



## Setting exploitation reference points for the reba carp *Cirrhinus reba* in a snow-fed river: study from the Saryu River ecosystem in northern India

Lavkush<sup>1</sup> • Radhakrishnan K. V.<sup>1</sup> • C. P. Singh<sup>1</sup> • Sunil Kant Verma<sup>1</sup> • Puneet K. Patel<sup>2</sup> • Pullagura Siva Nagendra<sup>1</sup> • Moira G. Momin<sup>1</sup> • Abhisek Gharai<sup>1</sup>

<sup>1</sup> Department of Fisheries Resource Management, College of Fisheries (COF), Acharya Narendra Deva University of Agriculture & Technology (ANDUAT), Kumarganj, Ayodhya, Uttar Pradesh–224 229, India

<sup>2</sup> Department of Aquaculture, College of Fisheries (COF), Acharya Narendra Deva University of Agriculture & Technology (ANDUAT), Kumarganj, Ayodhya, Uttar Pradesh–224 229, India

### Correspondence

Radhakrishnan K. V.; Department of Fisheries Resource Management, College of Fisheries (COF), Acharya Narendra Deva University of Agriculture & Technology (ANDUAT), Kumarganj, Ayodhya, Uttar Pradesh–224 229, India

 radhakrishnan.frm.cof@nduat.org

### Manuscript history

Received 14 May 2026 | Accepted 18 June 2026 | Published online 22 June 2026

### Citation

Lavkush, Radhakrishnan KV, Singh CP, Verma SK, Patel PK, Nagendra PS, Momin MG, Gharai A (2026) Setting exploitation reference points for the reba carp *Cirrhinus reba* in a snow-fed river: study from the Saryu River ecosystem in Northern India. Journal of Fisheries 14(2): 142217. DOI: 10.17017/j.fish.1311

### Abstract

This study examined length-weight relationships (LWRs), physiological condition, growth characteristics, recruitment pattern, probability of capture, mortality rates and exploitation status of *Cirrhinus reba* from the Saryu River of northern India, collected fortnightly from August 2024 to July 2025. Total length varied from 11.0 to 27.0 cm ( $17.974 \pm 0.142$  cm), while body weight varied between 13.0 and 264.1 g ( $73.080 \pm 6.928$  g). The LWR showed a strong correlation ( $r^2 \geq 0.915$ ). The Fulton's condition factor ( $K_f$ ) and relative condition factor ( $K_n$ ) ranged from  $1.133 \pm 0.134$  to  $1.366 \pm 0.237$  and  $0.832 \pm 0.143$  to  $2.025 \pm 0.23$  respectively, which indicated that the fish were healthy. Growth parameters estimated through von Bertalanffy model were  $L_\infty = 27.0$  cm,  $K = 0.65 \text{ year}^{-1}$  and  $\Phi' = 2.67$ . Recruitment occurred throughout the year with a major peak during the monsoon season. Total mortality, natural mortality and fishing mortality were estimated as 1.60, 0.73 and  $0.87 \text{ year}^{-1}$ , respectively. The probability of capture analysis indicated that the length at first capture  $L_{50}$  of *C. reba* was 15.5 cm. The exploitation rate ( $E$ ) 0.55 was higher than  $E_{opt}$  (0.50) indicating emerging overexploitation. Yield-per-recruit analysis indicated exploitation reference points of  $E_{max}$  as 0.62 and  $E_{0.1}$  as 0.48. Virtual Population Analysis revealed increasing fishing mortality with fish size, with the highest fishing mortality ( $F = 0.91 \text{ year}^{-1}$ ) recorded in larger individuals, indicating size-selective exploitation and potential pressure on stock sustainability. This study provides information on population and exploitation characteristics of *C. reba* in the Saryu River, which can be used to set reference points for sustainable fisheries management.

**Keywords:** *Cirrhinus reba*; condition factor; exploitation status; population parameters; Saryu River

### 1 | INTRODUCTION

Fish and fisheries resources play a vital role in global food and nutritional security, particularly in developing countries where they provide an affordable source of high-

quality animal protein and support rural livelihoods (FAO 2022, 2024). In India, inland fisheries play a major role in national production and employment for millions of people. and income generation (Rao *et al.* 2022; Das *et al.*

2026). Riverine fisheries, especially in the Ganga basin is of significant ecological and socio-economic value, but this habitat degradation, among other anthropogenic stressors, is impacting more ecosystems through pollution, alteration of flow and overfishing (Chakraborty 2021; Lavkush *et al.* 2024; Tabassum *et al.* 2025; Botle *et al.* 2026). Freshwater fish diversity and abundance have been decreasing due to these threats. In tropical river systems throughout the world, particularly when the impact of fish populations needs to be assessed systematically (Pelicice *et al.* 2021; Dudgeon and Strayer 2025).

*Cirrhinus reba* (Hamilton 1822), is a freshwater cyprinid fish, more commonly known as Reba carp. It is widely distributed throughout the Indian sub-continent especially in the river Ganga system (Talwar and Jhingran 1991; Jayaram 2010; Froese and Pauly 2024). The species play an important role in small-scale fisheries. It is one of the sources of income and nutrition for local fisherman (Bari *et al.* 2025; Sathiskumar *et al.* 2025). However, several studies have reported declining population trends of *C. reba* due to habitat modification, altered hydrological regimes and increasing fishing pressure (Sarkar *et al.* 2018; Palita 2022; Bihari *et al.* 2025). In India, the species has been considered as Vulnerable under regional conservation assessments (Ghosh *et al.* 2024; Patil *et al.* 2026), indicating the need for focused ecological and population-based studies.

The Saryu River, a major tributary of the mighty Ganga River system, supports diverse fish fauna and sustains local fisheries in northern India. Like many other snow-fed tributaries of Ganga, it is subjected to increasing environmental stress due to human activities (Ray 1998), which may affect fish population structure and productivity (Reid *et al.* 2019; Dudgeon 2024). Understanding the biological and population characteristics of fish species in such systems is essential for evaluating their ecological status. In this context, parameters such as length-weight relationship (LWR), condition factor, growth rate derived from the von Bertalanffy Growth Function, recruitment pattern, natural and total mortality rates, probability of capture, length at first capture, as well as exploitation parameters are widely used to describe population status, and sustainable exploitation of fish species (Le Cren 1951; Froese 2006; Froese *et al.* 2014).

