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Population Variation and Allometric Growth Patterns in Morphometric and Craniometric Traits of *Cirrhinus mrigala* Across Four Barrages in the Indus River Basin, Pakistan

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ABSTRACT

Cirrhinus mrigala is a freshwater fish species of the Cyprinidae family, which is economically significant and inhabits rivers, lakes and reservoirs and has been reported in the Indus River mainly, of Pakistan. **Objective:** To examine both morphmetric and craniometric differences of populations in four locations: Trimmu Barrage, Taunsa Barrage, Chashma Barrage and Sukkur Barrage, of *C. mrigala*. **Methods:** In this observational cross-sectional study, a total of 60 samples were used and 34 morphometric and 7 craniometric characters were measured. Multivariate analysis revealed the presence of significant differences between the morphmetric and craniometric characters. **Results:** Fish in the Sukkur barrage were found to record the highest mean values of some of the morphometric and craniometric characters with intermediate values of the Chashma barrage and lowest values of Trimmu barrage. It is also important to note that there was moderate or weak correlation between total length and other morphetric characters, and negative allometric growth at Taunsa Barrage which could have been due to a number of factors in the environment. However, fish at Chashma Barrage showed a positive correlation which implies that fish have a good environment to grow. The craniometric characters of Chashma Barrage were a medium to poor correlation. **Conclusion:** These results emphasized the separation of morphology and allometric growth pattern of *C. mrigala* which would be of valuable relevance to taxonomists, aquaculture farmers and conservationists.

INTRODUCTION

Cirrhinus mrigala often referred to as mrigal carp is among the noteworthy freshwater fish species utilized in aquaculture and has a broad adaptability to different water habitats. It is a native species of the South Asian rivers of India, Pakistan, Bangladesh and Myanmar. [1, 2]. Mrigal carp inhabit the muddy bottom of freshwater bodies such as ponds, lakes, and rivers [3]. This bottom-dwelling, detritivorous lifestyle makes the species particularly vulnerable to bioaccumulating pollutants from sediments [4]. *Cirrhinus mrigala* belongs to the omnivorous group of feeding habits, as [5] reported, who found decaying matter, phytoplankton, zooplankton, plant materials, and insects in its gut. Fish stocks can be accurately differentiated and discussed by their morphological traits, including morphometric measurements, meristic counts, shape and size of fish [6]. Many environmental factors, including diet, development, water quality, and nutrition, greatly impact the shape or morphology of fish. This variation in their morphological characteristics allows fish to adapt to their surrounding environments [7]. The analyses of morphometric variables determined ontogenetic changes and geographic variations among fish stocks. These were

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analyzed earlier by univariate comparisons but were soon followed by bivariate and multivariate analyses of relative growth [8]. The cranium of *Cirrhinus mrigala* is highly complex as it has numerous bony, muscular, and ligamentous elements [9]. Craniometric analysis is crucial in accurate species identification in systematics and taxonomic studies [10]. Skeletal morphology provides data about the phylogenetic relationships among various fish species [11, 12]. Recently, much work on aquatic toxicology, including hepatotoxicity and nephrotoxicity, diet and growth patterns, and exposure to various pollutants, has been done on *Cirrhinus mrigala*. Growth pattern about morphometry and craniometry is yet to be done.

The present study aimed to provide comprehensive baseline data of morphometric and craniometric characters of *Cirrhinus mrigala*, to find out the variations of morphometric and craniometric characters from four different sites, viz. Sukkur barrage, Chashma Barrage, Trimmu Barrage, and Taunsa Barrage, and to investigate the growth patterns of *C. mrigala* from these four sites. *Cirrhinus mrigala* is economically important and has been introduced to various countries.

METHODS

This study is an observational cross-sectional study investigating population-level variations and allometric growth patterns in morphometric and craniometric traits of *Cirrhinus mrigala* collected from four barrages along the Indus River Basin, Pakistan. Morphological and cranial measurements were analyzed using MANOVA and linear regression. A total of 15 samples from Trimmu barrage (31.147549° N, 72.143174° E), 15 from Taunsa barrage (30.520200° N, 70.855501° E), 10 from Chashma barrage (32.438939° N, 71.374248° E) and 20 from Sukkur barrage (27.673652° N, 68.847048° E) were collected with the help of local fishermen from December 2023 to March 2024. Sample sizes varied across sites due to differential fish availability and catch success at each barrage during the sampling period (Figure 1).

