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Spatial Distribution and Diversity of Ichthyofauna in the Intertidal Zone of the River Ganga.

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ABSTRACT

The intertidal zone of the River Ganga estuary is a dynamic and productive ecosystem influenced by tidal fluctuations, salinity gradients, and anthropogenic activities. This study investigated the spatial distribution of ichthyofaunal diversity along a 72 km stretch of the Ganga River estuary from Bally to Gadiara, West Bengal, India. The area was divided into six sampling zones representing urban-to-rural gradients, and seasonal sampling was conducted during pre-monsoon, monsoon, and post-monsoon periods using multiple fishing gears. Out of 84 fish species, 30 species representing freshwater, estuarine, and marine groups were analyzed using Canonical Correspondence Analysis (CCA) to determine relationships with environmental variables. Salinity, total dissolved solids (TDS), hardness, pH, and sediment composition were identified as major drivers of spatial variation. Axis 1 explained 65.99% of the variance and reflected salinity gradients, while Axis 2 (14.64%) represented sediment and water quality influences. Upstream zones were dominated by freshwater species, whereas downstream areas supported estuarine and marine fishes. Mid-estuarine zones showed highest diversity due to habitat heterogeneity. The findings highlight the importance of salinity and sediment characteristics in shaping fish distribution and emphasize the need for sustainable conservation and management of the Ganga estuary ecosystem.

Keywords: Estuarine ecology, Ganga estuary, Ichthyofaunal diversity, Spatial distribution.

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INTRODUCTION

The intertidal zone of a river is the stretch between the highest and lowest tidal limits, where tidal action is clearly observed. This zone experiences regular cycles of seawater intrusion during high tide and freshwater outflow during low tide, resulting in alternating saline and freshwater dominance. Such fluctuations create a dynamic brackish-water environment shaped by the interaction between marine and inland waters [1]. The intertidal zone of the Ganga River constitutes the largest estuarine ecosystem in India and is known for its high ecological and biological productivity. It extends approximately 295 km from the sea face to Nabadwip [2]. The Ganga River estuary is one of the major estuarine systems along the eastern coast of India, supporting rich biodiversity and extensive fisheries. The brackish environment develops through the mixing of upstream freshwater discharge during low tide and saline water intrusion during high tide [3]. The estuary is highly dynamic due to strong tidal forces, seasonal freshwater discharge, and monsoonal climatic influences. Semi-diurnal tides with considerable amplitude regularly expose and submerge intertidal habitats, leading to rapid fluctuations in temperature, turbidity, salinity, and dissolved oxygen. These variable conditions create environmental stress, favoring fish species with high physiological tolerance and behavioral adaptability [4].

Sediment characteristics also play a significant role in structuring intertidal fish assemblages. The intertidal flats are mainly composed of fine silts, clay, and sand derived from upstream erosion and deposited in the deltaic region. These soft-bottom habitats support abundant benthic invertebrates, which serve as major food sources for demersal and benthivorous fishes [5,6]. Intertidal estuarine areas are ecologically important as nursery grounds, feeding habitats, refuges from predators, and migratory corridors for freshwater, estuarine-resident, and marine fishes. Habitat heterogeneity such as mudflats, tidal creeks, and shallow channels creates multiple ecological niches that promote species coexistence [2]. Topographically, the estuary reflects the lower Gangetic alluvial plain shaped primarily by fluvial processes [7]. It forms a transition from an urban-industrial river corridor to peri-urban and rural estuarine landscapes. The region has extremely low relief, with elevations ranging from about 3 to 15 meters above mean sea level and a gentle southward slope toward the Bay of Bengal. The Bally to Gadiara stretch represents the middle to lower segment of the estuary and is influenced by fluvial, tidal, and anthropogenic processes [8]. Freshwater discharge regulated by the Farakka Barrage significantly affects flow and salinity patterns. Anthropogenic stressors including urbanization, industrial effluents, habitat alteration, and intensive fishing further modify the estuarine environment. Together, these factors create diverse ecological niches supporting freshwater, estuarine, and marine migratory fishes, resulting in complex spatial patterns of community organization [9].

Fish distribution within this dynamic system varies in response to environmental gradients [10]. Since fish diversity is closely linked to both abiotic and biotic factors, spatial variation in these parameters produces distinct assemblage patterns [11]. Because fish communities respond sensitively to changes in salinity, temperature, dissolved oxygen, turbidity, and nutrient levels, ichthyofaunal diversity is widely regarded as an indicator of estuarine health and habitat heterogeneity [2].

More than 100 fish species have been recorded from different stretches of the Ganga River estuary so far [12]. Although several studies have documented fish diversity in various segments of the estuary, detailed assessments focusing on spatial distribution patterns along the Bally to Gadiara stretch remain limited. Understanding spatial variability in fish community structure is essential for identifying critical habitats, assessing ecological responses to environmental gradients, and supporting conservation and sustainable fisheries management. The present study therefore aims to analyze the spatial distribution of ichthyofaunal diversity in the Ganga River estuary from Bally to Gadiara by examining species composition, abundance, across estuarine zones. The findings are expected to provide baseline ecological information for long-term monitoring and sustainable management of fish resources in the Ganga River estuary.

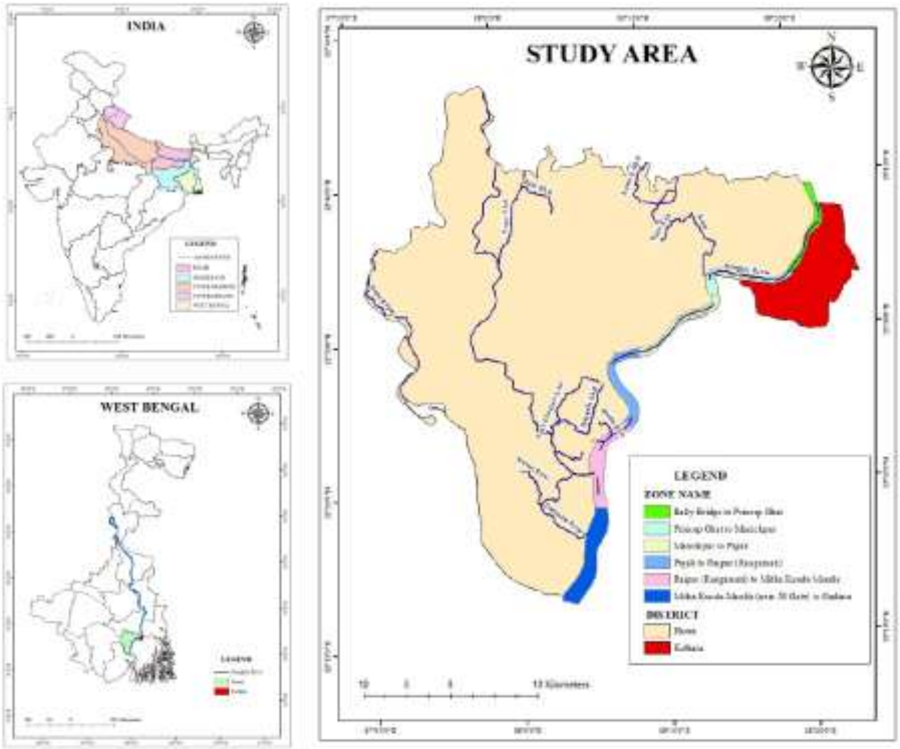
MATERIALS AND METHODS

Study area

The Ganga River estuary, forming the lower stretch of the river in India, lies between 21°31′N – 23°30′N latitude and 87°45′E – 88°45′E longitude. The present study covers an approximately 72 km segment of the estuary along the Ganga River, extending from Bally Bridge in the upstream region to Gadiara downstream (Fig.1). The area experiences a tropical monsoonal climate with marked seasonality.

