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Unraveling fish biodiversity: Spatial and temporal dynamics of ichthyofauna in the Godavari River Basin, Andhra Pradesh, India

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Abstract
The ichthyofaunal diversity captured from the selected six sampling sites along the Lower stretch of Godavari River, Andhra Pradesh from February 2022 to August 2023. The present study aimed to assess the spatio-temporal variations in the ichthyofaunal diversity using PRIMER v7 computer package. Throughout the sampling period, a total of 88 species including 10 brackish water and five exotic fish species belonging to 16 orders, 33 families and 62 genera were documented from the Godavari River. The present study revealed that highest spatial species diversity (H‘) value at Rajamahendravaram (5.616) and lowest at Polavaram (5.031) and the diversity fluctuated with the seasons, peak during North-East monsoon (5.630), 2022 and lowest during hot weather period (4.994), 2023. The Margalef species richness (d) was maximum at Rajamahendravaram (8.162) and minimum at Polavaram (3.816) whereas season-wise maximum (9.087) value was recorded during North-East monsoon, 2022 and minimum (4.190) was during hot weather period, 2022. This biodiversity study revealed that the Rajamahendravaram and Dowleswaram stretch of the Godavari River needs special attention for conservation as these places are rich in fish diversity. The study highlights the significant insights into the diversity and conservation status of species, suggesting that the fishery along the Godavari River is currently in a healthy state and provides a baseline information for sustainable management and conservation efforts.

Keywords: Ichthyofauna, Spatio-temporal variation, Godavari River, diversity

Introduction
Freshwater ecosystems are a subset of aquatic ecosystems on Earth. Despite occupying only 0.01% of the Earth’s total surface, they provide important ecological services such as food, water and energy to billions of people. According to Revenga *et al.,* (2005) [37] and Abell *et al*., (2008) [1], these areas possess a significant abundance of species and a wide range of habitats. They support at least 9.5% of all animal species (Balian *et al.,* 2008) [2] and 1/3 of all vertebrate species (Strayer and Dudgeon, 2010) [42]. Rivers, as part of the lotic ecosystem, support a diverse range of fish and other aquatic organisms. However, over the last decade, fisheries have been disrupted or severely stressed by changes in riparian structure and function, chemical and organic pollution, overfishing and destructive fishing practices, changes in hydrological regimes, and global climatic changes. (Bhat, 2019) [5]. The inland water resources harbour the original germplasm of one of the richest and diversified fish fauna of the world, comprising 930 fish species belonging to 326 genera, out of about 27,977 total fish species recorded world-wide (Nelson, 2006) [29]. The immense potential of our country's inland fisheries, particularly the potential of inland capture fisheries, has been severely threatened by pollution, diversion of water from water bodies, and development of water bodies and their catchment areas (Das, 2023) [13]. After the Ganges, the Godavari is India's second-longest river. Other names for it were "Dakshin Ganga" and "Ganga of the South.". The River Godavari runs approximately 1,440 km long from its origin near Trimbakeswar in Deolali Hills near Nashik, Maharashtra to its tidal limits below Rajahmundry, Andhra Pradesh (Jhingran, 1997) [16]. There are a number of rivulets seasonally active streams serving as minor tributaries. The catchment area of the river is 315,980 km^2 (Jhingran, 1997) [16].

The Godavari River is not only significant from a cultural and religious perspective, but also plays a vital role in supporting a diverse and valuable fishery resource. The Godavari River sustains a wide range of fish species, making it an important source of livelihood for many communities that depend on fishing. Rich biodiversity of any ecosystem is absolutely essential in order to maintain its stability and proper function of its food chains (Siddiqui *et al.*, 2014) [39]. The world's rivers are under immense pressure owing to various kinds of anthropogenic activities, among which indiscriminate extraction of sand and gravel is the most disastrous as it adversely affects the river systems (Sreebha and Padmalal, 2011) [41]. Pollution poses another significant challenge to the fishery resources in the Godavari River. The pollution level increases particularly in summer compared to winter and rainy seasons (Sontakke *et al.*, 2006) [40]. Recognizing the importance of the River Godavari's fishery resources, appropriate conservation measures need to be taken to protect the ecosystem. In order to formulate appropriate conservation measures, it is necessary to have a basic knowledge on biodiversity of a particular ecosystem which includes all the life forms that inhabit it Bayley, 1994 [4]. The study of the diversity of fish fauna and their identification is one of the interesting fields of biological research, which gives an idea about the morphological variations and population diversity of fauna in polluted and unpolluted sites of any particular habitat (Napit, 2013) [27]. Therefore, it is a prerequisite to know the fish fauna composition of every aquatic ecosystem before undertaking any conservative initiatives and frequent or repeated estimation of fish diversity of an ecosystem helps to predict the well-being of that ecosystem. In this context, the present research has been undertaken to investigate the current status of fish diversity of the Godavari River of Andhra Pradesh, thereby to update the existing database on this aspect

Materials and methods

Sampling methodology and species identification

Fish samples and fish landing data were gathered fortnightly from specific fish landing centres, namely six sampling stations *viz*, Kunavaram 17.573948 N, 81.251645 E (S1), Rajamahendravaram 16.997316 N, 81.769521 E (S2), Dowleswaram 16.964258 N, 81.783943 E (S3), Kovvur 17.023706 N, 81.730387 E (S4), Tallapudi 17.125425 N, 81.669358 E (S5), and Polavaram 17.249289 N, 81.647236 E (S6). Samples were collected from February 2022 to August 2023, utilizing a diverse array of fishing gears such as cast net, dragnet, Hook & line, gillnet and traps operated across different fishing grounds along the Godavari River (Fig. 1). The samples were then classified down to the species level using conventional taxonomic approaches such descriptive determinations, morphometric features, and meristic traits. Fischer and Bianchi (1984), Day (1986), Talwar and Jhingran (1991), Carpenter (1998), Jayaram (1999, 2010), Munro (2000), and FishBase (Froese and Pauly, 2020) guidelines were used to validate fish species identification.