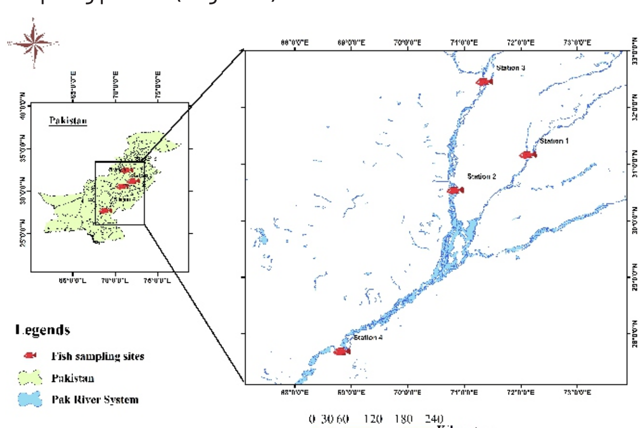

Figure 1: Geographic Location of Sampling Sites Along the Indus River Basin, Pakistan

Despite this imbalance, these sample sizes are adequate for MANOVA. The sites were selected purposively but fish specimens within each site were collected using random sampling to avoid bias. Although sex was not controlled for, fish size was measured and considered during data screening to ensure comparable size ranges across sites. The samples of *C. mrigala* were transferred in ice boxes to the Ecology and Evolutionary Biology Laboratory, Institute of Zoology, University of the Punjab, Quaid-e-Azam Campus, Lahore. Then, the samples were washed with tap water and dried using a towel. After precise identification by following the standard identification key by Mirza and Sandhu (2007), the fish was weighed on a digital weigh balance and then photographed on a measuring table. Using two softwares, tpsUtil32 and tpsDig2.31, landmarks were applied to the images, and morphometric variables of *C. mrigala* were measured digitally in centimeters (Figure 2).

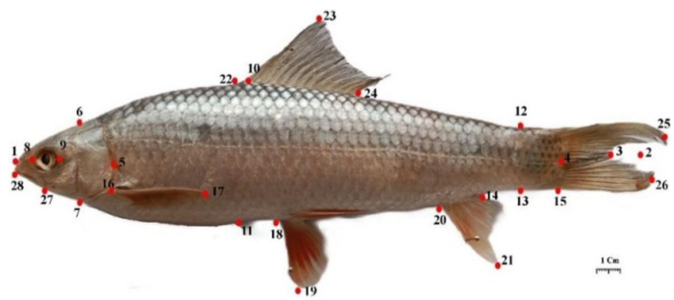

Figure 2: Lateral View of *Cirrhinus mrigala* showing the 28 Morphometric Landmarks used for Measurements

34 morphometric and 7 craniometric characteristics were selected for the morphometric and craniometric analysis of *C. mrigala*. All characteristics were measured in centimeters, except for the weight, which was recorded in grams (Table 1).

Table 1: Morphometric and Craniometric Measurements with Corresponding Landmark Points for *Cirrhinus mrigala*

Morphometric Characters	Landmarks
Total Length (TL)	1-2
Fork Length (Fl)	1-3
Standard Length (Sl)	1-4
Head Length (HL)	1-5
Head Depth (HD)	6-7
Pre-Orbital Length (PrOL)	1-8
Post-Orbital Length (PoOL)	9-5
Eye Diameter (ED)	8-9
Body Depth (BD)	10-11
Caudal Fin Length (CFL)	2-4
Caudal Peduncle Length (CPL)	14-15
Caudal Depth (CD)	12-13
Caudal Height (CH)	25-26
Pectoral Fin Length (PecFL)	16-17
Pre-Pectoral Length (PrPecL)	1-16