Temperatures range from 8°C to 44°C, and annual rainfall varies between 125 and 170 cm, accompanied by high humidity.

Figure 1: Study Area of the Ganga River, extending from Bally Bridge (22^{0} 39′ 09″ N, 88^{0} 21′ 06″ E) in the upstream region to Gadiara (22^{0} 12′ 41″ N, 88^{0} 03′ 32″ E) downstream.



This stretch displays diverse geomorphological, ecological, and anthropogenic characteristics that significantly influence the estuarine gradient, making it suitable for studying ichthyofaunal diversity. To assess spatial variation in fish communities, the area was divided into six sampling zones at roughly 12 km intervals from upstream Bally to downstream Gadiara (Table 1). Each zone includes both eastern and western banks, which differ in land use and environmental pressure.

Table 1: Different stretches in the study area with their GPS coordinates.

zone	Name of the stretch	GPS coordinates of stretches
1	Bally bridge to Princep ghat	(22^{0} 39′ 09″ N, 88^{0} 21′ 06″ E) to (22^{0} 33′ 22″ N, 88^{0} 19′ 35″ E)
2	Princep ghat to Manickpur	(22^{0} 33′ 22″ N, 88^{0} 19′ 35″ E) to (22^{0} 32′ 11″ N, 88^{0} 14′ 26″ E)
3	Manickpur to Pujali	(22^{0} 32′11″ N, 88^{0}14′ 26″ E) to (22^{0} 28′ 46″ N, 88^{0} 09′ 06″ E)
4	Pujali to Raipur (Rangamati)	(22^{0} 28′ 46″ N, 88^{0} 09′ 06″ E) to (22^{0} 24′ 10″ N, 88^{0} 08′ 01″ E)
5	Raipur (Rangamati) to Mitha Kundu Mandir (near 58 gate)	(22^{0} 24′10″ N, 88^{0} 08′ 01″ E) to (22^{0} 18′ 45″ N, 88^{0} 05′ 46″E)
6	Mitha Kundu mandir (near 58 gate) to Gadiara	(22^{0} 18′ 45″ N, 88^{0} 05′46″E) to (22^{0} 12′ 41″ N, 88^{0} 03′ 32″ E)

A gradual transition from dense urban to rural settings is evident along the Ganga River estuary from Zone 1 to zone 6 (Table 1). Zone 1 is highly urbanized and industrialized, including Bally, Belur, Liluah, Salkia, Shibpur, Howrah, and Kolkata city. This zone contains mills, workshops, markets, ferry terminals, and dense residential areas, receiving large amounts of industrial discharge, sewage, and other pollutants that degrade water quality [13,14]. Zone 2 represents an urban–peri-urban transition, characterized by Kolkata Port Trust activities, dockyards, transport infrastructure, expanding settlements, and pollution inputs through canals such as Hanskhali canal. Zones 3 and 4 are mainly semi-rural and wetlanddominated, where agriculture, aquaculture, and capture fisheries predominate. Limited industrial activity and the influence of embankments and tidal regimes support comparatively better ecological conditions. Zones 5 and 6 form the outer estuarine transition near the Rupnarayan confluence, characterized by tidal creeks, aquaculture ponds, floodplains, and agriculture shaped by estuarine dynamics. More than forty brick kilns along the estuary extract silt-rich sediments, altering local sediment dynamics [15]. Consequently, upstream zones exhibit higher pollution, whereas downstream zones show improved water quality and ecological conditions.

METHODS

A reconnaissance survey was conducted along the six-sampling zone (12 km each) covering a distance of 72 km stretch of the River Ganga, extending from Bally Bridge to Gadiara, to investigate spatial variation in ichthyofaunal diversity and its relationship with environmental factors. This zonal classification enabled assessment of changes in fish diversity and environmental conditions across varying ecological settings.

Seasonal random sampling was carried out during the pre-monsoon, monsoon, and post-monsoon periods to capture temporal variation in fish assemblages. Fish sampling was conducted in collaboration with local professional fishermen using traditional fishing boats while maintaining ethical and sustainable sampling procedures. Two netting operations were conducted daily at each site across a 2 km river stretch. Sampling points were selected randomly within each zone to include different habitat types such as mid-channel sections, peripheral areas, and various locations distributed throughout the 12 km sampling range. To ensure representative coverage and minimize sampling bias, a total of five ichthyofaunal sampling events were conducted per site during each season. Sampling schedules were designed to include both high and low tidal conditions, and a high sampling effort was maintained to reduce errors and improve data reliability. Multiple traditional fishing gears commonly employed in the Ganga estuarine region were used to capture a broad spectrum of fish species. Gill nets with mesh sizes of (2.5 × 2.5) cm^2, (3 × 3) cm^2, and (7 × 7) cm^2, with dimensions ranging from (75 × 1.5) m^2 to (50 × 5) m^2, were used for capturing medium- and large-sized fishes. Cast nets with mesh sizes of approximately (0.6 × 0.6) cm^2 were employed in shallow and near-bank habitats to capture smaller and agile species. Drag (seine) nets measuring approximately (80 × 2.5) m^2 with mesh size of (0.7 × 0.7) mm^2 were used to sample small-bodied fishes and benthic organisms from shallow margins and sand-mud flats. Small trawl nets were also employed where feasible to collect demersal and benthic species. The use of multiple gears and mesh sizes facilitated sampling across diverse ecological guilds, including pelagic, benthic, demersal, and estuarine-dependent fishes. Each gear type was operated multiple times at every site to minimize gear selectivity bias and ensure adequate sampling effort. Following capture, specimens were carefully removed from nets to avoid physical damage. Fish individuals were counted and morphometric measurements were recorded in the field, while body weight was measured using a portable digital balance whenever possible. Fish catches brought by local fishermen to nearby markets were also documented and weighed to supplement field data. In addition, secondary information obtained through interactions with fishermen was considered. Integration of both primary and secondary data facilitated comprehensive assessment of species composition and abundance across the study stretch.

Preliminary species identification was conducted onsite using standard taxonomic keys and published literature [16,17]. Specimens that could not be reliably identified in the field were preserved in 10% formalin and transported to the laboratory for detailed taxonomic verification.