Although the *C. reba* has been investigated in several South Asian river systems, no scientific information is currently available on its population dynamics, growth parameters or exploitation status in the Saryu River. The absence of baseline population exploitation data limits effective fisheries management in this ecologically important river. Therefore, the present study represents the first attempt to evaluate growth, mortality, recruitment pattern and stock status of *C. reba* in the Saryu River using length-based stock assessment models, providing fundamental information for sustainable fisheries man-

agement and future monitoring programs.

## 2 | METHODOLOGY

### 2.1 Study area and sampling

Study area included Saryu River (30.45°N 84.73°E) with a length of 570 km. in India (Figure 1). Sampling was conducted at three locations (S1-Paska; S2-Guptar Ghat; S3-Tanda) placed at 26.89°N 81.78°E; 26.80°N 82.14°E and 26.60°N 82.68°E respectively, covering an approximate stretch of 134 km in Uttar Pradesh, India. The research was conducted over a one-year period from August 2024 to July 2025. Fish samples were collected from fishermen who used a variety of traditional fishing gears, including gill nets (25–50 mm mesh size), cast nets (15 and 20 mm mesh size), seine nets (10–20 mm mesh size) and hand lines operated from small boats. Immediately after capture, specimens were preserved in iceboxes and transported to the laboratory for further analysis. Water temperature at each sampling site was recorded during every sampling event using a multiparameter probe (model: H98194, Hanna Instruments; Romania, Europe).

### 2.2 Fish identification and morphometric measurements

The specimens were identified to species level following standard taxonomic keys (Talwar and Jhingran 1991; Jayaram 2010). A total of 699 specimens of *C. reba* were analyzed during the study period. For each specimen, total length (TL) was measured in centimeters (cm) using a measuring scale and body weight (W) was recorded in grams (g) using a digital electronic balance with an accuracy of 0.01 g. Length measurements used in the analysis were converted from millimeters to centimeters where necessary. Standard methods for fish morphometric measurements were followed (King 2007).

### 2.3 Length - weight relationship

The length-weight relationship was estimated using the equation:

$$W = aL^b$$

where W = body weight (g), L = total length (cm), a = intercept and b = regression coefficient (Le Cren 1951). The parameters were estimated by linear regression after logarithmic transformation of the data. The coefficient of determination ( $r^2$ ) was used to evaluate the strength of the relationship (Froese 2006).

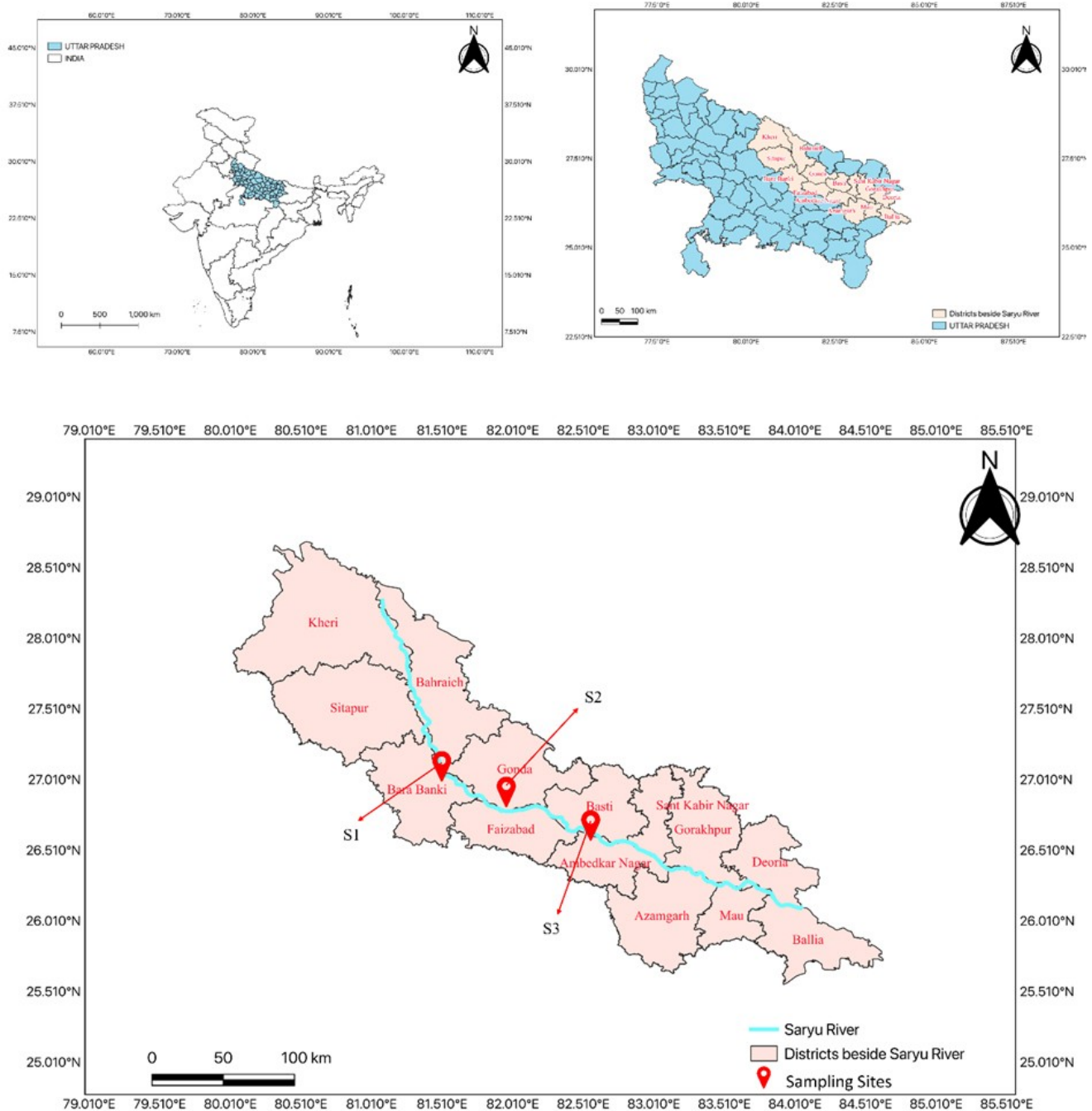
### 2.4 Condition factor

The condition of fish was evaluated using Fulton's condition factor ( $K_f$ ) and relative condition factor ( $K_n$ ) (Le Cren 1951; Froese 2006). Fulton's condition factor was calculated as:

