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Morphometric and Meristic characterization of the hillstream loach *Nemacheilus rubidipinnis* (Blyth) from river Mandal, Garhwal Himalaya

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Abstract: The present study investigates the morphometric and meristic characteristics of the hillstream loach *Nemacheilus rubidipinnis* (Blyth) inhabiting the Mandal River of the Garhwal Himalaya, Uttarakhand. A total of 57 specimens collected between January 2024 and December 2025 were examined to establish species-specific morphometric relationships and growth patterns. Twelve morphometric parameters and major meristic characters were recorded following standard taxonomic procedures. Fish specimens ranged from 5.0 to 8.3 cm in total length, with the majority belonging to the 6–7 cm size group. Morphometric analysis revealed a highly streamlined and elongated body adapted to life in flowing waters. The mean ratios of standard length, head length, and maximum body depth to total length were 0.813, 0.183, and 0.168, respectively. Regression analyses demonstrated strong positive correlations among most body parameters ($r > 0.90$), indicating coordinated growth and high morphological stability. Morphometric indices showed a slenderness ratio (SL/MBD) of 4.65, reflecting hydrodynamic efficiency and adaptation to hillstream habitats. Low variation in morphometric indices suggested largely isometric growth across size groups. The study provides the first detailed morphometric account of *N. rubidipinnis* from the Garhwal Himalaya and establishes baseline information valuable for taxonomy, biodiversity assessment, and future conservation studies.

Keywords: *Nemacheilus rubidipinnis* • Fish taxonomy • Morphometric relationships • Meristic counts • Hillstream fish • Garhwal Himalaya • Biodiversity assessment.

Introduction

Fish identification is based on interrelationships of different morphometric characters and specific meristic characters. These characters are highly specific to a particular species but may vary due to habitat specificity, temperature, stream characteristics and even differences in genetic makeup. Pioneering work on fish taxonomy from Indian waters was conducted by Day (1878), who analysed various body length parameters in relation to total length, standard length and head length of fish. Nikolsky (1961) opined that adaptation acquired by a particular fish in its environment has a great impact on species characterization. In recent years, Talwar and Jhingran (1991) have published taxonomic details of 932 freshwater and marine fishes of the Indian regions belonging to 255 genera, 95 families, and 19 orders. As far as the taxonomy of fishes from Uttarakhand is concerned, the primary record available is of Badola (1975), Singh et al. (1987), and Badola (2009). Recently, Uniyal and Uniyal (2021) reported 132 fish species from Uttarakhand.

Nemacheilus, commonly called "stone loaches" are small size bottom dwelling fishes native to Asia. These species are highly sensitive to pollution so are known as important bioindicators. More than 10 species of *Nemacheilus* are reported from the Garhwal region. *N. rubidipinnis* was for the first time reported by Blyth (1860), followed by Day (1878). However, we have observed this species frequently in the Mandal River, Pauri Garhwal, hence it was decided to study its biology in detail.

Some of the important contribution to the morphometric studies in fishes are made by Srivastava (1968), Singh et al. (1983),

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Dobriyal and Bahuguna (1987), Dobriyal et al. (1988, 2006), Talwar and Jhingran (1991), Uniyal et al. (2004), Badola (2009), Dobriyal (2013), Rashid et al. (2019), and Bansal et al. (2021), Tariq et al., (2022) and Sivakumar et al., (2024). However, there is no record available for the study of *Nemacheilus rubidipinnis*, hence the study is undertaken.

Materials and Methods

Physiography of the study area

The present study was conducted in the river Mandal, an important spring-fed tributary of Ramganga river in Uttarakhand, India, during January 2024 to December 2025 (Fig 1

Fig. 1: Location map of River Mandal in District Pauri Garhwal within Uttarakhand

The river flows through the Kalagarh Tiger Reserve, travelling a distance of 30 km from its origin. For the collection of fish samples, two sampling stations were selected along the Mandal River, Rathuadhab (29º 40' 08.5" N, 78º 51' 21.5" E) and Banja Devi (29º 39' 34.1" N, 78º 53' 07.7" E). The specimens were collected using a net and with the help of local village fisherman. The fish samples were preserved on-site in 5% formaldehyde solution. Fishes were then brought to the laboratory for further investigation.