Environmental variables of the Ganga estuary were analyzed using standard methods. Dissolved oxygen was determined using Winkler's method, alkalinity through titration, and hardness by EDTA method. Parameters including pH, salinity, and total dissolved solids (TDS) were measured using portable pH, Salinity and TDS meters (model no. EZ-9909SP), while sediment texture (sand, clay, and silt percentages) was determined by the pipette method. Water temperature at each site was recorded using a calibrated thermometer. Canonical Correspondence Analysis (CCA), performed using PAST 4.03 statistical software, to examine relationships between six sampling stations (Bally, Princepghat, Pujali, Rangamati, 58 gate & Gadiara), abiotic variables such as season, Ph, Salinity, D.O., TDS, Alkalinity, Hardness, Temperature, Sand, Clay, Silt and the selected ichthyofauna. This statistical analysis was computed to understand the distribution patterns, ecological niches, and niche overlap of different fish species across the study area.

RESULTS

A total of 84 fish species (Table 2) belonging to 39 families were recorded during the field investigation. Among the recorded families, Cyprinidae was the most dominant. Based on vertical habitat distribution, 21.42%, 26.20%, and 52.38% of species were distributed in the surface, middle, and bottom zones of the river, respectively. This pattern suggests distinct vertical niche segregation among fish species, likely reducing interspecific competition through resource partitioning. In addition to vertical stratification of fish species distribution, pronounced horizontal distribution patterns of the same were also observed along the river continuum. These variations are likely influenced by gradients of abiotic parameters in water and sediment from upstream to downstream regions.

Table 2: Ichthyofaunal diversity with their local name and species code

Sl. No	Scientific Name (Corrected)	Family	Vernacular Name	Species Code
1	*Otolithoides biauritus* (Cantor, 1849)	Sciaenidae	Poya bhola	Sp1
2	*Otolithoides pama* (Hamilton, 1822)	Sciaenidae	Madhu bhola	Sp2
3	*Polynemus paradiseus* (Linnaeus, 1758)	Polynemidae	Topse	Sp3
4	*Tenualosa ilisha* (Hamilton, 1822)	Clupeidae	Ilish	Sp4
5	*Scatophagus argus* (Linnaeus, 1766)	Scatophagidae	Paira chanda	Sp5
6	*Glossogobius giuris* (Hamilton, 1822)	Gobiidae	Chata bele	Sp6
7	*Sillaginopsis Panijus* (Hamilton, 1822)	Sillaginidae	Tool bele	Sp7
8	*Setipinna phasa* (Hamilton, 1822)	Engraulidae	Phasa fish	Sp8
9	*Bagarius bagarius* (Hamilton, 1822)	Sisoridae	Bagar fish	Sp9
10	*Pangasius pangasius* (Hamilton, 1822)	Pangasiidae	Pangus fish	Sp10
11	*Sperata aor* (Hamilton, 1822)	Bagridae	Aarh fish	Sp11
12	*Rita rita* (Hamilton, 1822)	Bagridae	Ritha fish	Sp12
13	*Nandus nandus* (Hamilton, 1822)	Nandidae	Nados fish	Sp13
14	*Liza macrolepis* (Smith, 1846)	Mugilidae	Parse	Sp14
15	*Rhinomugil corsula* (Hamilton, 1822)	Mugilidae	Tarui	Sp15
16	*Liza tade* (Forsskål, 1775)	Mugilidae	Bhangon	Sp16
17	*Eleutheronema tetradactylum* (Shaw, 1804)	Polynemidae	Gurjawali	Sp17
18	*Harpadon nehereus* (Hamilton, 1822)	Synodontidae	Lote fish	Sp18
19	*Coilia dussumieri* (Valenciennes), 1848	Engraulidae	Amadi fish	Sp19
20	*Pampus argenteus* (Euphrasen, 1788)	Stromateidae	Sada pomfret	Sp20
21	*Odontamblyopus rubicundus* (Hamilton, 1822)	Gobiidae	Kalo gule	Sp21
22	*Puntius sophore* (Hamilton, 1822)	Cyprinidae	Sona puti	Sp22
23	*Xenentodon cancila* (Hamilton, 1822)	Belonidae	Gangdhara	Sp23
24	*Gagata gagata* (Hamilton, 1822)	Sisoridae	Chanpkoli	Sp24
25	*Eutropiichthys vacha* (Hamilton, 1822)	Schilbeidae	Bacha	Sp25
26	*Lates calcarifer* (Bloch, 1790)	Latidae	Vetki	Sp26
27	*Pseudapocryptes lanceolatus* (Bloch & Schneider, 1801)	Gobiidae	Sada gule	Sp27
28	*Clupisoma garua* (Hamilton, 1822)	Schilbid	Gorcha	Sp28
29	*Mystus gulio* (Hamilton, 1822)	Bagridae	Nona tangra	Sp29
30	*Gudusia chapra* (Hamilton, 1822)	Clupeidae	Khoira / Chapra	Sp30
31	*Ailia colia* (Hamilton, 1822)	Ailiidae	Kajoli	Sp31
32	*Acanthopagrus latus* (Houttuyn, 1782)	Sparidae	Sea bream	Sp32

33	*Gerres filamentosus* (Cuvier, 1829)	Gerreidae	Moja/ silver bidky	Sp33
34	*Amblypharyngodon mola* (Hamilton & Buchanan 1822)	Cyprinidae	mouralla	Sp34
35	*Liza parsia* (Hamilton, 1822)	Mugilidae	Parse	Sp35
36	*Sicamugil cascasia* (Hamilton, 1822)	Mugilidae	Cascasia magur	Sp36
37	*Eleotris fusca* (Bloch & Schneider, 1801)	Eleotridae	goodgoody	Sp37
38	*Sillaginopsis panijus (*Hamilton*, 1822)*	Sillaginidae	Gangara	Sp38
39	*Anabus testudineus (*Bloch*, 1792)*	Anabantidae	koi	*Sp39*
40	*Colisa fasciatus* (Bloch & Schneider, 1801)	Osphronemidae	kholse	Sp40
41	*Colisa lalius (*Hamilton*, 1822)*	Osphronemidae	Lal kholse	Sp41
42	*Carangoides malabaricus (*Bloch & Schneider, 1801)	Carangidae	Trevali	Sp42
43	*Channa striatus* (Bloch 1793)	Channidae	Shol	Sp43
44	*Mastacembelus pancalus* (Hamilton, 1822)	Mastacembelidae	Pankal	Sp44
45	*Mastacembelus armatus* (Lacepede, 1800)	Mastacembelidae	Bain	Sp45
46	*Channa marulius* (Hamilton, 1822)	Channidae	Sal	Sp46
47	*Cynoglossus arel* (Bloch & Schneider, 1801)	Cynoglossidae	Chapta mach	Sp47
48	*Channa punctatus* (Bloch, 1793)	Channidae	Lata	Sp48
49	*Synaptura albomaculata* (Kaup,1858)	Soleidae	Bengal sole	Sp49
50	*Cynoglossus cynoglossus* (Hamilton, 1822)	Cynoglossidae	Tongue sole/ jiv mach	Sp50
51	*Secutor ruconius* (Hamilton, 1822)	Leiognathidae	Chanda mach	Sp51
52	*Euryglossa orientalis* (Bloch & Schneider, 1801)	Soleidae	Kanthal pata mach	Sp52
53	*Lepidocephalus guntea* (Hamilton, 1822)	Cobitidae	Gunti	Sp53
54	*Cirhinus mrigala* (Hamilton, 1822)	Cyprinidae	Mrigel	Sp54
55	*Labeo bata* (Hamilton, 1822)	Cyprinidae	Bata	Sp55
56	*Puntius conchonius* (Hamilton, 1822)	Cyprinidae	Punti	Sp56
57	*Catla catla* (Hamilton,1822)	Cyprinidae	Catla	Sp57
58	*Labeo kalbasu* (Hamilton, 1822)	Cyprinidae	Kalbose	Sp58
59	*Chirocentrus dorab* (Forskkal, 1775)	Chirocentridae	Chira	Sp59
60	*Labeo rohita* (Hamilton, 1822)	Cyprinidae	Rui mach	Sp60
61	*Sardinella melanura* (Cuvier, 1829)	Clupeidae	Sardine	Sp61
62	*Corica sobarna* (Hamilton, 1822)	Clupeidae	Kachki	Sp62
63	*Raconda russeliana* (Gray, 1831)	Ambassidae	Loitta	Sp63
64	*Clarius batrachus* (Linnaeus, 1758)	Clariidae	Magur	Sp64
65	*Notopterus notopterus* (Pallas, 1769)	Notopteridae	Folui	Sp65
66	*Notopterus chitala* (Hamilton, 1822)	Notopteridae	Chital	Sp66
67	*Pseudambassis ranga* (Hamilton, 1822)	Ambassidae	Ranga Chanda	Sp67
68	*Plotosus canius* (Hamilton, 1822)	Plotosidae	Gang magur	Sp68
69	*Pseudambassis lala* (Hamilton, 1822)	Ambassidae	Lal Chanda	Sp69
70	*Heteropneustes fossilis* (Bloch, 1794)	Heteropneustidae	Singhi	Sp70
71	*Gagata cenia* (Hamilton, 1822)	Sisoridae	Gagra	Sp71
72	*Puntius sarana* (Hamilton,1822)	Cyprinidae	Sarputi	Sp72
73	*Anguilla bengalensis* (Gray, 1831)	Anguillidae	Ban mach	Sp73
74	*Ompok pabo* (Hamilton, 1822)	Siluridae	Pabda	Sp74