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Pelvic Fin Length (PFL)	18-19
Pre-Pelvic Length (PrPL)	1-18
Anal Fin Length (AFL)	20-21
Pre-Anal Length (PrAL)	1-20
Dorsal Fin Length (DFL)	22-23
Pre-Dorsal Length (PrDL)	1-22
Dorsal Fin Base Length (DFBL)	22-24
Upper Jaw Length (UJL)	1-27
Lower Jaw Length (LJL)	27-28
Pelvic-Anal Fin Origin Distance (PeAD)	18-20
Pectoral-Anal Fin Origin Distance (PcAD)	16-20
Pectoral-Pelvic Fin Origin Distance (PcPeD)	16-18
Anal-Caudal Fin Origin Distance (ACD)	20-15
Anal-Dorsal Fin Origin Distance (ADD)	20-22
Pectoral-Dorsal Fin Origin Distance (PcDD)	16-22
Pectoral-Caudal Fin Origin Distance (PcCD)	16-15
Pelvic-Dorsal Fin Origin Distance (PeDD)	18-22
Pelvic-Caudal Fin Origin Distance (PeCD)	18-15
Caudal-Dorsal Fin Origin Distance (CDD)	15-22
Craniometric Characters	**Landmarks**
Skull Length (SL)	1-8
Skull Width (SW)	6-7
Eye Socket Length (EHL)	2-5
Inter-Orbital Length (IOL)	3-4
Pre-Orbital Length (Prol)	1-2
Eye Socket Depth (EHW)	9-10
Skull Height (SH)	11-12

For craniometric analysis, the heads of all the samples of *C. mrigala* were separated and boiled in hot water for five to seven minutes. After boiling, the heads were kept in cool water for some time to let them cool down. To extract the skulls, extra muscle and tissue were removed using a scalpel and forceps. The extracted skulls were kept in 10% formalin solution for seven days. After seven days, the skulls were washed with water and placed in a 70% solution of ethyl alcohol. After one week, the skulls were taken out of the ethyl alcohol solution and dried on blotting paper for a week at room temperature. After drying, the skulls were photographed from the dorsal, ventral, and lateral sides. Using tpsUtil32 and tpsDig2 landmarks on different positions were applied, and craniometric variables were measured digitally in centimeters. (a): Dorsal View of *Cirrhinus mrigala* Skull showing Craniometric Landmarks (Numbered 1-12). (b): Ventral View of *Cirrhinus mrigala* Skull showing Craniometric Landmarks (Figure 3).

Figure 3: (a) Dorsal View, (b) Ventral View and (c) of *Cirrhinus mrigala* Skull showing Craniometric Landmarks (Numbered 1-12)

To find out the variations of morphometric and craniometric characters from four different sites (Trimmu, Taunsa, Chashma, and Sukkur), multivariate analysis of variance (MANOVA) was applied using IBM SPSS 26. Furthermore, linear regression analysis was applied to investigate the correlation among different morphometric variables and to discuss the growth patterns of C. mrigala from these four sites. Data was analyzed using IBM SPSS 26. Multivariate analysis of variance (MANOVA) was employed to simultaneously compare multiple morphometric and craniometric variables across four sites. MANOVA was chosen over separate univariate tests because it accounts for intercorrelations among variables, controls Type I error inflation, and provides greater statistical power for detecting multivariate differences. Key assumptions were tested before the multivariate analysis was conducted. Boxs M test was used to test the homogeneity of variance- covariance matrices and revealed that there was no significant violation (Boxs M=112.45, 0.087). Correlations between dependent variables were checked in terms of correlation matrices and variance inflation factors (VIFs); bivariate correlation was less than 0.85, and the VIFs were between 1.2 and 4.3, which were acceptable rates of multicollinearity. ShapiroWilk tests on the residuals and visual inspection of QQ plots indicated no significant departure of the data to the normality. With these diagnostics, it is certain that the data satisfied the required assumptions of MANOVA. Bonferonni-corrected significant effects ($p < 0.05$) were then followed. post-hoc comparisons, with partial η^2 reported as effect size. Linear regression analysis ($Y = a + bX$) examined allometric relationships using total length and skull length as predictors of morphometric and craniometric traits, respectively. This approach quantifies how body proportions change with size. Correlation strength was classified by R values (strong ≥ 0.7, moderate 0.4-0.7, weak < 0.4), and the slope 'b' indicated growth patterns: negative allometry ($b < 3$), isometry ($b = 3$), or positive allometry ($b > 3$). Fish sampling and handling followed institutional and national ethical guidelines for the use of animals in research. No endangered species were involved, and all efforts were made to minimize stress and suffering during handling and processing.

