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Schizothorax esocinus (Heckel, 1838) in Dal Lake and Jhelum River: physiological traits and population trends in the Kashmir Himalayas

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Abstract

This study investigated the physico-chemical characteristics of Dal Lake and the Jhelum River along with evaluation of the morphometric traits, biometric growth parameters, biological indices, physiological attributes, and biochemical profiles of *Schizothorax esocinus* populations inhabiting these freshwater systems. The physico-chemical assessment revealed distinct environmental differences between the two habitats, with Dal Lake characterised by relatively warmer water, greater hardness, near-neutral pH, and comparatively lower dissolved oxygen levels than the Jhelum River. Correspondingly, fish from the Jhelum River exhibited greater body size and weight, whereas individuals from Dal Lake showed comparatively smaller morphometric dimensions. Biometric growth analysis indicated positive allometric growth in both populations, with notable variations in growth patterns between the two habitats. Biological indices differed between sites and sexes, reflecting habitat specific reproductive and metabolic conditions. Although haematological parameters showed no marked gender-based differences; however, site and age-related variations were evident, suggesting the influence of environmental conditions on physiological status. Overall, the findings highlight habitat driven differences in environmental quality and associated biological responses in *S. esocinus*, providing valuable insights for conservation planning and sustainable fisheries management in the freshwater ecosystems of Kashmir.

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Introduction

The Kashmir Himalayas host a diverse and ecologically significant ichthyofaunal assemblage, within which *Schizothorax esocinus* (Heckel, 1838) occupies a prominent position as a commercially and ecologically valuable cold-water fish species (Bharti *et al.*, 2023). Commonly known as snowtrout, *S. esocinus* is endemic to the riverine and lacustrine systems of the Trans-Himalayan region and plays a vital role in regional fisheries while also serving as an indicator species for assessing aquatic ecosystem health (Bhatt and Manish, 2023). The Kashmir Himalayan region supports a rich diversity of *Schizothorax* species that have evolved into distinct populations under unique ecological constraints, making them particularly sensitive to environmental changes.

Dal Lake and the Jhelum River represent two contrasting yet interconnected freshwater ecosystems within Kashmir, each characterised by distinct hydrobiological conditions. Dal Lake is a eutrophic lacustrine system subjected to substantial anthropogenic pressures, including nutrient enrichment, pollution, and habitat modification. In contrast, the Jhelum River is a lotic system with relatively unidirectional flow dynamics that influence habitat structure, water quality, and fish population processes (Wani *et al.*, 2019). Such habitat level differences are known to shape physiological performance, growth patterns, and population dynamics of resident fish species. *Schizothorax esocinus* is typically associated with well oxygenated and relatively pollution free waters and is therefore particularly vulnerable to habitat degradation and environmental stressors (Chandra *et al*., 2023).

Accurate assessment of population structure and ecological status of *S. esocinus* requires robust tools for species identification and population discrimination. Sun *et al*. (2023) emphasised that reliable species identification is fundamental for ecological assessment and conservation planning, and that integrative approaches combining morphological and molecular methods provide greater resolution. Among these, morphometric and meristic analyses remain indispensable for detecting intra and interspecific variations and for understanding population differentiation in natural fish stocks (Fahmi-Ahmad *et al.,* 2020).

At the population level, biometric analyses such as length–weight relationships and condition factor (Kn) provide essential information on fish growth, nutritional status, and habitat suitability (Santos *et al*., 2022). The relative condition factor (Kn), derived from length-weight relationships, is widely used as an indicator of environmental suitability for fish growth (Thakur *et al*., 2022). Kn values close to unity generally reflect favourable environmental conditions, whereas deviations may indicate ecological stress caused by pollution, food limitation, or habitat degradation (Ragheband Evelyn, 2023).

Biological and physiological indices further enhance understanding of habitat–fish interactions. Feeding intensity and energy allocation are commonly assessed using indices such as the gastro-somatic index (GSI), while reproductive status and metabolic condition are evaluated using the gonadosomatic index (GSI) and hepatosomatic index (HSI) (Kurbah *et al*., 2018; Pham *et al*., 2019). In addition, haematological and serum biochemical parameters including haemoglobin concentration, erythrocyte and leukocyte counts, haematocrit, glucose, protein levels, cholesterol profiles, and enzyme activities are widely recognised as sensitive biomarkers of fish health under varying environmental conditions (Ahmad *et al*., 2019; Tani *et al*., 2022). Variations in these parameters often reflect habitat quality, environmental stress, and overall physiological condition.

Despite its ecological and economic importance, *S. esocinus* is increasingly threatened by pollution, habitat degradation, and climate-induced environmental changes in Kashmir freshwater systems. Although previous studies have examined individual aspects of *Schizothorax* biology, comprehensive evaluations integrating habitat level physico-chemical conditions with morphometric, biometric, biological, and haematological responses of *S. esocinus* across contrasting freshwater environments remain limited. This study addresses this gap by comparatively assessing water quality, population structure, growth patterns, biological indices, and haematological profiles of *S. esocinus* inhabiting Dal Lake and the Jhelum River. It is hypothesised that significant variations exist between the two populations, reflecting differences in environmental conditions. By integrating environmental and biological indicators, the present study advances understanding of habitat suitability and population health of *S. esocinus*, contributing to informed conservation strategies and sustainable fisheries management in the Kashmir Himalayan region.

Materials and methods

Study area

A total of forty *S. esocinus* (Fig. 1) specimens (n=40; males=20, females=20) were examined during the study period from September 2022 to March 2023. Preliminary reconnaissance sampling was conducted in September 2022 to confirm species availability and size-class representation. Live specimens used for physiological and haematological analyses were collected between October and December 2022 from two ecologically distinct sites in the Kashmir Valley. Following completion of live specimen analyses, the same individuals were subsequently utilised for morphometric and biometric measurements during the later phase of the study (January–March 2023).

Samples were obtained from sites selected based on differences in habitat characteristics, accessibility, and hydrological conditions. To facilitate balanced age and habitat-wise comparisons, an age structured sampling design was adopted, comprising four age classes with 10 individuals per age group. Within each age class, equal representation was maintained by collecting five individuals from Dal Lake and five from the Jhelum River, resulting in 20 specimens from each habitat.

Site 1 is located along the Jhelum River at Chattabal in the Qamarwari region of Srinagar City (34° 05’ 19.68" N; 74° 47’ 26.52" E; Fig.2). Site 2, referred to as Hazratbal, is situated in the Hazratbal basin of Dal Lake (34° 07’ 55.92" N; 74° 50’ 31.92" E; Fig. 2).