$$K_f = (W / L^3) \times 100$$

$$K_n = W/W'$$

where W = observed weight, W' = predicted weight and L = total length



**FIGURE 1** Map of study area indicating locations (S1–S3) selected for sampling in Saryu River of northern India.

### 2.5 Growth parameters

Growth parameters were estimated using the von Bertalanffy Growth Function (VBGF) based on length-frequency data (von Bertalanffy 1938). The asymptotic length ( $L_{\infty}$ ) and growth coefficient ( $K$ ) were estimated using the ELEFAN routine implemented in FiSAT II software (Gayaniilo *et al.* 2005).

$$L_t = L_{\infty} (1 - e^{-K(t-t_0)})$$

The growth performance index ( $\Phi'$ ) was calculated using the equation proposed by Pauly and Munro (1984):

$$\Phi' = \log_{10} K + 2 \log_{10} L_{\infty}$$

The theoretical maximum age ( $t_{max}$ ) was estimated based on growth parameters following standard approaches (Pauly 1980).

### 2.6 Recruitment pattern

The recruitment pattern was analyzed using length-frequency data in FAO-ICLARM Stock Assessment Tools (FiSAT II, version 1.2.2). The NORMSEP routine was applied to separate normally distributed components of

length-frequency data and identify recruitment pulses through Gaussian distribution fitting (Moreau and Cuende 1991).

### 2.7 Probability of capture

The probability of capture was estimated from the backward extrapolation of the length-converted catch curve using logistic transformation (Sparre and Venema 1998). This method was used to determine the lengths at which 25%, 50% and 75% of the fish population are vulnerable to capture. The length at first capture ( $L_c$  or  $L_{50}$ ) was obtained from the probability curve. The  $L_{50}$  value corresponds to fish length at which 50% of individuals are retained by the fishing gear.

### 2.8 Length at first maturity

The length at first maturity ( $L_m$ ) was estimated using the empirical model developed by Binohlan and Froese (2009):

$$\log(L_m) = -0.1189 + 0.9157 \log(L_{max})$$

where  $L_{max}$  = maximum total length.

### 2.9 Mortality and exploitation rates

The instantaneous total mortality ( $Z$ ) was estimated using the length-converted catch curve method (Gayani *et al.* 2005). Total mortality is expressed as:

$$Z = M + F$$

Natural mortality ( $M$ ) was estimated using Pauly's empirical equation (Pauly 1980):

$$\log_{10}M = 0.0066 - 0.279 \log_{10}L_{\infty} + 0.6543 \log_{10}K + 0.4634 \log_{10}T$$

where  $T$  = mean annual water temperature ( $^{\circ}C$ ).

Fishing mortality ( $F$ ) was calculated as:

$$F = Z - M$$

The exploitation rate ( $E$ ) was determined as:

$$E = F / Z$$

### 2.10 Yield-per-recruit and biomass analysis

The relative yield-per-recruit ( $Y'/R$ ) and relative biomass-per-recruit ( $B'/R$ ) were estimated using the Beverton and Holt (1966) model based on the ratios of  $L_c / L_{\infty}$  and  $M / K$ . The relative yield-per-recruit was calculated as:

$$Y'/R = E(U^{(M/K)}) [1 - (3U / (1 + m)) + (3U^2 / (1 + 2m)) - (U^3 / (1 + 3m))]$$

where  $U = 1 - (L_c / L_{\infty})$ ,  $m = K/Z$  and  $E = F/Z$ .

The relative biomass-per-recruit ( $B'/R$ ) was estimated as:

$$B'/R = (Y'/R) / F$$

Biological reference points such as  $E_{max}$ ,  $E_{0.1}$  and  $E_{0.5}$  were determined from yield-per-recruit analysis.

### 2.11 Virtual population analysis

Length-structured Virtual Population Analysis (VPA) was performed using FISAT II to estimate population size and fishing mortality for each length class. The analysis incorporated growth parameters ( $L_{\infty}$ ,  $K$ ), mortality rates ( $M$ ,  $F$ ) and length-weight parameters ( $a$ ,  $b$ ).

## 3 | RESULTS

### 3.1 Length composition

A total of 699 specimens of *C. reba* were collected with length ranged from 11.0 to 26.8 cm and body weight varied from 13.0 to 264.1 g, respectively. The length - frequency distribution has been found well-structured population with dominance of intermediate size groups. Monthly length-class analysis (Figure 2) confirmed that mid-sized individuals (140–220 mm) were obtained in maximum throughout study period, whereas the recruitment of the smallest (101–120 mm) and larger (261–280 mm) size classes were irregular and less abundant.

### 3.2 Length-weight relationship

The estimated length-weight regression models exhibited high correlation coefficients ( $r^2 \geq 0.925$ ) and were statistically significant ( $p < 0.05$ ), indicating a strong relationship between fish length and body weight throughout the study period. The regression analysis indicated variation in growth pattern between sexes. Males exhibited mostly negative allometric growth ( $b < 3$ ), whereas females showed mostly positive allometric growth ( $b > 3$ ) during study period. The scatter plot and fitted regression lines demonstrate the strength of the relationship (Figure 3) and monthly variations in parameters are presented in Table 1.

