



OPEN Biometric analysis of *Oncorhynchus mykiss* (Walbaum, 1792) and *Salmo trutta*, Linnaeus, 1758 from the different habitat in Himachal Pradesh

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Biometric analysis offered important information on growth patterns, population differentiation, and habitat effects in trout. The present study aimed to evaluate variations among diverse ecological conditions and growth patterns across three farm sites of rainbow trout (*Oncorhynchus mykiss*) and three river sites of brown trout (*Salmo trutta*) in Himachal Pradesh. Length weight relationship (LWR) was estimated via a log-transformed linear model (LM), unweighted nonlinear least squares (NLS), and weighted NLS (wNLS). Analysis of covariance (ANCOVA) was used to test differences among rivers and farms. Morphometric and meristic variables were measured, and principal component analysis (PCA) was used to assess shape variation among sites. Rainbow trout specimens demonstrated isometric and positive allometric growth across all samples, with 'b' values ranging from 2.992 to 3.15. The brown trout population exhibited more variable growth patterns; S6 showed negative allometric growth ($b = 2.822\text{--}2.847$), while others approached isometric growth ($b = 2.936\text{--}2.993$), which reflect differences in body form. PCA revealed that size-related traits explain most of the variation for PC1 (principal component 1), while shape and cranial traits variation contribute to PC2, distinguishing populations among different habitats. Length-length relationships (LLRs) also showed a strong correlation between total length and standard length ($r^2 \geq 0.90$). Meristic features varied slightly between the populations. These findings underscore the phenotypic plasticity of both species and highlight the significance of localized habitat conditions. The study provides baseline data that can inform future biological assessments, conservation planning, and the sustainable development of coldwater aquaculture.

Keywords Morphometric, Meristic, Length–weight relationship, Length–length relationship, Rainbow trout, Brown trout, PCA

Trout includes various types of freshwater fish species within the Salmonidae family, predominantly classified under the genera *Oncorhynchus*, *Salmo*, and *Salvelinus*^{1–3}. Among them, rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) exhibit significant adaptation to the snow-fed rivers and aquaculture farms of Himachal Pradesh, respectively⁴. The rainbow trout is native to the coldwater rivers and lakes along the Pacific coasts of North America and Asia⁵, while the brown trout originated from the clear mountain waters of Western and Central Europe^{1,6}. These species were introduced to India during the British colonial period—brown trout in 1860 and rainbow trout in 1909—primarily for recreational activities^{1,6,7}. The transportation of eyed ova from Srinagar to Kullu Valley in 1909 marked a pivotal development in trout farming in Himachal Pradesh, establishing a foundation for the future of this promising aquaculture sector. The rapid growth, adaptability, and disease resistance of both species make them ideal for fish farming^{1,8}.

The Tirthan River, Uhl River, and Parbati River, are major tributaries of the Beas River drainage system, originating from Hanskund Peak situated at an altitude of ~ 4100 m; Thamar Glacier at an altitude of ~ 5080 m;

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and Mantalai Glacier at an altitude of ~ 4150 m; respectively. Their purposes include agriculture, hydroelectric power generation, tourism, control flooding, and the supply of drinking water⁹. The Department of fisheries releases brown trout fingerlings every year in trout stretch of 600 km of riverine length in the snow-fed rivers of Himachal Pradesh to promote conservation and angling activities in rivers. The agro-climatic conditions of upper river stretch provide optimum environment for brown trout growth and development¹⁰. Despite the presence of trout in Himachal Pradesh for over a century, scientific knowledge of them is still insufficient.

Length-weight relationship (LWR) is a fundamental tool for determining the fish biomass, conservation status, and population abundance^{11,12}. This analysis also helps in finding out the condition and health of fish, assuming that fish of a given length with higher weight are usually healthy in physiological conditions^{13,14}. Notably, the biologically acceptable range for the LWR parameter 'b' is 2.5–3.5¹⁵. LWR, even within the individuals of each species, is influenced by food availability, physiology, metabolism, and the population structure of aquatic animals in their habitat; consequently, it is affected by spatial-temporal factors, sex, ontogenetic developmental stages, body size, and prevailing fishing pressure on both fish and their prey^{15,16}. Using this basic data is also important for understanding genetic diversity and development rates of fish species, which help in sustainable management of genetic stocks and preservation of genetic variation during domestication^{17–19}.

Morphometric and meristic characteristics are basic measurements crucially used to assess fish stocks and investigate evolutionary trends^{20–22}. These characteristics play an important role in examining variations at the morphological level between geographically separated populations as well as provide information about their response to environmental changes, which helps in conservation and management practices^{19,23–28}.

The Himachal Pradesh State Fisheries Department has made remarkable progress in trout production, generating significant revenue from trout fish sales throughout the nation. The region's pristine snow-fed and glacier-fed streams, mountains, lakes, and springs provide ideal conditions for growing trout populations. However, there is currently a lack of comprehensive records encompassing the population characteristics based on the morphometric and meristic characteristics of these fish. This study aims to accurately assess the LWR and morphometric and meristic characteristics of brown trout and rainbow trout populations across six sites in Himachal Pradesh due to their considerable contribution to the coldwater fisheries along the north-western Himalayas.

Materials and methods

Study sites and sample collection

In the present study, rainbow trout and brown trout samples were collected between October 2023 and November 2024 across different sites in the Kullu, Mandi, and Kangra districts. Rainbow trout were collected from the: (S1) Trout fish farm Hamni, Banjar; (S2) Trout fish farm Barot, Mandi; and (S3) Trout fish farm Boh Valley, Kangra. Brown trout samples were collected from the following sites: (S4) Tirthan River, Banjar; (S5) Uhl River, Barot; and (S6) Parbati River, Kullu. (Fig. 1 & Table 1). The brown trout samples were collected randomly using cast nets (2.5 m; with mesh size: 1.0–5 cm), gill nets (5–10 cm; mesh size: 5–8 cm; height: 40–50 cm) and rod and lines with the assistance of licensed fishermen²⁹. Rainbow trout were also collected randomly from aquaculture farms with the help of different sized hand nets. Following collection, the specimens were transported in an icebox maintained at approximately 4 °C to the laboratory. Standard taxonomic keys were employed for the classification and identification of the specimens^{30,31}. A digital weighing balance with an accuracy of 0.1 g and a ruler with an accuracy of 0.1 cm were used for weight and length measurements.

Length weight relationship (LWR)

The length-weight relationship was calculated using an allometric equation, $W = aL^b$, where W represents the total weight (g), L denotes total length (cm), 'a' is a constant (intercept), and 'b' is the slope (indicating the change in weight per unit change in length)^{15,32}.

The parameters of LWR were calculated using three model methods, i.e., the log-transformed linear model (LM), nonlinear least squares (NLS, unweighted), and weighted nonlinear least squares (wNLS). In LM the data were log transformed and estimated with ordinary least squares (OLS): $\text{Log}(W) = \text{Log}(a) + b\text{Log}(L) + \epsilon$. The a and b estimates were back-transformed to the original scale to be interpreted. To ensure compatibility with NLSs, residuals were computed on the original weight scale. The NLS (unweighted) model, $W = aL^b$, was fitted directly on the original scale; no weights were applied, assuming homoscedastic error variance. In the wNLS, a nonlinear model was fitted, but weights inversely proportional to fish weights (1/W) to account for potential heteroscedasticity (increasing variance with body size)³³.

Standard errors (SE) of the parameter estimates were derived from the variance-covariance matrix. The student t-distribution was used to construct an approximately 95% confidence interval (CI). Model adequacy was evaluated in terms of information-theoretic criteria: Akaike information criterion (AIC) and Bayesian information criterion (BIC) (Burnham and Anderson, 2002). Lower AIC and BIC values indicate a better fit. The exponent b was compared with the theoretical cubic value ($b = 3$) to determine whether growth was isometric ($b = 3$) or allometric ($b \neq 3$)¹⁵.

Analysis of covariance (ANCOVA)

ANCOVA was used to estimate the relationship between length and weight among fish populations in the three farms or river with fish weight as the dependent variable, length as covariate, and farms or river as the categorical variable. The model had interaction terms (length* farms or river) that were used to determine the significant difference between slopes of farms or river. All statistical analyses were conducted in Python (v3.11) using open-source libraries for data processing, analyses, and visualization.