Fig. 1. *Schizothorax esocinus*

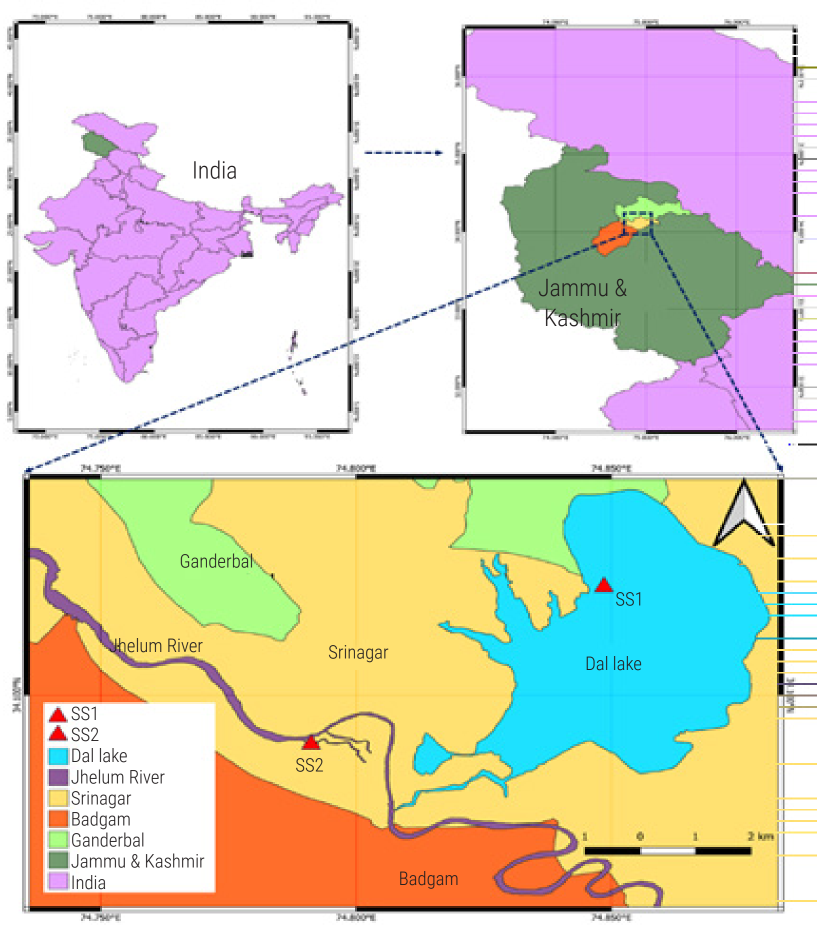

Fig. 2. Map showing the two sampling sites of *S. esocinus* in the Kashmir Valley

Age classification

Age classification of *S. esocinus* was performed using length-based grouping following Mir *et al*. (2019), in which age classes were established through otolith-based validation and linked to specific length ranges. The length intervals proposed by Mir *et al.* (2019) were applied, as they were developed for the same species from comparable Himalayan freshwater systems. Fish were assigned to four age classes based on total length, and the number of individuals per age class (Table 1).

Analysis of water quality parameters

Water quality parameters such as pH, temperature, dissolved oxygen, hardness, and alkalinity were measured at both sampling sites over the study period following standardised procedures (APHA, 2017).

Table 1. Length-based age classification and sample distribution of *S. esocinus*

Age class	Length range (mm)	No. of individuals
1+	133.48–237.70	n = 10
2+	243.66–256.24	n = 10
3+	285.06–327.32	n = 10
4+	348.89–415.56	n = 10

Morphometric and meristic characteristics

Morphometric characteristics

Morphometric measurements were obtained using a standard fish measuring board and a vernier caliper, ensuring precision to the nearest millimeter. The methodology followed the guidelines of Lagler *et al.* (1956), with reference to updated protocols by Froese (2006). A total of 12 morphometric parameters were recorded for each specimen, including total length (TL), standard length (SL), fork length (FL), pre-dorsal length (PDL), pre-anal length (PAL), pre-pelvic length (BPFL), pre-pectoral length (BDFL), eye diameter (ED), head length (HL), snout length (SnL), body depth (BD), and caudal fin length (CFL). All measurements were recorded in millimeters.

Meristic characteristics

Five meristic traits were examined for each specimen following standard laboratory procedures. Fin ray counts were conducted under adequate illumination and gentle manipulation using fine pins and dissection needles. The meristic characters assessed included dorsal fin rays (DFR), pectoral fin rays (PCFR), pelvic fin rays (PLFR), anal fin rays (AFR), and caudal fin rays (CFR).

Length-weight relationship

The length-weight relationship was analysed using the logarithmic transformation equation: $W = aL^b$, initially proposed by Hile (1936) and later refined by Froese (2006). In this equation, W represents the total weight of the fish (g), L denotes the total length (mm), a and b correspond to the initial growth constant and regression coefficient, respectively.

To evaluate the overall robustness or condition of the fish, the ponderal index (condition factor) was calculated using Fulton's formula:

Ponderal index (K) = $W \times 10^5 / (L^3)$

where, W is the total weight (g), L is the total length (mm), and the factor 10^5 is included to normalise the condition factor value.

Hepatosomatic, gonadosomatic and gastrosomatic indices

For analysis of hepatosomatic index (HSI), gonadosomatic index (GSI), and gastrosomatic index (GaSI). the total length and weight were measured with a precision to 0.01mm and 0.01 g, respectively. Following measurements, the fish were thoroughly washed, cleaned, and dissected with sterile blades to extract the target organs (liver for HSI, gonads for GSI, and gut for GaSI) in their intact form. The excised organs were then carefully weighed to calculate their respective indices.

HSI was calculated following Rajaguru (1992) and Richter *et al.* (2000) using the formula:

HSI (%) = Liver weight (g)/Total body weight x100

GSI was determined following Desai (1970) using the formula:

GSI (%) = Gonad weight (g)/Total body weight x100

GaSI was assessed according to Bhatnagar and Karamchandani (1970) using the formula:

GaSI (%) = Gut weight (g)/Total body weight x100

Physiological parameters

Haematological parameters

Wild-caught fish samples were collected from Dal Lake and the Jhelum River and transported live to the Fisheries Resource Management Laboratory in water from their respective habitats. The fish were allowed to acclimatise to the laboratory conditions for 5–6 h to minimise handling stress. Prior to blood collection, the fish were anesthetised using clove oil at a concentration of 250 mg l^{-1}. Blood samples were collected from the caudal vein using a sterile 2 ml hypodermic syringe fitted with a 24 gauge needle and transferred to EDTA-coated vials as an anticoagulant. The samples were subsequently analysed for haematological parameters following standard procedures (Ahmad and Sheikh, 2019).