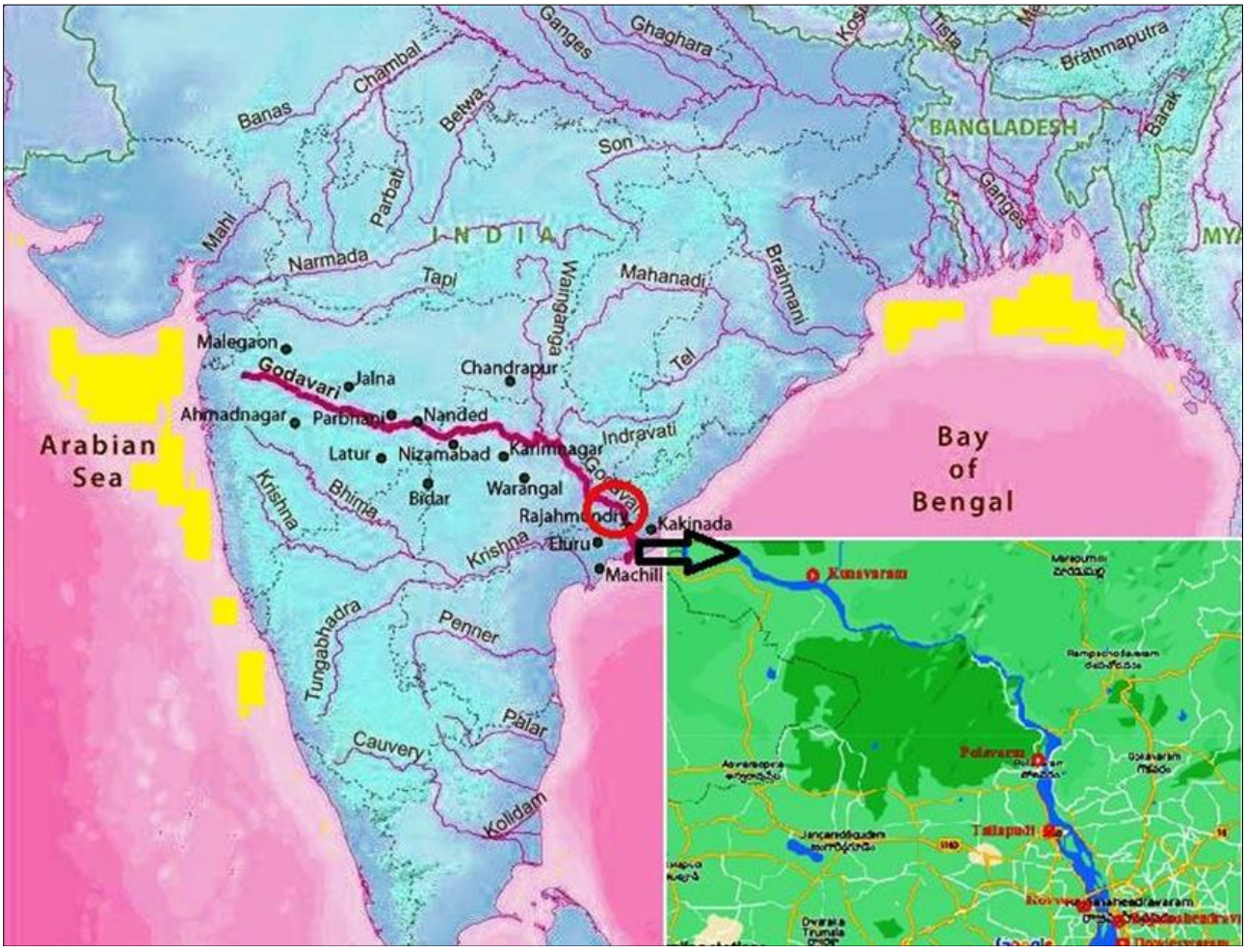

Fig 1. Map showing the Geographical location of the sampling station along the Godavari River, Andhra Pradesh

Biodiversity assessment

The Occurrence and abundance data collected were categorized into four seasons: Sampling was carried out at the six selected stations of Godavari from February, 2022 to August, 2023 at fortnightly intervals and grouped into Four seasons *viz*., Winter period (January to February), Hot weather period (March to May), South-West monsoon (June to September) and North-East monsoon (October to December) based on the local seasonal variations of the study area. Data on catch composition in terms of number of species and number of individuals in each species were collected in that region with the assistance of fishermen and auctioneers. Using the spatial and temporal species abundance and occurrence data, biodiversity indices such as species richness (d), species evenness (J'), Shannon-Wiener species diversity index (H'), Taxonomic diversity (Δ), Taxonomic distinctness index (Δ*), Average taxonomic distinctness index (Δ+), Total taxonomic distinctness (sΔ+), Variation in taxonomic distinctness (⁄ +), Total phylogenetic diversity (sPhi +) were calculated with the PRIMER v7 (Plymouth Routines In Multivariate Ecological Research) software package, developed at the Plymouth Marine Laboratory (Clarke and Warwick, 2001)[11]. The K-dominance curve was used to quantify diversity levels in both spatial and seasonal variations (Bhutekar *et al*., 2019). The K-dominance curve was generated by plotting the cumulative percentage of abundance against the species rank K on a logarithmic scale and the graphical depictions of dominance, similarity, and variances in the diversity of finfishes in the Godavari River have been generated using the same application