### 3.3 Condition factor

The Fulton's condition factor ( $K_f$ ) and relative condition factor ( $K_n$ ) of *C. reba* exhibited clear seasonal variation throughout the study period (Table 1). In males,  $K_f$  ranged from 0.868 to 1.376 with a mean value of  $1.133 \pm 0.134$ , while  $K_n$  varied between 1.559 and 2.347 with a mean of  $2.025 \pm 0.237$ . In females,  $K_f$  ranged from 0.951 to 1.814 with a mean value of  $1.366 \pm 0.237$ , whereas  $K_n$  varied from 0.677 to 1.101 with a mean of  $0.832 \pm 0.143$ . The higher value of condition factor was observed in the pre-monsoon and monsoon month, which shows that the condition of the fish body was better in these months. On the other hand, lower values recorded during the winter months indicate relatively reduced conditions.

### 3.4 Growth parameters

The growth parameters of *C. reba* estimated using the von Bertalanffy Growth Function (VBGF) showed the asymptotic length ( $L_{\infty} = 27.0$  cm) and the growth coefficient ( $K = 0.65 \text{ year}^{-1}$ ), indicating moderate growth of the species in the study area. The estimated  $L_{\infty}$  was close to the

maximum observed length, implying a good fit of the growth model. The theoretical maximum age ( $t_{max}$ ), derived from the growth parameters, was approximately 4.61 years, indicating a relatively short life span. The fitted growth curve is presented in Figure 4. The goodness-of-fit score ( $R_n$ ) value found was 0.679, indicating a moderately good alignment of the growth curve with the peaks and troughs of our observed length frequency data.

The response surface analysis of growth parameters showed a distinct peak, indicating an optimal combination of  $L_\infty$  and  $K$  values. This confirms the reliability of the estimated growth parameters derived from length-frequency data. The estimated value of growth performance index ( $\Phi$ ) was 2.67, indicating moderate growth performance typical of tropical cyprinid species under the prevailing environmental conditions (Figure 5).

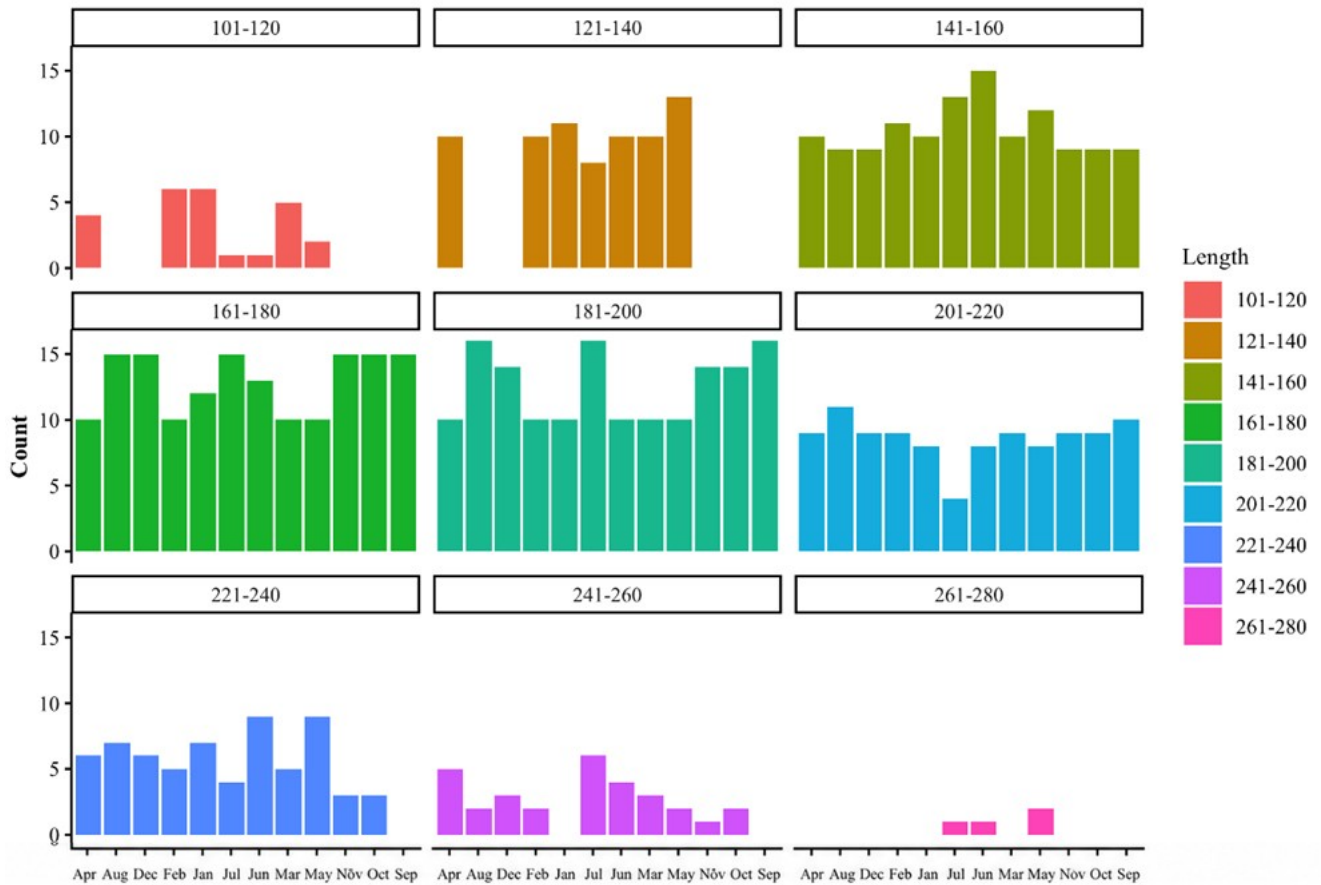


FIGURE 2 Facet plot of length-frequency distribution of *Cirrhinus reba* during the study period.