RESULTS

Baseline data of morphometric characters of *Cirrhinus mrigala* was provided in the form of each character's mean and standard deviation (Table 2).

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Table 2: Descriptive Statistics for Morphometric and Craniometric Traits of *Cirrhinus Mrigala* from Four Indus River Barrages, Pakistan

Morphometric Characters	Trimmu Barrage (n=15)	Taunsa Barrage (n=15)	Chashma Barrage (n=10)	Sukkur Barrage (n=10)
	Mean ± SD (cm)			
TL	21.59 ± 1.25	22.52 ± 0.44	25.60 ± 3.29	27.96 ± 2.64
FL	19.71 ± 1.05	20.69 ± 0.67	23.33 ± 3.21	25.37 ± 2.32
SL	18.44 ± 0.95	19.49 ± 0.62	21.98 ± 2.96	23.43 ± 2.40
HL	3.46 ± 0.16	3.57 ± 0.10	3.90 ± 0.51	4.49 ± 0.61
HD	2.64 ± 0.14	2.55 ± 0.11	2.84 ± 0.36	3.33 ± 0.39
PrOL	0.72 ± 0.09	0.73 ± 0.05	0.87 ± 0.15	0.92 ± 0.20
PoOL	1.96 ± 0.14	2.03 ± 0.12	2.29 ± 0.32	2.66 ± 0.34
ED	0.80 ± 0.06	0.86 ± 0.03	0.86 ± 0.09	0.94 ± 0.13
BD	4.54 ± 0.28	4.44 ± 0.30	5.33 ± 0.78	5.63 ± 0.70
CFL	3.15 ± 0.38	3.03 ± 0.29	3.62 ± 0.30	4.57 + 0.54
CPL	2.16 ± 0.13	1.39 ± 0.08	2.43 ± 0.40	1.69 ± 0.31
CD	2.10 ± 0.08	2.14 ± 0.16	2.46 ± 0.31	2.68 ± 0.28
CH	5.78 ± 0.53	4.68 ± 0.97	3.10 ± 0.40	3.96 ± 1.16
PecFL	3.13 ± 0.13	2.88 ± 0.41	3.74 ± 0.54	4.33 ± 0.65
PrPecL	3.70 ± 0.11	3.91 ± 0.44	4.14 ± 0.46	4.77 ± 0.60
PFL	2.91 ± 0.14	3.01 ± 0.24	3.00 ± 0.43	3.64 ± 0.46
PrPL	9.38 ± 0.50	9.85 ± 0.35	10.76 ± 1.52	12.10 ± 1.44
AFL	2.91 ± 0.21	3.09 ± 0.10	2.92 ± 0.38	3.54 ± 0.44
AFBL	1.43 ± 0.14	2.20 ± 0.21	1.55 ± 0.21	2.64 ± 0.45
PrAL	14.34 ± 0.93	15.5 ± 0.41	16.95 ± 2.42	18.63 ± 2.11
DFL	3.16 ± 0.32	3.5 ± 0.24	3.75 ± 0.52	4.66 ± 0.59
DFBL	3.95 ± 0.35	4.4 ± 0.50	4.56 ± 0.55	5.62 ± 0.73
PrDL	8.41 ± 0.46	8.7 ± 0.36	9.93 ± 1.42	11.08 ± 1.22
UJL	0.96 ± 0.06	1.1 ± 0.15	1.08 ± 0.36	1.15 ± 0.20
LJL	0.84 ± 0.07	0.9 ± 0.22	0.87 ± 0.33	0.95 ± 0.17
BW	106.18 ± 17.52	125.7 ± 10.17	170.71 ± 58.02	218.31 ± 74.70
PeAD	5.06 ± 0.52	5.9 ± 0.62	6.34 ± 0.89	6.69 ± 0.77
PcAD	10.69 ± 0.86	11.73 ± 0.57	12.84 ± 1.92	13.96 ± 1.69
PcPeD	5.69 ± 0.40	5.98 ± 0.47	6.65 ± 0.99	7.36 ± 1.03
ACD	3.56 ± 0.20	3.53 ± 0.17	3.95 ± 0.51	4.25 ± 0.45
ADD	7.63 ± 0.43	8.03 ± 0.33	9.18 ± 1.37	9.63 ± 1.11
PcDD	5.67 ± 0.40	5.83 ± 0.30	6.74 ± 1.01	7.48 ± 0.84
PcCD	14.15 ± 0.90	15.15 ± 0.48	16.71 ± 2.38	18.12 ± 1.96
PeDD	4.63 ± 0.24	4.26 ± 0.43	5.65 ± 0.85	5.80 ± 0.73
PeCD	8.58 ± 0.59	9.27 ± 0.35	10.28 ± 1.37	10.91 ± 1.06
CDD	10.48 ± 0.43	10.88 ± 0.36	12.52 ± 1.72	13.10 ± 1.31
SkL	3.22 ± 0.07	3.56 ± 0.30	3.38 ± 0.16	3.91 ± 0.37
SW	1.73 ± 0.04	1.76 ± 0.18	1.81 ± 0.16	2.21 ± 0.26
EWL	1.02 ± 0.04	1.09 ± 0.05	0.99 ± 0.03	1.19 ± 0.15
IOL	1.48 ± 0.08	1.64 ± 0.12	1.63 ± 0.16	1.98 ± 0.21
PrOSkL	0.72 ± 0.05	0.79 ± 0.10	0.67 ± 0.07	0.92 ± 0.10
EHW	0.96 ± 0.02	0.97 ± 0.07	1.02 ± 0.24	1.09 ± 0.16
SH	0.93 ± 0.06	0.93 ± 0.05	1.03 ± 0.24	1.13 ± 0.38