The haematological parameters assessed included haemoglobin concentration (Hb), total erythrocyte count (RBC), total leukocyte count (WBC), and haematocrit (Hct). Haemoglobin concentration was estimated using Sahli's method. Total RBC and WBC counts were determined using a Neubauer haemocytometer following standard dilution and counting techniques (Nutt and Herrick, 1952; Parida *et al*., 2012). Haematocrit was measured using Wintrobe's method (Wedemeyer *et al*., 1983). Erythrocyte indices *viz.* mean corpuscular volume (MCV), mean corpuscular haemoglobin (MCH), and mean corpuscular haemoglobin concentration (MCHC), were calculated using standard equations as described by Dacie and Lewis (1975).

Serum biochemical parameters

Blood samples collected in non-heparinised tubes were centrifuged at 7000 rpm for 7 min to separate the serum. The extracted serum was stored at −20°C until further analysis. Serum biochemical parameters were estimated using standard colourimetric methods: total protein by the Biuret method (Strickland *et al*., 1961), albumin by the bromocresol green method (Gornall *et al.*, 1949), triglycerides by the GPO–POD method Trinder, 1969b, blood glucose by the GOD–POD method (Trinder, 1969a), and urea by the Berthelot method (Chaney and Marbach, 1962). Globulin concentration was calculated as the difference between total protein and albumin

Statistical analysis

Statistical analyses were performed using SPSS (Version 25.0) to evaluate the physiological traits, population characteristics, and associated parameters of *S. esocinus*. Prior to analysis, all datasets were examined for compliance with the assumptions of parametric tests. Normality of data distribution was assessed using the Shapiro–Wilk test, and homogeneity of variances was evaluated using Levene's test. Data that met these assumptions were subjected to parametric statistical analyses. Physico-chemical water quality parameters, including pH, temperature, dissolved oxygen, hardness, and alkalinity, were compared between Dal Lake and the Jhelum River using independent sample t-tests. Differences in morphometric (*e.g.*, total length, standard length) and meristic characteristics (*e.g.*, dorsal fin rays, pectoral fin rays) between fish populations were assessed using one-way analysis of variance (ANOVA). The length–weight relationship was examined using linear regression and Pearson's correlation analysis to evaluate growth patterns across habitats. Biological indices, including the HSI, GSI, and GaSI, were analysed using one-way ANOVA, followed by Duncan's multiple range test to identify significant differences between populations from the two study sites. Principal component analysis (PCA) was applied to morphometric variables to identify the principal components explaining variation among populations. Haematological and serum biochemical parameters were compared between populations using independent sample t-tests. For all statistical tests, a significance level of $p<0.05$ was adopted, and results were expressed as statistically significant when this threshold was met.

Results

Water quality parameters

Water quality parameters (Table 2) showed an average pH of 7.17±0.12 in Dal Lake and 7.87±0.17 in the Jhelum River. Temperature readings were 12.93±1.33°C for Dal Lake and 8.60±1.30°C for the Jhelum River, both within standard ranges. Dissolved oxygen levels were recorded at 6.60±0.22 in Dal Lake and 7.31±0.16 in the Jhelum River. Water hardness values were comparable between Dal Lake (156.53±12.82) and the Jhelum River (153.63±7.81), whereas total alkalinity showed a marked difference, with Dal Lake at 119.70±11.82 and the Jhelum River at 206.50±10.86. These findings offer valuable insights into the ecological health of water bodies, supporting conservation and management efforts.

Table 2. Water quality parameters recorded for Dal Lake and Jhelum River during the study period (Mean±SE)

Parameters	Dal Lake	Jhelum River
pH	7.17±1.26	7.87±0.17
Temperature	12.93±1.33	8.60±1.30
Dissolved oxygen	6.60±0.22	7.31±0.16
Hardness	156.53±12.82	153.63±7.81
Alkanity	119.70±11.82	206.50±10.86

Morphometric characteristics

Significant sexual dimorphism in total length (TL) was observed in *S. esocinus*, with females (283.96±17.13 mm; n = 20) attaining a higher mean TL than males (259.81±19.32 mm; n=20) ($p<0.05$) (Fig. 3a). However, no significant sex-related differences were detected in other morphometric traits ($p>0.05$). Habitat-wise comparison showed slightly higher mean TL in fish from the Jhelum River (275.96±18.53 mm; n = 20) compared to Dal Lake (267.80±18.35 mm; n = 20); however, this difference, along with other morphometric parameters, was not statistically significant ($p>0.05$) (Fig. 3b), indicating limited habitat-related morphological variation. Age-wise analysis revealed a clear and significant increase in TL and associated morphometric parameters with advancing age ($p<0.05$). Mean TL increased from 165.42±12.70 mm in the 1+ age group to 377.69±6.68 mm in the 4+ age group, with similar ontogenetic trends observed for SL, FL, CFL, PAL, PDL, PPVL, PPCL, BD, HL, SNL, and ED (Fig. 3c). Overall, while sexual dimorphism was evident only in TL, other morphometric traits remained consistent across sexes and habitats. Age emerged as the dominant factor influencing body dimensions in *S. esocinus*. The observed sex-related difference in TL was interpreted cautiously due to the relatively small sample size.

Meristic characteristics

Meristic characteristics of *S. esocinus*, including dorsal fin rays (DFR), pectoral fin rays (PCFR), pelvic fin rays (PLFR), anal fin rays (AFR), and caudal fin rays (CFR), are presented in Fig 4a-c**.** Overall, meristic traits exhibited narrow ranges and substantial overlap across sex, habitat, and age groups. Sex-wise analysis showed no significant differences in DFR, PCFR, PLFR, or AFR between males and females ($p > 0.05$) (Fig. 4a). A statistically significant difference was detected in CFR counts; however, the observed variation was small, with mean values differing by less than one ray. Habitat-wise comparison between Dal Lake and Jhelum River populations revealed no significant differences in DFR, PCFR, PLFR, or AFR ($p>0.05$) (Fig. 4b). Minor differences in CFR counts were observed, but values remained within overlapping ranges. Age-wise variation in meristic traits is illustrated in Fig 4c. Differences in CFR counts were recorded among age classes ($p<0.05$), whereas other meristic characters showed consistent counts across age groups. Overall, meristic characters of *S. esocinus* remained largely conserved across sex and habitat, with limited variation observed in caudal fin ray counts.

