411418° E	Relatively less disturbed upstream riverine habitat with comparatively natural riparian surroundings.
		AS-2	Midstream	22.378418° N, 82.632855° E	River stretch experiencing moderate anthropogenic influence from nearby settlements and land-use activities.
		AS-3	Downstream	22.352203° N, 82.646825° E	Downstream habitat characterized by comparatively greater anthropogenic pressure and modified riverine conditions.
4	Chornai River	CS-1	Upstream	22.621206° N, 82.855717° E	Relatively less disturbed upstream habitat with comparatively natural riverine and riparian conditions.
		CS-2	Midstream	22.650031° N, 82.835992° E	Moderately disturbed river stretch influenced by local human activities and surrounding land use.
		CS-3	Downstream	22.637436° N, 82.806604° E	Downstream habitat experiencing comparatively greater anthropogenic influence and ecological disturbance.

Water Sampling Protocols and Measurements

Surface-water samples were collected from approximately 20–30 cm below the water surface using pre-cleaned 1 L polyethylene bottles, which were rinsed three times with site water before final collection. Samples for dissolved oxygen were collected separately in 300 mL BOD bottles without air bubbles. Water

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temperature, pH, DO and TDS were measured in situ using calibrated portable instruments, while samples for laboratory analysis were properly labelled, stored at approximately 4°C, transported within 24 hours, and analysed following APHA (2023) and Wetzel (2001). For statistical evaluation, temperature, pH, DO, BOD, COD, and TDS were selected because of their ecological relevance to freshwater habitat quality and fish-community structure.

Fish Sampling and Identification

Fish sampling was conducted simultaneously with water-quality assessment at all 12 sampling stations during the pre-monsoon, monsoon, and post-monsoon seasons. Sampling was carried out on weekends during the morning (07:00–10:00 AM) and evening (04:00–06:00 PM) using cast nets (10–15 mm), gill nets (20–35 mm), drag nets (10–20 mm), scoop nets, hand nets, and traditional fishing gears to cover different aquatic habitats. Captured fishes were temporarily maintained in aerated containers, and information on abundance, habitat, station code, season, and gear type was recorded. Identified live specimens were released wherever possible, whereas representative or taxonomically uncertain specimens were preserved in 10% buffered formalin for laboratory examination. Fish specimens were identified to the species level based on external morphology, fin arrangement, scale pattern, coloration, and meristic characteristics using standard taxonomic keys and regional ichthyological literature (Talwar & Jhingran, 1991; Jayaram, 2010).

Analysis of Physicochemical Variables

Physicochemical water-quality data, including temperature, pH, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, and total dissolved solids, were first organized and checked in Microsoft Excel. Descriptive statistics such as mean and standard deviation were calculated for each river and season. One-way ANOVA was used to compare river-wise differences, while two-way ANOVA examined the separate and combined effects of river and season. When significant differences were detected, Tukey's HSD test was applied for pairwise comparison among rivers. Pearson's correlation analysis was used to evaluate the direction and strength of relationships between water-quality variables and fish-diversity indices. SPSS and R were used for inferential analysis, while Excel and R were used to prepare tables, bar graphs, correlation plots, and heat maps. Statistical significance was considered at $p < 0.05$.

Ichthyofaunal Diversity Data Analysis

Fish-community data were analysed using species richness, abundance, Shannon–Wiener diversity, Simpson dominance, and Pielou evenness indices. These indices were calculated for each sampling station, river, and season using PAST software (Hammer et al., 2001) and verified in Microsoft Excel. Mean values and seasonal patterns were then compared using one-way and two-way ANOVA, followed by Tukey's HSD test where required. Pearson's correlation analysis was used to determine how fish-diversity indices responded to changes in temperature, pH, DO, BOD, COD, and TDS. Heat maps and graphical summaries were prepared to clearly present spatial and seasonal patterns in fish diversity and water quality across the Hasdeo River system.

Quality Assurance and Quality Control

Quality assurance and quality control procedures were maintained throughout water and fish sampling, laboratory analysis, and data processing. Sampling bottles and fishing equipment were cleaned before use, water-sampling containers were rinsed with site water, and field instruments were calibrated before each survey. Water samples were collected, labelled, preserved at approximately 4°C, transported within 24 hours, and analysed using standardized methods. Fish sampling followed consistent timing, effort, gears, and station-wise recording procedures, while specimen labels included site code, season, date, habitat, and gear type. Fish identification was based on standard taxonomic keys, morphological and meristic characters, and uncertain specimens were re-examined and cross-verified using recognized fish databases. Field records, laboratory results, species lists, and data entries were checked for completeness, consistency, transcription errors, and taxonomic duplication before statistical analysis.

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Ethical and Conservation Considerations

Fish sampling was conducted using the minimum effort required to obtain representative samples. Live specimens not required for preservation were released after identification wherever possible. Only representative specimens were retained for taxonomic examination. Local fishers were consulted during sampling, and traditional fishing knowledge was used only for scientific documentation and species detection.

RESULTS

Ichthyofaunal Composition and Species Distribution

A total of 64 fish species belonging to 24 families and 12 orders were recorded from the Hasdeo River and its tributaries. Species occurrence varied considerably among the four rivers, with Hasdeo supporting the highest number of species, followed by Ahiran, Tan, and Chornai. The systematic distribution and conservation status of the recorded ichthyofauna are presented in Table 2.

Table 2. Systematic checklist of fish species recorded from Hasdeo, Tan, Ahiran, and Chornai rivers of the Korba District, Chhattisgarh, India, during May 2025 to April 2026

S. No.	Order	Family	Species Name	Hasdeo	Tan	Ahiran	Chornai	IUCN Status
1.	*Anabantiformes*	*Channidae*	*Channa gachua*	+	+	+	+	LC
2.			*Channa punctatus*	+	+	+	+	LC
3.			*Channa morulius*	+	+	+	+	LC
4.			*Channa striatus*	+	+	+	+	LC
5.		*Anabantidae*	*Anabas testudineus*	+	+	+	+	LC
6.		*Nandidae*	*Nandus nandus*	+	+	+	+	LC
7.		*Osphronemidae*	*Trichogaster fasciatus*	+	-	-	-	LC
8	*Beloniformes*	*Belonidae*	*Xenentodon cancilla*	+	+	+	+	LC
9.	*Cichliformes*	*Cichlidae*	*Oreochromis mossambicus*	+	-	-	-	VU
10.			*Oreochromis niloticus*	+	+	+	+	LC
11.	*Clupeiformes*	*Clupeidae*	*Gudusia chapra*	+	+	+	-	LC
12.	*Cypriniformes*	*Cyprinidae*	*Catla catla*	+	+	+	+	LC
13.			*Cirrhinus mrigala*	+	+	+	+	LC
14.			*Labeo rohita*	+	+	+	+	LC
15.			*Labeo calbasu*	+	+	+	+	LC

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16.			*Labeo gonius*	+	+	+	+	LC
17.			*Labeo bata*	+	+	+	+	LC
18.			*Cirrhinus reba*	+	-	+	-	LC
19.			*Labeo angra*	+	-	+	-	LC
20.			*Labeo boga*	+	-	-	-	LC
21.			*Osteobrama cotio*	+	-	+	-	LC
22.			*Puntius chola*	+	+	+	+	LC
23.			*Puntius conchonicus*	+	+	+	+	LC
24.			*Puntius sarana*	+	+	+	+	LC
25.			*Puntius dorsalis*	+	+	+	+	LC
26.			*Puntius ticto*	+	+	+	+	LC
27.			*Puntius terio*	+	+	+	-	LC
28.			*Puntius punctatus*	+	+	+	+	LC
29.			*Ctenopharyngodon idella*	+	-	-	-	LC
30.			*Cyprinus carpio*	+	-	-	-	LC
31.			*Puntius sophore*	+	+	+	+	LC
32.		*Nemachidae*	*Acanthocobitis botia*	+	-	+	-	LC
33.		*Cobitidae*	*Lepidocephalichthys thermalis*	+	+	+	+	LC
34.			*Lepidocephalichthys guntea*	+	+	+	+	LC
35.		*Danionidae*	*Danio devario*	+	+	+	+	LC
36.			*Chela cachius*	+	-	-	-	LC
37.			*Esomus danricus*	+	+	+	+	LC
38.			*Rasbora daniconius*	+	+	+	+	LC
39.			*Amblypharyngodon mola*	+	+	+	+	LC
40.			*Salmostoma bacaila*	+	+	+	+	LC
41.			*Salmostoma phulo*	+	-	-	-	LC
42.	*Gobiiformes*	*Gobiidae*	*Glossogobius giuris*	+	+	+	+	LC

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43.	*Mugiliformes*	*Chandidae*	*Parambassis lala*	+	-	-	-	LC
44.	*Osteoglossiformes*	*Notopteridae*	*Notopterus notopterus*	+	+	+	+	LC
45.	*Perciformes*	*Ambassidae*	*Chanda nama*	+	+	+	+	LC
46.			*Parambassis ranga*	+	+	+	+	LC
47.	*Siluriformes*	*Bagridae*	*Mystus bleekeri*	+	+	+	+	LC
48.			*Mystus cavasius*	+	+	+	+	LC
49.			*Mystus seenghala*	+	+	-	-	LC
50.			*Mystus tengara*	+	+	+	+	LC
51.			*Mystus vittatus*	+	+	+	+	LC
52.			*Mystus aor*	+	-	-	-	LC
53.		*Clariidae*	*Clarias batrachus*	+	-	-	-	LC
54.		*Heteropneustidae*	*Heteropneustes fossilis*	+	+	+	+	LC
55.		*Pangasiidae*	*Pangasius pangasius*	+	-	-	-	LC
56.		*Ritidae*	*Rita rita*	+	+	+	-	LC
57.		*Siluridae*	*Ompok bimaculatus*	+	+	+	+	NT
58.			*Ompok pabda*	+	-	+	-	NT
59.			*Wallago attu*	+	-	-	-	VU
60.	*Synbranchiformes*	*Mastacembelidae*	*Macrognathus aculeatus*	+	+	+	+	LC
61.			*Macrognathus armatus*	+	+	+	+	LC
62.			*Mastacembelus pancalus*	+	+	+	+	LC
63.		*Synbranchidae*	*Ophichthys cuchia*	+	-	-	-	LC
64.	*Tetraodontiformes*	*Tetraodontidae*	*Leiodon cutcutia*	+	-	-	-	LC
Total	*12*	*24*	*64*	64	45	49	41	

Symbol : (+) Present , (-) Absent, (LC) Least concern, (VU) Vulnerable, (NT) Near threatened

The systematic checklist recorded 64 fish species from 24 families and 12 orders across the Hasdeo, Tan, Ahiran, and Chornai rivers. Hasdeo supported all 64 species, while 45 species were found in Tan, 49 in Ahiran, and 41 in Chornai. Several common species, such as *Channa gachua*, *Catla catla*, *Labeo rohita*, *Puntius sophore*, *Notopterus notopterus*, and *Mystus vittatus*, occurred in all four rivers. In contrast, species such as *Trichogaster fasciatus*, *Oreochromis mossambicus*, *Chela cachius*, *Wallago attu*, and *Leiodon cutcutia* were restricted to Hasdeo. Most species were classified as Least Concern, while *Ompok bimaculatus* and *Ompok*

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pabda were listed as Near Threatened, and *Oreochromis mossambicus* and *Wallago attu* as Vulnerable. Overall, the checklist highlights the high conservation value of the Hasdeo River and the need to protect threatened and habitat-specific species.