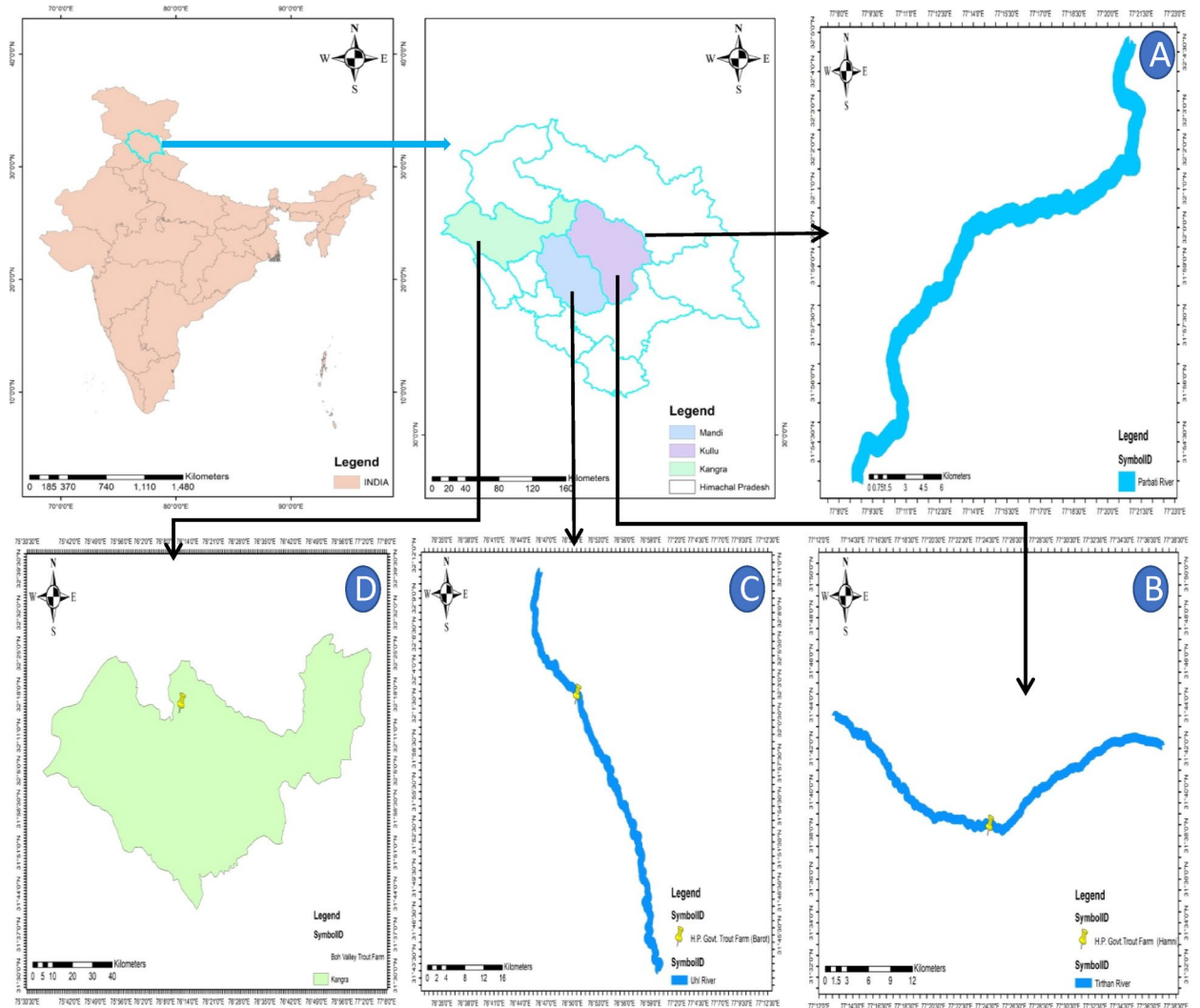


Fig. 1. Study area map showing different sampling sites.

Sr. No.	Species	Sampling sites	Code	Geo-coordinates		
				Latitude	Longitudes	Elevation
1	<i>Oncorhynchus mykiss</i>	HP Govt. Trout Farm Hamni, Banjar	S1	31°38'30.49''N	77°24'41.27''E	1515 msl
		HP Govt. Trout Farm Barot, Mandi	S2	32°02'17.86''N	76°50'35.30''E	1842 msl
		Trout fish farm Boh Valley, Kangra	S3	32°16'34.20''N	76°12'23.97''E	1243 m
2	<i>Salmo trutta</i>	Tirthan river, Banjar, Kullu	S4	31°38'38.43''N	77°26'20.24''E	1662 msl
		Uhl River, Barot, Mandi	S4	32°02'22.73''N	76°50'31.83''E	1852 msl
		Parbati River, Kullu	S6	31°54'28.55''N	77°09'14.33''E	1134 msl

Table 1. Showing sampling sites with geo-coordinates.

Morphometric and meristic measurements

Morphometric parameters including total weight (TW), total length (TL), standard length (SL), head length (HL), snout length (SL), maximum width (MW), maximum girth (MG), eye diameter (ED), intra orbital distance (IOD), pre-dorsal length (PDL), pre-pectoral length (PPL), pre-pelvic length (PPVL), pre-adipose dorsal length (PADL), pre-anal length (PAL), caudal fin length (CFL), caudal fin base (CFB), dorsal fin length (DFL), dorsal fin base (DFB), pectoral fin length (PFL), pectoral fin base (PFB), pelvic fin length (PVFL), pelvic fin base (PVFB), anal fin length (AFL), anal fin base (AFB), caudal depth (CD), and caudal penduncle length (CPL), were assessed using a digital calliper with an accuracy 0.01 mm, while meristic traits, including lateral line scales (LLS) pectoral fin rays (PFR), dorsal fin rays (DFR), anal fin rays (AFR), pelvic fin rays (PVFR), and caudal fin rays (CFR), were counted under a binocular magnifier²¹.

Sr. No.	Sampling sites	Length range (cm)	Weight range (g)	Model	Model parameters \pm SEM		95% CI parameters		Model performance			
					a \pm SEM	b \pm SEM	95% CI of a	95% CI of b	AIC	BIC		
1	S1	25.5–33	206–460	NLS (unweighted)	0.011131 \pm 0.001199	3.0428 0.0317	0.00868 0.0135	2.978062	3.107540	181.614	184.546	
				wNLS (weighted)	0.009036 \pm 0.001015	3.104370 0.033358	0.006963	0.011109	3.036244	3.172496	182.539	185.470
				LM (log scale)	0.009062 \pm 0.001030	3.103594 0.033751	0.007185 -0.011429	3.034666 3.172523	185.492	188.424		
2	S2	24.9–28.6	170.44–260	NLS (unweighted)	0.011449 \pm 0.001108	2.992933 0.029346	0.009186	0.013711	2.933001	3.052865	110.723	113.654
				wNLS (weighted)	0.011121 \pm 0.001093	3.001725 0.029879	0.008889	0.013353	2.940705	3.062746	110.820	113.751
				LM (log scale)	0.011143 \pm 0.001097	3.001139 0.029935	0.009113	0.013625	2.940003	3.062274	110.806	113.738
3	S3	25.8–36.9	182–544	NLS (unweighted)	0.006218 \pm 0.000680	3.152446 0.031224	0.004829	0.007607	3.088678	3.216214	212.686	215.617
				wNLS (weighted)	0.006528 \pm 0.000867	3.138015 0.038817	0.004758	0.008298	3.058740	3.217290	213.229	216.160
				LM (log scale)	0.006624 \pm 0.000869	3.134017 0.038379	0.005066	0.008660	3.055637	3.212397	213.213	216.144

Table 2. Length-Weight relationship models of *Oncorhynchus mykiss* with confidence intervals and performance metrics. NLS: Non-linear least square, LM: linear model, AIC: Akaike information criterion (AIC) BIC: Bayesian information criterion, CI: Confidence interval.

Farm	Adjusted mean weight at 28.87 cm (g)	95% CI (g)	Estimated slope (g/cm)	Significance	Overall interpretation
S1	314.07	310.86–317.29	33.70	$P < 0.001$	Steepest slope
S2	266.04	258.81–273.28	24.14	$P < 0.001$	Lowest slope
S3	256.71	253.11–260.32	33.26	Reference	Intermediate slope

Table 3. ANCOVA results of *Oncorhynchus mykiss* showing slope estimates, 95% confidence intervals, and interpretations.

Principle component analysis (PCA)

PCA was used to lower the dimensionality of the morphometric dataset and determine which variables were most responsible for the variation among the samples taken from six sites. The StandardScaler (Python v3.10) was used to normalize all variables (zero mean, unit variance). The first two components (PC1 and PC2) were then extracted for visualization using the PCA module of Scikit-learn. Matplotlib was used to create a biplot, in which trait loadings are shown as vectors that indicate their contribution to the principle's components, and sample scores are shown as scatter points. The percentage of total variance collected was assessed using the explained variance ratio for each major component.