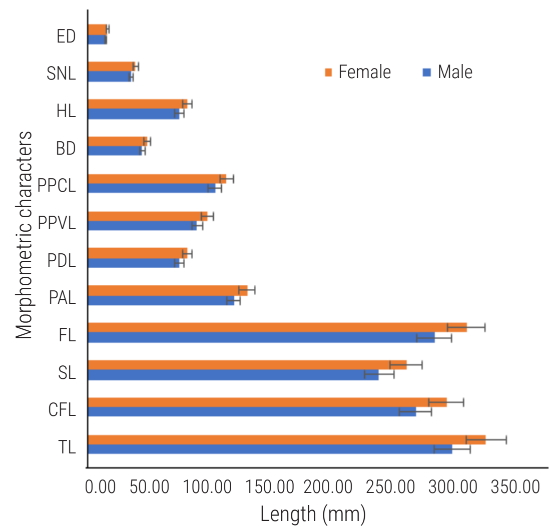

Fig. 3a. Morphometric differences between male and female species of *S. esocinus*

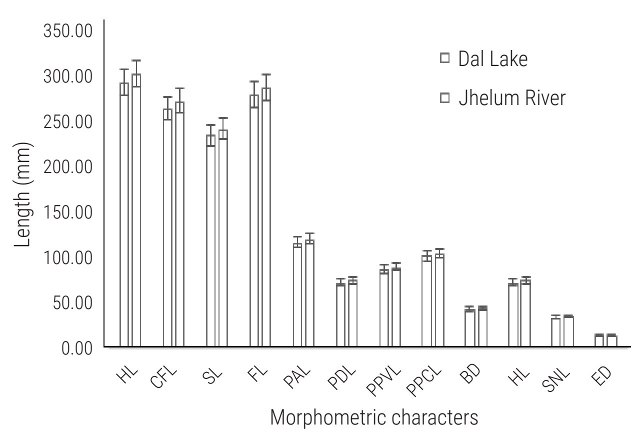

Fig. 3b. Comparison of morphometric features of *S. esocinus* between Dal Lake and Jhelum River

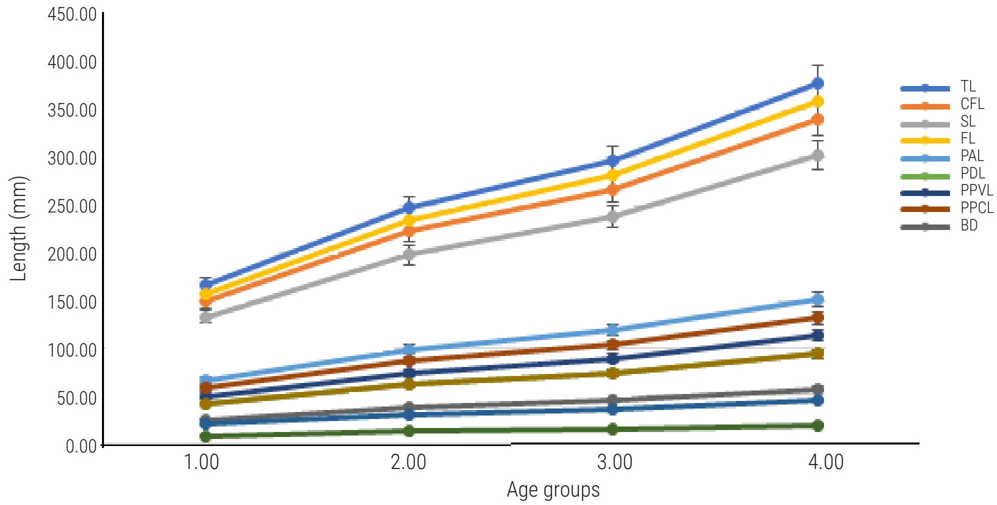

Fig 3c. Age-wise distribution of morphometric characters of *S. esocinus*

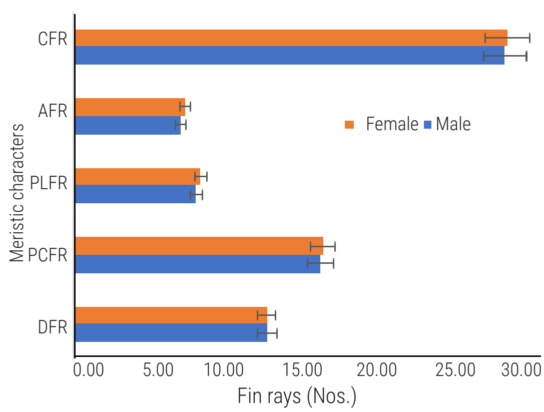

Fig. 4a. Meristic differences between male and female samples of *S. esocinus*

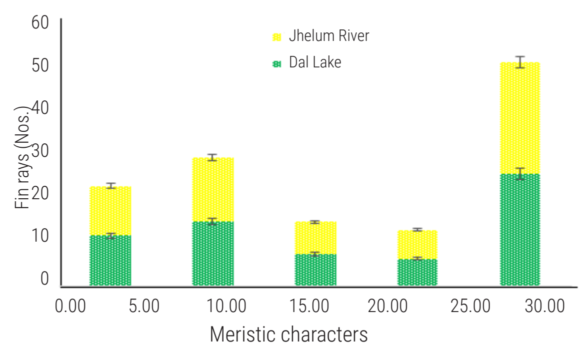

Fig.4b. Comparison of meristic characters of *S. esocinus* between Dal Lake and Jhelum River