Table 3. Order-wise species distribution

S. No.	Order	Family	Species
1	Anabantiformes	4	7
2	Beloniformes	1	1
3	Cichliformes	1	2
4	Clupeiformes	1	1
5	Cypriniformes	4	30
6	Gobiiformes	1	1
7	Mugiliformes	1	1
8	Osteoglossiformes	1	1
9	Perciformes	1	2
10	Siluriformes	6	13
11	Synbranchiformes	2	4
12	Tetraodontiformes	1	1
Total	12	24	64

The recorded ichthyofaunal assemblage comprised 64 fish species belonging to 24 families and 12 orders. Among the recorded orders, Cypriniformes was the most dominant, representing 30 species from four families, and accounted for nearly half (46.9%) of the total species richness.

Siluriformes was the second most species-rich order, comprising 13 species belonging to six families, followed by Anabantiformes with 7 species from four families. Synbranchiformes contributed four species from two families, whereas Cichliformes and Perciformes were represented by two species each.

The remaining orders - Beloniformes, Clupeiformes, Gobiiformes, Mugiliformes, Osteoglossiformes, and Tetraodontiformes - were represented by a single species each. Overall, the order-wise distribution indicates a clear predominance of Cypriniformes and Siluriformes, which together constituted 43 of the 64 recorded species (67.2%), reflecting their major contribution to the ichthyofaunal diversity of the study area.

River-wise and Seasonal Fish Abundance

Fish abundance differed considerably among rivers and seasons. Total abundance generally increased from the pre-monsoon to the monsoon and post-monsoon periods, while clear river-wise differences were also observed.

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Table 4. Total Fish Abundance across Four Rivers

River	Pre-monsoon Total Abundance	Monsoon Total Abundance	Post-monsoon Total Abundance	Total Fish Abundance
Hasdeo	1380	1533	1661	4574
Tan	801	879	992	2672
Ahiran	1082	1229	1395	3706
Chornai	637	719	883	2239
Grand Total	**3900**	**4360**	**4931**	**13191**

The four rivers supported a total abundance of 13,191 fish individuals. Hasdeo recorded the highest abundance (4,574), followed by Ahiran (3,706), Tan (2,672), and Chornai (2,239). Seasonally, abundance increased from 3,900 in pre-monsoon to 4,360 in monsoon and reached the highest level in post-monsoon (4,931)**.** This pattern suggests that improved water conditions, greater food availability, and expanded habitats after rainfall favour fish populations. Overall, Hasdeo and Ahiran provided comparatively better habitats, while Tan and Chornai showed lower abundance, possibly due to smaller habitat size and greater environmental stress.

River-Wise Variation in Fish Diversity

Mean species richness followed the order Hasdeo > Ahiran > Tan > Chornai. Hasdeo recorded the highest species richness (45.11 ± 3.22), Shannon diversity (3.61 ± 0.10), and evenness (0.95 ± 0.01), whereas Chornai recorded the lowest richness (28.22 ± 2.28), Shannon diversity (2.88 ± 0.10), and evenness (0.86 ± 0.01). Simpson dominance showed the reverse trend and was highest in Chornai, indicating greater dominance by fewer species.

Species Richness (S)

Species richness is the total number of fish species recorded at a sampling site.

S = Total number of species observed

Shannon–Wiener Diversity Index (H′)

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

where $p_i = n_i / N$.

Simpson's Dominance Index (D)

$D = \Sigma (p_i^2)$

where p_i = proportion of individuals belonging to species i.

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Pielou's Evenness Index (J′)

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

where H′ = Shannon–Wiener diversity index and S = total number of species.

Table 5. Fish Diversity Indices and Physicochemical Water Quality Variables across Rivers, Sampling Sites and Seasons (n = 36)

S. No.	River	Site Code	Season	Species Richness	Shannon H'	Simpson D	Pielou Evenness J'	Temp (°C)	pH	DO (mg/L)	BOD (mg/L)	COD (mg/L)	TDS (mg/L)
1	Hasdeo	HS-1	Pre-monsoon	40	3.46	0.09	0.94	29.6	7.08	6.6	3.9	16.5	98.4
2	Hasdeo	HS-1	Monsoon	43	3.54	0.08	0.94	25	6.62	8.3	3.5	15.4	146.7
3	Hasdeo	HS-1	Post-monsoon	45	3.60	0.07	0.95	20.3	6.78	8.2	2.7	11.5	78.3
4	Hasdeo	HS-2	Pre-monsoon	44	3.58	0.07	0.95	30	7.04	6.3	4.1	17.3	94.8
5	Hasdeo	HS-2	Monsoon	48	3.71	0.06	0.96	25.7	6.61	8.1	3.7	16.2	186.5
6	Hasdeo	HS-2	Post-monsoon	50	3.76	0.05	0.96	22.2	6.74	7.7	2.9	12.4	74.2
7	Hasdeo	HS-3	Pre-monsoon	42	3.52	0.08	0.94	30.7	7.18	6.1	4.3	18.4	100.6
8	Hasdeo	HS-3	Monsoon	46	3.62	0.07	0.95	25.4	6.59	7.8	3.9	17.2	134.9
9	Hasdeo	HS-3	Post-monsoon	48	3.68	0.06	0.95	23.7	6.84	7.2	3.1	13.5	84.7
10	Ahiran	AS-1	Pre-monsoon	34	3.16	0.11	0.90	30.6	7.56	6.1	4.5	21.4	214.6
11	Ahiran	AS-1	Monsoon	37	3.26	0.10	0.90	25.5	6.54	7.5	4.2	20.5	170.3
12	Ahiran	AS-1	Post-monsoon	39	3.34	0.09	0.91	19.8	7.79	8.2	3.4	16.4	88.5
13	Ahiran	AS-2	Pre-monsoon	36	3.22	0.10	0.90	31.3	7.66	5.9	4.7	22.3	226.8
14	Ahiran	AS-2	Monsoon	39	3.32	0.09	0.91	25.7	6.54	7.2	4.4	21.2	181.7
15	Ahiran	AS-2	Post-monsoon	41	3.4	0.08	0.92	20.4	6.93	8.4	3.6	17.2	92.4
16	Ahiran	AS-3	Pre-monsoon	32	3.1	0.12	0.89	32	7.46	5.7	4.9	23.2	255.9
17	Ahiran	AS-3	Monsoon	35	3.2	0.11	0.90	25.9	6.59	7.1	4.6	22.4	270.6
18	Ahiran	AS-3	Post-monsoon	37	3.28	0.10	0.91	20.8	6.61	8.1	3.8	18.3	85.8
19	Chornai	CS-1	Pre-monsoon	25	2.75	0.16	0.85	30.7	6.94	5.6	6.7	30.2	114.5

20	Chornai	CS-1	Monsoon	27	2.85	0.15	0.86	26	6.55	6.3	6.5	30.5	66.8
21	Chornai	CS-1	Post-monsoon	29	2.95	0.14	0.88	24.3	6.62	8.1	5.6	24.2	83.2
22	Chornai	CS-2	Pre-monsoon	27	2.81	0.15	0.85	31	7.06	5.3	7	32.1	118.4
23	Chornai	CS-2	Monsoon	29	2.89	0.14	0.86	27.2	6.57	6.6	6.8	32.4	68.6
24	Chornai	CS-2	Post-monsoon	31	2.99	0.13	0.87	24	6.87	8.5	5.9	26.1	61.7
25	Chornai	CS-3	Pre-monsoon	26	2.79	0.15	0.86	31.8	7.04	4.9	7.3	34.2	146.9
26	Chornai	CS-3	Monsoon	28	2.87	0.14	0.86	25.5	6.62	5.9	7.1	34.5	136.4
27	Chornai	CS-3	Post-monsoon	32	3.05	0.12	0.88	23.1	6.77	8.9	6.2	28.1	58.3
28	Tan	TS-1	Pre-monsoon	29	3.01	0.13	0.89	31	7.84	5.9	6	28.4	455.6
29	Tan	TS-1	Monsoon	31	3.11	0.12	0.91	26.7	6.56	6.4	5.8	28.5	255.8
30	Tan	TS-1	Post-monsoon	33	3.19	0.11	0.91	21	7.72	7.9	4.9	22.2	385.4
31	Tan	TS-2	Pre-monsoon	31	3.08	0.12	0.90	32.3	7.98	5.7	6.3	30.2	466.3
32	Tan	TS-2	Monsoon	33	3.15	0.11	0.90	26.2	6.6	6.9	6.1	30.4	245.9
33	Tan	TS-2	Post-monsoon	35	3.23	0.10	0.91	21.2	7.8	7.6	5.2	24.1	426.7
34	Tan	TS-3	Pre-monsoon	28	2.97	0.14	0.89	31.8	7.91	5.8	6.6	32.1	460.5
35	Tan	TS-3	Monsoon	30	3.05	0.13	0.90	26.5	6.68	7.1	6.4	32.2	166.4
36	Tan	TS-3	Post-monsoon	32	3.15	0.12	0.91	20.6	7.7	7.7	5.5	26.3	420.8

This table comprises 36 observations from four rivers, with 9 observations per river (3 sites × 3 seasons). Hasdeo showed the highest overall fish diversity, with species richness ranging from 40 to 50, Shannon diversity from 3.46 to 3.76, and evenness from 0.94 to 0.96, while Simpson dominance remained low (0.05–0.09). In contrast, Chornai recorded lower richness (25–32) and Shannon diversity (2.75–3.05) with higher Simpson dominance (0.12–0.16).