Results

Checklist of Ichthyofaunal diversity

By collecting specimens from the six selected landing locations along the Godavari River, 88 fish species—10 of which are brackish water and five of which are exotic-were documented for the present study. After confirming with published literature and online resources like FishBase, (Froese and Pauly, 2020) and Eschmeyer's Catalog of Fishes, a current comprehensive checklist of finfish was created, featuring their common and scientific names as well as brief details about their habitat preference, trophic level, abundance, human utility, and conservation status (Table 1). The order Cypriniformes was found to have contributed the greatest amount to species diversity among the 16 orders (4 families, 19 genera, and 33 species). Siluriformes (7 families, 12 genera, and 19 species); Anabantiformes (3 families, 3 genera, and 6 species); Perciformes (4 families, 5 genera, and 5 species); Gobiiformes (2 families, 4 genera, and 4 species); Cichliformes (1 family, 3 genera, and 3 species); Clupeiformes and Beloniformes each (2 families, 2 genera, and 2 species); Osteoglossiformes and Synbranchiformes each (1 family, 2 genera, and 2 species); Anguilliformes (1 family, 1 genus, and 2 species); Cyprinodontiformes, Elopiformes, Gonorynchiformes, and Mulliformes each (1 family, 1 genus, and 1 species). The percentage composition of Common (42.05%), Rare (25.00%), Moderate (19.31%), and Abundant (13.63%) fish species was determined by classifying the population status. The majority of the species that were documented had an IUCN status of Least Concern (81.81%), with Near Threatened (8.64%), Vulnerable (6.81%), Data Deficient (2.27%), and Not Evaluated (1.13%) following closely behind. Vulnerable and near threatened species made up 15.45% of the total. 53.40% of the 88 species found in the river were found to be food fishes that meet human nutritional needs, followed by ornamental fishes (28.40%), food and ornamental fish (12.5%), and food and game fish (5.68%). 29 species were deemed to be of medium importance in this region, 37 species to be commercial, and 21 species to be very commercial. Furthermore, compared to other seasons, the monsoon season had the largest species diversity. A notable disparity is evident in the observed number of finfish species when compared to earlier records. In a previous study, Praveenkumar (2014) [33] documented a total of 100 species of ichthyofauna in the freshwater zone of River Godavari, Andhra Pradesh. These species were classified into 31 families and 60 genera, encompassing both resident and migratory fish species. KrishnaPrasad *et al.,* (2012) [20] conducted a study of the fish fauna found in the inland water bodies of East Godavari, specifically focusing on lentic systems. Their findings revealed the presence of 9 Orders, 59 Genera, and 146 species within these ecosystems. Khedkar *et al.,* (2014) [19] documented a total of 114 species within the Godavari River basin. In contrast to the present study, the findings of these three authors indicated a greater level of species diversity in the River Godavari systems, encompassing canals, minor reservoirs, and extensive tanks. Moreover, a total of 16 orders were documented in the present study, indicating a greater count compared to the previous research conducted by KrishnaPrasad *et al.,* (2012) [20], where only 9 orders were reported. Chinnababu *et al.,* (2021) [7] documented a comprehensive inventory of fish species in the Godavari River near Rajamahendravaram. Their study revealed the presence of 50 fish species, distributed among 6 orders and 13 families. However, it is important to note that this number is far lower than the total number of fish species currently recorded in the Godavari River. According to the CIFE (2011) [9], a comprehensive assessment identified a total of 64 distinct fish species, which were classified into 15 distinct families and 38 different genera. These findings were obtained from Gangapur dam to Raher of the Godavari River in Maharashtra. The ichthyofaunal diversity of the Krishna River in Sangli District was found to be 73 species according to Vishwakarma *et al.,* (2014) [46], whereas in Mahabubnagar district, it was reported to be 106 species according to Laxmappa *et al.,* (2015) [24]. The present assemblage of species documented in the Godavari River has a level of fish species diversity that is similar to that observed in the Krishna River. Additionally, it was noted that the species richness in the Godavari River was comparatively greater than what was previously reported by Shillewar & Nanware (2008) [38] and Balkhande *et al.,* (2015) [3]. Similar findings were reported by various investigators in Narmada River (Pathak *et al.,* 2014; Vishwakarma *et al.,* 2014; Ravindra Kumar and Rajendra Kumar, 2014; and Siddiqui *et al.,* 2014) [31, 46, 35, 39]. Kumar (2014) [23] reported 56 species belonging to 35 genera, 19 families in the Hirakud dam to Banki stretch of the river Mahanadi in Odisha. Patel *et al.,* (2016) [30] recorded 54 fish species under 36 genera and 21 families from the Mahanadi River. The study was conducted between the years 2017 and 2019, encompassing a total of 11 stations situated along the river ranging from Bhagamandala in Karnataka to Poompuhar in Tamil Nadu. The research findings, as reported by CIFRI in 2019[10], revealed the documentation of 146 distinct fish species belonging to 52 different families.

Table 1: Checklist of ichthyofaunal diversity along the Godavari River, Andhra Pradesh, India

10	Cypriniformes/ Cyprinidae	*Garra gotyla* (Gray, 1830)	Sucker head	FW	2	Ornamental	M	LC
11	Cypriniformes/ Cyprinidae	*Garra annandalei* (Hora, 1921)	Annandale Garra	FW	-	Ornamental	M	LC
12	Cypriniformes/ Cyprinidae	*Gymnostomus ariza* (Hamilton, 1807)	Reba carp	FW	2.7	Food fish	C	LC
13	Cypriniformes/ Cyprinidae	*Labeo bata* (Day, 1878)	Bata	FW	-	Food fish	C	LC
14	Cypriniformes/ Cyprinidae	*Labeo boggut* (Sykes, 1839)	Boggut labeo	FW	-	Food fish	M	LC
15	Cypriniformes/ Cyprinidae	*Labeo calbasu* (Hamilton-Buchanan, 1822)	Black rohu	FW	2	Food fish	C	LC
16	Cypriniformes/ Cyprinidae	*Labeo fimbriatus* (Bloch, 1795)	Fringed- lipped peninsula carp	FW	2	Food fish	C	LC
17	Cypriniformes/ Cyprinidae	*Labeo rohita* (Hamilton, 1822)	Rohu	FW	2.2	Food fish	A	LC
18	Cypriniformes/ Cyprinidae	*Osteobrama cotio (Hamilton, 1822)*	Cotio	FW	2.9	Food fish	A	LC
19	Cypriniformes/ Cyprinidae	*Osteobrama belangeri (Valencienues, 1844)*	Belengee	FW	2.8	Food fish	C	NT
20	Cypriniformes/ Cyprinidae	*Osteobrama vigorsii (Sykes, 1839)*	Godavari osteobrama	FW	2.8	Food fish	C	LC
21	Cypriniformes/ Cyprinidae	*Puntius chola (Hamilton, 1822)*	Swamp barb	FW	2.5	Ornamental	M	LC
22	Cypriniformes/ Cyprinidae	*Puntius ticto (Hamilton, 1822)*	Ticto barb	FW	2.2	Ornamental	M	LC
23	Cypriniformes/ Cyprinidae	*Puntius sophore (Hamilton, 1822)*	Spot-fin swamp barb	FW	2.6	Ornamental	C	LC
24	Cypriniformes/ Cyprinidae	*Puntius terio (Hamilton, 1822)*	One spot barb	FW	2.6	Ornamental	R	LC
25	Cypriniformes/ Cyprinidae	*Systomus sarana (Hamilton, 1822)*	Olive barb	FW	2.9	Food fish / Ornamental	C	LC
26	Cypriniformes/ Cyprinidae	*Rohtee ogilbii (Sykes, 1839)*	Vatani rohitee	FW	2.8	Ornamental	R	LC
27	Cypriniformes/ Danionidae	*Barilius barila (Hamilton, 1822)*	Barred baril	FW	3.2	Ornamental	R	LC
28	Cypriniformes/ Danionidae	*Danio devario (Hamilton, 1822)*	Sind danio,	FW	3	Ornamental	C	LC
29	Cypriniformes/ Danionidae	*Amblypharyngodon microlepis (Bleeker, 1853)*	Indian carplet	FW	3.3	Ornamental	C	LC
30	Cypriniformes/ Danionidae	*Amblypharyngodon mola (Hamilton, 1822)*	Mola carplet	FW	3.3	Ornamental	C	LC
31	Cypriniformes/ Danionidae	*Esomus danrica (Hamilton, 1822)*	Flying barb	FW	2.4	Ornamental	M	LC
32	Cypriniformes/ Danionidae	*Rasbora daniconius (Hamilton, 1822)*	Slender rasbora	FW	3.1	Ornamental	M	LC
33	Cypriniformes/ Danionidae	*Salmostoma bacaila (Hamilton, 1822)*	Large razorbelly minnow	FW	3.2	Ornamental	C	LC
34	Cypriniformes/ Danionidae	*Salmostoma phulo (Hamilton, 1822)*	Finescale razorbelly minnow	FW	3.2	Ornamental	C	LC
35	Cypriniformes/ Nemacheilidae	*Nemacheilus corica (Hamilton, 1822)*	Polka Dotted Loach	FW	2.8	Ornamental	R	LC
36*	Cypriniformes/ Xenocyprididae	*Ctenopharyngodon idella (Valencienues, 1844)*	Grass carp	FW	2	Food fish	M	LC
37*	Cypriniformes/ Xenocyprididae	*Hypophthalmichthys molitrix (Valencienues,1844)*	Silver carp	FW	2	Food fish	M	NT
38	Cyprinodontiforme s/ Aplocheilidae	*Aplocheilus panchax (Hamilton, 1822)*	Blue panchax	FW	3.8	Ornamental	C	LC
39 @	Elopiformes/ Megalopidae	*Megalops cyprinoides (Broussonet, 1782)*	Cundinga	BW	3.5	Food fish	R	DD
40 @	Gonorynchiformes / Chanidae	*Chanos chanos (Forsskal, 1775)*	Milkfish	BW	2.4	Food fish / game fish	C	LC
41	Siluriformes/ Bagridae	*Mystus bleekeri (Day, 1877)*	Day's mystus	FW	3.3	Food fish / Ornamental	A	LC
42	Siluriformes/ Bagridae	*Mystus cavasius (Hamilton, 1822)*	Gangetic mystus	FW	3.4	Food fish / Ornamental	A	LC
43	Siluriformes/ Bagridae	*Mystus tengara*	Tengara mystus	FW	3.2	Food fish /	A	LC