Morphometrics: A total of twelve body parameters were considered for the morphometrics analysis. These measurements, expressed in centimeters, included total length (TL), standard length (SL), caudal length (CL), head length (HL), maximum body depth (MBD), pre-dorsal length (PDL), pre-pectoral length (PPL), pre-ventral length (PVL), pre-anal length (PAL), snout length (Snt-L), eye diameter (ED), and post-orbital length (POL). To evaluate proportional growth and shape variation, these variables were studied in relation to total length, standard length, and head length separately (Fig 2).

Measurement:

Morphometric characters were measured with the help of sharp-pointed dividers and a stainless-steel ruler marked in millimeters, and an electronic digital balance, with a precision of 0.001 g, was used to determine the body weight. Different lengths (cm) were measured as described below:

Total length (TL): The total distance from the tip of the snout to the posterior end of the caudal fin.

Standard length (SL): The distance from the tip of the snout to the base of the caudal peduncle.

Caudal length (CL): The distance between the base of the caudal fin and the tip of the caudal ray, or the farthest end of the caudal fin.

Head length (HL): The straight distance from the tip of the snout to the posterior opercular edge.

Pre-dorsal length (PDL): A straight- line distance from the anterior-most part of the head or snout tip to the origin of the dorsal fin.

Pre-ventral length (PVL): The distance from the snout tip to the proximal end of the pelvic fin.

Pre-Pectoral length (PPL): The distance from the snout tip to the anterior base of the Pectoral fin.

Pre-anal length (PAL): The distance between the rostral tip and the anal fin base.

Eye diameter (ED): The maximum horizontal distance from the anterior margin to the posterior margin of the eyeballs.

Snout length (Snt. L): A straight measurement from the anterior-most tip of the snout to the anterior margin of the orbit.

Post-orbital length (Po.OL): A great distance from the back edge of the eye to the posterior end of the gill cover.

Maximum body depth (MBD): The maximum vertical distance from the dorsal-most point to the ventral surface.

Meristic characters

The meristic characters, like rays and spines of dorsal, pectoral, pelvic, and anal fins, were made with the help of fine forceps and a hand lens.

The morphometric and meristic counts were evaluated by following Day (1878) and Talwar and Jhingran (1991).

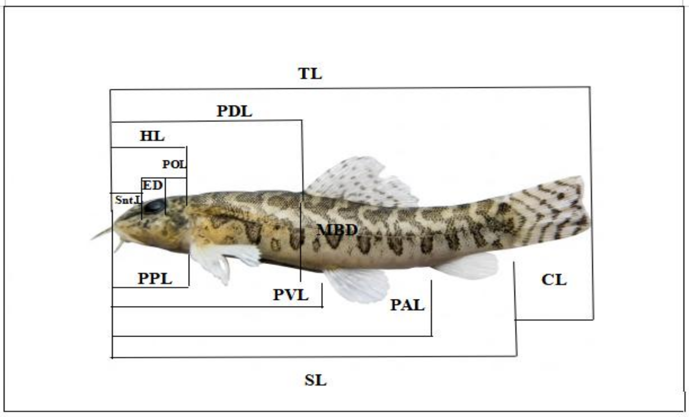

Fig 2: Morphometric and Meristic diagram of fish *Nemacheilus rubidipinnis* (Blyth) (TL-total length, SL- standard length, CL- caudal length, PDL- pre dorsal length, PPL- pre pectoral length, PVL- pre ventral length, PAL- pre anal length, Snt L- snout length, HL- head length, ED- eye diameter, POL- post orbital length, MBD- maximum body depth)

Regression analysis

For regression analysis, the original data were grouped into class intervals, and the average values for the dependent variables (Y) and the independent variables (X) were calculated. These values were then analysed using Microsoft Excel 2016 to compute the correlation coefficient (r), the regression coefficient (b), and the intercept (a). The relationships were determined by fitting the data to the following linear equation:

$Y= a+b X$ (where Y is the dependent variable, X is the independent variable, a and b are the intercept and slope, respectively). The linearity of the regression was tested by Analysis of Variance (F Test).

Linear morphometric profile and morphometric proportions and growth summary

A fish's linear morphometric profile is the quantitative assessment of its body shape and size using exact straight-line measurements between specific anatomical landmarks. These ratios and dimensions are used by ichthyologists for species identification, stock differentiation, and to evaluate overall health (Strauss & Bookstein, 1982). A morphometric statistical summary in fisheries quantifies the size and shape of fish to aid in taxonomy, stock identification, and growth assessment (Elliott et al., 1995).