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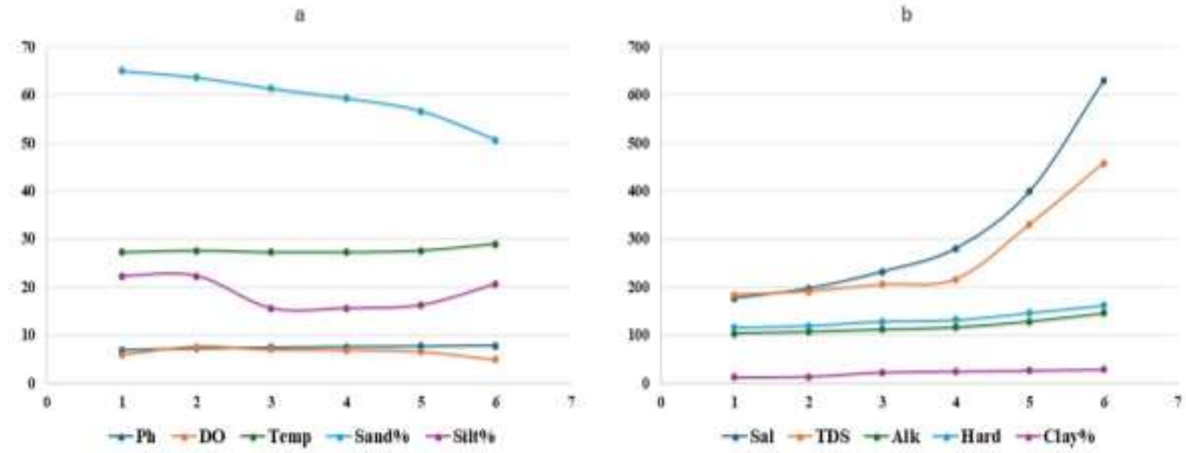
75	*Wallago attu* (Bloch & Schneider, 1801)	Siluridae	Boyal	Sp75
76	*Chela bacaila* (Hamilton,1822)	Cyprinidae	Chela	Sp76
77	*Macrognathus aral* (Bloch & Schneider, 1801)	Mastacembelidae	Tara bain	Sp77
78	*Salmophasia bacaila* (Hamilton,1822)	Cyprinidae	Chela	Sp78
79	*Boleopthalmus dusumieri* (Valenciennes, 1837)	Gobiidae	kaday lafano mach/ Mudskipper	Sp79
80	*Rita gogra* (Sykes, 1839)	Bagridae	Gogra	Sp80
81	*Apocryptes bato* (Hamilton, 1822)	Gobiidae	Mudskipper	Sp81
82	*Arius gagora* (Hamilton, 1822)	Ariidae	Samudrik catfish gogra	Sp82
83	*Gagata sexualis* (Roberts Ferraris, 1998)	Sisoridae	Gagra	Sp83
84	*Johnnius gangeticus* (Lal Mohan, 1976)	Sciaenidae	Gangeo pama	Sp84

After analysis of physicochemical parameters of 6 different studied sites, it was observed that pH, Temp, Silt, Sand, DO showed a gradual decreasing trend from upstream Bally to downstream Gadiara sites. But Salinity, TDS, Alkalinity, Hardness, and Clay content generally increased from upstream to Gadiara (towards sea) direction, indicating increasing estuarine influence (Fig. 2).

Figure 2: Spatial Variation of Physico -Chemical parameters across 6 different Sampling Sites. a: Factors decreasing from upstream to downstream direction; b: Factors increasing from upstream to downstream direction.



To investigate the relationship between spatial distribution of fishes and environmental factors, 30 out 84 species were selected for further statistical analyses involving sampling stations, seasons, and environmental variables. The selection was based on their frequency and availability (both in quantum of fishing and its related information from the fishermen of different studied zone). Some species which were certainly increased or decreased from their habitat in recent dated (*Otolithoides pama, Polynemus paradiseus, Xenentodon cancila etc*) as per the information of the local fishermen were also taken into account. When the mean percentage frequency across six sampling sites (Table 3) of the selected 30 fish species were studied,it was observed that *Otolithoides biauritus, Otolithoides pama, Polynemus paradiseus, Tenualosa Ilisha, Scatophagus argus, Liza macrolepis, Rhinomugil corsula, Liza tade, Eleutheronema tetradactylum, Harpadon nehereus, Coilia dussumieri, Pampus argenteus & Mystus gulio* exhibited greater association with the estuarine lower river zone at 58 Gate & Gadiara, characterized by elevated salinity, TDS & tidal amplitude. In contrast, *Glossogobius giuris, Sillaginopsis Panijus, Setipinna phasa, Bagarius bagarius, Pangasius pangasius, Sperata aor, Rita rita, Nandus nandus, Puntius sophore, Xenentodon cancila, Gagata gagata, Eutropiichthys vacha, Pseudapocryptes lanceolatus, Clupisoma garua & Gudusia chapra* were predominantly associated with freshwater habitats at Bally & Princepghat. *Odontamblyopus rubicundus and Lates calcarifer* showed highest affinity for the transitional mid-river stretch (Table 3).