		(Hamilton, 1822)				Ornamental		
44	Siluriformes/ Bagridae	*Mystus vittatus (Bloch, 1794)*	Striped dwarf catfish	FW	3.1	Food fish / Ornamental	A	LC
45	Siluriformes/ Bagridae	*Sperata aor (Hamilton, 1822)*	Long- whiskered catfish	FW	3.6	Food fish / Ornamental	C	LC
46	Siluriformes/ Bagridae	*Sperata seenghala (Sykes, 1839)*	Gaint river catfish	FW	3.8	Food fish / Ornamental	C	LC
47	Siluriformes/ Bagridae	*Rita kuturnee (Sykes, 1839)*	Gokra	FW	3.5	Food fish / Ornamental	A	LC
48	Siluriformes/ Bagridae	*Rita rita (Hamilton, 1822)*	Rita	FW	3.7	Food fish / game fish	R	LC
49	Siluriformes/ Clariidae	*Clarias batrachus (Linnaeus, 1758)*	Air breathing catfishes/ Magur	FW	3.4	Food fish	M	LC
50*	Siluriformes/ Clariidae	*Clarias gariepinus (Burchell, 1822)*	African catfish	FW	3.8	Food fish/Exotic	R	LC
51	Siluriformes/ Heteropneustidae	*Heteropneustes fossilis (Bloch, 1794)*	Stinging catfish	FW	3.6	Food fish	M	LC
52	Siluriformes/ Pangasiidae	*Pangasius pangasius (Hamilton, 1822)*	Pangas catfish	FW	3.4	Food fish	R	LC
53	Siluriformes/ Schilbeidae	*Eutropiichthys vacha (Hamilton, 1822)*	Batchwa vacha	FW	3.9	Food fish	A	LC
54	Siluriformes/ Schilbeidae	*Proeutropiichthys taakree (Sykes, 1839)*	Indian taakree, Halati	FW	3.2	Food fish	C	LC
55	Siluriformes/ Schilbeidae	*Silonia silondia (Hamilton, 1822)*	Silond catfish	FW	3.5	Food fish	R	LC
56	Siluriformes/ Siluridae	*Ompok bimaculatus (Bloch, 1794)*	Butter Catfish	FW	3.9	Food fish	C	NT
57	Siluriformes/ Siluridae	*Ompok pabda (Hamilton, 1822)*	Pabdah catfish	FW	3.8	Food fish	C	NT
58	Siluriformes/ Siluridae	*Wallago attu (Bloch & Schneider, 1801)*	Wallago	FW	3.7	Food fish / game fish	C	VU
59	Siluriformes/ Sisoridae	*Bagarius bagarius (Hamilton, 1822)*	Goonch	FW	3.7	Food fish	R	VU
60	Anguilliformes/ Anguillidae	*Anguilla bengalensis (Gray, 1830)*	Indian Long fin eel	FW	3.8	Food fish / game fish	M	NT
61	Anguilliformes/ Anguillidae	*Anguilla bicolour (McClelland, 1844)*	Indian short fin eel	FW	3.6	Food fish	R	NT
62	Beloniformes/ Belonidae	*Xenentodon cancila (Hamilton, 1822)*	Freshwater garfish	FW	3.9	Ornamental	R	DD
63	Beloniformes/ Hemiramphidae	*Hyporhamphus limbatus (Valencienues, 1847)*	Congaturi halfbeak	FW	3.1	Ornamental	R	LC
64	Anabantiformes/ Channidae	*Channa marulius (Hamilton, 1822)*	Great snakehead	FW	4.5	Food fish	C	LC
65	Anabantiformes / Channidae	*Channa orientalis (Bloch & Schneider, 1801)*	Walking snakehead	FW	3.8	Food fish	C	VU
66	Anabantiformes / Channidae	*Channa punctata (Bloch, 1793)*	Spotted snakehead	FW	3.8	Food fish	A	LC
67	Anabantiformes / Channidae	*Channa striata (Bloch, 1793)*	Striped snakehead	FW	3.6	Food fish	C	LC
68	Anabantiformes / Osphronemidae	*Trichogaster fasciata (Bloch and Schneider, 1801)*	Banded gourami	FW	2.8	Ornamental	R	LC
69	Anabantiformes / Anabantidae	*Anabas testudineus (Bloch, 1792)*	Climbing perch	FW	3	Food fish / Ornamental	M	LC
70	Synbranchiformes/ Mastacembelidae	*Mastacembelus armatus (Lacepède, 1800))*	Zig zag eel	FW	2.8	Food fish	C	LC
71	Synbranchiformes/ Mastacembelidae	*Macrognathus pancalus (Hamilton, 1822)*	Barred spiny eel	FW	3.5	Food fish	A	LC
72	Gobiiformes/ Gobiidae	*Psammogobius biocellatus (Valencienues, 1847)*	Sleepy goby	FW	3.4	Food fish	M	LC
73	Gobiiformes/ Gobiidae	*Glossogobius giuris (Hamilton, 1822)*	Tank/Bar- eyed goby	FW	3.7	Food fish	A	LC
74	Gobiiformes/ Gobiidae	*Awaous grammepomus (Bleeker, 1849)*	Scribbled goby	FW	3.3	Food fish	C	LC
75	Gobiiformes/ Eleotridae	*Eleotris fusca (Forster, 1801)*	Dusky sleeper	FW	3.8	Food fish	R	LC
76*	Cichliformes/ Cichlidae	*Oreochromis mossambicus (Peters, 1852)*	Mozambique Tilapia	FW	2.2	Food fish / Ornamental	C	VU
77	Cichliformes/ Cichlidae	*Pseudetroplus maculatus (Bloch, 1795)*	Ornage chromid	FW	2.7	Ornamental	C	LC
78	Cichliformes/ Cichlidae	*Etroplus suratensis*	Pearl spot	FW	2.9	Food fish /	C	LC