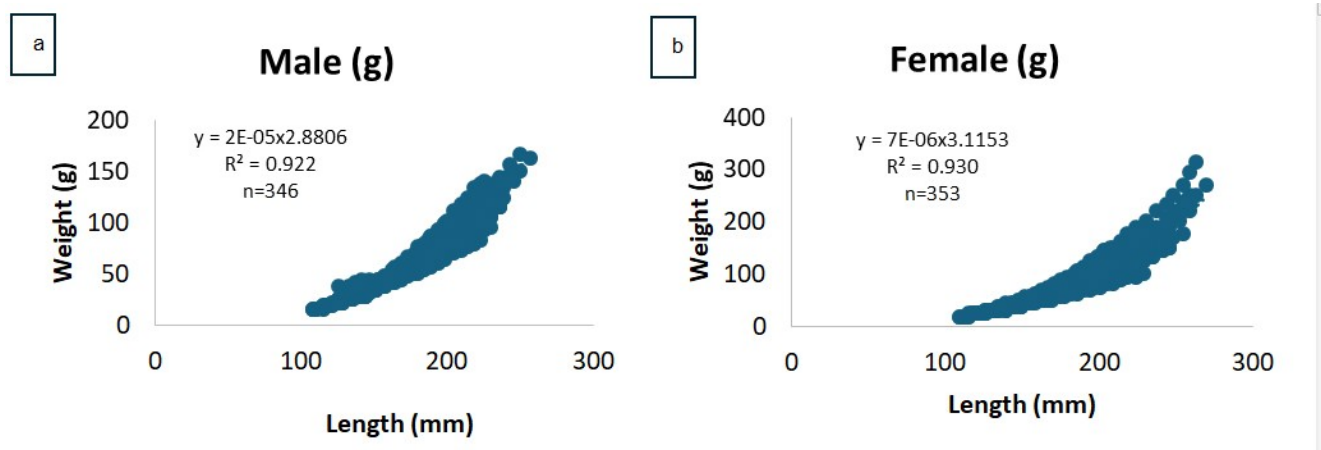
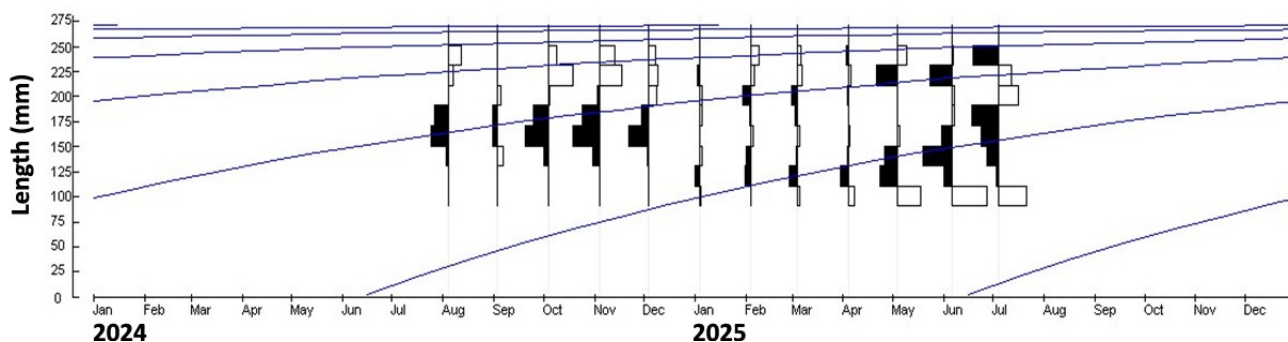


FIGURE 3 Length-weight relationship of *Cirrhinus reba* showing regression lines for (a) males and (b) females.

**TABLE 1** Monthly variation in length-weight relationship parameters ( $a, b, r, r^2$ ) for male and female *Cirrhinus reba*.

Sex	Month	$b$ value	Growth form	$a$	$r$	$r^2$	$K_f$	$K_n$
Male	Jan	2.787	A <sup>-</sup>	0.010	0.941	0.908	1.009	1.797
	Feb	2.845	A <sup>-</sup>	0.009	0.947	0.927	1.070	1.907
	Mar	2.916	A <sup>-</sup>	0.008	0.939	0.930	1.213	2.164
	Apr	2.991	A <sup>-</sup>	0.007	0.953	0.935	1.271	2.272
	May	2.990	A <sup>-</sup>	0.008	0.886	0.913	1.376	2.347
	Jun	2.898	A <sup>-</sup>	0.009	0.949	0.915	1.138	2.041
	Jul	3.331	A <sup>+</sup>	0.003	0.908	0.932	1.159	2.067
	Aug	3.283	A <sup>+</sup>	0.001	0.917	0.913	1.129	2.017
	Sep	3.130	A <sup>+</sup>	0.002	0.934	0.942	1.116	1.998
	Oct	3.260	A <sup>+</sup>	0.004	0.947	0.902	1.229	2.202
	Nov	2.440	A <sup>-</sup>	0.003	0.911	0.948	1.019	1.825
	Dec	2.190	A <sup>-</sup>	0.014	0.909	0.902	0.868	1.559
	Mean± SD	2.922±0.338	A <sup>-</sup>	0.007±0.004	0.928±0.005	0.922±0.009	1.133±0.134	2.025±0.237
Female	Jan	2.905	A <sup>-</sup>	0.009	0.937	0.943	1.189	0.729
	Feb	2.900	A <sup>-</sup>	0.009	0.943	0.913	1.255	0.767
	Mar	3.045	A <sup>+</sup>	0.007	0.949	0.930	1.460	0.890
	Apr	3.176	A <sup>+</sup>	0.005	0.901	0.928	1.621	0.987
	May	3.376	A <sup>+</sup>	0.003	0.945	0.930	1.814	1.101
	Jun	3.180	A <sup>+</sup>	0.005	0.942	0.943	1.499	0.908
	Jul	3.870	A <sup>+</sup>	0.004	0.947	0.926	1.498	0.917
	Aug	3.527	A <sup>+</sup>	0.003	0.932	0.914	1.313	0.799
	Sep	3.250	A <sup>+</sup>	0.004	0.938	0.923	1.185	0.721
	Oct	3.450	A <sup>+</sup>	0.024	0.897	0.924	1.459	0.886
	Nov	2.660	A <sup>-</sup>	0.025	0.946	0.945	1.149	0.698
	Dec	2.320	A <sup>-</sup>	0.030	0.914	0.940	0.951	0.677
	Mean± SD	3.138±0.413	A <sup>+</sup>	0.011±0.010	0.933±0.002	0.930±0.004	1.366±0.237	0.832±0.143