Table 3: Mean percentage frequency of 30 fish species in 6 sampling sites of the study area.

Species	Bally	Princep ghat	Pujali	Rangamati	58 Gate	Gadiara
Sp1	3.61±0.31	6.02±0.33	11.97±0.84	16.35±1.37	26.89±1.35	35.17±1.54
Sp2	2.22±1.03	3.57±1.05	11.41±2.12	16.50±0.76	28.85±2.12	37.47±2.99
Sp3	7.53±1.65	9.30±1.56	15.70±2.27	15.49±1.91	23.02±0.79	29.06±3.70
Sp4	8.63±0.47	10.60±0.72	12.92±0.69	18.14±1.62	22.28±0.49	27.44±1.53
Sp5	7.60±1.39	10.57±0.66	12.98±0.89	17.21±0.70	21.81±0.90	29.83±1.51
Sp6	31.48±2.58	22.97±1.67	15.76±1.64	13.99±0.51	10.49±0.86	5.31±1.11
Sp7	31.02±3.69	23.61±1.41	17.45±1.84	13.44±0.75	9.59±0.84	4.89±1.38
Sp8	29.60±1.45	21.06±0.27	15.87±0.69	14.49±0.81	11.85±0.21	7.14±0.24
Sp9	25.05±1.67	19.91±0.72	17.07±0.88	16.03±1.42	13.86±0.54	8.08±0.59
Sp10	26.71±1.92	18.82±1.28	18.70±1.46	15.24±1.07	11.39±1.15	9.13±1.80
Sp11	24.66±0.31	20.98±0.57	18.21±0.88	15.77±0.86	11.29±0.93	9.10±1.01
Sp12	26.33±0.96	20.57±1.23	17.19±0.35	14.59±0.88	12.25±0.37	9.06±0.81
Sp13	27.97±0.82	21.56±1.12	16.78±1.95	13.98±0.41	11.46±0.73	8.25±0.21
Sp14	3.19±0.15	7.25±1.19	14.44±1.08	17.78±1.63	26.49±0.86	30.85±1.87
Sp15	10.07±0.89	11.80±0.43	15.41±0.78	18.31±0.30	19.81±0.51	24.59±0.33
Sp16	0.00±0.00	3.63±3.15	8.12±0.40	12.90±1.47	19.97±1.78	55.38±2.78
Sp17	0.00±0.00	0.00±0.00	2.93±2.57	10.34±8.96	31.79±1.52	54.93±10.27
Sp18	0.00±0.00	0.00±0.00	2.44±2.38	5.74±5.05	31.80±8.25	60.02±3.63
Sp19	0.00±0.00	0.00±0.00	0.00±0.00	6.36±5.53	29.62±0.92	64.01±6.43
Sp20	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	18.30±16.44	81.70±16.44
Sp21	3.61±0.19	18.88±0.48	22.48±0.79	25.46±1.03	19.52±1.59	10.06±0.93
Sp22	58.81±7.17	31.16±2.41	10.03±8.71	0.00±0.00	0.00±0.00	0.00±0.00
Sp23	42.82±5.16	23.18±1.62	14.69±2.16	11.66±1.80	5.96±0.95	1.68±1.46
Sp24	37.85±2.14	22.35±1.43	16.69±1.02	17.59±1.48	5.52±1.57	0.00±0.00
Sp25	34.25±3.05	24.65±0.76	21.43±0.40	10.72±0.20	7.27±0.31	1.68±1.50
Sp26	10.88±0.86	14.45±0.79	15.83±0.54	19.61±0.38	21.29±1.53	17.93±0.41
Sp27	18.70±0.92	23.38±1.15	19.04±1.73	16.03±1.55	12.69±0.55	10.16±1.78
Sp28	26.44±1.97	24.04±1.94	18.12±1.52	12.54±0.26	10.86±1.43	7.99±1.49
Sp29	0.00±0.00	7.13±1.29	12.16±2.53	17.54±2.74	26.14±2.56	36.33±2.16
Sp30	25.74±1.42	20.20±1.65	18.43±1.96	15.56±1.53	11.35±0.95	8.72±1.59

To visualize fish community structure and species abundance across sampling stations, a heatmap (Fig. 3) was generated using Origin Pro 2018 software. The heatmap revealed considerable spatial heterogeneity in fish distribution across the Bally to Gadiara stretch. Most species exhibited low to moderate abundance (blue - cyan shades) across stations, whereas a few species displayed high abundance (yellow - red patches) at specific locations, indicating localized dominance (Fig. 3). Species such as *Puntius sophore and Xenentodon cancila* exhibited high abundance at particular sites, reflecting specific habitat preference. Many species remained consistently low in abundance, suggesting rare occurrence or restricted distribution. Site-wise clustering was also evident, as adjacent stations displayed similar abundance patterns, indicating comparable ecological conditions and fish assemblages. Sudden shifts in color patterns suggested changes in habitat characteristics such as salinity, substrate composition, or pollution levels. Moreover, this result demonstrated that fish assemblages along the study stretch were spatially heterogeneous and strongly influenced by habitat variability and environmental gradients.

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Figure 3: Heatmap of Relative Abundance (%) of 30 fish species across sampling stations (72km stretch of river Ganga from Bally to Gadiara).