		(Bloch, 1790)				Ornamental		
79	Perciformes / Nandidae	*Nandus nandus (Hamilton, 1822)*	Gangetic leaf fish	FW	3.9	Ornamental	M	LC
80	Perciformes / Ambassidae	*Chanda nama (Hamilton, 1822)*	Elongate glass perchlet	FW	3.6	Ornamental	C	LC
81	Perciformes/ Ambassidae	*Parambassis ranga (Hamilton, 1822)*	Indian glassy fish	FW	3.5	Ornamental	C	LC
82 @	Perciformes/ Sciaenidae	*Johnius coitor (Hamilton, 1822)*	Coitor Croaker	BW	3.4	Food fish	R	LC
83 @	Perciformes/ Latidae	*Lates calcarifer (Bloch, 1790)*	Barramundi	BW	3.8	Food fish / Game fish	M	LC
84 @	Mulliformes/ Mullidae	*Upeneus vittatus (Forsskål,, 1775)*	Yellow striped Goat fish	BW	3.6	Food fish	R	LC
85 @	Mugiliformes / Mugilidae	*Mugil cephalus (Linnaeus, 1758)*	Flathead grey mullet	BW	2.5	Food fish	C	LC
86 @	Mugiliformes/ Mugilidae	*Planiliza macrolepis (Smith, 1846)*	Largescale mullet	BW	2.6	Food fish	R	LC
87 @	Mugiliformes / Mugilidae	*Planiliza parsia (Hamilton, 1822)*	Goldspot mullet	BW	2	Food fish	C	NE
88	Mugiliformes / Mugilidae	*Rhinomugil corsula (Hamilton, 1822)*	Corsula mullet	FW	2.4	Ornamental	C	LC

(@ indicates brackish water fish species, * indicates Exotic fish species)

Table 2: Spatio - temporal variations in ichthyofaunal diversity indices of Godavari River

Spatial variation in ichthyofaunal diversity indices of Godavari River								
Landing stations	**H'(log2)**	**d**	**J'**	**Δ**	**Δ***	**Δ+**	**ʌ+**	**sphi+**
Kunavaram	5.368	6.095	0.898	69.549	71.779	72.288	213.962	2700
Rajamahendravaram	5.616	8.162	0.869	70.350	72.308	74.237	165.849	4000
Dowleswaram	5.553	8.043	0.864	70.807	72.880	74.194	167.989	3940
Kovvur	5.473	7.807	0.860	70.500	72.685	73.917	176.191	3740
Tallapudi	5.455	7.031	0.884	70.366	72.536	73.810	182.505	3220
Polavaram	5.031	3.816	0.952	69.153	71.744	70.175	265.151	1660
Temporal variation in ichthyofaunal diversity indices of Godavari River								
Winter-2022	5.316	6.097	0.911	70.060	72.380	73.057	202.931	2500
Hot weather-2022	5.000	4.190	0.946	68.820	71.397	70.445	274.700	1620
S-W monsoon -2022	5.442	8.688	0.856	70.114	72.340	74.369	161.368	3760
N-E monsoon -2022	5.630	9.087	0.873	70.405	72.616	74.311	165.664	3960
Winter-2023	5.430	7.254	0.892	70.196	72.422	73.388	188.251	3020
Hot Weather -2023	4.994	4.611	0.920	70.808	73.608	72.203	235.121	1940
S-W monsoon -2023	5.440	7.891	0.876	69.397	71.524	74.727	159.690	3500