**FIGURE 4** Von Bertalanffy growth curve fitted to length-frequency data of *Cirrhinus reba* using ELEFAN in FISAT II.

### 3.5 Recruitment pattern

The recruitment pattern of *C. reba* indicated continuous recruitment throughout the year, with a distinct peak during the monsoon season (Figure 6). The highest recruitment was recorded between June and August, with a maximum contribution of 17.61%, followed by moderate recruitment during May and September. The presence of multiple recruitment pulses suggests prolonged recruitment of the species in the study area.

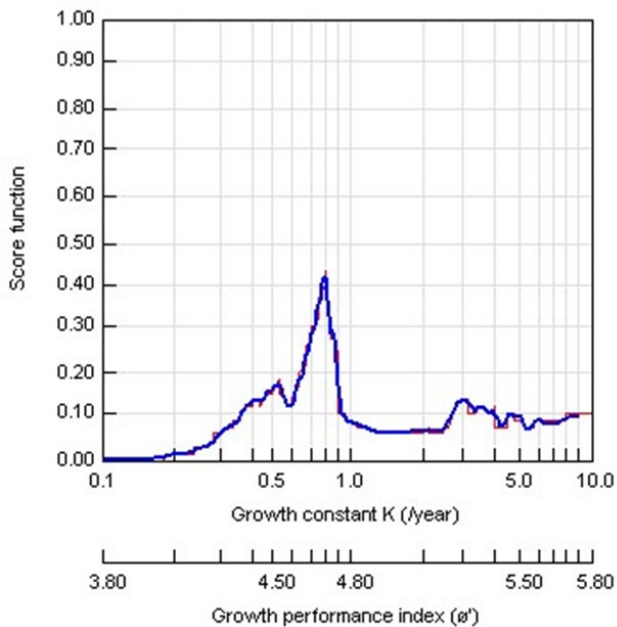
### 3.6 Probability of capture

The probability of capture increased sigmoidally with increasing fish length, indicating gradual recruitment into

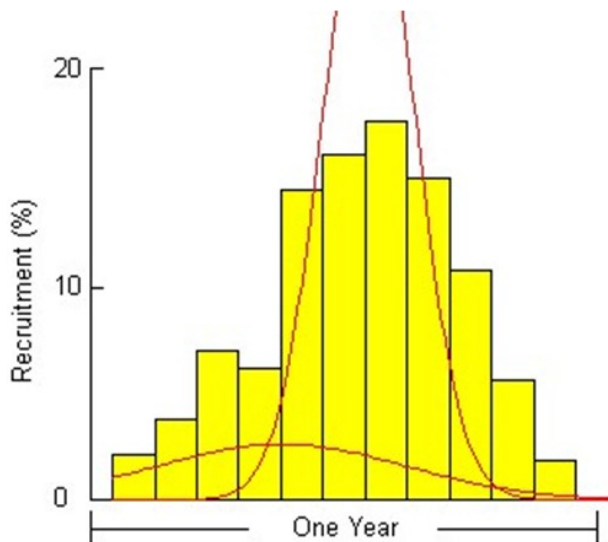
the fishery. The estimated lengths at capture were approximately  $L_{c25} \approx 13.5$  cm,  $L_{50} \approx 15.5$  cm and  $L_{c75} \approx 18.0$  cm (Figure 7). The estimated length at first maturity ( $L_m = 14.45$  cm) was less than length at first capture ( $L_{50} = 15.5$  cm), *i.e.*, fishes are getting at least one chance of reproduction before it is harvested, indicating sustainable exploitation. Furthermore,  $L_{c75}$  (18.0 cm) suggests that only a smaller fraction of the population survives to attain larger size classes, reflecting moderate fishing pressure on the stock.

### 3.7 Length/size at first maturity ( $L_m$ )

The estimated  $L_m$  of *C. reba* was 15.45 cm.



**FIGURE 5** ELEFAN response surface plot showing the estimation of asymptotic length ( $L_{\infty}$ ), growth coefficient ( $K$ ) and growth performance index ( $\Phi'$ ) for *Cirrhinus reba*.



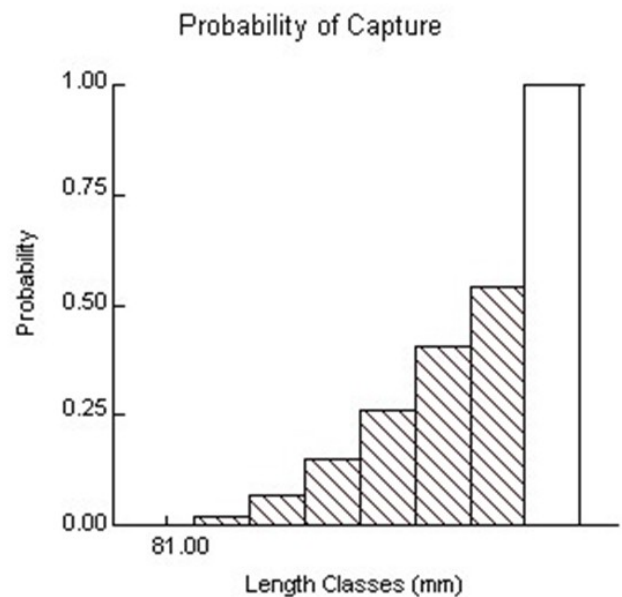
**FIGURE 6** Recruitment pattern of *Cirrhinus reba* shows monthly variation in recruitment percentage.