Across seasons, species richness and Shannon diversity generally increased from pre-monsoon to post-monsoon, whereas Simpson dominance declined. DO increased to as high as 8.9 mg/L, while BOD and COD generally decreased after the monsoon. Tan recorded the highest TDS values, reaching 466.3 mg/L, whereas Chornai showed the highest BOD (7.3 mg/L) and COD (34.5 mg/L). Overall, the dataset indicates better ecological conditions in Hasdeo and greater pollution stress in Tan and Chornai.

One-Way Analysis of Variance (ANOVA)

One-way ANOVA showed highly significant river-wise differences in species richness, Shannon diversity, Simpson dominance, and Pielou evenness (all $p < 0.001$). Significant differences were also observed for pH,

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BOD, COD, and TDS, whereas temperature and dissolved oxygen did not differ significantly among rivers. These results confirmed distinct ecological and water-quality conditions across the four rivers.

Formula:

$$F = MS\_between / MS\_within$$
$$MS\_between = SS\_between / (k - 1)$$
$$MS\_within = SS\_within / (N - k)$$

where SS = Sum of Squares, MS = Mean Square, k = number of groups, and N = total observations.

Table 6. One-way ANOVA (River-wise) for Fish Diversity and Water Quality Variables

Variable	Hasdeo Mean±SD	Tan Mean±SD	Ahiran Mean±SD	Chornai Mean±SD	df	F-value	p-value	Inference
Species Richness	45.11±3.22	31.33±2.18	36.67±2.78	28.22±2.28	F(3,32)	70.13	<0.001***	Very Highly Significant
Shannon H′	3.61±0.10	3.10±0.09	3.25±0.09	2.88±0.10	F(3,32)	95.64	<0.001***	Very Highly Significant
Simpson D	0.07±0.01	0.12±0.01	0.10±0.01	0.14±0.01	F(3,32)	56.99	<0.001***	Very Highly Significant
Pielou J′	0.95±0.01	0.90±0.01	0.90±0.01	0.86±0.01	F(3,32)	132.12	<0.001***	Very Highly Significant
Temperature (°C)	25.84±3.61	26.37±4.68	25.78±4.77	27.07±3.31	F(3,32)	0.19	0.905 NS	Not Significant
pH	6.83±0.22	7.42±0.61	7.08±0.53	6.78±0.20	F(3,32)	4.09	0.014*	Significant
DO (mg/L)	7.37±0.85	6.78±0.86	7.13±1.03	6.68±1.47	F(3,32)	0.78	0.512 NS	Not Significant
BOD (mg/L)	3.57±0.56	5.87±0.57	4.23±0.52	6.57±0.57	F(3,32)	56.80	<0.001***	Very Highly Significant
COD (mg/L)	15.38±2.39	28.27±3.47	20.32±2.44	30.26±3.54	F(3,32)	47.81	<0.001***	Very Highly Significant
TDS (mg/L)	111.01±37.40	364.82±112.07	176.29±72.67	94.98±34.32	F(3,32)	27.02	<0.001***	Very Highly Significant

Note: For one-way ANOVA, the degrees of freedom are Between groups = 3 (4 rivers − 1) and Within groups = 32 (36 observations − 4 groups). Therefore, all F statistics are reported as F(3,32). NS = Not Significant ($p \geq 0.05$); * = Significant ($p < 0.05$); ** = Highly Significant ($p < 0.01$); *** = Very Highly Significant ($p < 0.001$).

Interpretation: One-way ANOVA was performed using River (Hasdeo, Ahiran, Tan, and Chornai) as the independent variable, while fish diversity indices (species richness, Shannon diversity, Simpson dominance,

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and Pielou evenness) and physicochemical water-quality variables (temperature, pH, dissolved oxygen, BOD, COD, and TDS) were analysed separately as dependent variables. The analysis was based on F(3,32), where the degrees of freedom were 3 for between-river variation and 32 for within-river variation.

The results revealed significant river-wise differences in species richness, Shannon diversity (H′), Simpson dominance (D), Pielou evenness (J′), pH, BOD, COD, and TDS ($p < 0.05$), indicating distinct ecological and water-quality conditions among the four rivers. However, temperature ($F(3,32) = 0.19$, $p = 0.905$) and dissolved oxygen (DO) ($F(3,32) = 0.78$, $p = 0.512$) did not differ significantly, suggesting that their mean values were statistically similar across the rivers.

Overall, the results indicate that Hasdeo exhibited better ecological conditions and higher fish diversity, whereas Chornai showed greater organic pollution and ecological stress.

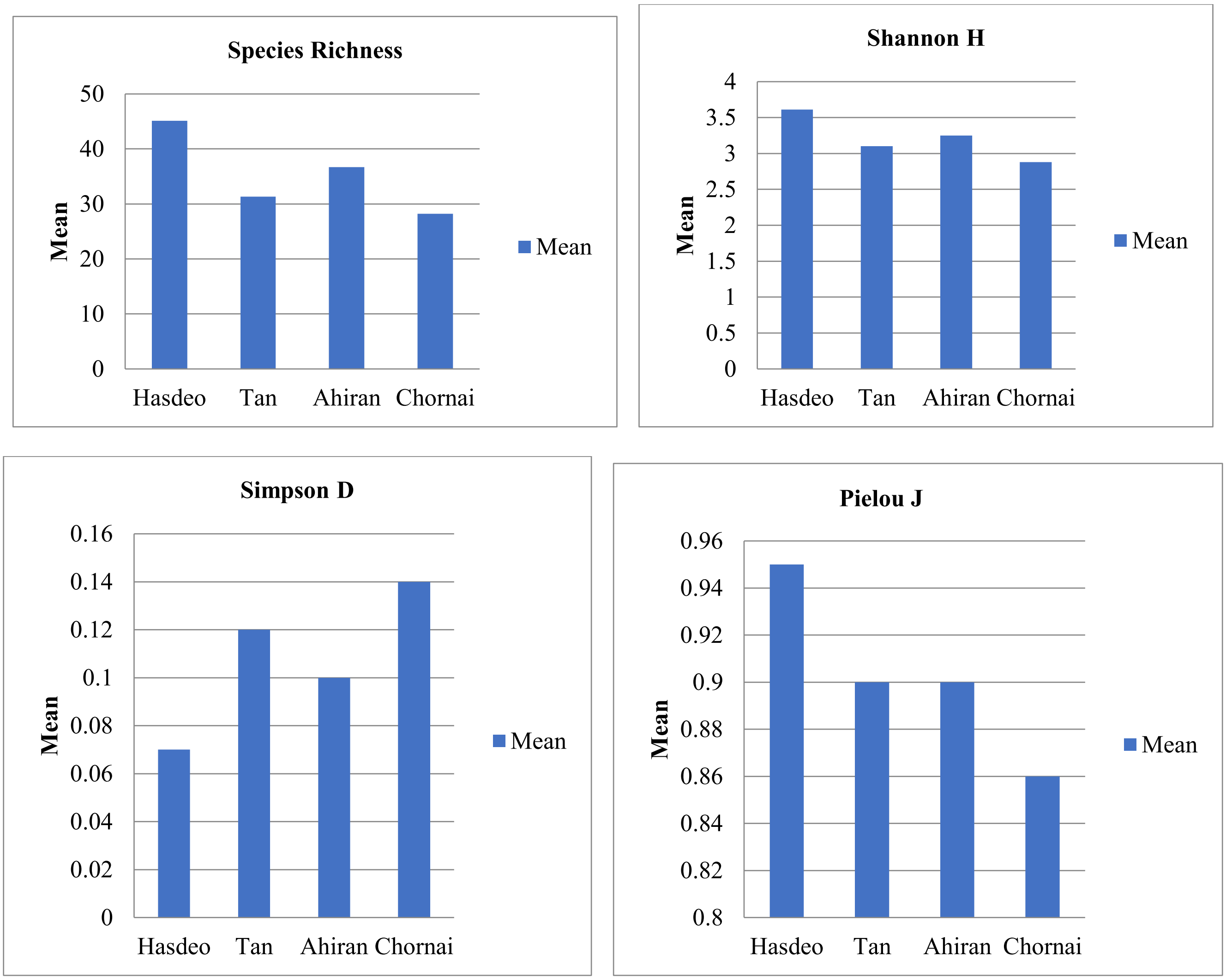

Figure 2. River-wise variation in fish-diversity indices across the Hasdeo, Tan, Ahiran, and Chornai rivers.