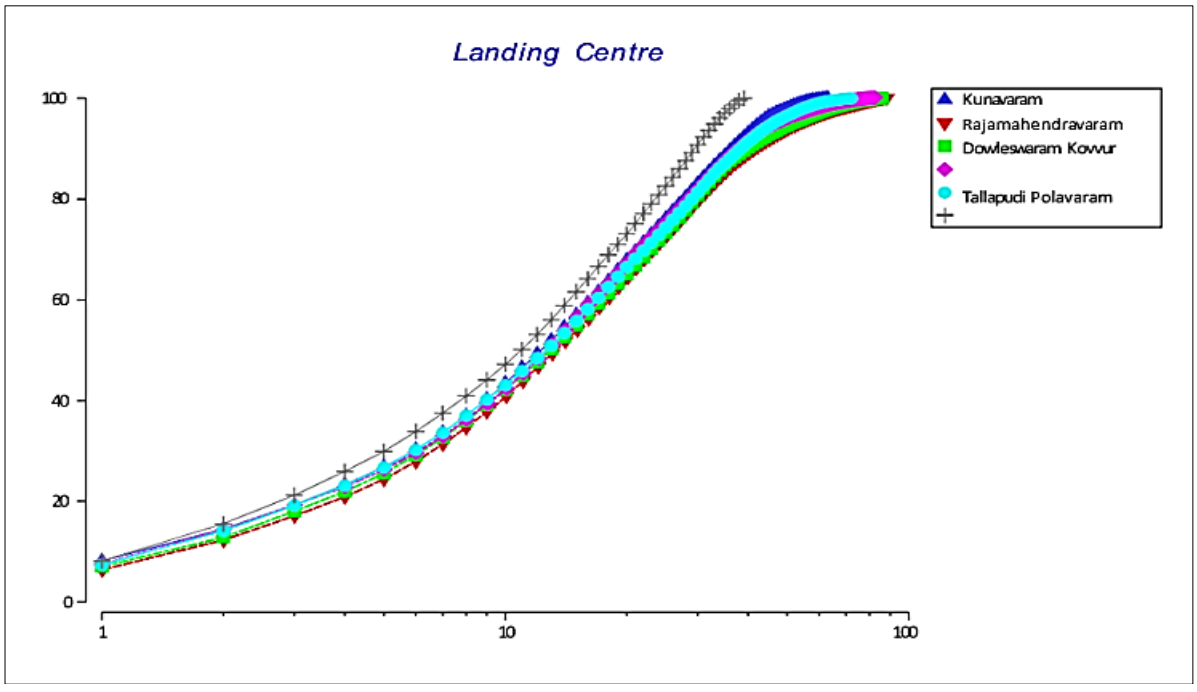

Fig 2: K-Dominance plot among six sampling stations in Godavari River

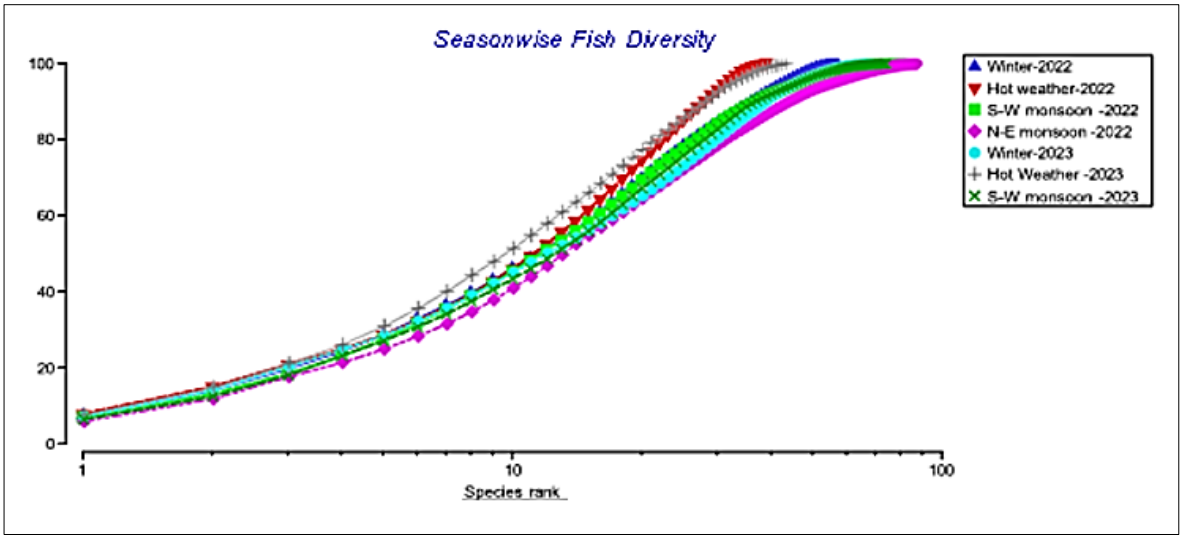

Fig 3: K-Dominance plot among different seasons in Godavari River

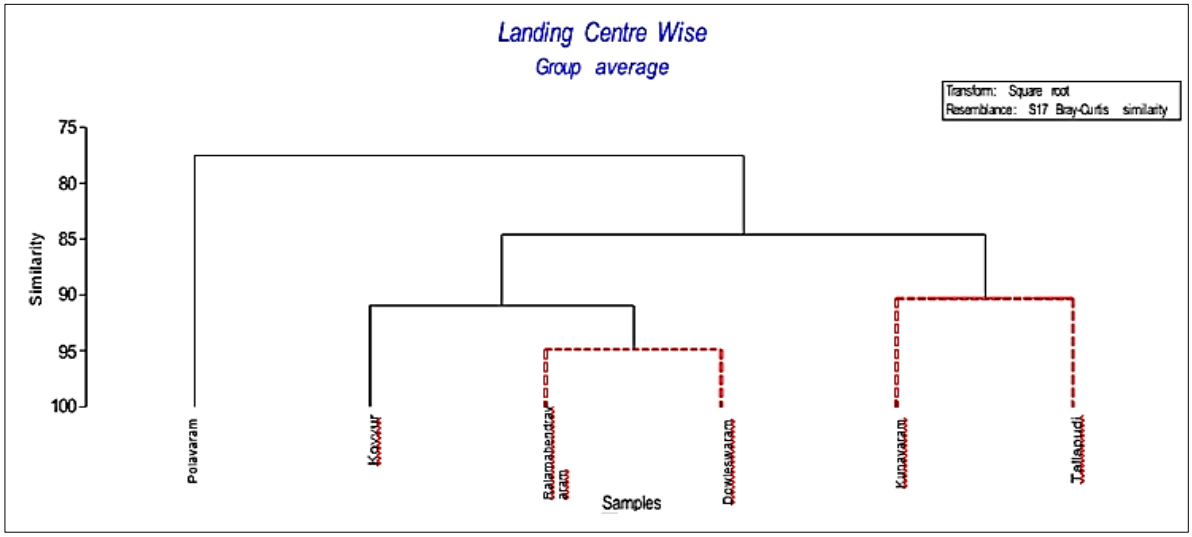

Fig 4: Bray - curtis similarities among six sampling stations based on the composition of ichthyofauna collected from Godavari River