MANOVA revealed the variations among all characters; the characters having p values less than 0.05 were considered as showing significant differences. All characters showed significant differences among the four sites except three: eye diameter (ED), upper jaw length (UJL), and lower jaw length (LJL), Pre-orbital length (PrOL). Partial eta squared values indicated moderate to large effect sizes for most morphometric traits, suggesting biologically meaningful population-level differences despite sample size variation (Table 3).

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Table 3: Multivariate Analysis of Morphometric and Craniometric Characters

Tests of Between-Subjects Effects					
Morphometric Characters	Type III Sum of Squares	Mean Square	F	Sig.	Partial Eta Squared
TL	216.005[a]	72.002	12.230	.000*	.559
FL	165.597[b]	55.199	11.597	.000*	.545
SL	122.821[c]	40.940	8.481	.000*	.467
HL	6.098[d]	2.033	7.431	.001*	.435
HD	3.651[e]	1.217	10.170	.000*	.513
PrOL	.245[f]	.082	2.847	.055*	.227
PoOL	2.795[g]	.932	10.076	.000*	.510
ED	.086[h]	.029	2.355	.093	.196
BD	8.305[i]	2.768	6.897	.001*	.416
CFL	14.589[j]	4.863	21.471	.000*	.690
CPL	3.177[k]	1.059	12.755	.000*	.569
CD	1.931[l]	.644	10.039	.000*	.509
CH	17.168[m]	5.723	5.374	.005*	.357
PecFL	11.440[n]	3.813	11.365	.000*	.540
PrPecL	6.106[o]	2.035	7.194	.001*	.427
PFL	3.560[p]	1.187	7.064	.001*	.422
PrPL	39.150[q]	13.050	7.966	.001*	.452
AFL	2.539[r]	.846	5.626	.004*	.368
AFBL	7.611[s]	2.537	17.524	.000*	.644
PrAL	86.144[t]	28.715	7.902	.001*	.450
DFL	11.797[u]	3.932	14.275	.000*	.596
DFBL	14.055[v]	4.685	10.884	.000*	.530
PrDL	39.507[w]	13.169	10.816	.000*	.528
UJL	.127[x]	.042	1.005	.405	.094
LJL	.066[y]	.022	.580	.633	.057
BW	65454.639[z]	21818.213	5.387	.005*	.358
PeAD	9.563[aa]	3.188	5.766	.003*	.374
PcAD	47.626[ab]	15.875	6.692	.001*	.409
PcPeD	14.468[ac]	4.823	5.715	.003*	.372
ACD	3.144[ad]	1.048	6.268	.002*	.393
ADD	19.922[ae]	6.641	6.455	.002*	.400
PcDD	18.550[af]	6.183	10.270	.000*	.515
PcCD	75.063[ag]	25.021	7.801	.001*	.447
PeDD	12.360[ah]	4.120	9.036	.000*	.483
PeCD	24.635[ai]	8.212	8.400	.000*	.465
CDD	36.123[aj]	12.041	8.215	.000*	.459
SkL	2.323[ak]	0.774	7.468	0.001*	0.436
SW	1.582[al]	0.527	10.46	0*	0.52
EWL	.222[am]	0.074	4.933	0.007*	0.338
IOL	1.288[an]	0.429	12.215	0*	0.558
PrOSkL	.303[ao]	0.101	11.565	0*	0.545
EHW	.109[ap]	0.036	1.579	0.216	0.14
SH	.259[aq]	0.086	0.877	0.464	0.083