### 3.8 Mortality and exploitation rates

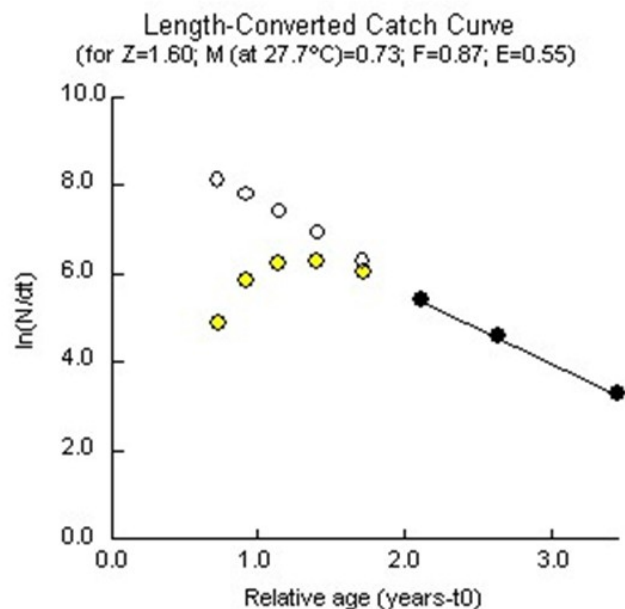
The total mortality coefficient ( $Z$ ) was estimated at  $1.60 \text{ year}^{-1}$ , while natural mortality ( $M$ ) and fishing mortality ( $F$ ) were  $0.73 \text{ year}^{-1}$  and  $0.87 \text{ year}^{-1}$ , respectively. The exploitation rate ( $E$ ) was  $0.55$  and exceeded the optimum level.

The length-converted catch curve shows a linear decline in the logarithm of fish abundance with increasing relative age, representing the fully recruited phase of the population. The slope of the regression line was used to estimate total mortality ( $Z$ ). The distribution of smaller

individuals before the regression phase indicates incomplete recruitment and gear selectivity. The length-converted catch curve used for mortality estimation is shown (Figure 8).



**FIGURE 7** Probability of capture curve showing length at first capture ( $L_{50}$ ) for *Cirrhinus reba*.



**FIGURE 8** Length-converted catch curve of *Cirrhinus reba* used to estimate total mortality ( $Z$ ).

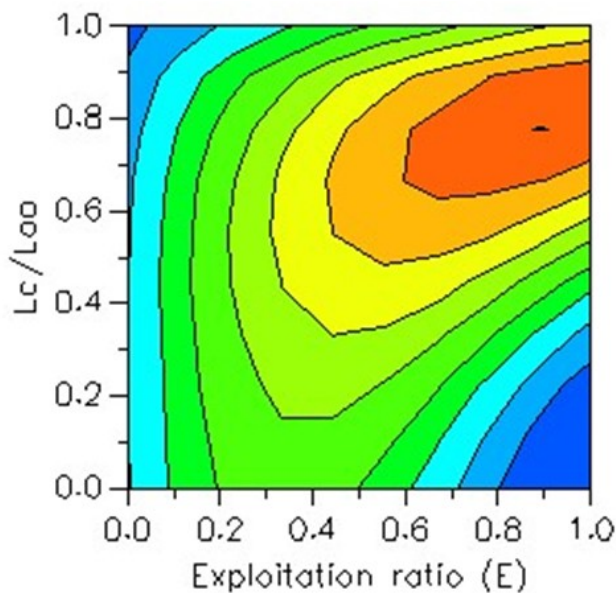
### 3.9 Yield-per-recruit analysis

The relative yield-per-recruit ( $Y'/R$ ) analysis of *C. reba* exhibited a typical dome-shaped response to increasing exploitation rate, indicating an optimum level of fishing pressure beyond which yield declines. The biological ref-

erence points estimated from the Beverton and Holt yield-per-recruit model were  $E_{max} = 0.62$ ,  $E_{0.1} = 0.48$  and  $E_{0.5} = 0.34$ .

The current exploitation rate ( $E = 0.55$ ) lies slightly above the optimum exploitation level ( $E_{0.1}$ ) but remains below  $E_{max}$ , suggesting that the stock is approaching full exploitation. This condition indicates that further increases in fishing effort may reduce spawning biomass and long-term yield sustainability.

The contour plot demonstrated the relationship between exploitation rate ( $E$ ) and  $L_c/L_\infty$  ratio. The results indicate that maximum yield is achieved at intermediate exploitation levels and moderate size at first capture. Lower  $L_c/L_\infty$  values indicate premature harvesting, which can reduce long-term yield and biomass (Figure 9).



**FIGURE 9** Contour plot of yield-per-recruit as a function of exploitation rate and  $L_c / L_\infty$  for *Cirrhinus reba*.

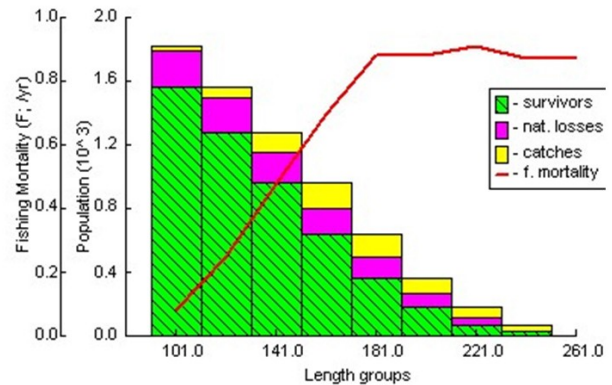
### 3.10 Virtual population analysis (VPA)

The length-structured Virtual Population Analysis (VPA) revealed that population abundance decreased progressively with increasing size classes, while fishing mortality increased in larger individuals. The maximum fishing mortality ( $F \approx 0.91$ ) was observed in size groups from 180 to 260 mm, indicating selective removal of bigger fish (Figure 10). The increasing fishing mortality in larger size classes observed in VPA supports the higher  $F$  (0.87 year<sup>-1</sup>) assessed from catch curve analysis. Despite these limitations, the agreement between VPA and catch curve analyses in the present study suggests higher fishing pressure on larger individuals of *C. reba*.