Principal Component Analysis: Principal Component Analysis (PCA) was performed using size-adjusted morphometric variables to eliminate the influence of overall body size and emphasize shape variation among specimens (Strauss & Bookstein, 1982).

Results and Discussion

A total of 57 specimens of *Nemacheilus rubidipinnis* (Blyth) were considered for this study, which were collected in a span of two years from River Mandal. There was no significant size difference between male and female specimens hence, pooled data was taken into consideration. The fish were grouped into four categories (Table 1) based on size variation (5-6 cm, 6-7 cm, 7-8 cm and 8-9 cm). In general, the fish body is slender, loach-like with small eyes and nostrils close to each other. Colour of the body is reddish brown with 12-14 irregular darkish bands. Mouth is semicircular with fleshy lips. Barbels are thread like. Caudal fin has a black ocellus (spot) on its upper half of the base. This description is close to that discussed by Talwar and Jhingran (1991).

Table 1: Summarized data on the morphometrics of *Nemacheilus rubidipinnis* collected during 2024-2025 from the Mandal River.

SN	Length Group (cm)	TL (cm)	SL (cm)	CL (cm)	PDL (cm)	PPL (cm)	PVL (cm)	PAL (cm)	HL (cm)	ED (cm)	Snt. L (cm)	POL (cm)	MBD (cm)
1	05-06 (15)	5.77 ± 0.27	4.64 ±0.28	1.13 ±0.08	2.21 ±0.1	1.23 ±0.09	2.53 ±0.16	3.77 ±0.23	1.09 ±0.09	0.3 ±0	0.48 ±0.09	0.37 ±0.07	1 ±0.09
2	06-07 (27)	6.53 ±0.27	5.32 ±0.25	1.22 ±0.10	2.518 ±0.1	1.38 ±0.12	2.88 ±0.14	4.24 ±0.20	1.22 ±0.13	0.31 ±0.03	0.51 ±0.12	0.41 ±0.05	1.15 ±0.1
3	07-08 (12)	7.58 ±0.24	6.19 ±0.24	1.38 ±0.10	2.89 ± 0.1	1.51 ± 0.14	3.36 ±0.12	4.96 ±0.21	1.35 ±0.12	0.36 ±0.12	0.56 ±0.13	0.44 ±0.08	1.3 ±0.16
4	08-09 (03)	8.20 ±0.1	6.70 ± 0.1	1.50 ±0.13	3.10 ±0.1	1.67 ±0.12	3.70 ±0.1	5.43 ±0.12	1.5 ±0	0.4 ±0	0.67 ±0.06	0.47 ±0.06	1.3 ±0.17

(Number of fish in bracket)

The maximum number of fish (27) were collected in a range of 6-7 cm followed by the length group 5-6 cm (15), 7-8 cm (12) and least in the group 8-9 cm (03). The maximum size obtained was 8.3 cm. The different parameters studied were total length, standard length, caudal length, pre-dorsal length, pre-pectoral length, pre-ventral (pelvic) length, pre- anal length, head length, snout length, eye diameter, post-orbital length and maximum body depth. It is observed that all body parts grow in accordance with the total length.

The details of body parameters growing in ratio of total length in different size length is presented in Table 2.

On an average it is observed that in ratio of total length the standard length grows to 1: 0.813±0.01, caudal length 1: 0.187± 0.01, pre-dorsal length 1 : 0.381± 0.003, pre-pectoral length 1: 0.205±0.006, pre-ventral length 1: 0.442± 0.005, pre-anal length 1: 0.654±0.005, head length 1:0.183± 0.005, eye diameter 1: 0.048±0.001, snout length 1: 0.078±0.004, post-orbital length 1: 0.059±0.003 and maximum body depth 1: 0.168±0.007.