'*' represents significant value ($p \leq 0.05$)

To identify the growth patterns, a bivariate linear regression analysis was conducted whereby the total length was the independent variable and all other morphometric characters were the dependent variables of each of the four locations (Trimmu, Taunsa, Chashma and Sukkur barrages). The correlation coefficient (R) was used to show that most of the characters had a positive correlation with total length, and the strength of the correlations was strong to very weak across the sites. There were a few exceptions where there was no association between the characters through which PcPeD and ACD occurred at Taunsa and UJL and LJL at Sukkur. Interesting to note; in all sites, the regression coefficient (b) was found to provide negative allometric growth ($b < 3$) in all morphometric characters except body weight (BW), which exhibited positive allometry. R-values that are very large (almost at 1.00) are considered to be strong linear correlations and it is observed that near perfect correlations are possibly due to rounding (Table 4).

Table 4: Regression Analysis of Morphometric and Craniometric Variables from Trimmu, Taunsa, Chashma and Sukkur Barrage

Morphometric Characters	Trimmu Barrage		Taunsa Barrage		Chashma Barrage		Sukkur Barrage	
	Y=a + bX	R	Y=a + bX	R	Y=a + bX	R	Y=a + bX	R
FL	1.993 + 0.821X	0.98	-9.602 + 1.345X	0.87	-1.650 + 0.976X	1	1.884 + 0.840X	0.95
SL	2.359 + 0.745X	0.98	-9.366 + 1.281X	0.89	-1.103 + 0.902X	1	-1.485 + 0.891X	0.98
HL	0.828 + 0.122X	0.94	-0.998 + 0.203X	0.87	-0.026 + 0.153X	0.9	-0.900 + 0.193X	0.83
HD	0.311 + 0.108X	0.97	-0.497 + 0.135X	0.51	0.052 + 0.109X	0.98	-0.532 + 0.138X	0.92
PrOL	-0.505 + 0.057X	0.78	2.169 + (-0.064)X	0.56	-0.241 + 0.043X	0.92	-0.163 + 0.039X	0.52
PoOL	-0.362 + 0.108X	0.99	-4.177 + 0.276X	0.96	-0.241 + 0.099X	1	-0.709 + 0.120X	0.92
ED	1.366 + (-0.026) X	0.54	2.175 + (-0.058) X	0.74	0.260 + 0.023X	0.8	0.143 + 0.028X	0.58
BD	-0.179 + 0.218X	0.98	0.332 + 0.182X	0.26	-0.724 + 0.236X	0.99	-0.899 + 0.234X	0.88
CFL	-2.187 + 0.247X	0.82	9.413 + (-0.284) X	0.42	1.262 + 0.092X	0.99	1.441 + 0.112X	0.54
CPL	2.773 + (-0.029)X	0.26	3.394 + (-0.089) X	0.51	0.119 + 0.090X	0.75	0.398 + 0.046X	0.39
CD	0.815 + 0.059X	0.93	-4.670 + 0.302X	0.8	0.038 + 0.095X	0.98	-0.122 + 0.100X	0.96
CH	4.603 + 0.082X	0.19	11.093+(-0.285)X	0.12	0.035+0.120X	0.98	-1.502+ 0.195X	0.44
PecFL	0.963 + 0.100X	0.93	-9.015 + 0.528X	0.55	0.393 + 0.161X	0.97	-1.997 + 0.226X	0.91
PrPecL	1.974 + 0.080X	0.91	-0.307 + 0.187X	0.18	0.557 + 0.140X	0.99	-0.539 + 0.190X	0.84
PFL	1.002 + 0.088X	0.8	-5.909 + 0.396X	0.72	-0.380 + 0.132X	0.99	-0.278 + 0.140X	0.8
PrPL	0.831 + 0.396X	0.99	4.721 + 0.228X	0.28	-1.014 + 0.460X	0.99	-2.445 + 0.520X	0.95