LLRs

Length-length relationships (LLRs) were determined using the linear regression equation $y = a + b \cdot x$, where TL (cm) serving as the dependent variable (y), and twenty-four morphometric features served as independent variables (x). The assessment of data was conducted through the coefficient of determination (r^2), a crucial statistic in this analysis.

Result

In the study of the farm rainbow trout population, the length range was between 24.9 and 36.9 cm, and the weight range was between 93 and 488 g across all three sites (S1, S2, and S3). The LWR was assessed by using three models: LM, NLS (unweighted), and wNLS, with fitted parameters, standard errors, 95% CI, and performance indices summarized in Table 2. The model performance indicators AIC and BIC vary across sites, with the lowest observed for NLS (unweighted) in S2 (AIC = 110.723 and BIC = 113.654), indicating slightly better fit model among all three models. The regression coefficient showed that the 'a' value ranged from 0.006 to 0.011, while the allometric exponent 'b' values ranged from 2.992 to 3.15, indicating that weight increased at a disproportionately higher rate than length. The coefficient of determination (r^2) was consistently high ($r^2 > 0.99$), indicating strong length-weight relationships. All rainbow trout populations exhibited isometric and positive allometric growth pattern, with the most significant 'b' observed in samples from the S3 ($b = 3.15$). ANCOVA showed that the farm and length had a very significant effect on fish weight ($F = 15.58$, $p < 0.001$, $r^2 = 0.991$) (Table 3). Weight increased significantly with length in all farms ($p < 0.001$), and there were significant interaction effects (farm \times length), indicating that the LWR differed among farms. At the overall mean length of 28.87 cm, the adjusted mean weights were highest in S1 (314.07 g), followed by S2 (266.05 g) and S3 (256.72 g). These differences were

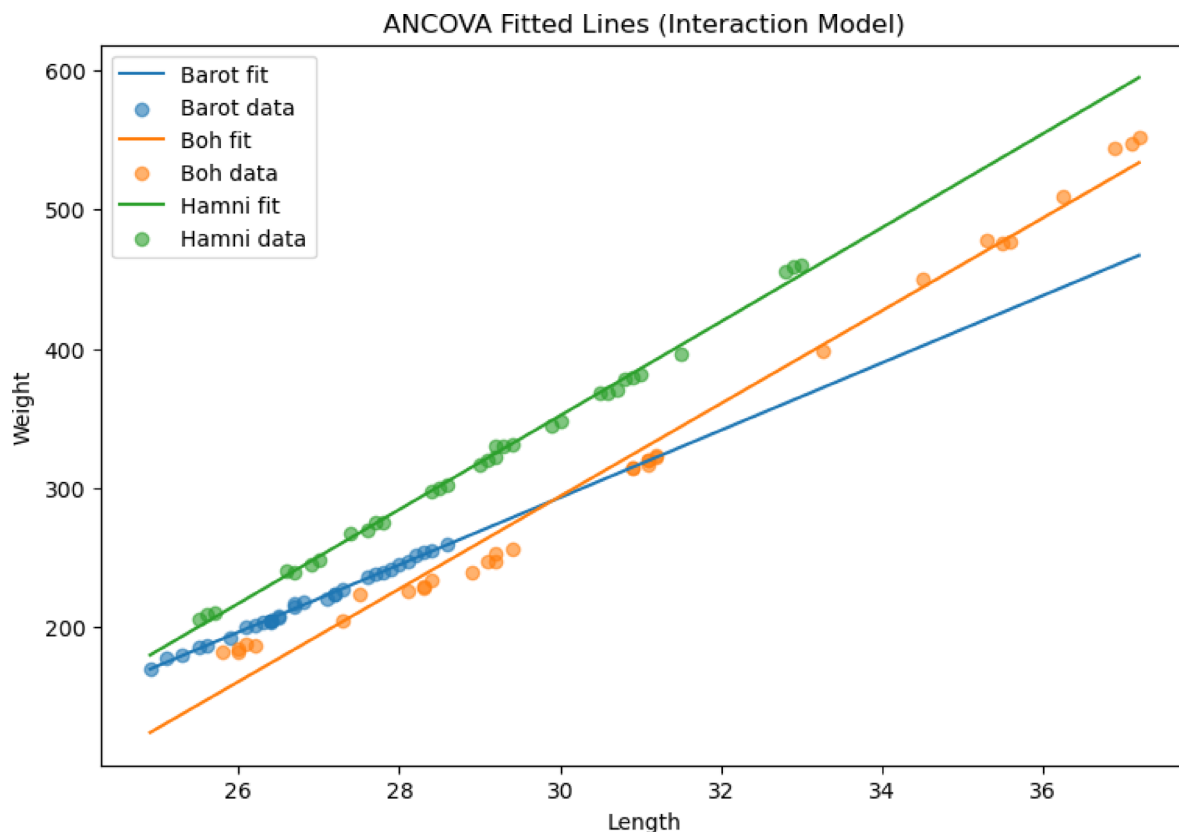


Fig. 2. Analysis of covariance of length-weight relationships in rainbow trout across farms.

Sr. No.	Sampling sites	Length range (cm)	Weight range (g)	Model	Model parameters ± SEM		95% CI parameters		Model performance	
					a ± SEM	b ± SEM	95% CI of a	95% CI of b	AIC	BIC
1	S4	19.8–27.7	93–258	NLS (unweighted)	0.0150 ± 0.0013	2.936 ± 0.0274	0.0122–0.0177	2.880–2.992	160.446	163.61
				wNLS (weights=1/W)	0.0124 ± 0.0009	2.993 ± 0.0230	0.0106–0.0143	2.946–3.040	162.558	165.725
				LM (log scale)	0.0125 ± 0.0009	2.992 ± 0.023	0.0107–0.0145	2.956–3.040	164.86	168.03
2	S5	23.7–35.7	144–488	NLS (unweighted)	0.01321 ± 0.0008	2.943 ± 0.0198	0.0113–0.0150	2.903–2.984	201.31	204.48
				wNLS (weighted)	0.0115 ± 0.0008	2.984 ± 0.0219	0.0098–0.0132	2.939–3.028	205.811	208.97
				LM (log scale)	0.0115 ± 0.0008	2.984 ± 0.0221	0.0099–0.0134	2.939–3.029	205.973	209.140
3	S6	19.7–30.4	93–320	NLS (unweighted)	0.0209 ± 0.0012	2.822 ± 0.0188	0.0183–0.0236	2.784–2.861	166.43	169.60
				wNLS (weighted)	0.0193 ± 0.0013	2.847 ± 0.0211	0.0167–0.0220	2.804–2.890	168.270	171.43
				LM (log scale)	0.0194 ± 0.0013	2.846 ± 0.0213	0.0169–0.0223	2.802–2.889	168.159	171.3

Table 4. Length-Weight relationship models of *Salmo trutta* with confidence intervals and performance metrics.

confirmed by the fitted regression slopes: S1 had the steepest slope (33.70 g/cm); thus, S1 fish displayed a higher weight gain per length than the other farms (Fig. 2).

For wild brown trout populations, the length ranged between 19.7 and 35.7 cm, and the weight ranged between 93 and 488 g across all three sites (S4, S5, S6) (Table 4). The model comparison showed that the lowest AIC and BIC (160.446 and 163.610) were the unweighted NLS in S4, which indicated that it gave the best fit to the observed data (Table 4). The wNLS and LM in the log-transformed data gave nearly identical estimates with slightly large AIC/BIC values, indicating slightly low model adequacy. The regression coefficient 'a' in brown

River	Adjusted mean weight at 25.95 cm (g)	95% CI (g)	Estimated slope (g/cm)	Significance	Overall interpretation
S4	215.4	212.7-218.1	21.2	$P > 0.05$	Similar growth to Parbati river
S5	191.8	188.7-194.8	28.2	$(P < 0.05)$	Faster growth with length, lighter at mean size
S6	211.7	209.0-214.5	21	Reference	Standard growth pattern

Table 5. ANCOVA results of *Salmo trutta* showing slope estimates, 95% confidence intervals, and interpretations.