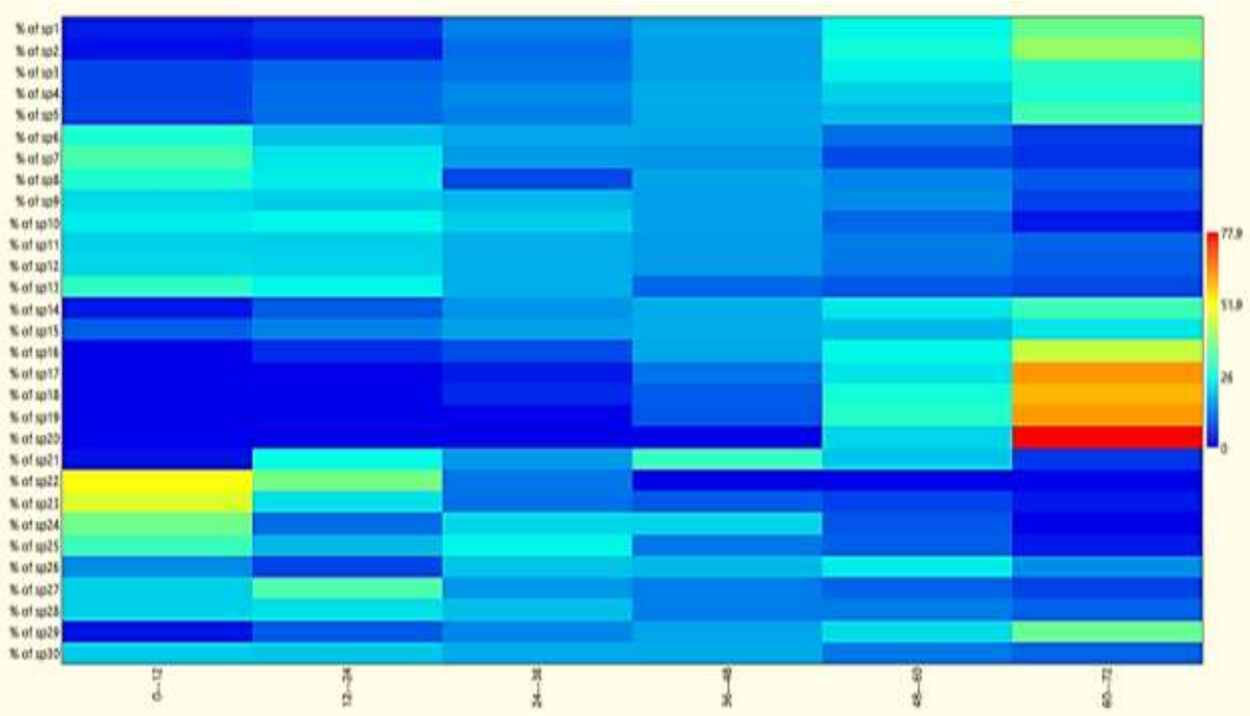
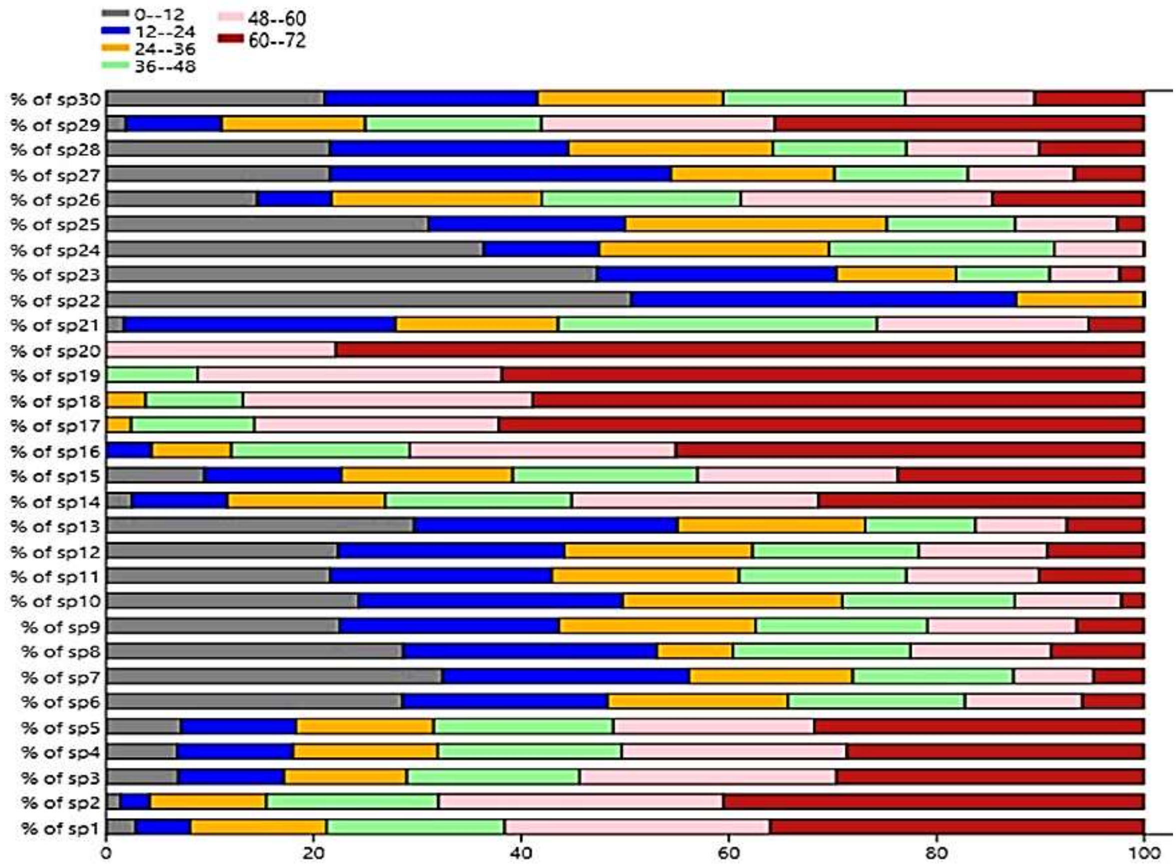


Figure 4: Stacked Bar Diagram showing population distribution (%) of 30 fish species across sampling stations (72 km stretch of river Ganga from Bally to Gadiara).



A considerable spatial variation in species composition and abundance was noted (Fig. 4). It was observed that in the downstream stations (60 -72 km) estuarine and marine-associated species such as *Otolithoides pama*, *Liza tade*, *Eleutheronema tetradactylum*, *Harpadon nehereus*, *Coilia dussumieri*, and *Pampus argenteus*, *Mystus gulio* are predominant as most of their population percentage were found to be restricted in this stretch (an average of 53.57% SD. 14.672 of their total population present in this stretch), this indicates strong estuarine influence in the lower stretches of the study area (Fig.4). The commercially important species *i.e.* *Tenualosa ilisha* and *Polynemus paradiseus* were distributed throughout the river stretch but showed relatively higher abundance in the middle and lower stretches. Freshwater species such as *Puntius sophore*, *Gagata gagata* and *Xenentodon cancila* were more abundant in the upstream sections. An average of 44.33% SD. 7.371 of their total population was found to be restricted in this section which reflecting their preference for freshwater habitats. Species including *Glossogobius giuris*, *Sillaginopsis panijus*, *Bagarius bagarius*, *Pangasius pangasius*, *Sperata aor*, *Rita rita*, *Nandus nandus*, *Eutropiichthys vacha*, *Lates calcarifer*, *Clupisoma garua*, and *Gudusia chapra* exhibited comparatively broader distributions across multiple sampling stations, suggesting greater ecological adaptability (Fig. 4). Overall, the observed distribution pattern demonstrates a clear longitudinal gradient in fish assemblage structure, with freshwater species predominating in the upper reaches and estuarine - marine species becoming increasingly dominant towards the downstream sections near Gadiara, highlighting the influence of salinity intrusion and habitat heterogeneity on fish community composition in the lower Ganga.