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AFL	0.832 + 0.096X	0.58	4.546 + (-0.065) X	0.27	0.354 + 0.100X	0.86	-0.339 + 0.139X	0.82
AFBL	-0.845 + 0.105X	0.97	0.650 + 0.069X	0.14	0.034 + 0.059X	0.94	-0.639 + 0.117X	0.69
PrAL	-1.048 + 0.713X	0.96	-4.599 + 0.894X	0.96	-1.904 + 0.736X	1	-2.868 + 0.769X	0.96
DFL	-1.669 + 0.224X	0.88	1.124 + 0.106X	0.19	0.857 + 0.113X	0.71	0.698 + 0.142X	0.64
DFBL	-1.447 + 0.250X	0.88	16.779 + (-0.548)X	0.48	0.410 + 0.162X	0.97	-0.287 + 0.211X	0.76
PrDL	0.457 + 0.368X	1	-7.958 + 0.741X	0.89	-1.078 + 0.430X	1	-1.428 + 0.447X	0.97
UJL	0.485 + 0.022X	0.43	-5.927 + 0.313X	0.93	-0.537 + 0.063X	0.57	1.036 + 0.004X	0.06
LJL	0.437 + 0.018X	0.35	-10.086 + 0.491X	0.99	-0.496 + 0.053X	0.53	0.877 + 0.002X	0.04
BW	186.475 + 13.557X	0.97	313.323 + 19.495X	0.84	272.605 + 17.317X	0.98	25.520 + 8.720X	0.31
PeAD	-2.462 + 0.349X	0.83	-14.099 + 0.892X	0.63	-0.613 + 0.271X	1	-0.414 + 0.254X	0.87
PcAD	-3.467 + 0.656X	0.96	-3.768 + 0.688X	0.53	-2.103 + 0.584X	1	-2.402 + 0.585X	0.92
PcPeD	-1.273 + 0.322X	1	5.978 + 0.000X	0	-0.976 + 0.298X	0.99	-2.183 + 0.341X	0.88
ACD	1.815 + 0.081X	0.51	3.794 + (-0.012)X	0.03	0.229 + 0.145X	0.93	0.605 + 0.130X	0.77
ADD	0.502 + 0.330X	0.97	-4.940 + 0.576X	0.77	-1.474 + 0.416X	1	-1.334 + 0.392X	0.94
PcDD	-0.934 + 0.306X	0.95	-8.816 + 0.650X	0.95	-1.131 + 0.307X	1	-1.103 + 0.307X	0.96
PcCD	-0.857 + 0.695X	0.96	0.261 + 0.661X	0.6	-1.744 + 0.721X	1	-1.564 + 0.704X	0.95
PeDD	0.585 + 0.187X	0.97	-12.518 + 0.745X	0.75	-0.917 + 0.256X	0.99	-1.123 + 0.248X	0.9
PeCD	-0.472 + 0.419X	0.89	-6.779 + 0.713X	0.88	-0.338 + 0.415X	1	0.352 + 0.378X	0.95
CDD	3.623 + 0.317X	0.93	1.887 + 0.400X	0.48	-0.753 + 0.518X	0.99	0.110 + 0.464X	0.94
SW	2.382 + (-0.204) X	0.24	0.348 + 0.400X	0.7	-1.344 + 0.934X	0.96	0.029 + 0.557X	0.78
EWL	1.012 + 0.630X	0.95	0.936 + 0.041X	0.25	0.902 + 0.029X	0.12	0.025 + 0.299X	0.78
IOL	3.035 + (0.487) X	0.37	-2.017 + 1.076X	0.96	2.017 + 1.076X	0.96	0.040 + 0.494X	0.78
PrOSkL	2.286 + (-0.490) X	0.63	0.017 + 0.196X	0.5	0.017 + 0.196X	0.5	0.264 + 0.165X	0.57
EHW	1.805 + (-0.262) X	0.9	-0.057 + 0.316X	0.22	0.057 + 0.316X	0.22	0.246 + 0.217X	0.53
SH	1.719 + 0.822X	0.96	-3.418 + 1.322X	0.97	3.418 + 1.322X	0.97	1.041 + 0.558X	0.58