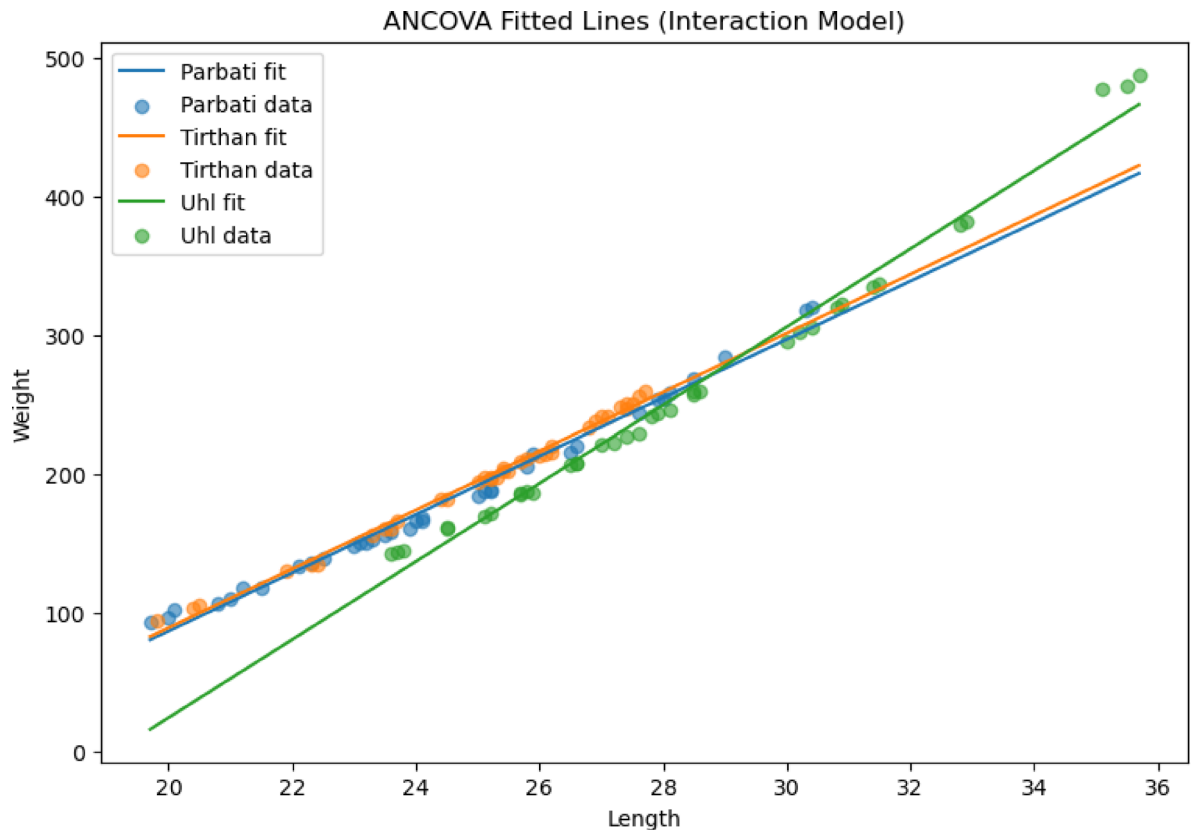


Fig. 3. Analysis of covariance of length-weight relationships in brown trout across rivers.

trout ranged from 0.011 to 0.020, and the allometric coefficient 'b' varied from 2.82 to 2.99. The r^2 remains consistently high $r^2 > 0.99$, signifying a strong relationship between length and weight across all sites. Growth pattern differs among the sites; specimens collected from S6 exhibited negative allometric growth ($b = 2.82\text{--}2.84$), whereas those from S4 and S5 approached positive allometric growth, which indicates that S6 fish becoming relatively slenderer with size. Although parameter 'b' values fall within biologically acceptable range of 2.5-3.5¹⁵. The ANCOVA model explained a very large percentage of variance of fish body weight ($r^2 = 0.991$, $p < 0.001$) (Table 5). The length ($F = 8992.96$, $p < 0.001$) and the interaction between length and river ($F = 94.4$, $p < 0.001$) were both significantly high, meaning that the slope of LWR varied across rivers. The main effect of the river is also significant ($F = 44.5$, $p < 0.001$). At an overall mean length of 25.95 cm, adjusted mean weights were 211.7 g (S6), 215.4 g (S4), and 191.8 g (S5). Despite S5 showing the steepest slope (28.17 g/cm), its fish had lower average weight at moderate length compared to S4 and S6 fish (Fig. 3).

The morphometric and meristic traits among all three sites of rainbow trout are summarized with descriptive statistics (Tables 6, 7). The PCA consistently showed that the majority of variation in PC1 was due to size-related variables, while PC2 indicated some subtle finer shape-related variation. At S1, PC1 explained 78.31% of the total variance, corresponding to size traits and cranial traits like SL, TL, HL, PAL, PPL, PVFL, SNL, and CPL, reflecting a general allometric gradient that separates larger from smaller individuals. PC2 contributed 6.76% variance, and was associated with shape traits CD, PDL, DFL, MW, CFB, PFB, MG, and PPL and negatively with CFL and ED (Fig. 4a). This suggests that, beyond size, specimens vary along a secondary axis of locomotor versus visual adaptation, with some individuals emphasizing stability and others favouring fin extension and visual performance. In the case of S2, PC1 contributes 67.62% of variance and was primarily associated with SL, TL, PAL, PPL, HL, SNL, and CPL; this represents a general size gradient, separating larger from smaller individuals. PC2 though accounting for a smaller fraction of the variance (7.76%), revealed a functional trade-

Parameters	Sampling sites		
	S1 (Mean ± SD)	S2 (Mean ± SD)	S3 (Mean ± SD)
TW	296.66 ± 44.92	228.39 ± 22.55	326.23 ± 139.68
TL	27.94 ± 2.39	26.46 ± 1.22	31.05 ± 4.10
SL	24.57 ± 2.03	23.29 ± 1.14	26.29 ± 3.15
HL	5.93 ± 0.72	5.66 ± 0.35	6.32 ± 0.92
SNL	1.05 ± 0.27	0.73 ± 0.17	1.10 ± 0.44
MW	6.0 ± 0.76	5.54 ± 0.45	7.05 ± 1.35
MG	12.74 ± 1.68	11.07 ± 0.89	14.12 ± 2.73
ED	1.13 ± 0.09	1.1 ± 0.08	1.35 ± 0.16
IOD	2.19 ± 0.23	2.14 ± 0.15	2.35 ± 0.59
PDL	11.67 ± 1.10	11.43 ± 0.45	12.75 ± 1.45
PPL	5.39 ± 0.24	5.31 ± 0.39	5.70 ± 0.75
PPVL	13.05 ± 1.21	12.66 ± 0.71	14.25 ± 1.39
PADL	19.75 ± 1.82	19.53 ± 0.37	21.43 ± 2.57
PAL	18.45 ± 1.66	17.71 ± 0.98	20.1 ± 2.31
CFL	4.58 ± 0.64	4.43 ± 0.96	5.13 ± 0.80
CFB	2.83 ± 0.20	2.6 ± 0.30	3.09 ± 0.52
DFL	1.96 ± 0.65	2.27 ± 0.78	3.20 ± 0.65
DFB	3.42 ± 0.39	3.18 ± 0.34	3.54 ± 0.38
PFL	3.38 ± 0.44	3.36 ± 0.29	4.06 ± 0.88
PFB	1.11 ± 0.14	1.06 ± 0.11	1.16 ± 0.15
PVFL	2.77 ± 0.28	2.61 ± 0.16	3.35 ± 0.61
PVFB	0.82 ± 0.07	0.81 ± 0.12	1.02 ± 0.20
AFL	2.46 ± 0.48	2.12 ± 0.19	3.23 ± 0.58
AFB	2.61 ± 0.33	2.42 ± 0.27	2.71 ± 0.39
CD	2.67 ± 0.29	2.27 ± 0.26	2.92 ± 0.64
CPL	4.82 ± 0.39	4.45 ± 0.40	4.84 ± 0.55

Table 6. Descriptive statistics of the morphometric characters of *Oncorhynchus mykiss* populations. Total Weight (gms)- TW, Total length (cm)-TL, Standard Length (cm)-SL, Head Length (cm)-HL, Snout Length (cm)-SNL, Max. width (cm)-MW, Max. Girth (cm), Eye Diameter (cm)-ED, Intra orbital Distance (cm)-IOD, Pre- dorsal length (cm)-PDL, Pre- pectoral length (cm)-PPL, Pre- pelvic length (cm)-PPVL, Pre-adipose dorsal length (cm)-PADL, Pre-anal length (cm)-PAL, Caudal fin Length (cm)-CFL, Caudal fin base (cm)-CFB, Dorsal fin length (cm)-DFL, Dorsal fin base (cm)-DFB, Pectoral fin length (cm)-PFL, Pectoral fin base (cm)-PFB, Length of pelvic fin (cm)-PVFL, Pelvic fin base (cm)-PVFB, Anal fin length (cm)-AFL, Anal fin base (cm)-AFB, Caudal depth (cm)-CD, Caudal Penduncle length (cm)-CPL, Body depth (cm)-BD.