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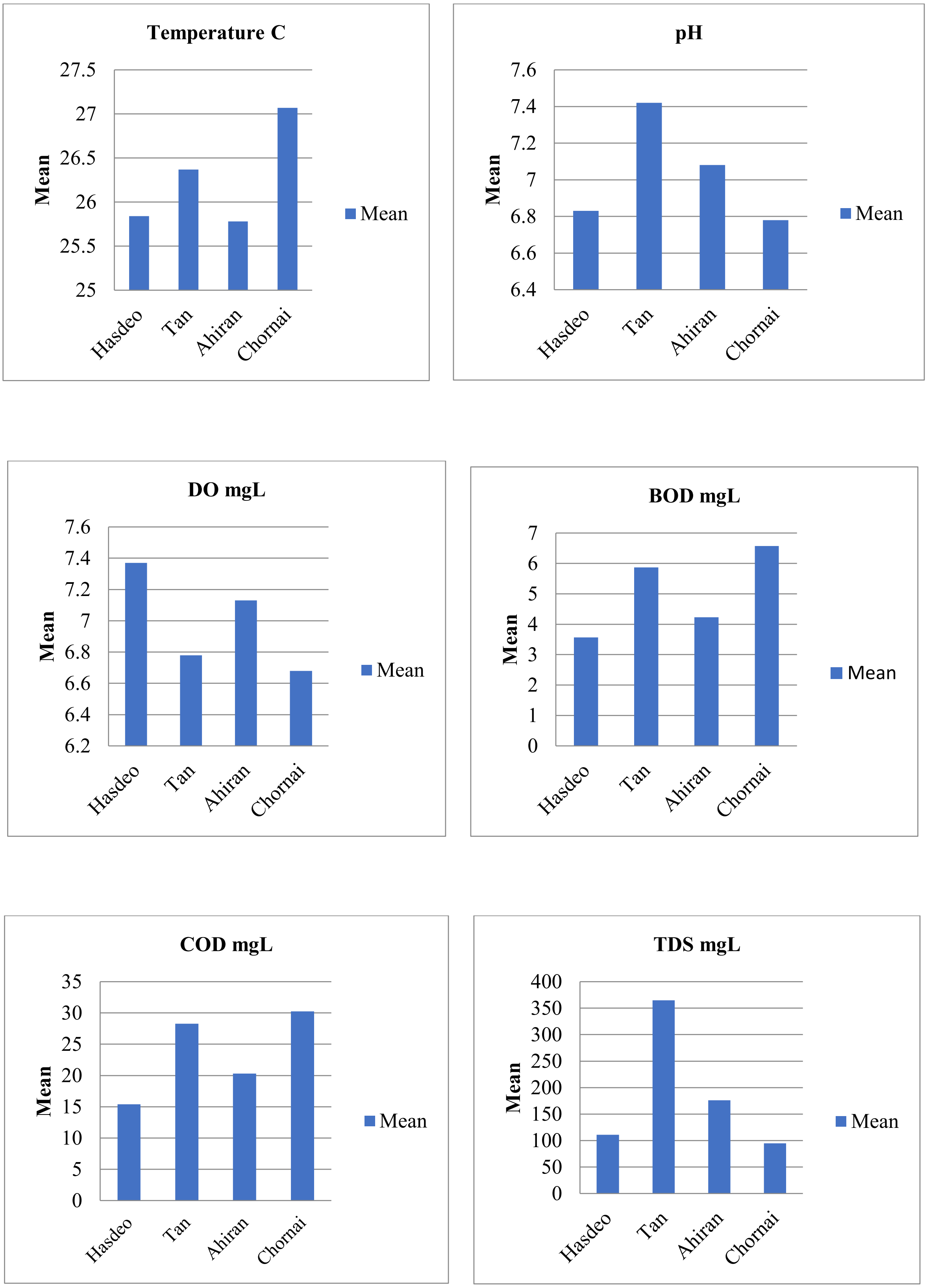

Figure 3. River-Wise Variation in Physicochemical Water-Quality Variables across The Hasdeo, Tan, Ahiran and Chornai Rivers.

Interpretation: One-way ANOVA indicated significant river-wise differences for Species Richness, Shannon diversity, Simpson dominance, Pielou evenness, pH, BOD, COD and TDS ($p < 0.05$). Temperature and dissolved oxygen did not differ significantly among rivers when all 36 observations were analysed together.

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Hasdeo exhibited the highest fish diversity and the lowest pollution indicators (BOD and COD), whereas Chornai generally showed the highest dominance and organic pollution. Tan recorded the highest TDS values.

Combined Effects of River and Season on Fish Diversity and Water Quality Variables

Two-way ANOVA demonstrated significant effects of both river and season on all fish-diversity indices. However, River × Season interactions were non-significant for species richness, Shannon diversity, Simpson dominance, and Pielou evenness, indicating broadly similar seasonal responses across the rivers. For physicochemical variables, significant river and seasonal effects were observed for temperature, pH, DO, BOD, COD, and TDS. Significant River × Season interactions occurred for temperature, pH, DO, and TDS, whereas BOD and COD showed comparatively consistent seasonal trends among rivers.

Two-way Analysis of Variance (ANOVA)

Two-way ANOVA demonstrated significant main effects of both river and season on all fish diversity indices ($p < 0.001$). Species richness, Shannon diversity, Simpson dominance, and Pielou's evenness differed significantly among rivers and seasons, whereas the River × Season interaction was not statistically significant. These findings indicate that although diversity varied spatially and seasonally, the seasonal response pattern remained broadly similar among rivers.

Similarly, significant river and seasonal effects were observed for all major physicochemical variables. Significant interaction effects were detected for temperature, pH, dissolved oxygen, and total dissolved solids, suggesting that seasonal changes in these parameters differed among rivers. In contrast, interaction effects for BOD and COD were not significant, indicating relatively consistent seasonal responses across rivers.

Two-Way Analysis of Variance (ANOVA):

$F = MS\_factor / MS\_error$

For each source of variation (River, Season, and River × Season):
$MS = SS / df$

where SS = Sum of Squares and df = Degrees of Freedom

Table 7. Two-way ANOVA showing the effects of river, season, and River x Season interaction on fish diversity indices and physicochemical water quality variables.

Variable	Source of variation	df	F-value	p-value	Significance	Interpretation
Species Richness	River	3	128.46	<0.001***	Very Highly Significant	Spatial effect
	Season	2	21.10	<0.001***	Very Highly Significant	Seasonal effect
	River × Season	6	0.19	0.977 NS	Not Significant	Similar seasonal pattern among rivers
Shannon H′	River	3	252.32	<0.001***	Very Highly Significant	Spatial effect

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	Season	2	30.74	<0.001***	Very Highly Significant	Seasonal effect
	River × Season	6	0.22	0.967 NS	Not Significant	Similar seasonal pattern among rivers
Simpson D	River	3	95.28	<0.001***	Very Highly Significant	Spatial effect
	Season	2	14.66	<0.001***	Very Highly Significant	Seasonal effect
	River × Season	6	0.03	1.000 NS	Not Significant	Similar seasonal pattern among rivers
Pielou J′	River	3	76.29	<0.001***	Very Highly Significant	Spatial effect
	Season	2	17.83	<0.001***	Very Highly Significant	Seasonal effect
	River × Season	6	0.06	0.999 NS	Not Significant	Similar seasonal pattern among rivers
Temperature (°C)	River	3	5.17	0.007**	Highly Significant	Spatial effect
	Season	2	435.04	<0.001***	Very Highly Significant	Seasonal effect
	River × Season	6	5.00	0.002**	Highly Significant	Effect varies by season
pH	River	3	20.22	<0.001***	Very Highly Significant	Spatial effect
	Season	2	54.57	<0.001***	Very Highly Significant	Seasonal effect
	River × Season	6	5.07	0.002**	Highly Significant	Effect varies by season
DO (mg/L)	River	3	9.18	<0.001***	Very Highly Significant	Spatial effect
	Season	2	152.67	<0.001***	Very Highly Significant	Seasonal effect
	River × Season	6	10.29	<0.001***	Very Highly Significant	Effect varies by season

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BOD (mg/L)	River	3	269.27	<0.001***	Very Highly Significant	Spatial effect
	Season	2	63.50	<0.001***	Very Highly Significant	Seasonal effect
	River × Season	6	0.12	0.994 NS	Not Significant	Similar seasonal pattern among rivers
COD (mg/L)	River	3	176.10	<0.001***	Very Highly Significant	Spatial effect
	Season	2	44.40	<0.001***	Very Highly Significant	Seasonal effect
	River × Season	6	0.40	0.872 NS	Not Significant	Similar seasonal pattern among rivers
TDS (mg/L)	River	3	147.32	<0.001***	Very Highly Significant	Spatial effect
	Season	2	18.17	<0.001***	Very Highly Significant	Seasonal effect
	River × Season	6	20.71	<0.001***	Very Highly Significant	Effect varies by season

Note: NS = Not Significant ($p \geq 0.05$); * = Significant ($p < 0.05$); ** = Highly Significant ($p < 0.01$); *** = Very Highly Significant ($p < 0.001$). Two-way ANOVA was performed to evaluate the effects of River (df = 3)**,** Season (df = 2)**,** and their interaction River × Season (df = 6) on fish diversity indices and physicochemical parameters. The numerator degrees of freedom correspond to the number of river groups (4 − 1 = 3), seasons (3 − 1 = 2), and their interaction [(4 − 1) × (3 − 1) = 6], respectively.

Interpretation: Two-way ANOVA was performed to evaluate the individual and interactive effects of River (independent variable 1) and Season (independent variable 2) on fish diversity indices and physicochemical water-quality parameters (dependent variables). The results revealed that the main effect of River was significant for all biological and water-quality variables ($p < 0.05$), indicating that ecological conditions and water quality differed significantly among the four rivers. Similarly, the main effect of Season was significant for all biological and physicochemical variables, demonstrating that seasonal changes influenced fish diversity and water-quality characteristics during the study period.

However, the River × Season interaction effect was not significant ($p > 0.05$) for the variables where interaction was non-significant, indicating that the seasonal pattern of variation was generally similar across all rivers. In other words, although both river and season independently affected the measured parameters, the magnitude and direction of seasonal changes did not vary significantly from one river to another.

Overall, the results indicate substantial river-specific and seasonal variation in fish diversity and water quality, while River × Season interactions were significant only for selected physicochemical variables.