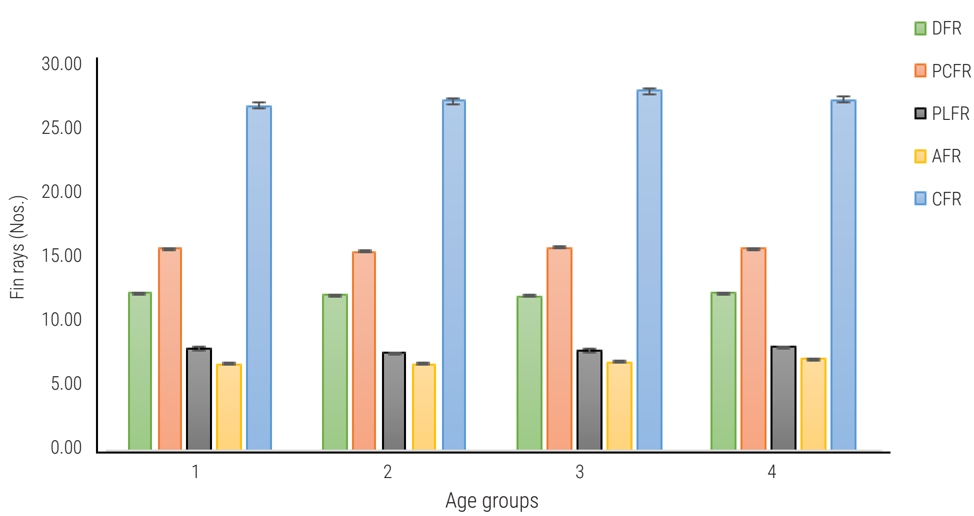

Fig. 4c. Age-wise distribution of meristic characters of *S. esocinus*

Biometric growth parameters and biological indices

Length-weight relationship (LWR) parameters

The length–weight relationship (LWR) of *S. esocinus* was estimated separately for site-wise, sex-wise, and age-wise groupings (Table 3). In all cases, the regression coefficients showed a strong fit between total length and total weight, with coefficients of determination (R^2) ranging from 0.90 to 0.98. Site-wise analysis indicated b values of 1.92 for Dal Lake and 1.95 for the Jhelum River. Although the b value was marginally higher in the Jhelum River population, both estimates were well below 3, indicating negative allometric growth at both sites. Sex-wise LWRs revealed b values of 2.01 for males and 1.70 for females. Both sexes exhibited negative allometric growth, with females showing comparatively lower b values, suggesting reduced weight gain relative to length increase. Age-wise analysis showed variation in b values across age classes, ranging from 2.25 (2+ age group) to 2.68 (4+ age group). Despite this variation, all age groups consistently displayed b values <3, confirming negative allometric growth throughout ontogenetic development. Higher R^2 values in older age classes indicate a stronger length–weight relationship with advancing age. Overall, the LWR analysis demonstrates consistent negative allometric growth in *S. esocinus* across habitats, sexes, and age groups, with only modest numerical differences among categories.

Condition factor (K)

The condition factor (K) of *S. esocinus* was evaluated across sexes, habitats, and age groups (Table 4). Mean K values were comparable between males (1.09±0.10) and females (1.12±0.09), with no statistically significant difference ($p>0.05$). Similarly, no significant difference in K was observed between specimens from Dal Lake (1.10±0.09) and the Jhelum River (1.10±0.10) ($p>0.05$). In contrast, condition factor varied significantly among age groups ($p<0.05$). The highest mean K was recorded in the 1+ age group (1.52±0.08), followed by a progressive decline in subsequent age classes: 2+ (1.34±0.07), 3+ (1.00±0.05), and 4+ (0.54±0.04). This pattern indicates age-related variation in body condition within the population. Overall, the results indicate that condition factor did not differ significantly with sex or habitat, but showed a clear and significant association with age in *S. esocinus*.

HSI, GSI and GaSI

The biometric growth parameters and biological indices analysis of male (n=20) and female (n=20) specimens of *S. esocinus* revealed no significant differences in HSI, GSI and GaSI, between the sexes ($p>0.05$) (Table 5). However, a slight trend suggesting potential differences in GSI was observed ($p=0.06$), with females showing a marginally higher mean value (3.58±2.59) compared to males (3.32±2.81). Similarly, comparisons between specimens from Dal Lake (n=20) and the Jhelum River (n=20) indicated no statistically significant differences in HSI, GSI or GaSI, ($p>0.05$). The mean values for GSI were 3.50±2.81 in Dal Lake and 3.39±2.60 in the Jhelum River, while GaSI values were 14.41±8.56 and 14.14±7.80, respectively. HSI values also remained comparable between the two sites, with means of 10.44±6.37 in Dal Lake and 10.23±5.75 in the Jhelum River. However, when analysing biometric growth parameters and biological indices across different age groups, significant variations were found in HSI, GSI and GaSI, ($p<0.05$). HSI exhibited progressive increase with age (Fig. 5). HSI, GSI and GaSI across different age groups ranged

Table 3. Estimated LWRs parameters of *S. esocinus*

Parameters	n	TL (cm)		TW (g)		Regression parameters				
		Min	Max	Min	Max	a	95% CI a	b	95% CI b	R^2
Site-wise										
Dal Lake	20	13.54	39.43	32.56	307.15	0.0039	0.0037-0.0041	1.92	1.90-1.94	0.91
Jhelum River	20	13.35	41.56	42.14	425.94	0.0035	0.0033-0.0036	1.95	1.93-1.97	0.94
Sex-wise										
Male	20	13.48	38.96	32.56	315.67	0.0023	0.0021-0.0024	2.01	1.99-2.03	0.90
Female	20	15.78	41.56	50.20	425.94	0.0145	0.0143-0.0146	1.70	1.68-1.72	0.96
Age-wise										
1+	10	13.35	23.77	32.56	198.56	0.0012	0.00118 – 0.00121	2.65	2.63-2.67	0.92
2+	10	24.37	25.62	155.82	276.50	0.0002	0.0000864 - 0.0001196	2.25	2.23-2.27	0.93
3+	10	28.51	32.73	174.06	341.48	0.0011	0.0011 – 0.0012	2.53	2.51-2.55	0.98
4+	10	34.89	41.56	245.25	425.94	0.0001	0.0001804 - 0.0002196	2.68	2.66-2.70	0.95

n: Sample size; TL: Total length; TW: Total weight; a: Intercept; b: Slope; CI: Confidence intervals; R^2: Co-efficient of determination; *Estimate is tentative

Table 4. Condition factor (K) across various sites, sexes, and age groups of *S. esocinus*

		Condition factor (K)
Sex	Male	1.09±0.10
	Female	1.12±0.09
Site	Dal Lake	1.10±0.09
	Jhelum River	1.10±0.10
Age	1+	1.52±0.08
	2+	1.34±0.07
	3+	1.00±0.05
	4+	0.54±0.04
	Over All	1.10±0.07

Table 5. HSI, GSI and GaSI across various sites and sexes of *S. esocinus*

Parameters	GaSI	GSI	HSI
Sex			
Male	13.82 ± 1.93	3.32 ± 0.63	9.93 ± 1.42
Female	14.73 ± 1.72	3.58 ± 0.58	10.73 ± 1.28
Site			
Dal Lake	14.41 ± 1.91	3.5 ± 0.63	10.44 ± 1.42
Jhelum River	14.14 ± 1.75	3.39 ± 0.58	10.23 ± 1.29

from 4.24±1.69 in age 1 to 18.30±2.66 in age 4. Similarly, GaSI increased from 6.18±2.11 in age 1 to 25.10±3.45 in age 4, while GSI showed a notable rise from 0.69±0.38 in age 1 to 7.10±1.07 in age 4. These findings highlight significant age-related variations in biometric growth parameters and biological indices in *S. esocinus*, suggesting that physiological and reproductive changes intensify with increasing age (Fig. 5).