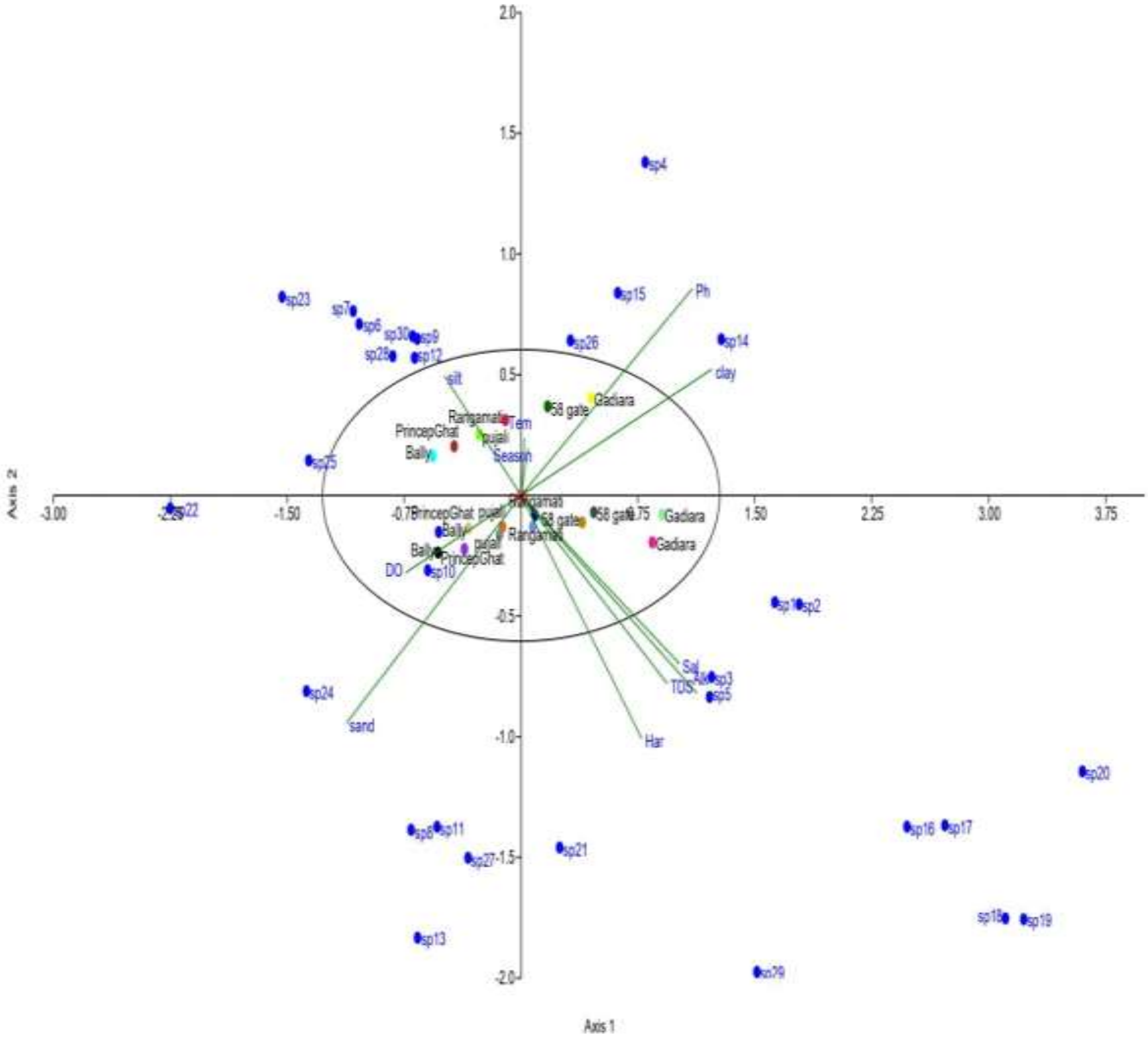
The constrained CCA model (Table 4) yielded a total inertia value of 0.2996, and the permutation test (N=999) indicated a highly significant relationship between fish assemblages and environmental variables (P=0.001). Axis 1 exhibited the highest eigenvalue (0.1977) and explained 65.99% of total variance, whereas Axis 2 contributed an additional 14.64%. Together, the first two axes accounted for 80.63% of the constrained variation. The first six axis along with axis 8,9 and 10 were statistically significant ($P < 0.05$), while subsequent axis contributed comparatively lower variance (Table 4).

Table 4: The eigenvalues and percentage variance explained by each canonical axis:

Axis	Eigenvalue	Explained variance (%)	P value
1	0.1977	65.99	0.001
2	0.0439	14.64	0.001
3	0.0281	9.392	0.001
4	0.0188	6.285	0.001
5	0.0051	1.697	0.001
6	0.0034	1.14	0.001
7	0.0009	0.3267	0.266
8	0.0008	0.2721	0.017
9	0.0005	0.159	0.033
10	0.0003	0.0932	0.02
11	0	0	0.924

The CCA ordination diagram (Fig. 5) illustrated the association among fish species, sampling stations, and environmental variables. Axis 1 represented the major environmental gradient and was strongly associated with salinity, TDS, and hardness. The positive side of Axis 1 represented downstream estuarine conditions characterized by elevated ionic concentration and mineralization, particularly at Gadiara station. Species including *Liza tade*, *Eleutheronema tetradactylum*, *Harpadon nehereus*, *Coilia dussumieri*, *Pampus argenteus*, and *Mystus gulio* showed strong associations with this region, suggesting preference for saline and high TDS habitats. In contrast, the negative side represented sand-dominated and lower-salinity environments associated with upstream stations such as Bally and Princep ghat. Species such as *Sillaginopsis panijus*, *Setipinna phasa*, *Bagarius bagarius*, *Puntius sophore*, *Xenentodon cancila*, *Gagata gagata*, *Clupisoma garua* and *Gudusia chapra* were associated with these habitats, reflecting a longitudinal transition from freshwater sandy zones to mineral rich estuarine environments.

Figure 5: CCA representing different abiotic factors & ichthyofaunal species in different study sites along the Axis 1 & Axis 2.

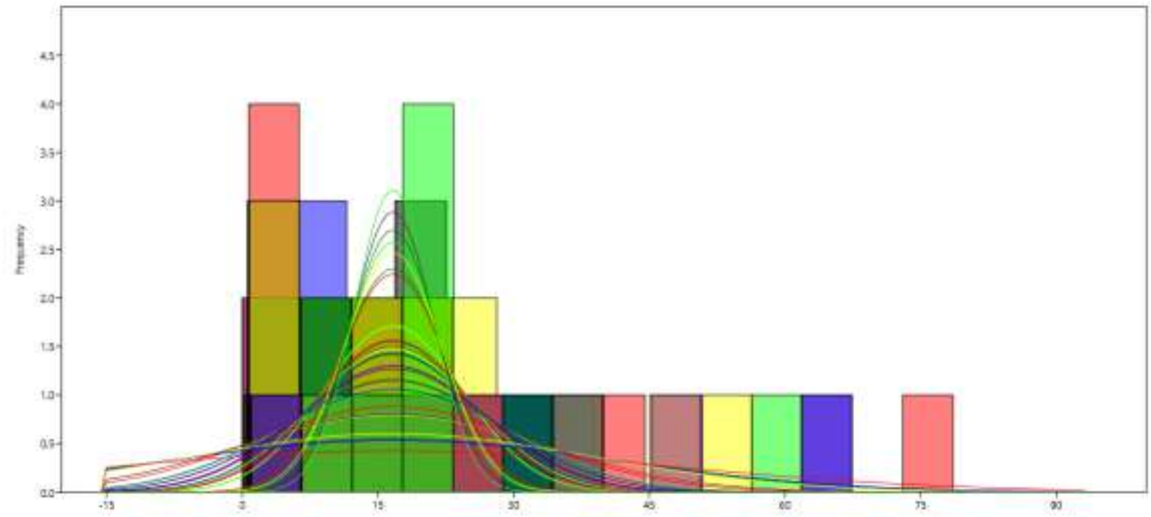


Axis 2 represented secondary environmental gradients related to sediment composition and water quality. The positive side was associated with pH and clay content and included species such as *Tenualosa ilisha, Liza macrolepis, Rhinomugil corsula,* and *Lates calcarifer*, suggesting preference for nutrient rich fine sediment habitats. Conversely, the negative side was associated with salinity, TDS, hardness, content and included species such as *Otolithoides biauritus*, *Polynemus paradiseus*, *Scatophagus argus, Odontamblyopus rubicundus*, and *Otolithoides pama*, *Pseudapocryptes lanceolatus*. Environmental vectors further indicated strong positive relationships among salinity, TDS, and hardness, whereas sand exhibited an inverse relationship with these variables. Dissolved oxygen occupied a central position, indicating a relatively uniform effect across stations.