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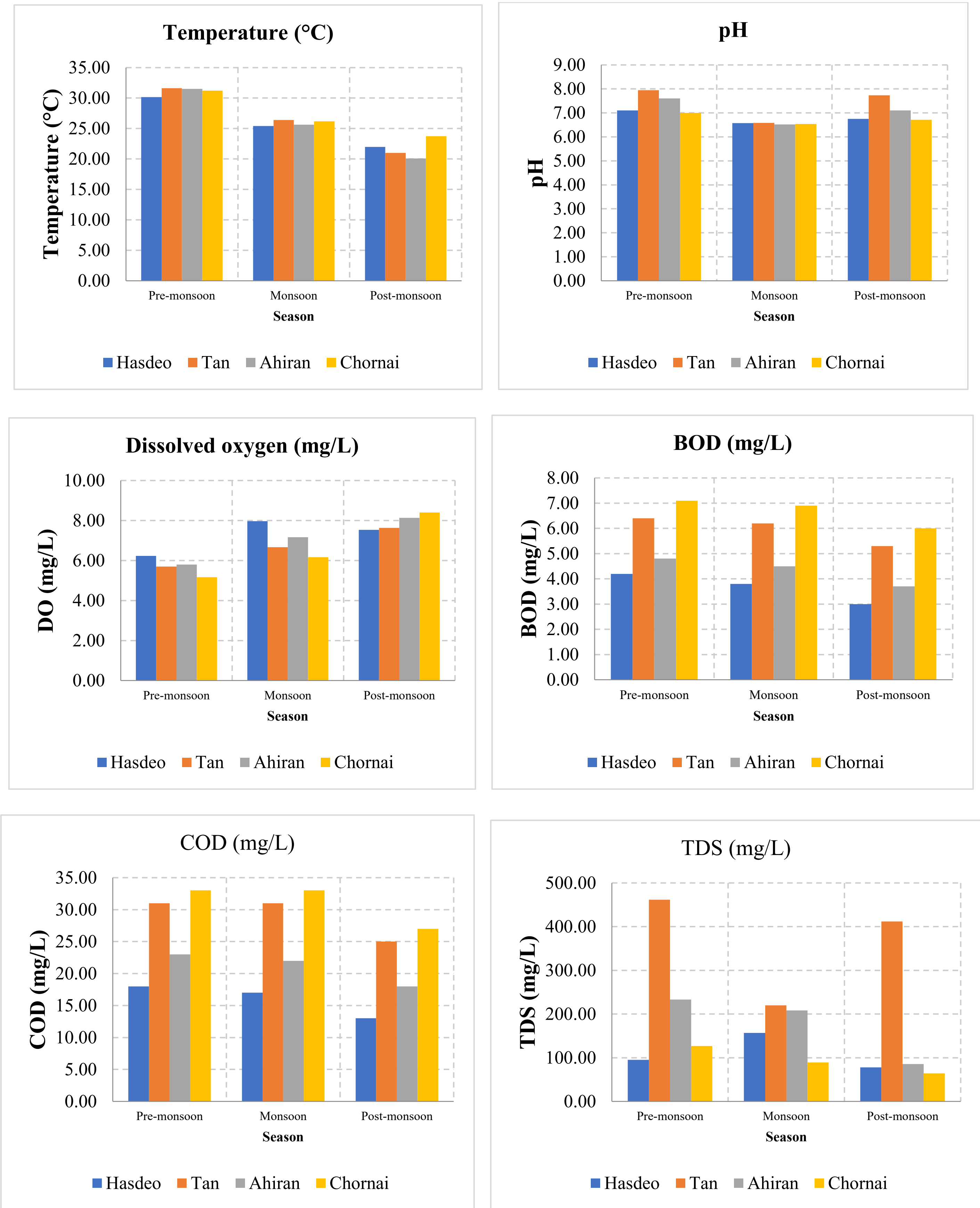

Figure 4: Seasonal variation in fish diversity indices across four rivers for two way ANOVA

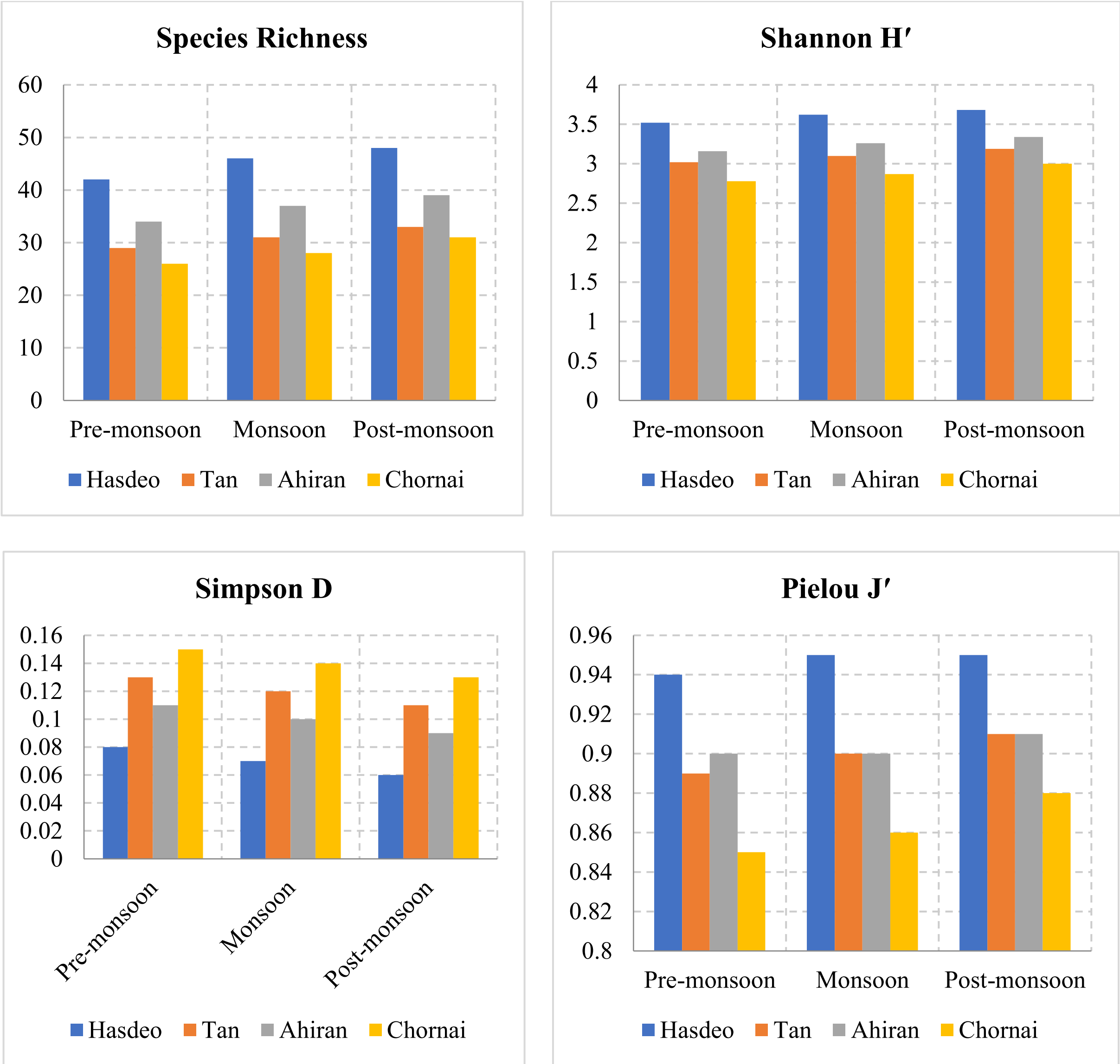

Figure 5: Seasonal variation of physicochemical parameters for two-way ANOVA

Tukey HSD Comparisons of Water Quality and Fish Diversity

Tukey HSD analysis showed that Chornai had significantly higher temperature than Hasdeo and Ahiran, while Tan recorded significantly higher pH than the other rivers. Hasdeo had significantly higher dissolved oxygen than Tan and Chornai. BOD increased significantly in the order Hasdeo < Ahiran < Tan < Chornai**,** while COD showed a similar pattern, although Tan and Chornai did not differ significantly. TDS was highest in Tan and significantly exceeded the other rivers. For fish diversity, Hasdeo consistently recorded the highest richness, Shannon diversity, and evenness, whereas Chornai showed the highest Simpson dominance. Shannon diversity differed significantly among all river pairs, while evenness was statistically similar between Ahiran and Tan.

Tukey's Honestly Significant Difference (HSD) Test

$$HSD = q\alpha \times \sqrt{(MS\_error / n)}$$

where $q\alpha$ = Studentized range statistic,

MS_error = Mean Square Error from ANOVA, and

n = number of observations per group

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Table 8. River-wise Tukey HSD Post Hoc Test for Water Quality Variables

Table 8.1. Tukey HSD comparison for Water Temperature

River comparison	Mean difference (I–J)	95% CI	Adjusted p-value	Result
Hasdeo – Ahiran	0.07 °C	−0.87 to 1.00	0.997	Not significant
Hasdeo – Tan	−0.52 °C	−1.46 to 0.41	0.429	Not significant
Hasdeo – Chornai	−1.22 °C	−2.16 to −0.29	0.007	Significant
Ahiran – Tan	−0.59 °C	−1.52 to 0.34	0.326	Not significant
Ahiran – Chornai	−1.29 °C	−2.22 to −0.36	0.004	Significant
Tan – Chornai	−0.70 °C	−1.63 to 0.23	0.192	Not significant

River means: Hasdeo = 25.84 °C; Ahiran = 25.78 °C; Tan = 26.37 °C; Chornai = 27.07 °C.

Interpretation: Mean temperature was highest in Chornai (27.07°C)**,** followed by Tan (26.37°C), Hasdeo (25.84°C) and Ahiran (25.78°C)**.** Chornai differed significantly from Hasdeo (mean difference = 1.22°C, p = 0.007) and Ahiran (1.29°C, p = 0.004)**.** Other river comparisons were not significant.

Table 8.2. Tukey HSD comparison for pH

River comparison	Mean difference (I–J)	95% CI	Adjusted p-value	Result
Hasdeo – Ahiran	−0.244	−0.489 to −0.000	0.050	Significant at boundary
Hasdeo – Tan	−0.590	−0.834 to −0.346	<0.001	Significant
Hasdeo – Chornai	0.049	−0.196 to 0.293	0.945	Not significant
Ahiran – Tan	−0.346	−0.590 to −0.101	0.004	Significant
Ahiran – Chornai	0.293	0.049 to 0.538	0.015	Significant
Tan – Chornai	0.639	0.394 to 0.883	<0.001	Significant

River means: Hasdeo = 6.831; Ahiran = 7.076; Tan = 7.421; Chornai = 6.782.