Physiological parameters

Haematological parameters

Hematological parameters of *S. esocinus* did not differ significantly between males and females (p>0.05; Table 6). Mean haemoglobin (Hb) levels were 6.35±0.26 g dl^{-1} in males and 6.39±0.27 g dl^{-1} in females. Red blood cell (RBC) counts were 2.43±0.14×10^{6} mm^{-3} in males and 2.36±0.16×10^{6} mm^{-3} in females, while white blood cell (WBC) counts were 6.53±0.29 and 5.91±0.25×10^{4} mm^{-3}, respectively in males and females. Hematocrit (Hct) values were 46.81±1.53% in males and 46.37±1.44% in females. Erythrocyte indices (MCV, MCH, and MCHC) and leukocyte differentials also showed no statistically significant sex-based differences (p>0.05). Site-wise comparison revealed no significant differences in haematological parameters between Dal Lake and the Jhelum River populations (p>0.05; Table 7). Hb concentration was 6.20±0.26 g dl^{-1} in Dal Lake and 6.45±0.27 g dl^{-1} in the Jhelum River. RBC counts were 2.40±0.16 and 2.38±0.13×10^{6} mm^{-3}, while WBC counts were 6.28±0.23 and 6.15±0.31×10^{4} mm^{-3}, respectively. Hematocrit values, erythrocyte indices, R/W ratio, and leukocyte profiles did not differ significantly between sites.

In contrast, several haematological parameters differed significantly among age groups (Table 7). Haemoglobin concentration ranged from 7.06±0.40 g dl^{-1} in age group 1+ to 5.58±0.21 g dl^{-1} in age group 2+ ($p < 0.05$). RBC counts declined from 2.76 ± 0.21×10^{6} mm^{-3} (1+) to 2.01±0.20×10^{6} mm^{-3} (3+) ($p<0.05$). Haematocrit values decreased from 57.12±0.50% in the youngest group to 41.04±0.34% in the oldest group ($p<0.05$). The R/W ratio and MCHC also showed significant age-related variation ($p<0.05$), whereas MCH and MCV did not differ significantly among age groups ($p>0.05$). Leukocyte

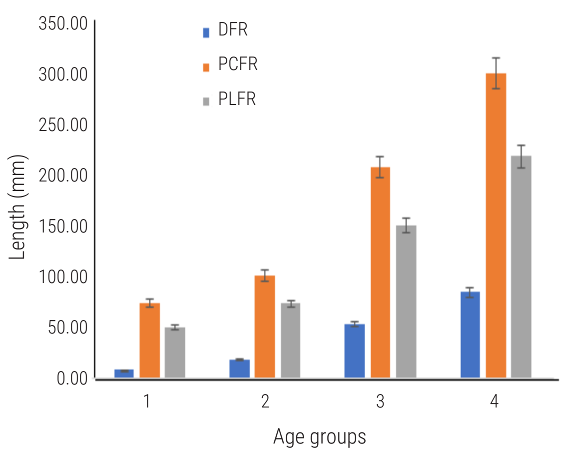

Fig. 5. HSI, GSI and GaSI across different age group of *S. esocinus*

Table 6. Haematological parameters of *S. esocinus* by sex and site

Parameter	Male	Female	Dal Lake	Jhelum River
Hb (g dl^{-1})	6.35±0.26	6.39±0.27	6.2±0.26	6.45±0.27
RBC (10^{6} mm^{-3})	2.43±0.14	2.36±0.16	2.4±0.16	2.38±0.13
WBC (10^{4} mm^{-3})	6.53±0.29	5.91±0.25	6.28±0.23	6.15±0.31
R/W	0.39±0.03	0.41±0.03	0.39±0.03	0.40±0.02
Hct (%)	46.81±1.53	46.37±1.44	46.15±1.42	47.01±1.54
MCH	28.33±2.46	29.83±2.83	28.97±2.94	29.18±2.34
MCV	204.54±12.97	211.97±13.43	209.2±15.22	207.3±10.86
MCHC	13.80±0.69	13.91±0.63	13.75±0.61	13.94±0.70
Neutrophil (%)	61.85±2.51	61.10±2.57	61.45±2.56	61.50±2.52
Monocytes (%)	31.35±1.84	31.20±1.77	31.15±1.83	31.40±1.76
Eosinophils (%)	1.84±0.10	1.88±0.08	1.86±0.09	1.85±0.08
Lymphocytes (%)	5.62±0.74	6.18±0.91	6.09±0.80	5.70±0.84

Table 7. Haematological parameters of *S. esocinus* by age

Parameter	Age 1	Age 2	Age 3	Age 4	Total	Significance
Hb (g dl^{-1})	7.06±0.40	5.58±0.21	6.24±0.38	6.59±0.37	6.37±0.19	p < 0.05
RBC (nx10^{6} mm^{-3})	2.76±0.21	2.61±0.19	2.01±0.20	2.19±0.20	2.39±0.11	p < 0.05
WBC (nx10^{4} mm^{-3})	6.06±0.41	6.27±0.44	6.32±0.35	6.23±0.40	6.22±0.19	p > 0.05
R/W	0.48±0.05	0.43±0.04	0.32±0.04	0.36±0.03	0.40±0.02	p < 0.05
Hct (%)	57.12±0.50	46.08±0.52	42.11±0.26	41.04±0.34	46.59±1.04	p < 0.05
MCH (fl)	27.22±3.28	22.05±1.34	34.15±4.68	32.90±3.87	29.08±1.86	p > 0.05
MCV (pg)	219.59±19.27	182.30±9.20	228.68±22.38	202.45±19.54	208.25±9.23	p > 0.05
MCHC (%)	12.38±0.72	12.13±0.48	14.85±0.96	16.06±0.91	13.85±0.46	p < 0.05
Neutrophils (%)	47.50±0.50	55.70±0.60	66.00±0.47	76.70±0.56	61.48±1.77	p < 0.05
Monocytes (%)	42.50±0.50	33.70±0.70	26.80±0.42	22.10±0.53	31.28±1.26	p < 0.05
Eosinophils (%)	1.34±0.05	1.70±0.05	2.20±0.05	2.18±0.06	1.86±0.06	p < 0.05
Lymphocytes (%)	8.66±0.65	8.90±0.20	5.00±0.82	1.02±0.24	5.90±0.58	p < 0.05

differentials exhibited significant age-related differences ($p<0.05$), with neutrophil percentages increasing from 47.50±0.50% (1+) to 76.70±0.56% (4+), while monocyte percentages decreased correspondingly.