Parameters	S1 (Mean ± SD)	S2 (Mean ± SD)	S3 (Mean ± SD)
LLS	128–145	128–145	112–150
PFR	12–15	12–15	11–16
DFR	9–14	9–14	11–15
AFR	7–14	7–14	11–14
PVFR	9–15	9–15	9–11
CFR	18–19	18–19	19–21

Table 7. Meristic character of *Oncorhynchus mykiss* populations.

off between cranial measures and fin traits. Positive loadings were associated with MG, MW, PVFB, DFL, CFB, and PVL, while negative loadings were associated with AFL, CFL, ED, PFL, HL, and CD (Fig. 4b). This suggests ecological divergence, where some individuals emphasize cranial robustness and fin base development, while others invest in locomotor efficiency and visual adaptation. At S3, PC1 contributes 75.89% of the variance and is strongly associated with cranial and body length variables HL, SL, PPL, SNL, TL, PAL, AFL, and PFL, indicating general body size and allometry gradient. PC2 7.83% of variance, reflected a shape-based trade-off, associated positively with cranial traits and shape measures (IOD, CFB, CD, DFB, MW, MG) and negatively with CFL, PFL, and ED (Fig. 4c). This suggests functional divergence, where some individuals exhibit relatively broader heads while others invest in elongated fins and larger eyes, potentially corresponding to differences in feeding strategies, locomotor demands, or habitat specialization.

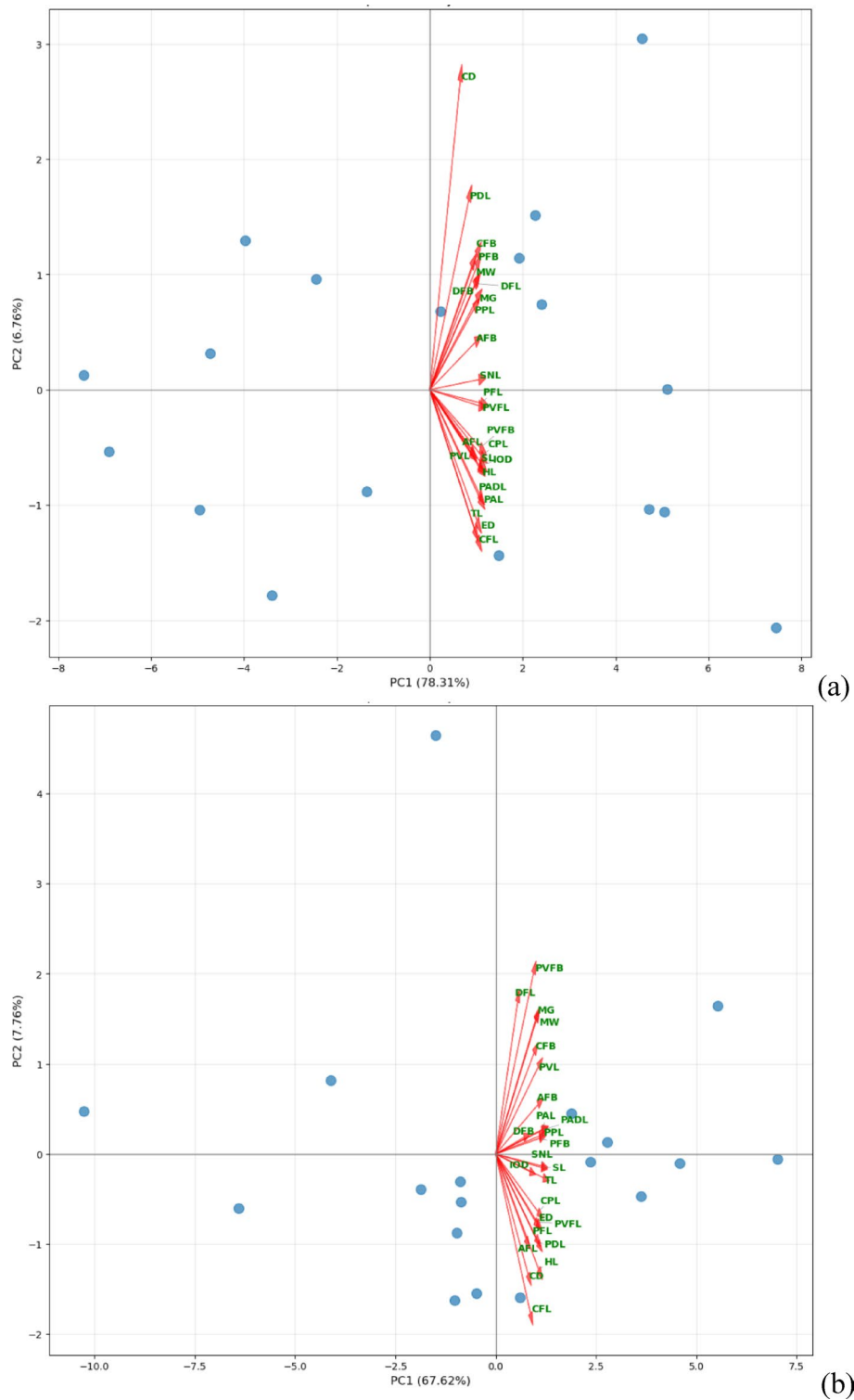


Fig. 4. (a) Principal component analysis of morphometric parameters in Rainbow trout from Hamni trout Farm (S1). (b) Principal component analysis of morphometric parameters in Rainbow trout from Barot trout farm (S2). (c) Principal component analysis of morphometric parameters in Rainbow trout Boh valley trout farm (S3).

Descriptive statistics of morphometric and meristic traits among all three sites of wild brown trout are summarized in Tables 8 and 9. Across all sites, size-related features dominated PC1, indicating that body size is the primary cause of morphological variation (Fig. 5a, b, and c). However, PC2 differed significantly among sites, reflecting site-specific shape contributions. At S4, the first two principles component account for 86.23% of

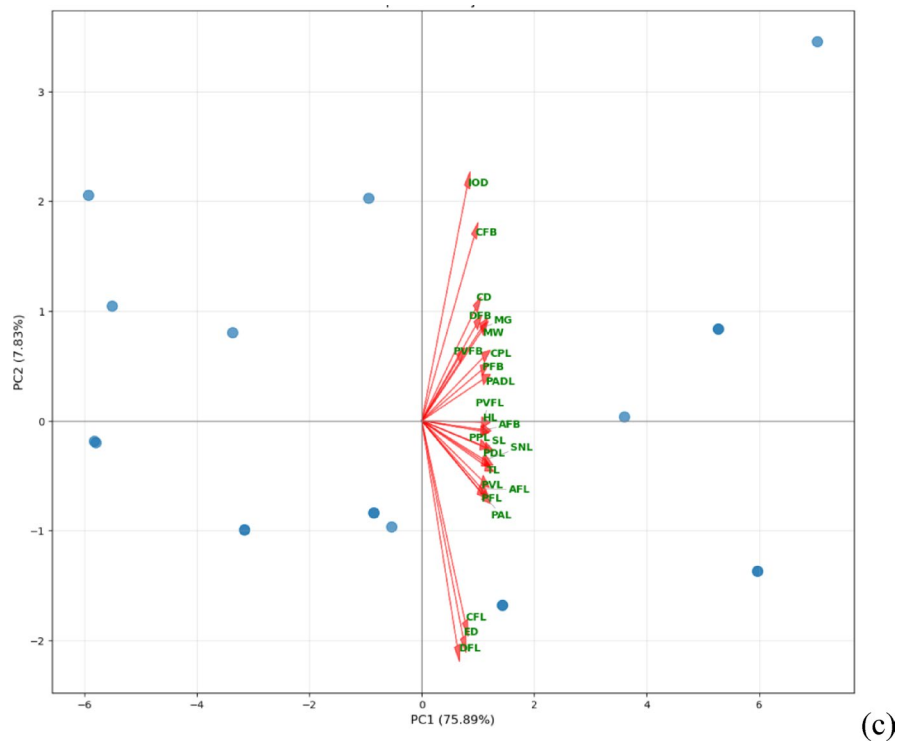


Fig. 4. (continued)