Table 2: Summarized data on growth of body parts in ratio of Total Length in *Nemacheilus rubidipinnis.*

SN	Size groups (cm)	SL (cm)	CL (cm)	PDL (cm)	PPL (cm)	PVL (cm)	PAL (cm)	HL (cm)	ED (cm)	Snt. L (cm)	POL (cm)	MBD (cm)
1	5-6 (5.5± 0.5)	0.802± 0.017	0.196± 0.017	0.382± 0.014	0.212± 0.014	0.438 ±0.018	0.654± 0.020	0.189± 0.015	0.051±0 .002	0.083±0 .0160	0.063± 0.011	0.172±0.014
2	6-7 (6.5± 0.5)	0.814± 0.014	0.186± 0.015	0.385± 0.017	0.210± 0.021	0.440 ±0.019	0.648± 0.023	0.186± 0.022	0.047±0 .005	0.078±0 .019	0.062± 0.008	0.169±0.033
3	7-8 (7.5± 0.5)	0.818± 0.01	0.182± 0.013	0.381± 0.013	0.198± 0.018	0.442 ±0.01	0.654± 0.023	0.177± 0.016	0.047±0 .014	0.073±0 .018	0.057± 0.009	0.175±0.018
4	8-9 (8.5± 0.5)	0.816± 0.019	0.182± 0.019	0.377± 0.010	0.203± 0.016	0.450 ±0.015	0.662± 0.008	0.182± 0.002	0.048±0 .0005	0.081±0 .007	0.056± 0.007	0.158±0.020
	Mean	0.813± 0.01	0.187± 0.01	0.381± 0.003	0.205± 0.006	0.442 ±0.005	0.654± 0.005	0.183± 0.005	0.048±0 .001	0.078±0 .004	0.059± 0.003	0.168±0.007

Standard length is also considered as an independent parameter other than TL. Growth of body parts were also analysed in ratio of standard length and presented in Table 3.

Table 3: Summarized data on growth of body parts in ratio of Standard Length in *Nemacheilus rubidipinnis.*

PSN	Size groups (cm)	CL (cm)	PDL (cm)	PPL (cm)	PVL (cm)	PAL (cm)	HL (cm)	ED (cm)	Snt.L (cm)	POL (cm)	MBD (cm)
1	5-6	0.244± 0.026	0.476±0.020	0.265±0.021	0.545±0.025	0.811±0.030	0.235±0.020	0.06± 0.004	0.103±0.020	0.078±0.013	0.215± 0.018
2	6-7	0.229± 0.023	0.473±0.022	0.259±0.026	0.541±0.026	0.797±0.034	0.229±0.027	0.06±0.007	0.096±0.023	0.107±0.163	0.216± 0.018
3	7-8	0.223± 0.020	0.466±0.015	0.243±0.023	0.542±0.013	0.800±0.029	0.218±0.018	0.06±0.018	0.09± 0.021	0.07± 0.011	0.214± 0.020
4	8-9	0.223± 0.028	0.462±0.021	0.248±0.014	0.552±0.020	0.810±0.028	0.223±0.003	0.06±0.001	0.099±0.007	0.069±0.008	0.194± 0.028
	Mean	0.229± 0.009	0.469±0.006	0.253±0.01	0.545±0.004	0.804±0.007	0.226±0.007	0.06±0.002	0.097±0.005	0.081±0.01	0.209± 0.01

In ratio of standard length the caudal length grows to 1: 0.229± 0.009, pre-dorsal length 1: 0.469± 0.006, pre-pectoral length 1: 0.253±0.01, pre-ventral length 1: 0.545± 0.004, pre-anal length 1: 0.804±0.007, head length 1: 0.226± 0.007, eye diameter 1: 0.06± 0.002, snout length 1: 0.097±0.005, post-orbital length 1: 0.081±0.01 and maximum body depth 1: 0.209±0.01.

In taxonomic study of fish, the head length becomes an important independent parameter which is correlated with minor body

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parameters and body depth. The growth of body parameters in ratio of head length is presented in Table 4. In ratio of head length, the eye diameter grows 1: 0.27± 0.01, snout length 1:0.42±0.02, post-orbital length 1: 0.33±0.01, and maximum body depth 1: 0.93±0.05.