Biochemical parameters

Serum biochemical parameters did not differ significantly between males and females ($p>0.05$; Table 8). Mean total protein concentrations were 6.32±0.65 g%, albumin 3.74±0.57 g%, and globulin 2.58±0.45 g%. Glucose, urea, and triglyceride levels also showed no statistically significant sex-based variation. Site-wise comparison indicated statistically significant variation in globulin levels between Dal Lake and Jhelum River populations ($p<0.05$), whereas total protein, albumin, albumin/globulin ratio, glucose, urea, and triglycerides did not differ significantly between sites ($p>0.05$). Age-wise analysis revealed significant variation in glucose and triglyceride concentrations ($p<0.05$) (Fig. 6a). Mean glucose levels ranged from 67.67±17.08 mg dl^{-1} in age group 1+ to 53.45±6.50 mg dl^{-1} in age group 4+. Triglyceride concentrations varied from 145.32±12.71 mg dl^{-1} (2+) to 97.55±14.84 mg dl^{-1} (4+). Other biochemical parameters, including total protein, albumin, globulin, albumin/globulin ratio, and urea, did not show statistically significant age-related differences ($p>0.05$) (Fig. 6b).

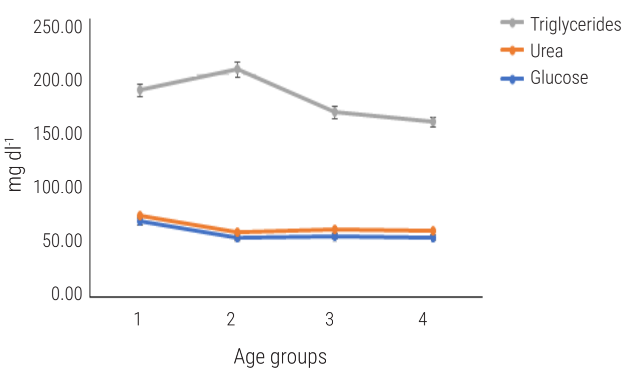

Fig. 6a. Biochemical parameters (glucose, urea and triglycerides) of *S. esocinus* by age

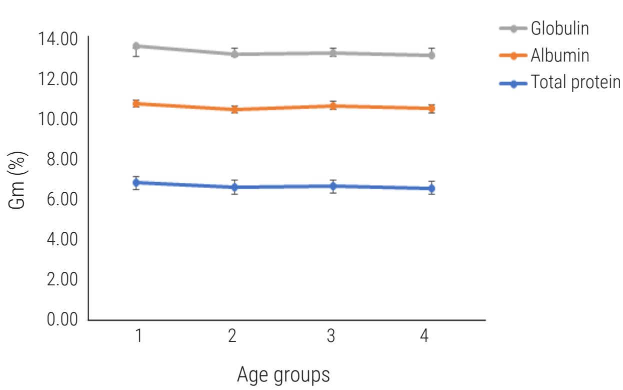

Fig. 6b. Biochemical parameters (globulin, albumin and total protein) of *S. esocinus* by age

Table 8. Haematological parameters of *S. esocinus* by sex and site

Parameter	Male	Female	Dal Lake	Jhelum River
Total protein (g %)	6.20±0.16	6.44±0.13	6.31±0.17	6.34±0.12
Albumin (g %)	3.65±0.12	3.84±0.14	3.81±0.15	3.68±0.10
Globulin (g %)	2.55±0.11	2.60±0.09	2.50±0.09	2.66±0.11
Albumin/Globulin	1.50±0.09	1.52±0.09	1.57±0.09	1.45±0.09
Glucose (mg dl^{-1})	62.17±3.27	52.03±1.76	56.44±2.50	57.77±3.20
Urea (mg dl^{-1})	5.18±0.21	5.89±0.17	5.45±0.20	5.61±0.20
Triglycerides (mg/dl)	113.18±6.34	117.44±5.82	113.25±5.77	117.37±6.38

Discussion

The physico-chemical characteristics of Dal Lake and the Jhelum River indicate environmental variability that can influence the physiological and ecological performance of *S. esocinus*. The alkaline pH recorded in both systems is typical of Himalayan freshwater ecosystems and supports favourable conditions for fish metabolism and survival (Osibanjo *et al*., 2011). Slightly higher temperatures in Dal Lake compared to the Jhelum River may influence metabolic activity and reproductive physiology, as temperature is a key regulator of enzymatic processes and spawning behaviour in coldwater fishes (Shafi *et al.,* 2022). Seasonal fluctuations further modulate growth and behaviour, with lower winter temperatures constraining metabolic activity. Dissolved oxygen concentrations remained within suitable limits at both sites, supporting respiratory efficiency and metabolic functioning (Rahman and Aminur, 2023). However, comparatively lower DO levels in Dal Lake may reflect anthropogenic pressures and reduced self-purification capacity, as reported earlier for lentic systems in the region (Otieno, 2008; Mir *et al.,* 2013; Mohammad, 2017). Higher hardness and alkalinity values in Dal Lake, driven by calcium and magnesium inputs from agricultural runoff and other human activities, may influence osmoregulatory processes while maintaining buffering capacity characteristic of hard waters (Moyle, 1945; Gopal, 1990; Kaur *et al*., 2003). Despite these differences, overall water quality at both sites appears suitable for the growth and persistence of *S. esocinus*, underscoring the importance of continued monitoring for sustainable conservation.