DISCUSSION

Cirrhinus mrigala is a freshwater fish species, which is economically significant, and has a wide distribution range in river systems of the Indian subcontinent. Its morphology and development patterns have been reported to be affected by various environmental conditions among them the quality of water, the structure of the habitat as well as anthropogenic stressors like pollution. Morphological evolution may also be further promoted by decreased gene flow and local adaptation as populations become separated by artificial barriers such as barrage. Exploring these variations is important in comprehending the plasticity of the species and the wellbeing of the populations. In this study, the morphological variation of four main barrages of *C. mrigala* is studied to evaluate the influence of different environments. The current research observed a major morphological difference in *Cirrhinus mrigala* among four barrages. The population of Sukkur had the highest mean of most morphometric and all craniometric features with Trimmu population having the lowest. The cause of this difference is probably associated with the environmental specifics of the sites; the less growth of Trimmu could be connected with the increased level of pollution and metal deposition [13, 14]. Moreover, the high phenotypic plasticity of the species makes morphological adaptation possible to local environments, and genetic divergences due to the decreased gene circulation among separated populations may also be a feature of such noticeable variations [15]. The patterns of growth in all locations were marked by employing negative allometry (b<3), in which linear body sizes grow at a reduced rate compared to total body size. This tendency was the most noticeable at Taunsa barrage that is also characterized by the smallest correlations between total length and other morphmetric features indicating that its environment has the most significant influence on morphological development [7, 16]. Our results of negative allometric growth are consistent with the past reports of similar cyprinids such as *C. mrigala* and other cyprinids such as *Labeo rohita*, implying that these biological variables follow a similar pattern of growth due to functional constraints [17-19]. These new craniometric data offer a good baseline to the study of skeletal analysis of *C. mrigala* in the future. Correlation between craniometric and morphometric characteristics also varied with site, being less at Chashma but higher elsewhere, which may represent variations in environmental pressure or genetic adaptations [20]. In general, this paper highlights the co-operative effect of environmental conditions and inherent plasticity on morphology and provides the necessary background information on taxonomic, evolutionary, and growth pattern studies on this species.

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CONCLUSIONS

This study shows significant morphometric and craniometric variations in *Cirrhinus mrigala* populations across four barrages in Pakistan. Due to site-specific environmental conditions and pollution levels, fish from Trimmu Barrage have the lowest growth metrics compared to Sukkur Barrage. Negative allometric growth in most traits indicates that the growth patterns of fish are affected by environmental stressors. This study provides information critical for taxonomists, aquaculture practitioners, and conservationists and highlights the need for conservation and sustainable management efforts for this important freshwater species.

Authors Contribution

Conceptualization: AB
Methodology: UI, AF, A
Formal analysis: IH, SN, AF
Writing and drafting: MA, AF
Review and editing: AB, UI, AF, A, IH, SN, MA

All authors approved the final manuscript and take responsibility for the integrity of the work.

Conflicts of Interest

All the authors declare no conflict of interest.

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