Table 4: Summarized data on growth of body parts in ratio of Head Length in *Nemacheilus rubidipinnis.*

S.N.	Size groups (cm)	ED (cm)	Snt.L (cm)	POL (cm)	MBD (cm)
1	5-6	0.28±0.02	0.44±0.06	0.34±0.06	0.92±0.06
2	6-7	0.26±0.09	0.41±0.07	0.34±0.05	0.95±0.11
3	7-8	0.27±0.09	0.41±0.07	0.33±0.05	0.99±0.11
4	8-9	0.27±0.01	0.45±0.04	0.31± 0.03	0.87±0.11
	Mean	0.27±0.01	0.42±0.02	0.33±0.01	0.93±0.05

Interrelationship between different independent and dependent parameters were statistically modelled through regression analysis. The data related to total length and related dependent variables and presented in Table 5.

Table 5: Statistical modelling of interrelationships between Total length and other body parameters in *Nemacheilus rubidipinnis.*

S.N.	Body relationships	Intercept 'a'	Regression coefficient 'b'	Coefficient of correlation 'r	Analysis of Variance "F"
1	TL/SL	**-0.22468**	**0.8459**	**0.99982**	**0.0094 NS**
2	TL/CL	**0.24129**	**0.15191**	**0.99607**	**64.993***
3	TL/HL	**0.15715**	**0.1614**	**0.99273**	**39.49***
4	TL/PDL	**0.11926**	**0.36484**	**0.99924**	**414.602***
5	TL/PPL	**0.24094**	**0.17191**	**0.99163**	**45.24***
6	TL/PVL	**-0.23395**	**0.4775**	**0.99939**	**533.16***
7	TL/PAL	**-0.19488**	**0.68315**	**0.99934**	**674.23***
8	TL/Snt.L	**0.045527**	**0.072587**	**0.93974**	**3.90 NS**
9	TL/ED	**0.048743**	**0.041853**	**0.97349**	**16.24***
10	TL/Postorb.L	**0.14698**	**0.039255**	**0.99295**	**13.643***
11	TL/MBD	**0.26406**	**0.13264**	**0.94301**	**78.36***

Critical Value $F_{0.05}$= 4.02 (* Significant at 5% level of significance), NS = Non-significant

Data indicates that the linear relationship between total length: standard length (F= **0.0094**) and total length: snout length (F= **3.90**) was found insignificant at 5 % level of significance. Other relationships varied significantly. The data related to standard length and related dependent variables are presented in Table 6.

Table 6: Statistical modelling of interrelationships between Standard length and other body parameters in *Nemacheilus rubidipinnis.*

SN	**Body relationships**	**Intercept 'a'**	**Regression coefficient 'b'**	**Coefficient of correlation 'r**	**Analysis of Variance "F"**
1	SL/CL	**0.28363**	**0.17923**	**0.99432**	**36.994**
2.	SL/HL	**0.20103**	**0.19063**	**0.99198**	**41.699**
3	SL/PDL	**0.21523**	**0.43147**	**0.99979**	**407.89**

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4	SL/PPL	**0.28716**	**0.20312**	**0.99132**	**45.441**
5	SL/PVL	**-0.1046**	**0.56404**	**0.99879**	**442.83**
6	SL/PAL	**-0.0087748**	**0.80679**	**0.99851**	**497.26**
7	SL/Snt.L	**0.067354**	**0.085365**	**0.93503**	**4.58**
8	SL/ED	**0.061201**	**0.049243**	**0.96904**	**12.816**
9	SL/Postorb.L	**0.15715**	**0.046451**	**0.99408**	**17.838**
10	SL/MBD	**0.29523**	**0.15751**	**0.94745**	**77.421**

Critical Value $F_{0.05}$= 4.02 ((All relationships vary significantly)

The relationship between standard length and snout length was also very close to being insignificant. Other parameters fluctuated significantly at the level of 5 %.

The data related to head length and related dependent variables are presented in Table 7.

The relationship between head length and all other related body parameters (snout length, eye diameters, post-orbital length, and maximum body depth) varied significantly. However, the coefficient of correlation was always high (> 0.9), which indicates a close positive growth among all parameters.

Table 7: Statistical modelling of interrelationships between Head length and other body parameters in *Nemacheilus rubidipinnis.*

SN	Body relationships	Intercept 'a'	Regression coefficient 'b'	Coefficient of correlation 'r'	Analysis of Variance "F"
1	HL/Snt.L	**-0.038456**	**0.46004**	**0.96835**	**84.325**
2	HL/ED	**0.0095578**	**0.2581**	**0.97605**	**7.694**
3	HL/Postorb.L	**0.11045**	**0.2419**	**0.99483**	**24.306**
4	HL/MBD	**0.1878**	**0.78078**	**0.90254**	**29.116**

Critical Value $F_{0.05}$= 4.02 ((All relationships vary significantly)

The linear morphometric proportion visualization was analysed based on Strauss and Bookstein (1982) and is presented in Fig 3.