total variance (PC1 = 78.87%, PC2 = 7.36%). PC1 is dominated by cranial and body size traits (SL, TL, HL, PAL, PPL, CPL, PVFL), reflecting a strong allometric gradient that separates large- and small-bodied individuals. PC2 highlighted a functional trade-off, associated positively with PFB and SNL, while negative loadings were reflected with ED, DFL, CD, and CFB, suggesting that fish with broad pectoral fins and a long snout are better at making sharp turns and moving precisely. This helps them live in rocky or reef habitats, where they need to slip into tight spaces or pick food from cracks. At S5, PCA biplot revealed that the first two components account for 80.23% of total variance. PC1 was primarily associated with cranial and size traits (TL, PAL, SNL, PPL), consistent with the allometric scaling axis separating larger from smaller individuals. PC2 reflected a functional trade-off between cranial and fin traits, positively with CD, IOD, and ED and negatively with CFL, AFL, DFL, and PFL, suggesting divergent ecological or functional strategies among individuals. At S6, the first two PCs explained 87.2% of the total variance, PC1 primarily associated with overall body size and cranial traits (TL, HL, SL, PPL, PAL, and SNL), thus reflecting general allometric growth and separating individuals by size. PC2 accounted for a smaller fraction of the variance but highlighted a shape-based trade-off between positively with cranial traits (PFB, CFB, DFB, CD, ED) and negatively with fin elongation traits (PFL, CFL, AFL). This suggests potential ecological specialization, with some individual investing more heavily in cranial traits and others in locomotor traits. A heterogeneous population structure was indicated by S4 variance in size and shape. Size-driven variation is exclusive at S6, indicating a homogeneous population with little morphological variation. S5 dominated by size traits, revealed a stronger role for fin and caudal shape, indicating localized adaptations that may be influenced by ecological conditions.

In LLR, a total of 24 linear regression equations were analyzed, revealing that nine parameters, including SL, HL, SNL, PDL, PPL, PVL, PADL, AFB, PAL, PFB, and CPL, demonstrated strong correlations with total length, as indicated by r^2 values of ≥ 0.75 in rainbow trout samples (Table 10 and supplementary Figs. 1, 2 & 3). The brown trout linear regression analysis of total length versus SL, HL, SNL, PDL, PPL, PVL, PADL, AFB and PAL, revealed high r^2 values of ≥ 0.75 (Table 11 and supplementary Figs. 4, 5 & 6). The most significant correlation was observed between total length and standard length, exhibiting the highest r^2 values, which ranged from 0.995 to 0.996 in rainbow trout and 0.90 to 0.97 in brown trout.

Discussion

The present study demonstrated that LWRs of both rainbow trout and brown trout varied significantly among sites, underscoring the impact of ecological factors on growth patterns and morphological variations of these economically significant coldwater fish species.

All populations of rainbow trout exhibited isometric and positive allometric growth ($b = 2.992\text{--}3.15$); fish gained weight at a faster rate than they increased in length. According to Froese (2006) parameter b values fall within biologically acceptable range of 2.5–3.5¹⁵. These results are consistent with global studies that reported similar or higher b -values, such as 3.34³⁹, 3.063⁴⁰, and 3.096⁴¹, suggesting that the species inherently exhibits a propensity for robust growth under controlled or enriched environments. S1 displayed the steepest regression

Parameters	Sampling sites		
	S4 (Mean ± SD)	S5 (Mean ± SD)	S6 (Mean ± SD)
TW	153.41 ± 34.54	270.70 ± 38.90	195.5 ± 34.4
TL	24.04 ± 2.68	28.86 ± 3.36	26.36 ± 1.32
SL	20.74 ± 2.40	25.26 ± 3.35	23.23 ± 1.24
HL	5.21 ± 0.73	6.09 ± 0.55	5.96 ± 0.40
SNL	0.79 ± 0.17	1.11 ± 0.15	0.89 ± 0.12
MW	4.89 ± 0.61	6.01 ± 1.07	4.57 ± 0.42
MG	9.82 ± 1.17	12 ± 2.13	9.14 ± 0.85
ED	1.06 ± 0.19	1.11 ± 0.08	0.95 ± 0.12
IOD	1.55 ± 0.36	2.1 ± 0.31	1.78 ± 0.18
PDL	9.84 ± 1.30	11.9 ± 1.41	10.99 ± 0.79
PPL	4.98 ± 0.68	5.72 ± 0.47	5.52 ± 0.42
PPVL	11.74 ± 1.48	14.17 ± 1.67	12.97 ± 0.47
PADL	17.35 ± 2.03	21 ± 2.67	18.94 ± 1.06
PAL	15.96 ± 2.05	19.47 ± 2.27	17.99 ± 1.23
CFL	4.08 ± 0.62	5.17 ± 0.58	4.39 ± 0.28
CFB	2.52 ± 0.29	2.97 ± 0.39	2.69 ± 0.19
DFL	3.25 ± 0.45	3.57 ± 0.69	3.33 ± 0.21
DFB	2.99 ± 0.39	3.54 ± 0.47	3.42 ± 0.46
PFL	3.49 ± 0.42	4.04 ± 0.38	3.84 ± 0.27
PFB	1.05 ± 0.14	1.28 ± 0.20	1.13 ± 0.06
PVFL	2.72 ± 0.36	3.15 ± 0.42	3.01 ± 0.30
PVFB	0.78 ± 0.20	0.94 ± 0.13	0.83 ± 0.06
AFL	2.99 ± 0.48	3.53 ± 0.49	3.38 ± 0.32
AFB	2.13 ± 0.37	2.51 ± 0.39	2.35 ± 0.21
CD	2.20 ± 0.33	3.61 ± 1.31	2.5 ± 0.21
CPL	3.91 ± 0.60	4.61 ± 0.44	4.52 ± 0.23

Table 8. Descriptive statistics of the morphometric characters of *Salmo trutta*.

Parameters	S4 (Mean ± SD)	S5 (Mean ± SD)	S6 (Mean ± SD)
LLS	117–128	120–130	120–132
PFR	11–14	12–15	12–14
DFR	12–13	11–13	11–14
AFR	9–12	9–11	9–11
PVFR	9–10	9–10	9–10
CFR	18–20	19–20	19–20

Table 9. Meristic characters of *Salmo trutta* populations.

slope and the highest adjusted mean weight, indicating effective energy allocation towards growth; conversely, fish from S2 and S3 had shallower slopes and relatively lower adjusted mean weights. Variations in LWR parameters among different habitats may be result from management or environmental factors, such as food availability, water quality, genetic differences, season, habitat, sex, and environmental pressures^{15,42}.

The brown trout populations displayed site-specific variation of growth pattern. Trout from S5 displayed the steepest regression slope, suggesting a faster rate of weight gain per unit length; however, their adjusted mean body weight at the overall mean weight was lower than the other two rivers. This discrepancy suggested that although growth in length were faster, environmental constraints such as limited food resources or higher intraspecific competition may have restricted overall body mass accumulation⁴³. By contrast, fish from S4 and S6 exhibited more moderate slopes but higher adjusted mean weights, suggesting that this habitat provided more stable growth opportunities at intermediate sizes. The negative allometric growth pattern observed in S6 indicated that fish there invested less in body weight relative to length, which may invest more energy in lengthwise growth than in body mass accumulation, possibly due to limited prey availability, higher current velocity, or increased competition⁴⁴. These findings are consistent with those reported in previous studies, such as 2.897⁴⁵ and 3.035 and 3.037–3.000⁴⁶. Three potential models-wNLS, NLS (unweighted), and LM-were used in this study to assess the model performance for farmed rainbow trout and wild brown trout. The LWR in both farmed and wild trout populations was better fitted by NLS (unweighted), which consistently produced the lowest AIC and BIC values across all sites. This finding contrasts with the previous results³³, who reported the