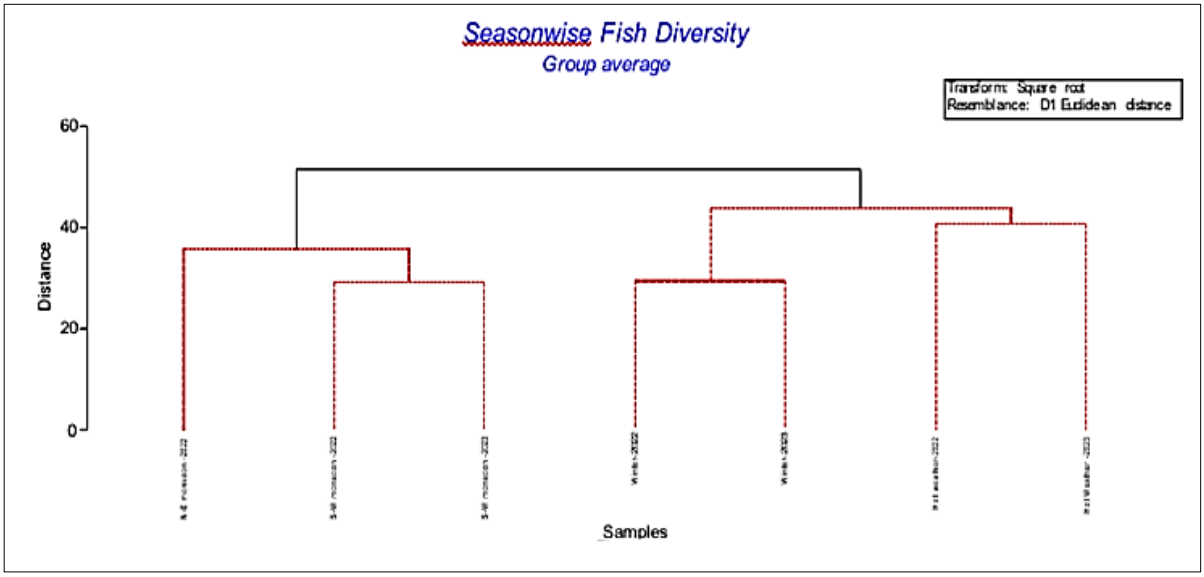

Fig 5: Bray - Curtis similarities among different seasons based on the composition of ichthyofauna collected from Godavari River

Classical diversity indices

An ecological community's biodiversity can be determined by employing classical diversity indexes. With an average of 5.61, Rajamahendravaram had the greatest Shannon-Wiener diversity index (H′) among the stations, while Polavaram had the lowest at 5.01. The North-East monsoon season (5.630) in 2022 showed the highest diversity index, while the hot weather period (4.994) in 2023 had the lowest.

Rajamahendravaram was also in the highest place with the greatest value of 8.162 in terms of Margalef's species richness (d), while Polavaram had the lowest value at 3.816. Seasonally, the North-East monsoon in 2022 had the highest species richness (9.087), while the hot weather in 2022 had the lowest species richness (4.190). The Pielou's evenness index has a range of 0 to 1, with 1 denoting total evenness and 0 denoting no evenness. The Pielou's evenness index has a range of 0 to 1, with 1 denoting total evenness and 0 denoting no evenness. Pielou's evenness (J') achieve as lowest spatially at Kovvur (0.860) and highest at Polavaram (0.952). In terms of temporal variation, the N-E monsoon in 2022 had the lowest temporal evenness (0.873) and the hot weather in 2022 the most (0.946) (Table 2).

Functional diversity indices

The highest spatial variation in taxonomic diversity (Δ) was observed at Dowleswaram, with a value of 70.807. Similarly, Dowleswaram additionally showed the highest value for the taxonomic distinctness index (Δ*), with a value of 72.880. Taxonomic diversity indices are quantitative tools used to assess the diversity, distinctness, and relatedness of species within an ecological community. In contrast, the highest average taxonomic distinctness (Δ^+) was observed at Rajamahendravaram (74.237), while the greatest variation in taxonomic distinctness (Λ^+) was found at Polavaram (265.151). Seasonally, taxonomic diversity (Δ) reached its peak during the North East Monsoon of 2022 (70.405) and was lowest during the Hot weather of the same year (68.820). Taxonomic distinctness (Δ∗) attained its highest value during the Hot weather in 2023 (73.608) and its lowest during the Hot weather in 2022 (71.397). Average taxonomic distinctness (Δ^+) was at its maximum (74.727) in the Southwest Monsoon of 2023 and at its minimum (70.445) during the hot weather of 2022. The variation in taxonomic distinctness (Λ^+) was highest in the Hot weather of 2022 (274.700) and lowest during the Southwest Monsoon of 2023 (159.690) (Table 2). The current findings indicate that there is variance in taxonomic diversity across different spatial locations. Among the locations studied, Dowleswaram exhibited the highest value of taxonomic diversity (70.807), followed by Kovvur (70.500), Tallapudi (70.366), Rajamahendravaram (70.350), Kunavaram (69.549), and Polavaram had the lowest value (69.153). The period of hot weather had the highest taxonomic diversity value (70.808), which coincides with the findings reported by Murugan *et al.,* (2014) [25] for the Vellar estuary. According to Freedman *et al.,* (2014) [14], the current data indicates that the presence of dams might have a negative impact on the taxonomic variety of fish populations. Taxonomic distinctness (Δ*) for spatial variation was found to be the lowest value for Polavaram (71.744) and the highest values for Dowleswaram (72.880). The taxonomic distinctness for seasonal variation was observed to be in the range of 71.397 to 73.608. In general, downstream areas were more taxonomically diverse than upstream ones. This suggests that severely disrupted locations in river valleys would not show a drop in taxonomic distinctness compared to a random expectation. Season-wise taxonomic distinctness indicates range between 71.392 (hot weather 2022) and 73.608 (hot weather 2023). It is observed that there is no significant variation between the season-wise taxonomic distinctness index and this further emphasis the river is in good condition throughout the seasons. Sengupta and Homechaudhuri (2015) [37], however, concluded that the highest taxonomic distinctness during monsoon and autumn with a declining trend through winter, spring and summer in the river system of West Bengal. Higher value of taxonomic distinctness in Dowleswaram indicates the establishment of different genera with taxonomic diversity.

The average taxonomic distinctness index (Δ +) was observed to be the lowest for Polavaram (70.175) and the greatest for Rajamahendravaram (74.237). The study revealed that the taxonomic distinctness showed a seasonal variation, with an average range of 70.445 to 74.727.