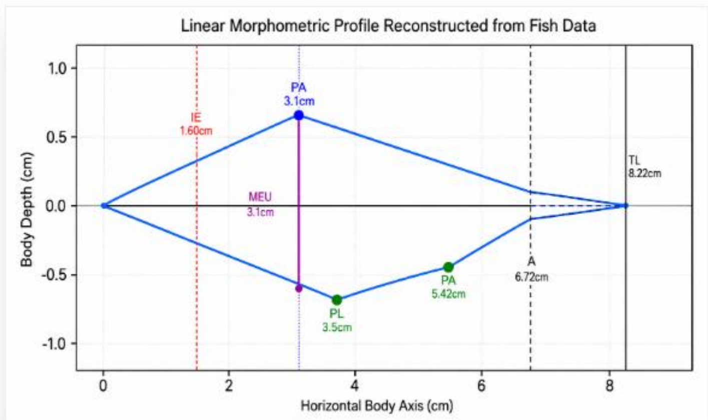

Fig 3: Linear morphometric proportion visualization in *N. rubidipinnis* (Blyth)

The study indicated that:

1. The body is highly streamlined and torpedo-shaped. This shape cuts through water easily, meaning the fish is a fast, active swimmer that likely lives in open water.
2. The head takes up about 22% (roughly one-quarter) of the fish's total body length. This is a perfectly normal, balanced head size for a standard bony fish.
3. The pectoral fin is positioned perfectly right behind the gill covers.
4. The dorsal fin starts just before the middle of the back, which gives the fish excellent steering stability.
5. The Anal fin is positioned far back, leaving a short tail section that is built for quick bursts of speed.

The morphometric proportions and growth trends calculated based on Elliott (1995) are presented in Fig 4 and Table 8.

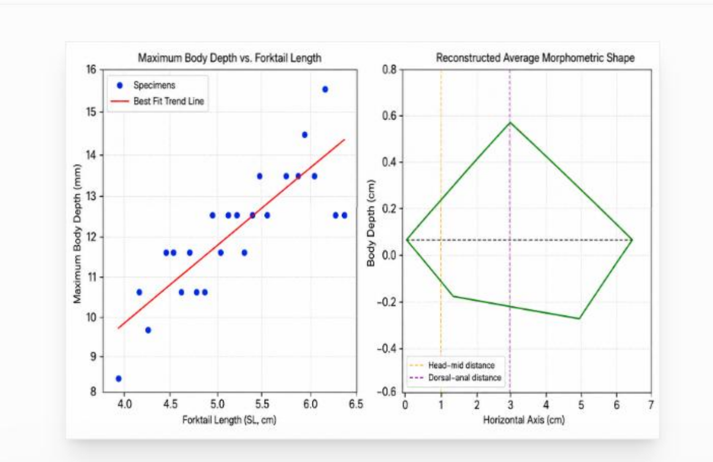

Fig 4: Morphometric proportions and growth trends calculated based on Elliott (1995)
The result of the above analysis is presented in Table 8.

Table 8: Morphometric Statistical Summary calculated based on Elliott (1995)

Morphometric Index Ratio	Mean Value	Minimum Ratio	Maximum Ratio	Standard Deviation
Body Elongation Index (\(MBD/SL\))	**0.215**	0.172	0.260	0.019
Relative Head Size (\(HL/SL\))	**0.229**	0.179	0.271	0.024
Pre-Dorsal Positioning (\(PDL/SL\))	**0.472**	0.439	0.511	0.020
Pre-Anal Positioning (\(PAL/SL\))	**0.803**	0.741	0.891	0.032
Eye Diameter vs. Head (\(ED/HL\))	**0.266**	0.214	0.538	0.048

Interpretation of the data based on the above analysis is as follows:

1. Hydrodynamic Efficiency and Elongation: The sample displays an average Body Elongation Index (\(MBD/SL\)) of 0.215, which translates to a standard slenderness ratio (\(SL/MBD\)) of 4.65. In functional ecology, structural ratios between 4.0 and 5.0 define a highly efficient fusiform body profile. This minimizes drag and indicates that this cohort is adapted for steady, continuous locomotion in open or flowing water systems.
2. Growth Allometry (Size vs. Shape): The low standard deviation values across all body indices (\(\sigma \) ranging from 0.019 to 0.032) demonstrate strong isometry. As these specimens grow from

an \(SL\) of 4.0 cm up to 6.7 cm (pp. 1, 3), their regional dimensions expand at uniform rates relative to each other. This indicates that the dataset consists of a single, well-defined age class or cohort experiencing stable environmental conditions.

3. Fin Anchor Topography: Pre-Dorsal Line (\(PDL/SL \approx 47.2\%\)): The dorsal fin maps precisely slightly anterior to the exact center point of the body length. This provides optimized stabilization during yawing motions.

Pre-Anal Tail Region (\(PAL/SL \approx 80.3\%\)): The tail segment accounts for approximately 19.7% of total structural execution, reserving the rear fifth of the body for propulsion mechanics.

3. Ocular & Cephalic Shifts: The Eye Diameter vs. Head Size (\(ED/HL = 0.266\)) indicates that the eyes occupy a significant portion (roughly 26.6%) of the total head length. A high eye-to-head ratio points toward visually oriented foraging behavior. Specimen No. 51 shows an outlier leap in eye diameter (\(0.7\text{ cm}\)), which may indicate a recording artifact or localized morphological variation.

Morphometric studies are also conducted on other species of *Nemacheilus*. Dobriyal and Bahuguna (1987) studied *N. montanus* collected from Khanda Stream. Dobriyal et al. (1988) examined *N. denisonii* and *N. multifasciatus* from the same stream. All these reports observed a single stock of population. Earlier, Dobriyal (2013) studied the morphometrics of *Lepidocephalus guntea* from the Mandal River and opined that these characters are an indicator of taxonomy and stock assessment studies. Uniyal et al. (2004) investigated morphometric characters in the dark mahseer (*Tor chelynoides*) from the Western Nayar River and reported its significance in fish identification.

Meristic characters are also considered important in the identification of fish species (Table 9).

A comparison of the meristic characterization on *N. rubidipinnis* observed by Day (1878), Talwar and Jhingran (1991), and the present investigation is presented in Table 9. There is no any significant difference between all observations.

Table 9: Comparison of meristic characters of *Nemacheilus rubidipinnis* (Blyth) with the findings of other workers.

SN	Workers	Barbels	Dorsal fin (Spine/ Rays)	Pectoral fin (Spine/ Rays)	Pelvic fin (Spine/ Rays)	Anal fin (Spine/ Rays)	Caudal fin (Spine/ Rays)
1	Day (1878)	3 pairs	2/13-14	14	8	2/5	19
2	Talwar & Jhingran (1991)	NM	3/14-15	1/12	1/7	2/5	NM*
3	Present study (2024-25)	3 pairs	2/11-12	1/9-10	8	1/5	18-19

* Not Mentioned

Principal Component Analysis (PCA) was performed using size-adjusted morphometric variables to eliminate the influence of overall body size and emphasize shape variation among specimens. The PCA score plot revealed the distribution of individuals along the first two principal components (PC1 and PC2), which together accounted for a substantial proportion of the total morphometric variation. (Fig 5)

. The scatter of specimens in the ordination space indicated moderate variability in body shape among individuals. Most specimens formed a central cluster, suggesting a high degree of morphological similarity within the population. The absence of clearly separated groups in the PCA space indicates that the sampled individuals belong to a relatively homogeneous stock with limited morphometric differentiation.

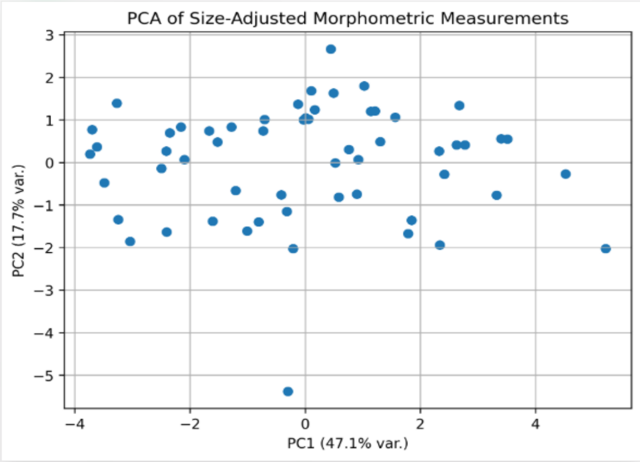

Fig 5: PCA of size-adjusted morphometric measurements

However, a few specimens were positioned away from the main cluster, reflecting individual variation in certain morphometric traits.