Interpretation: Tan recorded the highest mean pH **(**7.421), followed by Ahiran (7.076), Hasdeo (6.831) and Chornai **(**6.782). Tan differed significantly from Hasdeo (difference = 0.590, p < 0.001), Ahiran (0.346, p = 0.004) and Chornai **(**0.639, p < 0.001). Hasdeo and Chornai did not differ significantly (p = 0.945).

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Table 8.3. Tukey HSD comparison for Dissolved Oxygen (DO)

River comparison	Mean difference (I–J)	95% CI	Adjusted p-value	Result
Hasdeo – Ahiran	0.23 mg/L	−0.15 to 0.62	0.360	Not significant
Hasdeo – Tan	0.59 mg/L	0.20 to 0.97	0.002	Significant
Hasdeo – Chornai	0.69 mg/L	0.30 to 1.07	<0.001	Significant
Ahiran – Tan	0.36 mg/L	−0.03 to 0.74	0.078	Not significant
Ahiran – Chornai	0.46 mg/L	0.07 to 0.84	0.016	Significant
Tan – Chornai	0.10 mg/L	−0.29 to 0.49	0.890	Not significant

River means: Hasdeo = 7.37 mg/L; Ahiran = 7.13 mg/L; Tan = 6.78 mg/L; Chornai = 6.68 mg/L.

Interpretation: Mean DO was highest in Hasdeo (7.37 mg/L), followed by Ahiran (7.13 mg/L), Tan (6.78 mg/L) and Chornai (6.68 mg/L). Hasdeo had significantly higher DO than Tan (difference = 0.59 mg/L, $p = 0.002$) and Chornai (0.69 mg/L, $p < 0.001$). Ahiran also differed significantly from Chornai (0.46 mg/L, $p = 0.016$).

Table 8.4. Tukey HSD comparison for Biochemical Oxygen Demand (BOD)

River comparison	Mean difference (I–J)	95% CI	Adjusted p-value	Result
Hasdeo – Ahiran	−0.67 mg/L	−1.00 to −0.34	<0.001	Significant
Hasdeo – Tan	−2.30 mg/L	−2.63 to −1.97	<0.001	Significant
Hasdeo – Chornai	−3.00 mg/L	−3.33 to −2.67	<0.001	Significant
Ahiran – Tan	−1.63 mg/L	−1.96 to −1.30	<0.001	Significant
Ahiran – Chornai	−2.33 mg/L	−2.66 to −2.00	<0.001	Significant
Tan – Chornai	−0.70 mg/L	−1.03 to −0.37	<0.001	Significant

River means: Hasdeo = 3.57 mg/L; Ahiran = 4.23 mg/L; Tan = 5.87 mg/L; Chornai = 6.57 mg/L.

Interpretation: Mean BOD increased in the order Hasdeo (3.57 mg/L) < Ahiran (4.23 mg/L) < Tan (5.87 mg/L) < Chornai (6.57 mg/L). All six pairwise comparisons were significant ($p < 0.001$). The highest difference occurred between Hasdeo and Chornai (3.00 mg/L), indicating greater organic pollution in Chornai.

Table 8.5. Tukey HSD comparison for Chemical Oxygen Demand (COD)

River comparison	Mean difference (I–J)	95% CI	Adjusted p-value	Result
Hasdeo – Ahiran	−4.94 mg/L	−6.94 to −2.95	<0.001	Significant

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River comparison	Mean difference (I–J)	95% CI	Adjusted p-value	Result
Hasdeo – Tan	−12.89 mg/L	−14.88 to −10.89	<0.001	Significant
Hasdeo – Chornai	−14.88 mg/L	−16.87 to −12.88	<0.001	Significant
Ahiran – Tan	−7.94 mg/L	−9.94 to −5.95	<0.001	Significant
Ahiran – Chornai	−9.93 mg/L	−11.93 to −7.94	<0.001	Significant
Tan – Chornai	−1.99 mg/L	−3.98 to 0.01	0.051	Not significant

River means: Hasdeo = 15.38 mg/L; Ahiran = 20.32 mg/L; Tan = 28.27 mg/L; Chornai = 30.26 mg/L.

Interpretation: COD was lowest in Hasdeo (15.38 mg/L), followed by Ahiran (20.32 mg/L), Tan (28.27 mg/L) and Chornai (30.26 mg/L). Most comparisons were significant ($p < 0.001$); however, Tan and Chornai did not differ significantly (difference = 1.99 mg/L, $p = 0.051$).

Table 8.6. Tukey HSD comparison for Total Dissolved Solids (TDS)

River comparison	Mean difference (I–J)	95% CI	Adjusted p-value	Result
Hasdeo – Ahiran	−65.28 mg/L	−101.37 to −29.19	<0.001	Significant
Hasdeo – Tan	−253.81 mg/L	−289.90 to −217.72	<0.001	Significant
Hasdeo – Chornai	16.03 mg/L	−20.06 to 52.12	0.617	Not significant
Ahiran – Tan	−188.53 mg/L	−224.62 to −152.44	<0.001	Significant
Ahiran – Chornai	81.31 mg/L	45.22 to 117.40	<0.001	Significant
Tan – Chornai	269.84 mg/L	233.75 to 305.94	<0.001	Significant

River means: Hasdeo = 111.01 mg/L; Ahiran = 176.29 mg/L; Tan = 364.82 mg/L; Chornai = 94.98 mg/L.

Interpretation: Tan recorded the highest TDS (364.82 mg/L), followed by Ahiran (176.29 mg/L), Hasdeo (111.01 mg/L) and Chornai (94.98 mg/L). Tan differed significantly from all rivers ($p < 0.001$). Ahiran was also significantly higher than Hasdeo and Chornai, whereas Hasdeo and Chornai did not differ significantly ($p = 0.617$).

Overall Interpretation: The Tukey HSD analysis showed clear river-wise differences in water-quality variables. Chornai had significantly higher temperature than Hasdeo and Ahiran, while Tan recorded the highest pH and differed significantly from the other rivers. DO was significantly higher in Hasdeo than in Tan and Chornai, and Ahiran also had higher DO than Chornai.

All BOD comparisons were significant, with the order Chornai > Tan > Ahiran > Hasdeo. COD was significantly lower in Hasdeo and Ahiran than in Tan and Chornai, although Tan and Chornai did not differ significantly ($p = 0.051$). TDS was highest in Tan (364.82 mg/L) and differed significantly from all other

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rivers, whereas Hasdeo and Chornai were not significantly different. Overall, Hasdeo showed comparatively better water quality, while Tan and Chornai exhibited greater pollution stress.

Table 9. Tukey HSD Pairwise Comparison of Fish Diversity Indices among Rivers

Table 9.1. Species Richness

River comparison	Mean difference (I–J)	95% CI	Adjusted p-value	Result
Hasdeo – Ahiran	8.44	6.07 to 10.82	<0.001	Significant
Hasdeo – Tan	13.78	11.40 to 16.15	<0.001	Significant
Hasdeo – Chornai	16.89	14.51 to 19.26	<0.001	Significant
Ahiran – Tan	5.33	2.96 to 7.71	<0.001	Significant
Ahiran – Chornai	8.44	6.07 to 10.82	<0.001	Significant
Tan – Chornai	3.11	0.74 to 5.49	0.007	Significant

River means: Hasdeo = 45.11, Ahiran = 36.67, Tan = 31.33, Chornai = 28.22. **Interpretation**: Hasdeo recorded the highest mean species richness (45.11 ± 3.22), followed by Ahiran (36.67 ± 2.78), Tan (31.33 ± 2.18) and Chornai (28.22 ± 2.28). All pair-wise comparisons were statistically significant ($p < 0.05$), except Tan vs Chornai ($p = 0.007$), indicating comparable species richness between these two rivers. Overall order: Hasdeo > Ahiran > Tan > Chornai.

Table 9.2. Shannon Diversity (H′)

River comparison	Mean difference (I–J)	95% CI	Adjusted p-value	Result
Hasdeo – Ahiran	0.354	0.280 to 0.429	<0.001	Significant
Hasdeo – Tan	0.503	0.429 to 0.578	<0.001	Significant
Hasdeo – Chornai	0.724	0.650 to 0.799	<0.001	Significant
Ahiran – Tan	0.149	0.075 to 0.223	<0.001	Significant
Ahiran – Chornai	0.370	0.296 to 0.444	<0.001	Significant
Tan – Chornai	0.221	0.147 to 0.295	<0.001	Significant

Interpretation: The highest Shannon diversity was observed in Hasdeo (3.61 ± 0.10), followed by Ahiran (3.25 ± 0.09), Tan (3.10 ± 0.09) and Chornai (2.88 ± 0.10). All pairwise comparisons were statistically significant ($p < 0.05$), including the comparison between Tan and Chornai ($p = 0.007$), indicating significant differences in species richness among all four rivers.

Diversity declined in the order Hasdeo > Ahiran > Tan > Chornai.

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Table 9.3. Simpson Dominance (D)

River comparison	Mean difference (I–J)	95% CI	Adjusted p-value	Result
Hasdeo – Ahiran	-0.030	-0.042 to -0.018	<0.001	Significant
Hasdeo – Tan	-0.050	-0.062 to -0.038	<0.001	Significant
Hasdeo – Chornai	-0.072	-0.084 to -0.060	<0.001	Significant
Ahiran – Tan	-0.020	-0.032 to -0.008	<0.001	Significant
Ahiran – Chornai	-0.042	-0.054 to -0.030	<0.001	Significant
Tan – Chornai	-0.022	-0.034 to -0.010	<0.001	Significant

Interpretation: Simpson dominance was lowest in Hasdeo (0.07 ± 0.01) and highest in Chornai (0.14 ± 0.01), with Ahiran (0.10 ± 0.01) and Tan (0.12 ± 0.01) showing intermediate values. All pairwise comparisons were significant ($p < 0.01$), indicating clear differences in species dominance across rivers.

Dominance order: Chornai > Tan > Ahiran > Hasdeo.