The taxonomic distinctness index variation (Λ+) supplements the previously stated average taxonomic distinctness index. The variance in taxonomic distinctness index (Λ+) in the six landing centres was found to be the lowest in Rajamahendravaram (165.849) and the greatest in Polavaram (265.151). The seasonally average Λ+ was determined to be between 161.368 and 274.700. The lowest variation in taxonomic distinctness was observed at Rajamahendravaram followed by Dowleswaram indicating that fish had the most uniform classification orders in these places. A low variance in the taxonomic distinctness index at the Rajamahendravaram station implies a more homogeneous distribution of taxonomic groupings along the evolutionary framework.

Phylogenetic diversity indices

The total phylogenetic diversity ($sPhi^+$) reached its highest value at Rajamahendravaram (4000), while the lowest value was recorded at Polavaram (1660). Temporally, the highest total phylogenetic diversity ($sPhi^+$) was observed during the North East Monsoon of 2022 (3960), whereas the lowest value occurred during the Hot weather period of 2022 (1620) (Table 2).

Univariate metrics

Plotting the percentage of cumulative abundance versus species rank, K, on a logarithmic scale generated the K-Dominance curve. Figure 2 depicts the geographic variation plot dominance among the six Godavari River sampling points that were chosen. Rajamahendravaram has the highest cumulative abundance of the six sampling locations, followed by Dowleswaram. Furthermore, the curve for Rajamahendravaram and and Dowleswaram reached the cumulative 100% due to the occurrence of a greater number of species as evident in the X-axis. The dominance plot for seasonal variations at Godavari River are shown in Figure 3 The curve representing season, North East monsoon was at the bottom, showing. more diversity and hot weather period at the top showing less diversity. The total phylogenetic diversity index (sPhi+), which verifies the taxonomic breadth of the biota, also demonstrated Rajamahendravaram's (4000) highly diverse nature, followed by Dowleswaram (3940), Kovvur (3740), Tallapudi (3220), Kunavaram (2700), and Polavaram, which had the lowest phylogenetic diversity (sPhi+) value of 1660. Total phylogenetic diversity (sPhi+) values were computed seasonally and were found to be in the range of 1620 to 3960. During the monsoon season, all stations showed the highest sPhi+ values, which might be attributed to the abundance of species and the presence of a significant number of individuals. The findings of this study were lower than those of Karuppasamy *et al*. (2020) [17] for the biodiversity of fish species along the Wadge bank and higher than those of Pavinkumar (2014) [32] for the diversity of fishes in the Korampallam Thermal, Punnaayal, and

Manakudy estuaries and Murugan *et al*. (2014) [25] for the diversity of fishes of Vellar estuary. Among the different biodiversity indices employed, it is evident that the total phylogenetic diversity (sPhi+) effectively distinguishes across stations and seasons. The elevated sPhi+ values seen during the monsoon season provide compelling evidence of a greater taxonomic variety, as well as a larger degree of phylogenetic distance among the species. The taxonomic diversity exhibits an upward trend during the monsoon period, potentially because to the heightened presence of small-sized and migratory fishes in both the monsoon and post- monsoon periods. The current study analysis indicated that total phylogenetic diversity (sPhi+) values were computed and found to be positive at six Godavari River sample locations. We examined the temporal variations in species, phylogenetic, and functional diversity of fish assemblages throughout the six landing stations of Godavari River using field surveys and thorough literature searches. Our research sought to investigate the temporal changes in species, phylogenetic, and functional diversity, as well as to determine how non-native species invasions and native species extinctions influenced changes in the three dimensions of biodiversity. Overall, the species diversity indices indicate a good correlation with species richness across the sampling sites and could be utilised for biodiversity conservation. Variations in fish diversity indices are minimal in both temporal and spatial level

Analysis of similarity

An effective measure for comparing the compositions of two different locations or seasons is Bray-Curtis similarity (Fig. 4,5). By grouping data using cluster analysis, similarities within and between these groupings can be assessed. Based on the numerical data collected, the Bray-Curtis similarity is helpful in assessing how similar the occurrence of ichthyofaunal species is among the stations. The greater spatial similarity was observed between Rajamahendravaram and Dowleswaram (94.94%), followed by Kovvur and Dowleswaram (92.16%), and the lowest was calculated between Rajamahendravaram and Polavaram (69.08%) (Table 4.4). The greater seasonal similarity was observed between winter period 2022 and winter period 2023 (86.30%) followed by South-West monsoon 2022 to South-West monsoon 2023 (86.29%) and the lowest between SW monsoon'22 and hot Weather 2023 (69.63%). In the present study that examined six selected sampling sites, it was observed that Rajamahendravaram exhibited the highest cumulative abundance, with Dowleswaram ranking second in terms of abundance. The Rajamahendravaram and Dowleswaram curves have a relatively low position on the dominance plot and demonstrate a gradual ascent, which can be attributed to their higher species richness. The elevated Polavaram dominance curve represented less diverse fish assemblage and low diversity. The analysis of seasonal K dominance plots revealed that the North east monsoon season exhibited a greater level of species dominance whereas the hot weather period had the lowest dispersion and abundance of the fish community. The present results align with the observations made by Thilaka (2018) [44], who documented November as the month with the highest productivity for elasmobranchs along the South Tamil Nadu coast. However, they contrast with the findings of Karuppasamy (2020) [17], who reported a greater cumulative relative abundance of elasmobranchs during the post-monsoon period along the Wadge bank. The study conducted by Kumar Naik *et al.*, (2014) [21] in the Chulkinala Reservoir revealed that the monsoon season had a significantly higher density of fish species as indicated by the K-dominance curve, in comparison to the other two seasons. During the current study it was observed that the K dominance plot curves were mostly overlapping indicating the variation among the species diversity between stations and seasons could be relatively less.

Conclusion

The ichthyofaunal diversity of fishes along the Godavari River in Andhra Pradesh is baselined in this study. It demonstrates that the highest range of species and occurrence was found in Rajamahendravaram. The North-East monsoon season of 2022 witnessed the highest occurrences, while the hot weather season of 2023 recorded the lowest. The sustainability of fish stocks, especially in the Godavari River, depends on the conservation of these fish populations. Furthermore, fishing nets with larger mesh sizes catch fewer undersized fish, which aids in population recovery and long-term sustainability. Fishery managers should collaborate with fishing communities to implement sustainable practices and protect habitats, ensuring the long-term survival of fish species. This study on ichthyofaunal diversity aid in the effective management of these resources along the Godavari River. Hence, it is recommended to strictly implement the existing conservation and management measures and raise public awareness on this aspect.

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Conflict of Interest

The authors declare there is no conflict of interest

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