The dispersion along PC1 was greater than along PC2, suggesting that PC1 represented the major axis of shape variation within the population. Traits with high loadings on PC1 and PC2 contributed most strongly to the observed morphological differences and may be associated with variation in body depth, head proportions, and fin positioning. Such variation may arise from environmental influences, ontogenetic changes, feeding ecology, or phenotypic plasticity.

The Principal Component Analysis (PCA) performed on size-adjusted morphometric variables The Principal Component Analysis (PCA) performed on size-adjusted morphometric variables revealed the major patterns of shape variation among the examined fish specimens. The first principal component (PC1) explained **42.76%** of the total variation, while the second principal component (PC2) accounted for **18.43%**, together explaining **61.19%** of the overall morphometric variability.

The PCA biplot (Fig 6) shows the distribution of specimens in the PC1–PC2 space along with the contribution of individual morphometric traits represented by loading vectors. Specimens are dispersed around the origin, indicating moderate morphological variation within the population, but the overlap among groups suggests overall morphological similarity and the absence of distinct morphotypes.

Traits such as Head Length (HL), Maximum Body Depth (MBD), Pre-Dorsal Length (PDL), and Pre-Pectoral Length (PPL) exhibited strong positive loadings on PC1, indicating that these measurements contributed substantially to the primary axis of morphological variation. In contrast, Snout Length (SNL), Pre-Anal Length (PAL), and Post-Orbital Length (POL) showed negative associations with PC1. The second principal component (PC2) was mainly influenced by Eye Diameter (ED), Caudal Length (CL), and Post-Orbital Length (POL), which loaded positively on this axis, whereas Pre-Ventral Length (PVL), Pre-Pectoral Length (PPL), and Pre-Anal Length (PAL) were negatively associated with PC2. This suggests that variation in head and eye-related characters primarily contributed to the secondary axis of differentiation.

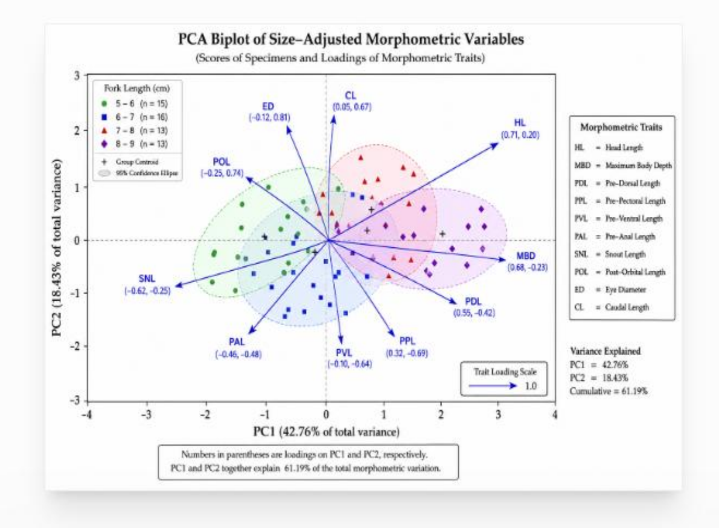

Figure 6. PCA biplot of size-adjusted morphometric variables showing the distribution of fish specimens and the loading vectors of morphometric traits. PC1 and PC2 explained 42.76% and 18.43% of the total variance, respectively, accounting for 61.19% of the overall morphometric variation. The length and direction of vectors indicate the magnitude and nature of each trait's contribution to the observed morphological variation.

The close orientation of some vectors indicates positive correlations among corresponding traits, while vectors pointing in opposite directions suggest negative relationships. Overall, the PCA demonstrates that variation in body depth, head dimensions, and fin positions are the principal factors governing morphological differentiation within the studied population.

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