The histogram with overlaid frequency curves distribution is positively skewed (right - skewed), indicating that most fish species occurred at relatively low to moderate frequencies, while only a few species exhibited high frequencies (Fig. 6). The highest concentration of observations is clustered between approximately 10 and 25 frequency units, with the modal class occurring around 15-20 units, suggesting that the majority of species were moderately abundant within the study area.

The frequency curves show a pronounced peak around the central classes, followed by a gradual decline towards higher frequency values (Fig. 6). This pattern indicates that fish assemblages are dominated by species of intermediate abundance, whereas highly abundant species are comparatively rare. The long right tail extending beyond 40, 50, and up to nearly 75 frequency units reflects the presence of a few dominant species that contributed disproportionately to the overall fish community structure.

Figure 6: Histogram along with frequency curve showing frequency distribution of 30 fish species across a 72 km stretch of river Ganga (Bally to Gadiara).



DISCUSSION

The results indicate a very high taxonomic diversity of ichthyofauna within the 72 km stretch of the River Ganga (from Bally to Gadiara). Apart from their distinct vertical assemblage a clear horizontal zonation with overlapping niches and distinct niche partitioning was detected in the present study. The heatmap highlights pronounced spatial variation in fish assemblages along the Bally - Gadiara stretch, indicating that species distribution is strongly influenced by local environmental conditions. The localized dominance of species such as *Puntius sophore* and *Xenentodon cancila* suggests habitat specialization, whereas the low abundance of many species reflects restricted distribution or niche specific occurrence. Similar abundance patterns among adjacent stations indicate comparable ecological conditions, while abrupt changes between sites likely correspond to variations in salinity, substrate characteristics, and anthropogenic influences. These findings emphasize the importance of environmental heterogeneity in shaping fish community structure within the estuarine ecosystem.

The observed longitudinal distribution pattern reflected in the stack diagram indicated the strong influence of salinity gradients on fish assemblage structure in the lower Ganga estuary. The dominance of estuarine and marine-associated species in downstream stations indicates increasing estuarine influence, while the higher abundance of freshwater species upstream reflects their preference for low-salinity habitats. Species with broader distributions across multiple stations appear to possess greater ecological tolerance and adaptability to varying environmental conditions. Similar type of findings was also noted in CCA analysis. The distribution of fish species along environmental gradients reveals clear niche differentiation within the estuarine ecosystem. Species associated with high-salinity zones are habitat specific and adapted to estuarine conditions, whereas those occurring in low-salinity areas represent freshwater assemblages. Species positioned near the center of the ordination space are likely euryhaline taxa with broader ecological tolerance. This pattern reflects species sorting driven mainly by physiological adaptability, particularly osmoregulatory capacity. Sediment characteristics also influence fish assemblage structure in the intertidal zone. Sandy substrates support species adapted to coarse, well-drained habitats, while clay-rich sediments provide organic-rich environments with higher productivity. Silt-dominated areas are linked to depositional conditions that affect feeding behavior and habitat use [18,19]. The separation of sediment variables in the CCA biplot highlights the role of habitat heterogeneity in maintaining fish diversity. In the ordination plot (Figure 3), species located at the extremes of environmental gradients likely represent the capability to narrow ecological tolerances, whereas centrally positioned species exhibit broader tolerance ranges and greater adaptive plasticity. Generalist species are expected to be more resilient to environmental fluctuations, while specialists may be more vulnerable to disturbances [20,21].

The results indicate that physicochemical factors, particularly salinity, TDS, and hardness, are the primary drivers of fish assemblage structure, while sediment composition exerts a secondary but significant influence. The present findings emphasize the sensitivity of the Ganga estuary to hydrological alterations and anthropogenic pressures, including sewage discharge, industrial effluents, dam construction, and numerous brick kilns along the riverbanks [15,22]. Maintaining natural salinity gradients is therefore crucial for conserving ichthyofaunal diversity and ecological stability in the Ganga River estuary [23].

The positively skewed distribution indicates that most fish species occurred at low to moderate frequencies, while only a few species were highly abundant. The dominance of intermediate-abundance species suggests a relatively balanced community structure, whereas the long right tail reflects the disproportionate contribution of a few dominant taxa. Such patterns are typical of estuarine fish assemblages shaped by environmental heterogeneity.

The absence of a bimodal or multimodal pattern indicates that the fish community does not consist of distinctly separate abundance groups but rather follows a continuous gradient of species occurrence. The concentration of most species within the lower and intermediate frequency classes, coupled with the presence of a few highly abundant taxa, is typical of riverine fish communities where environmental filtering, habitat availability, salinity gradients, food resources, and species-specific ecological adaptations influence population structure.

CONCLUSION

The present study documented a high level of ichthyofaunal diversity within the 72 km Bally–Gadiara stretch of the lower Ganga and demonstrated distinct patterns of vertical and longitudinal niche segregation among fish species. Variations in fish assemblage structure were closely associated with environmental gradients, particularly salinity, total dissolved solids (TDS), hardness, and sediment characteristics. The downstream increase in salinity and changes in substrate composition emerged as the principal factors regulating species distribution, resulting in a clear spatial transition from freshwater-dominated assemblages in upstream regions to estuarine and marine-associated communities downstream.

Multivariate analyses, including Canonical Correspondence Analysis (CCA) and stacked distribution patterns, further confirmed that habitat heterogeneity and physicochemical conditions are the primary drivers of fish community organization along the studied stretch. However, the observed distribution patterns are also likely influenced by biotic components, particularly the spatial variability of phytoplankton and zooplankton communities that constitute major food resources for fishes. Therefore, integrated investigations incorporating both abiotic and biotic factors are necessary to better understand the ecological niches and distributional dynamics of fish species within the lower Ganga estuarine system.
The findings provide valuable baseline information on fish diversity and habitat associations in a region characterized by pronounced environmental gradients. Such information is essential for long-term biodiversity monitoring, conservation planning, and sustainable fisheries management. Identification of habitat-specific and environmentally sensitive species can serve as an effective tool for assessing ecological changes driven by climate variability, salinity intrusion, pollution, and river regulation. Consequently, future conservation and restoration strategies should incorporate the spatial heterogeneity of environmental conditions to maintain ecological integrity, enhance fish population resilience, and ensure the sustainable conservation of ichthyofaunal diversity in the lower Ganga estuary.

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