Table 9.4. Pielou Evenness (J′)

River comparison	Mean difference (I–J)	95% CI	Adjusted p-value	Result
Hasdeo – Ahiran	0.044	0.037 to 0.052	<0.001	Significant
Hasdeo – Tan	0.047	0.039 to 0.054	<0.001	Significant
Hasdeo – Chornai	0.086	0.078 to 0.093	<0.001	Significant
Ahiran – Tan	0.002	-0.005 to 0.010	0.846	Not significant
Ahiran – Chornai	0.041	0.034 to 0.049	<0.001	Significant
Tan – Chornai	0.039	0.031 to 0.046	<0.001	Significant

River means: Hasdeo = 0.949, Ahiran = 0.904, Tan = 0.902, Chornai = 0.863. **Interpretation**: Hasdeo exhibited the highest evenness (0.95 ± 0.01), followed by Tan (0.90 ± 0.01), Ahiran (0.90 ± 0.01) and Chornai (0.86 ± 0.01). Most pairwise comparisons were significant ($p < 0.05$); however, Tan and Ahiran did not differ significantly ($p > 0.05$), indicating similar species distribution patterns in these two rivers.

Overall Interpretation: The Tukey HSD results confirmed Hasdeo as the river with the highest fish diversity and most even species distribution, whereas Chornai exhibited the lowest diversity and highest species

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dominance. Tan and Ahiran showed intermediate ecological conditions, with similar species evenness but significant differences in richness and diversity

Heat-Map Interpretation

The heat map of two-way ANOVA F-values visually confirmed strong river and seasonal effects on both biological and physicochemical variables. Shannon diversity, BOD, COD, DO, and TDS showed comparatively high F-values, indicating comparatively stronger statistical variation among river and/or seasonal groups.

To facilitate visual interpretation of the statistical results, the F-values obtained from the two-way ANOVA were summarized using a heat map. The graphical representation clearly demonstrates that river and season exerted strong influences on fish diversity and water quality variables, whereas interaction effects were significant only for selected physicochemical parameters such as temperature, pH, dissolved oxygen, and total dissolved solids. The heat map provides a concise overview of the relative magnitude of statistical effects and highlights the dominant environmental factors governing ichthyofaunal diversity within the Hasdeo River basin.

Figure 6. Heat map showing F-values obtained from two-way ANOVA for river, season, and River × Season effects on fish diversity indices and physicochemical water quality variables.

Pearson Correlation Between Water Quality and Fish Diversity

Dissolved oxygen showed significant positive correlations with species richness ($r = 0.487$), Shannon diversity ($r = 0.479$), and Pielou evenness ($r = 0.428$), and a negative correlation with Simpson dominance ($r = -0.490$). In contrast, BOD and COD showed very strong negative correlations with species richness, Shannon diversity, and evenness, and strong positive correlations with Simpson dominance. Temperature showed moderate negative associations with diversity, whereas pH and TDS were weakly and non-significantly related to the fish-diversity indices.

Overall, dissolved oxygen emerged as the principal positive factor supporting ichthyofaunal diversity, while BOD and COD were the strongest indicators of ecological stress in the Hasdeo River system.

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Pearson's Correlation Coefficient

$$r = \Sigma[(X_i - \bar{X})(Y_i - \bar{Y})] / \sqrt{[\Sigma(X_i - \bar{X})^2 \times \Sigma(Y_i - \bar{Y})^2]}$$

where Xi and Yi are paired observations, and $\bar{X}$ and $\bar{Y}$ are their respective means.

Level of Statistical Significance

Statistical significance was evaluated at:
$p < 0.05$ (significant)
$p < 0.01$ (highly significant)
$p < 0.001$ (very highly significant)

Table 10. Pearson Correlation Between Water Quality and Fish Diversity

Water-quality variable	Species richness	Shannon H′	Simpson D	Pielou J′
Temperature	−0.368*	−0.354*	0.381*	−0.305 ns
pH	−0.200 ns	−0.133 ns	0.119 ns	−0.050 ns
DO	0.487**	0.479**	−0.490**	0.428**
BOD	−0.916***	−0.917***	0.919***	−0.861***
COD	−0.918***	−0.914***	0.909***	−0.854***
TDS	−0.292 ns	−0.193 ns	0.196 ns	−0.050 ns

Note: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; ns = not significant

Pearson correlation showed BOD and COD were the strongest factors negatively associated with fish diversity. BOD was strongly negatively correlated with species richness ($r = -0.916$), Shannon diversity ($r = -0.917$) and Pielou evenness ($r = -0.861$), while showing a strong positive correlation with Simpson dominance ($r = 0.919$; $p < 0.001$). Similar relationships were recorded for COD, including species richness ($r = -0.918$), Shannon diversity ($r = -0.914$) and Simpson dominance ($r = 0.909$; $p < 0.001$).

DO showed significant positive correlations with species richness ($r = 0.487$), Shannon diversity ($r = 0.479$) and evenness ($r = 0.428$), but a negative correlation with Simpson dominance ($r = -0.490$; $p < 0.01$). Temperature had weak-to-moderate negative correlations with richness ($r = -0.368$) and Shannon diversity ($r = -0.354$; $p < 0.05$). In contrast, pH and TDS showed no significant correlations with the diversity indices. Overall, higher DO supported fish diversity, whereas increasing BOD and COD indicated ecological stress and reduced diversity.

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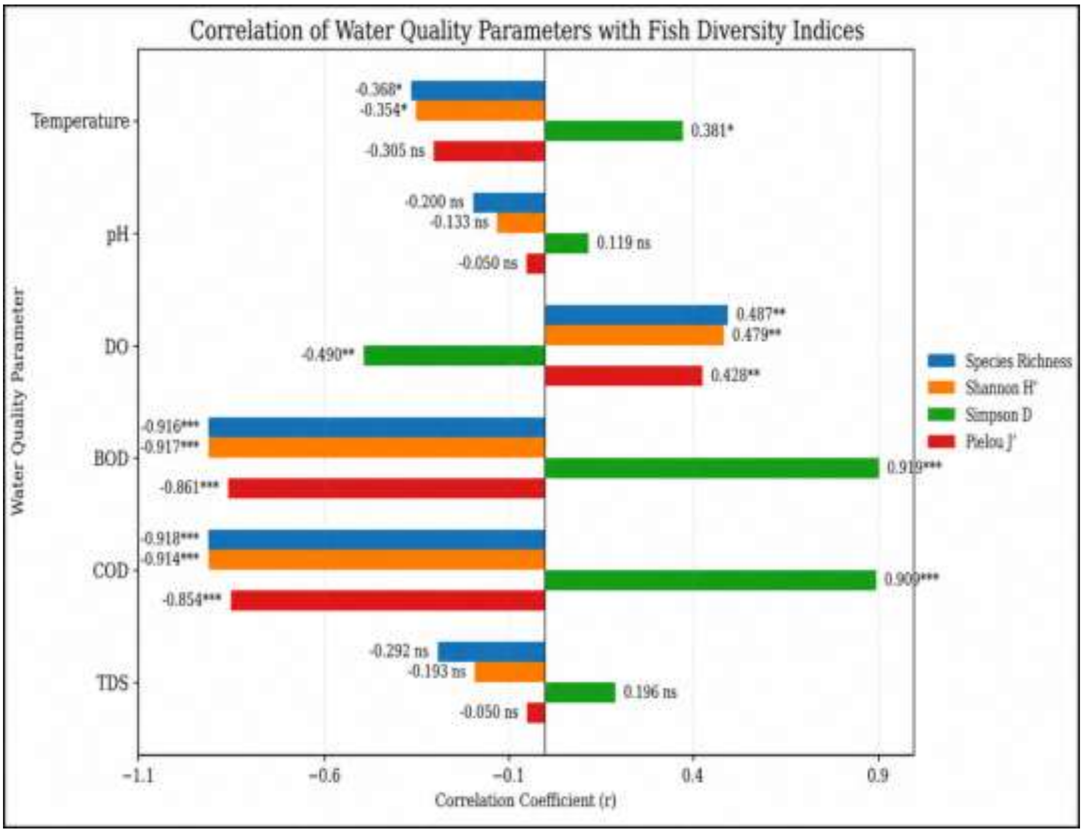

Figure 7. Pearson Correlation between water-quality variables and fish-diversity indices

Integrated Ecological Interpretation

The combined results from ANOVA, Tukey HSD, heat-map visualization, and correlation analysis consistently showed that higher dissolved oxygen was positively associated with fish diversity, whereas elevated BOD and COD were strongly associated with reduced diversity and increased species dominance. Based on the overall biological and physicochemical condition, the ecological status of the rivers followed the order:

Hasdeo > Ahiran > Tan > Chornai

The Hasdeo River represented the healthiest ecological condition, while Chornai showed the greatest organic pollution stress and the poorest fish-community structure.

DISCUSSION

Influence of Water Quality on Ichthyofaunal Diversity

Ichthyofaunal diversity in the Hasdeo River system was closely linked to physicochemical water quality. Rivers with higher dissolved oxygen and lower BOD and COD supported richer and more evenly distributed fish communities, whereas poorer water quality was associated with reduced diversity and greater dominance. The contrasting ecological conditions of the Hasdeo and Chornai Rivers therefore suggest that differences in habitat quality and organic pollution were major drivers of fish-community structure. This interpretation was consistently supported by the ANOVA, Tukey HSD, correlation, and heat-map results.

Spatial Variation among Rivers

The significant river-wise differences observed in the present study indicate that the four rivers differed markedly in their ecological condition and habitat quality. The Hasdeo River consistently maintained a healthier aquatic environment that supported a more diverse and evenly distributed fish community, whereas

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the Chornai River reflected comparatively greater ecological stress, characterized by reduced diversity and increased dominance of pollution-tolerant species. This pattern suggests that differences in water quality and habitat condition play a key role in shaping fish-community structure across the basin.

The Ahiran River represented an intermediate ecological condition with relatively stable fish assemblages, while the Tan River exhibited moderate diversity despite elevated dissolved solids. These observations indicate that individual rivers were influenced by different environmental pressures. The observed BOD and COD patterns suggest greater organic pollution stress in the Chornai River, whereas elevated TDS was more characteristic of the Tan River. Overall, the spatial variation observed across the four rivers highlights the combined influence of local habitat conditions and physicochemical water quality on the distribution and composition of ichthyofaunal communities.