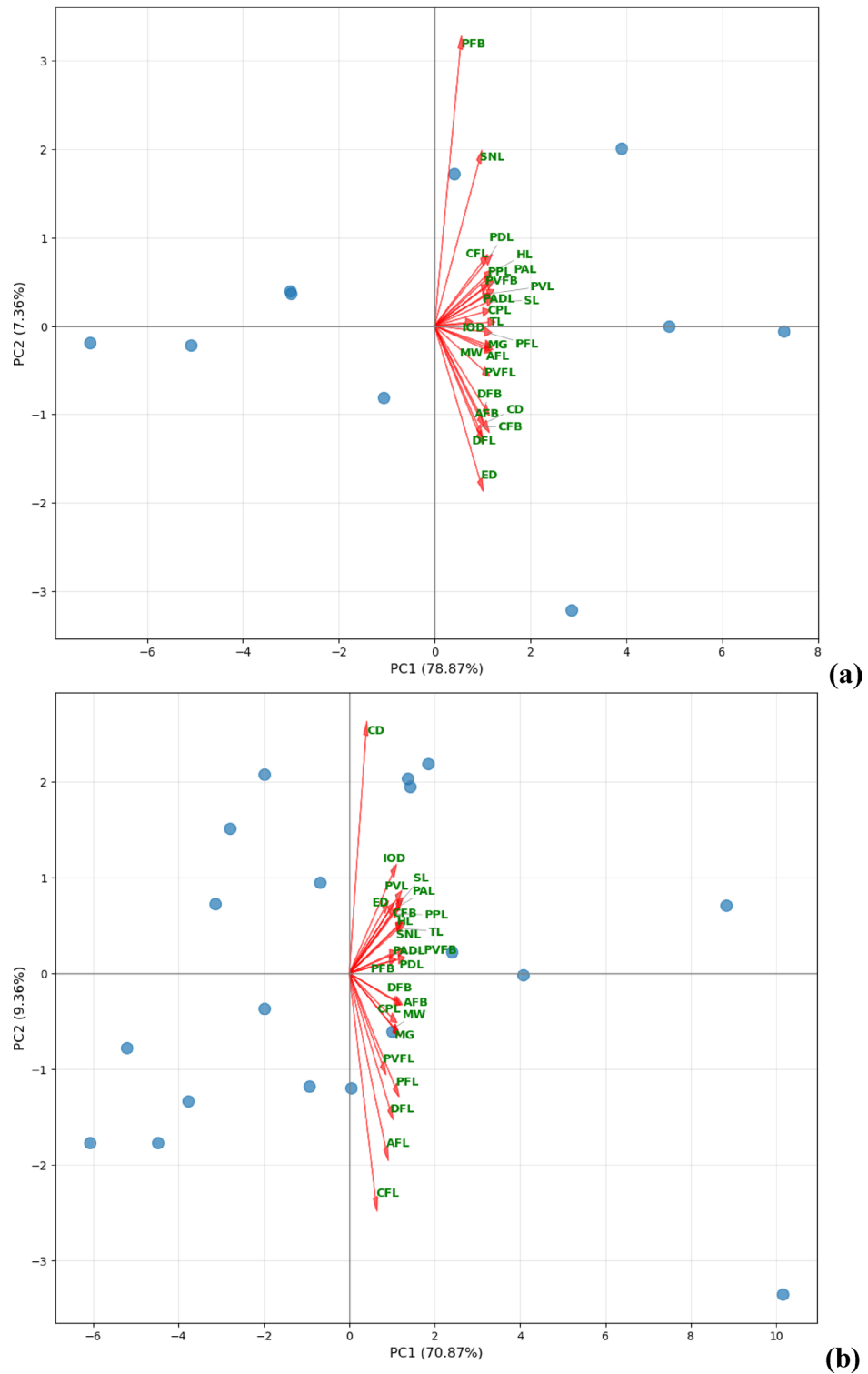


Fig. 5. (a) Principal component analysis of morphometric parameters in brown trout from Tirthan River (S4). (b) Principal component analysis of morphometric parameters in brown trout from Uhl River (S5). (c) Principal component analysis of morphometric parameters in brown trout from Parbati River (S6).

poorest performance of NLS for marine fishes, where heteroscedasticity in LW data was more noticeable and wNLS or LM was preferred. These differences may have arisen from the narrower size ranges and more uniform variance structure in trout populations.

ANCOVA confirmed that both habitat and the interaction of habitat with length significantly had a substantial impact on body weight. It was found that LWR is shaped not only by intrinsic growth potential but also by

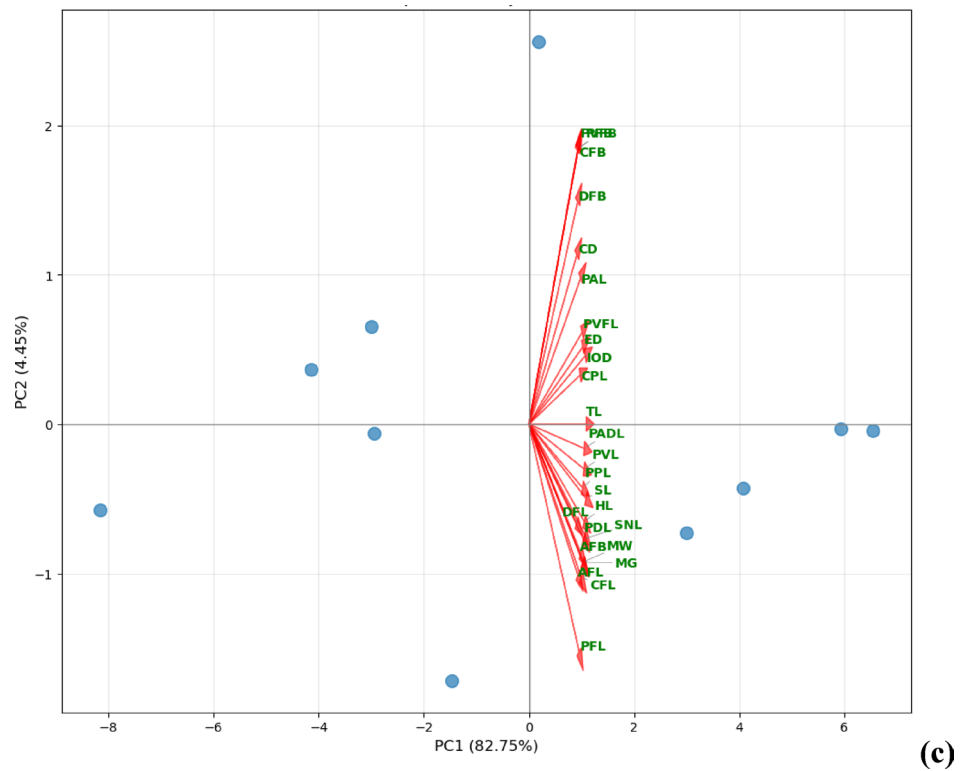


Fig. 5. (continued)

extrinsic site conditions. These findings highlight that the growth responses in salmonids are highly habitat dependent, with different sites having different effects on somatic investment patterns⁴⁷. The analysis of LWR yielded high coefficients of determination ($r^2 \geq 0.99$), indicating a strong relationship between body length and weight across both species and sampling sites⁴⁸.

The morphometric analysis revealed size variability among populations, with rainbow trout specimens revealing a maximum total length of 37.1 cm—substantially larger than those previously reported from the Champawat farm (9.8–15 cm)²¹. The fin ray counts found were as follows: DFR 9–14, AFR 7–14, PVFR 9–15, PFR 12–16, and CFR 18–21. These results are consistent with earlier findings that documented DFR counts of 14 to 15, PFR counts from 13 to 15, PVFR counts from 10 to 11, AFR counts from 12 to 14, and CFR of around 20²¹. The LLR in rainbow trout indicated a strong correlation between TL and SL, HL, SNL, PAL, PPVL, PPL, PDL, PADL, and CPL, with r^2 values exceeding 0.75. The results align with earlier research showing that the r^2 values between TL and several measurements, such as FL, SL, HL, PDL, PPL, PPVL, PAL, GL, AL, and BD, were higher than 0.83⁴⁸.

The brown trout specimens ranged from 19.7 cm to 35.7 cm, consistent with previous studies ranged from 12.8 cm to 48.0 cm⁴³. Another study in Turkish streams recorded the largest specimen, measuring 38.7 cm in length and weighing 683.13 g⁴⁹. These variations in body size reflect the result of interactions among genetic composition and environmental factors^{50–52}. The LLR in brown trout specimens demonstrates a strong correlation ($r^2 > 0.75$) between total length and SL, HL, SNL, PAL, PPVL, PPL, PDL, PADL, and CPL. These results are consistent with those of previous studies that showed strong relationships between TL and PPL (0.94), PVL (0.98), SL (0.99), HL (0.97), SNL (0.98), FL (0.99), CL (0.93), DL (0.98), AL (0.99), and MD (0.95)⁶, and SL (1.1178)⁴⁶. These results indicated that the morphometric characteristics exhibited positive growth as the length of fish increased⁵³.