Habitat-based variation in morphometric traits of *S. esocinus* was limited, with most body proportions remaining consistent between Dal Lake and the Jhelum River. Slight differences in total length suggest that local environmental conditions such as hydrodynamics, food availability, and habitat structure may influence growth trajectories, although the overall body shape remains conserved. Ontogenetic increases in morphometric parameters reflect normal growth progression and are consistent with established growth patterns reported in schizothoracine fishes (Negi and Negi, 2010; Bhat *et al*., 2013). Sexual dimorphism was restricted primarily to total length, with females attaining larger sizes, likely reflecting reproductive investment and fecundity advantages, while similar allometric patterns across sexes indicate stable growth strategies. Comparable observations have been documented in *Schizothorax* populations from River Lidder (Bhat *et al.,* 2013), *Botiabirdi* from the Indus basin (Sharma *et al*., 2014), and *S. zarudnyi* (Gharaie, 2012) . Strong correlations among morphometric traits further reinforce the structural stability of body proportions in this species (Negi and Negi, 2010).

Meristic characteristics exhibited high stability across sex, habitat, and age classes, with no meaningful differences detected in most fin ray counts. Minor numerical variations, particularly in pectoral fin rays, are unlikely to represent biologically significant divergence and may reflect natural developmental variability or subtle environmental influences during early growth stages (Allendorf *et al*., 1987; Swain *et al*., 2020). The absence of pronounced meristic differentiation suggests that *S. esocinus* populations from both habitats share a common morphological framework, consistent with previous reports in cold water cyprinids (Khan *et al.*, 2021; Shafi *et al*., 2021). Age-related stability in meristic traits further supports the notion that fin ray counts are conservative characters, with limited plasticity during ontogeny. Such morphological consistency highlights the species' capacity to maintain structural integrity across variable environmental conditions (Shafi *et al*., 2021; Karthik *et al*., 2024).

Length-weight relationship analysis revealed predominantly negative allometric growth across habitats, sexes, and age groups, indicating proportionally greater increases in length relative to weight. Although near-isometric growth was observed at the species level, variation in growth coefficients suggests differential energy allocation influenced by habitat and biological factors. Slightly higher growth coefficients in the riverine environment may reflect enhanced water flow, oxygen availability, and foraging efficiency relative to the lentic system (Khan *et al*., 2021). Sex-based differences in growth patterns likely arise from reproductive energy investment, particularly in females, as reported for other schizothoracine fishes (Bhat *et al*., 2013). Age-related increases in growth coefficients indicate shifts in energy allocation as individuals mature. The moderate vulnerability and low resilience associated with *S. esocinus* further emphasise the need for cautious management, particularly given its Vulnerable status under IUCN criteria (Allendorf *et al*., 1987).

Condition factor values suggest generally favourable physiological status across both habitats and sexes, reflecting adequate nutritional conditions (Jobling, 2002; Akhter *et al*., 2024). However, similar condition factor values between Dal Lake and the Jhelum River should not be interpreted as evidence of identical environmental conditions, as condition factor primarily reflects individual health rather than direct habitat equivalence. The observed decline in condition factor with advancing age likely reflects a shift from somatic growth to reproductive investment, a common pattern in long-lived freshwater fishes.

Biological indices (HSI, GSI, and GaSI) showed limited variation between habitats and sexes, indicating broadly comparable physiological conditions, while age-related increases highlight intensified metabolic and reproductive activity in older individuals (Froese, 2006; Baulier *et al*., 2017; Akhter *et al*., 2024). These trends underscore the dominant role of ontogeny in shaping physiological investment strategies in *S. esocinus*.

Haematological parameters exhibited minimal variation across habitats and sexes but demonstrated clear age-related trends, reinforcing the importance of ontogenetic influences on physiological functioning (Sheikh and Ahmed, 2016). Higher haemoglobin, red blood cell counts, and haematocrit values in younger fish may reflect elevated metabolic demands during early growth stages (Wedemeyer *et al*., 1983; Sharma *et al*., 2017; Ahmad and Sheikh, 2019). The decline in these parameters with age contrasts with reports of age-related increases in some species (Preston, 1960; Murray, 1984; Karthik *et al*., 2024), suggesting species-specific or environment-mediated physiological responses potentially linked to oxidative stress or cellular degradation (Joshi and Tandon, 1977; Tavares-Dias and Moraes, 2003). Increasing white blood cell counts with age may indicate enhanced immune competence in mature individuals, as documented in other freshwater fishes (Joshi and Tandon, 1977). The absence of pronounced sex-based differences aligns with previous studies attributing haematological stability to similar metabolic demands across sexes (Lin *et al*., 1998; Tang *et al*., 2015). Comparable haematological profiles between sites suggest that adaptive physiological mechanisms help maintain internal homeostasis under differing environmental conditions, although seasonal influences cannot be ruled out (Sheikh and Ahmed, 2016).

Serum biochemical parameters further reflect the influence of age and habitat on metabolic regulation. While sex-related differences were minimal, site-specific variation in globulin levels suggests ecological modulation of immune and metabolic processes (Zarejabad *et al.*, 2010; Karthik *et al*., 2024). Higher glucose and triglyceride concentrations in younger individuals likely reflect increased energy demands associated with growth and development, consistent with previous findings (Fazio *et al*., 2020; Nabi *et al*., 2022). Correlations between biochemical parameters, age, and size underscore dynamic metabolic adjustments throughout the life cycle (Gupta *et al*., 2012; Fazio *et al*., 2020). Collectively, these findings contribute baseline physiological information essential for health assessment and conservation planning of *S. esocinus* populations.

This study provides a comprehensive assessment of the physiological, biological, and morphometric characteristics of *S. esocinus* populations in Dal Lake and Jhelum River, highlighting key variations influenced by habitat conditions. The morphometric and meristic analyses demonstrated stable body proportions across habitats, with slight variations in specific traits influenced by environmental conditions. The biometric growth parameters confirmed a near-isometric growth pattern, with site-wise and sex-based differences, where males exhibited a slightly higher growth coefficient (b-value) than females, likely due to reproductive energy allocation. Haematological assessments indicated that younger individuals had higher ahematocrit levels, and while no significant gender-based differences were observed, site-based variations were evident, emphasising the influence of local environmental conditions on fish physiology. The study also confirmed the stability of meristic traits across populations, reinforcing the genetic and morphological consistency of *S. esocinus* across habitats. The species' condition factor and length-weight relationship suggest that Jhelum River provides slightly better growth conditions compared to Dal Lake. However, its classification as a Vulnerable species (IUCN) underscores the need for sustainable fisheries management and conservation measures. Overall, these findings contribute valuable insights into the biological and physiological adaptations of *S. esocinus*, emphasising the importance of regular monitoring and habitat protection to ensure the sustainability of this commercially and ecologically significant species. Further studies incorporating molecular and genetic analyses would enhance our understanding of population dynamics and adaptive responses to changing environmental conditions.

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