Seasonal Influence on Water Quality and Fish Diversity

Seasonal variation played an important role in shaping both water quality and fish-community structure across the Hasdeo River system. Fish diversity generally improved from the pre-monsoon to the post-monsoon season, reflecting more favourable ecological conditions associated with increased river discharge, pollutant dilution, improved habitat connectivity, and higher dissolved oxygen. The non-significant River × Season interactions for the diversity indices indicate that, despite differences in overall ecological condition among rivers, their seasonal response patterns remained broadly similar, highlighting the dominant influence of monsoonal hydrology on fish-community dynamics.

Season also significantly influenced major physicochemical variables, particularly temperature and dissolved oxygen. Significant River × Season interactions for temperature, pH, DO, and TDS suggest that seasonal changes in these parameters varied among rivers, probably because of differences in local hydrology, riparian conditions, and anthropogenic disturbances. In contrast, the absence of significant interactions for BOD and COD indicates a relatively consistent seasonal pattern of organic pollution across the basin. The heat-map analysis further supported these findings by highlighting strong river and seasonal effects on both biological and physicochemical variables.

Role of Dissolved Oxygen

Dissolved oxygen emerged as the principal positive water-quality variable associated with fish diversity. It was positively correlated with species richness, Shannon diversity, and Pielou evenness, and negatively correlated with Simpson dominance. The positive correlations indicate that well-oxygenated conditions support a greater number of species and a more even distribution of individuals, as adequate oxygen availability is essential for fish metabolism, growth, survival, and reproduction (Wetzel, 2001; Boyd, 2020).

The negative relationship between dissolved oxygen and Simpson dominance suggests that low-oxygen conditions favour the dominance of fewer tolerant species. In contrast, higher oxygen levels allow both sensitive and tolerant species to coexist, thereby improving overall diversity and evenness (Wetzel, 2001; Boyd, 2020). The Hasdeo River, which had the highest mean dissolved oxygen, also had the greatest fish diversity, while Chornai, with lower dissolved oxygen, had lower diversity and greater dominance. This consistency between river-wise means and correlation results strengthens the ecological interpretation.

Influence of BOD and COD

BOD and COD were the strongest negative predictors of fish diversity in the present dataset. Both variables showed very strong negative correlations with species richness, Shannon diversity, and evenness, together with strong positive correlations with Simpson dominance. These relationships indicate that increasing organic and chemical oxygen demand was associated with a decline in fish-community complexity.

Elevated BOD reflects increased microbial consumption of dissolved oxygen during the decomposition of organic matter, whereas high COD indicates a greater concentration of chemically oxidizable substances in

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water. Both conditions can reduce oxygen availability and create unfavourable environments for pollution-sensitive fish species (APHA, 2023; Boyd, 2020). The elevated BOD and COD values recorded in the Chornai and Tan Rivers were therefore consistent with their lower fish diversity relative to the Hasdeo River. Tukey HSD results further confirmed significant river-wise differences in BOD, while COD showed a similar ecological pattern, with Tan and Chornai exhibiting comparatively higher values.

These findings indicate that BOD and COD are not merely general indicators of pollution but are closely associated with the biological condition of fish communities. Their strong relationships with reduced richness, diversity, and evenness support their use as reliable indicators of organic pollution and ecological stress in the Hasdeo River basin (APHA, 2023; Boyd, 2020).

Influence of Secondary Physicochemical Variables

Temperature, pH, and TDS showed comparatively weaker relationships with ichthyofaunal diversity than dissolved oxygen, BOD, and COD. Temperature exhibited a moderate negative association with species richness and Shannon diversity, suggesting that higher temperatures may reduce habitat suitability by increasing metabolic demand and decreasing oxygen solubility (Wetzel, 2001; Boyd, 2020). Although one-way ANOVA did not detect significant river-wise differences, two-way ANOVA revealed significant effects of river, season, and their interaction, indicating that temperature variation was primarily driven by seasonal processes rather than consistent spatial differences.

In contrast, pH and TDS varied significantly among rivers but were not significantly correlated with the fish-diversity indices. This suggests that, within the observed range, these variables did not independently regulate fish-community structure. Their ecological influence is likely indirect and mediated through interactions with other environmental factors, particularly dissolved oxygen and organic pollution (Chapman, 1996; Wetzel, 2001). Therefore, while temperature, pH, and TDS contributed to overall environmental variability, their influence on ichthyofaunal diversity was less pronounced than that of DO, BOD, and COD.

Interpretation of Tukey HSD Comparisons

Tukey HSD analysis showed that fish diversity and water-quality characteristics differed significantly among rivers, confirming distinct ecological conditions across the basin. The Hasdeo River consistently represented the healthiest aquatic environment, whereas the Chornai River reflected comparatively greater ecological stress. The intermediate condition of the Ahiran and Tan Rivers suggests that each river experienced different environmental pressures, resulting in distinct patterns of fish-community structure and water quality.

Anthropogenic Implications

The comparatively poorer ecological condition of the Tan and Chornai Rivers may be associated with pressures from mining, thermal power activities, agricultural runoff, urban settlements, and domestic discharge. These activities can increase organic load and dissolved solids, thereby affecting water quality and fish-community structure (CPCB, 2023; UNEP, 2023). However, the observed relationships indicate association rather than direct causation; source-specific chemical analyses are required to distinguish the relative contributions of industrial, agricultural, mining, and domestic pollution.

International Comparison

The present findings are consistent with international studies showing that dissolved oxygen and habitat quality are major determinants of freshwater fish diversity. In the Yangtze River Basin, higher oxygen availability and better environmental conditions supported greater species richness, whereas anthropogenic disturbance reduced fish diversity (Fu *et al.,* 2003). Similarly, studies from Neotropical rivers reported that habitat degradation and altered water quality promoted the dominance of a few tolerant species (Agostinho *et al*., 2008). This pattern closely matches the present results, where the Hasdeo River showed higher dissolved

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oxygen, richness, Shannon diversity, and evenness, while the Chornai River exhibited higher BOD, COD, and Simpson dominance.

At the global level, freshwater biodiversity decline has been strongly linked with pollution, habitat modification, hydrological alteration, and increasing human pressure (Dudgeon *et al*., 2006; Reid *et al*., 2019). Tickner *et al*. (2020) further emphasized that improving water quality and ecological connectivity is essential for reversing freshwater biodiversity loss. Therefore, the strong positive association of dissolved oxygen and the marked negative effects of BOD and COD observed in the Hasdeo basin are consistent with wider international ecological trends, confirming these variables as reliable indicators of river health across different geographical regions.

Overall Ecological Interpretation

The integrated findings indicate a clear ecological gradient among the four rivers, with the overall condition ranked as Hasdeo > Ahiran > Tan > Chornai. The Hasdeo River maintained the most favourable ecological condition, characterized by higher fish diversity, better oxygen availability, and lower organic pollution. Ahiran showed a comparatively stable intermediate condition, whereas Tan was affected mainly by elevated dissolved solids and organic load. Chornai exhibited the greatest ecological stress, reflected in lower diversity and evenness together with greater species dominance.

Both spatial and seasonal processes influenced ichthyofaunal diversity across the basin. River-wise differences were more pronounced than River × Season interactions, indicating that each river retained a distinct ecological condition despite showing broadly similar seasonal trends. Fish diversity generally improved from pre-monsoon to post-monsoon as dissolved oxygen increased and BOD and COD declined, highlighting the role of monsoonal hydrology in improving habitat quality (Tickner et al., 2020).

Overall, the results identify dissolved oxygen, BOD, COD, and fish-diversity indices as useful indicators of river health in the Hasdeo basin. Regular seasonal monitoring and targeted control of organic pollution are particularly important for improving ecological conditions in the Tan and Chornai Rivers, thereby supporting freshwater biodiversity conservation and sustainable river management (Reid et al., 2019; Tickner et al., 2020).

Study Limitations and Future Research

The present study examined the relationship between ichthyofaunal diversity and selected water-quality parameters, including water temperature, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total dissolved solids (TDS). These parameters provided useful insights into the ecological conditions of the Hasdeo River and its tributaries. However, the basin is also affected by mining, thermal power plants, urban development, agriculture, and other human activities that may introduce additional pollutants into the aquatic environment. Parameters such as heavy metals, suspended solids, sediment-associated pollutants, and specific industrial contaminants were beyond the scope of the present study. Therefore, the findings mainly reflect the relationships between fish diversity and the physicochemical variables examined here. Future studies covering a wider range of pollutants, along with sediment quality and biological indicators, would help provide a more complete understanding of ecological conditions and human-induced pressures in the Hasdeo River system.

CONCLUSION

The present study demonstrates that physicochemical water quality is a major determinant of ichthyofaunal diversity in the Hasdeo River system. Among the evaluated variables, dissolved oxygen emerged as the principal factor positively associated with species richness, diversity, and evenness, whereas elevated BOD and COD were the strongest indicators of organic pollution and ecological degradation. Spatial differences among rivers exerted a greater influence on fish-community structure than seasonal interactions, although

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seasonal improvements in water quality, particularly during the post-monsoon period, enhanced overall fish diversity.

Based on the integrated assessment of biological and physicochemical parameters, the ecological condition of the rivers followed the order Hasdeo > Ahiran > Tan > Chornai. The Hasdeo River maintained comparatively healthy ecological conditions, while the Tan and Chornai Rivers exhibited greater environmental stress associated with elevated organic pollution and deteriorated habitat quality. The combined application of diversity indices, ANOVA, Tukey HSD, Pearson correlation, and heat-map analysis provided a comprehensive evaluation of the ecological status of the river system.

Overall, the findings confirm that dissolved oxygen, BOD, COD, and fish-diversity indices are reliable indicators for assessing river health and freshwater ecosystem quality. The study provides baseline scientific information for long-term ecological monitoring, freshwater biodiversity conservation, pollution assessment, and sustainable management of the Hasdeo River basin under increasing anthropogenic pressure. Future studies including heavy metals, suspended solids, and sediment quality could provide a clearer understanding of human impacts on the ecological health of the Hasdeo River system.

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