In rainbow and brown trout populations, PCA of morphometric and meristic features revealed both site-specific and conserved variation. Body size is the primary determinant structuring morphological variation in both species, since PC1 consistently showed a size-related allometric gradient. According to earlier research on rainbow trout, rearing environment has less of an impact on morphological variance than genetically based ecotypic divergence⁵⁴. Our findings, on the other hand, highlight how ecological plasticity shapes growth and morphology under aquaculture circumstances, with variance between farm sites reflecting habitat quality and management techniques. The site-specific variations in PC2 indicate that cranium and fin structures may be influenced by farm parameters such as water quality, stocking density, and feeding schedule. Fish from S1 prioritized body stability and cranial strength, while fish from S2 and S3 displayed more fin and eye development, suggesting that farm-level environmental factors may influence morphology^{55,56}. However, in brown trout, PC2 revealed ecologically interpretable shape variation associated with habitat use. At S4, longer snouts and wider pectoral fins were linked to better hydrodynamic stability, indicating adaptation to turbulent and fast-flowing environments^{34–37}. At S5, individuals diverged along head and fin traits, indicating distinct preferences

Equation	S1			S2			S3		
	Regression parameters		r^2	Regression parameters		r^2	Regression parameters		r^2
	a	b		a	b		a	b	
TL = a + b * SL	1.12	1.002	0.93	1.59	0.89	0.90	0.92	1.08	0.97
TL = a + b * HL	9.61	0.60	0.81	8.42	0.66	0.79	7.51	0.76	0.82
TL = a + b * SNL	27.70	0.31	0.89	28.03	0.18	0.86	30.59	0.29	0.94
TL = a + b * MW	8.05	0.67	0.70	12.75	0.43	0.55	8.27	0.68	0.83
TL = a + b * MG	7.72	0.51	0.66	9.51	0.43	0.54	5.22	0.67	0.83
TL = a + b * ED	25.43	0.78	0.61	25.13	0.54	0.64	25.60	0.38	0.62
TL = a + b * IOD	18.50	0.52	0.46	19.01	0.43	0.43	21.94	0.48	0.41
TL = a + b * PDL	3.54	0.84	0.87	2.13	1.03	0.76	2.16	1.05	0.87
TL = a + b * PPL	1.70	1.65	0.75	10.91	0.53	0.77	6.59	0.89	0.82
TL = a + b * PPVL	3.11	0.85	0.85	4.13	0.73	0.77	1.14	1.24	0.84
TL = a + b * PADL	1.89	0.90	0.95	2.54	0.79	0.89	1.48	0.99	0.83
TL = a + b * PAL	1.9	0.92	0.94	2.71	0.79	0.92	1.14	1.10	0.95
TL = a + b * CFL	14.79	0.42	0.56	21.88	0.13	0.50	12.94	0.53	0.45
TL = a + b * CFB	9.984	0.98	0.65	19.86	0.29	0.54	15.40	0.62	0.58
TL = a + b * DFL	29.40	0.08	0.14	25.25	0.06	0.20	21.16	0.33	0.22
TL = a + b * DFB	14.67	0.53	0.53	19.96	0.24	0.33	9.93	0.89	0.54
TL = a + b * PFL	14.38	0.55	0.80	15.68	0.43	0.65	14.50	0.54	0.83
TL = a + b * PFB	26.11	0.62	0.92	25.75	0.43	0.79	27.28	0.85	0.77
TL = a + b * PVFL	14.70	0.62	0.63	14.41	0.63	0.73	14.02	0.66	0.87
TL = a + b * PVFB	31.9	0.67	0.70	27.74	0.54	0.22	30.72	0.42	0.34
TL = a + b * AFL	22.7	0.23	0.25	20.32	0.35	0.41	14.05	0.68	0.86
TL = a + b * AFB	17.0	0.52	0.63	19.69	0.33	0.64	13.32	0.85	0.83
TL = a + b * CD	15.48	0.60	0.65	20.89	0.29	0.50	19.06	0.45	0.51
TL = a + b * CPL	5.52	1.03	0.93	13.53	0.45	0.75	5.37	1.10	0.85

Table 10. The estimated parameters of the length-length relationship (LLR), ($y = a + b * x$) of *Oncorhynchus mykiss*.

for foraging strategies and habitat complexity⁴⁴. The majority of variation is due to environmental factors like prey availability and flow conditions that promote shape adaptive plasticity^{55,56}. The biological characteristics analyzed in this study help in determining the conservation status of fish, aquaculture practices, breeding, and fisheries management³⁸.

Conclusion

This study presents the first assessment of biometric analysis of both exotic trout populations in Himachal Pradesh. The findings showed that both species exhibit adaptability for meeting the changing environmental conditions within their respective habitats. The rainbow trout population from all study sites showed isometric and positive allometric growth, highlighting different body forms, whereas brown trout populations displayed variable growth patterns, with Site 6 relatively become more slenderer with size, and also foregrounding a more significant correlation of length with weight and length with morphometric characteristics. The meristic counts exhibit little variation and were consistent in the population from different sites. PCA also showed that morphological variation is dominated by size-related features, while shape differences indicate rearing effects or site-specific adaptations. The biological characteristics analyzed in this study helps in determining the conservation status of fish, aquaculture practices, breeding, and fisheries management. To improve the understanding of fish dynamic patterns future research should incorporate long-term observation, seasonal variation, water quality parameters, food resources, and genetic variability.

Equation	S4			S5			S6		
	Regression parameters			Regression parameters			Regression parameters		
	a	b	r ²	a	b	r ²	a	b	r ²
TL = a + b* SL	1.37	0.94	0.95	1.94	0.83	0.95	1.44	0.92	0.96
TL = a + b* HL	6.91	0.76	0.92	3.44	1.18	0.86	7.5	0.70	0.92
TL = a + b* SNL	26.82	0.45	0.82	26.62	0.76	0.85	27.48	0.34	0.96
TL = a + b* MW	6.41	0.83	0.84	11.19	0.53	0.67	13.17	0.46	0.79
TL = a + b* MG	3.23	0.88	0.86	7.76	0.53	0.66	9.6	0.46	0.79
TL = a + b* ED	23.37	0.50	0.57	25.34	1.21	0.58	26.94	0.40	0.85
TL = a + b* IOD	21.45	0.26	0.34	17.37	0.75	0.80	20.46	0.44	0.87
TL = a + b* PDL	3.94	0.79	0.86	2.64	0.97	0.93	5.27	0.67	0.94
TL = a + b* PPL	6.93	0.77	0.87	3.41	1.22	0.8	8.83	0.64	0.92
TL = a + b* PPVL	2.90	0.86	0.94	2.29	0.96	0.94	0.95	1.30	0.90
TL = a + b* PADL	1.98	0.87	0.84	1.96	0.89	0.93	2.12	0.86	0.91
TL = a + b* PAL	2.30	0.85	0.96	1.78	0.94	0.92	4.03	0.65	0.81
TL = a + b* CFL	9.39	0.67	0.80	7.72	0.80	0.72	9.59	0.68	0.81
TL = a + b* CFB	11.11	0.83	0.77	14.07	0.66	0.56	14.94	0.57	0.69
TL = a + b* DFL	10.50	0.70	0.75	15.10	0.51	0.49	12.19	0.64	0.69
TL = a + b* DFB	10.62	0.75	0.83	11.74	0.71	0.68	17.82	0.32	0.71
TL = a + b* PFL	8.12	0.87	0.90	6.95	1.02	0.65	11.71	0.60	0.71
TL = a + b* PFB	23.48	0.53	0.41	24.67	0.63	0.65	24.24	0.69	0.69
TL = a + b* PVFL	11.53	0.73	0.77	16.35	0.49	0.29	15.93	0.45	0.89
TL = a + b* PVFB	26.84	0.41	0.82	29.88	0.65	0.61	28.94	0.49	0.69
TL = a + b* AFL	11.59	0.66	0.91	15.81	0.48	0.30	15.82	0.42	0.65
TL = a + b* AFB	15.88	0.55	0.77	15.53	0.67	0.79	17.59	0.47	0.75
TL = a + b* CD	14.04	0.69	0.84	24.04	0.34	0.19	18.96	0.36	0.64
TL = a + b* CPL	11.19	0.56	0.70	6.06	1.02	0.65	7.92	0.80	0.73

Table 11. The estimated parameters of the Length-Length relationship (LLR), ($y = a + b*x$) of *Salmo trutta*.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

R.K. and B.K.D., Conceptualization and Design; H.K., Writing Original Draft and Data Collection; H.K., and K.T. Analysis, and Interpretation; A.K.T., B.B., S.K., and D.M., Review and Editing.

Declarations

Competing interests

The authors declare no competing interests.

Ethical approval

This research did not involve any invasive procedures, and all necessary permissions for sample collection were obtained from the appropriate authorities. The institutional approval number is: IAEC/CUHP/2023/I-1.17 and the permission granted by the Department of Fisheries, Himachal Pradesh, for collecting the fish samples is the file No. FSH-F (2)-42/2004-ARC-IV-6478.

Additional information

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