## 4 | DISCUSSION

Our study provided comprehensive information on popu-

lation and exploitation parameters of *C. reba* from the Saryu River, integrating length-weight relationships, condition factors, growth dynamics, recruitment behavior, mortality structure and exploitation level. The combined population indicators offer important insights into the ecological status and fishery sustainability of this commercially valuable minor carp within the middle Ganga basin.



**FIGURE 10** Virtual Population Analysis (VPA) - length structured, population size, fishing mortality and biomass by length classes.

The observed length range (11.0–27.0 cm) and dominance of intermediate size classes suggest a well-structured population, suggesting regular recruitment and stability. Similar size distribution patterns have been reported for tropical freshwater fishes in Indian rivers, where continuous recruitment contributes to population maintenance (King 2007; Welcomme 2001; Sarkar *et al.* 2018).

The correlation of length - weight shows a high correlation ( $r^2 \geq 0.925$ ), which means the correlation between length and weight is definite. Sex differences in growth pattern were observed: negative allometric growth pattern in males and positive in females, which reflects differences in energy allocation, frequently linked with reproductive investment. Variabilities are widely reported in freshwater fishes, especially in the cyprinids (Le Cren 1951; Froese 2006; Das 2018). The estimated exponent values fall within the expected biological range for fishes, as reported in previous studies (Froese 2006; Moutopoulos and Stergiou 2002; Raghavan *et al.* 2012).

Seasonal variations were observed in condition factors ( $K_f$  and  $K_n$ ) with higher values during pre-monsoon and monsoon months and lower values during winter. Many studies have reported seasonal changes in the condition factor of freshwater fishes and the main factors affecting condition factor are environmental conditions, feeding activity and reproductive status (Froese 2006; Gomiero and Braga 2005; Parihar *et al.* 2016; Jisr *et al.* 2018). Similar seasonal variations in condition factors

have also been reported for *C. reba* in the Ganges River, northwestern Bangladesh where fluctuations were associated with feeding intensity and gonadal development (Gupta 1975).

The growth parameters ( $L_{\infty} = 27.0$  cm and  $K = 0.65$  year<sup>-1</sup>) indicated moderate growth performance of *C. reba* in the study area. The close agreement between the estimated asymptotic length and observed maximum length suggests a good fit of the von Bertalanffy Growth Function. Similar growth patterns have been reported for freshwater fishes from Indian rivers and other tropical systems (Pauly 1980; Sparre and Venema 1998; Chakraborty 2021; Ramulu *et al.* 2022).

The growth performance index ( $\Phi' = 2.67$ ) falls within range reported for tropical cyprinids and serves as a useful comparative tool across species and habitats (Pauly and Munro 1984; Froese and Binohlan 2000). Comparable  $\Phi'$  values have been documented for related carp species in Indian and Southeast Asian waters, indicating consistency in growth characteristics under similar ecological conditions (Dutta 2022; Masood *et al.* 2022). The estimated maximum age ( $t_{max} \approx 4.15$  years) further supports the classification of the species as short-lived, which is typical of small to medium-sized tropical fishes (Welcomme 2001; King 2007).

The recruitment pattern revealed continuous recruitment throughout the year, with a pronounced peak during the monsoon season. This suggests prolonged spawning activity, which is a common feature of tropical riverine fishes influenced by seasonal hydrological cycles. Enhanced recruitment during monsoon months has been widely documented and is associated with increased water flow, habitat expansion and nutrient availability (Welcomme 2001; King 2007; Sarkar *et al.* 2018; Gupta *et al.* 2023).

Generally, the growth, condition factor and recruitment characteristics observed in this study indicate that *C. reba* maintains stable population dynamics under the prevailing environmental conditions of the Saryu River. These findings are consistent with established ecological patterns in tropical freshwater fishes and provide a valuable baseline for future ecological and fisheries-related investigations.

The close proximity between the estimated length at first maturity ( $L_m = 15.45$  cm) and length at first capture ( $L_{50} = 15.5$  cm) indicates that *C. reba* are generally recruited into the fishery after attaining sexual maturity. This pattern is considered favorable for sustaining natural recruitment and maintaining spawning stock biomass. Similar findings have been reported in tropical freshwater fisheries, where capture sizes near maturity length are associated with balanced exploitation and reduced risk of recruitment overfishing (Froese 2004; Froese *et al.* 2016). However, prolonged fishing pressure near the maturity threshold may negatively affect stock productivity over

time, emphasizing the need for regulated mesh size and sustainable harvesting practices (Gwinn *et al.* 2015).

The mortality estimates revealed that fishing mortality exceeded natural mortality, indicating that anthropogenic extraction is the primary driver of stock reduction. The exploitation rate ( $E = 0.55$ ) slightly surpasses the optimum exploitation threshold ( $E \approx 0.50$ ), suggesting emerging overexploitation. Similar exploitation levels have been reported for minor carps in intensively fished South Asian rivers (Ray *et al.* 2023; Dwivedi *et al.* 2026).

According to Gulland (1971), exploitation rates exceeding optimal reference points increase the risk of recruitment overfishing. The probability of capture analysis further indicated harvesting of individuals at relatively small sizes ( $L_{50} \approx 15.5$  cm), implying growth overfishing caused by premature capture before maximum biomass accumulation. Comparable observations have been documented in exploited river fisheries where mesh selectivity favors capture of sub-adult fish (Sparre and Venema 1998).

The yield-per-recruit analysis showed a classical dome-shaped curve consistent with Beverton and Holt equilibrium theory (Beverton and Holt 1957). The current exploitation rate lies slightly above  $E_{0.1}$ , indicating that the stock is approaching full exploitation but has not yet reached maximum yield potential (Pauly and Soriano 1986). Similar  $Y'/R$  responses have been reported for Indian major and minor carps where increased fishing pressure results in declining biomass-per-recruit despite temporary yield increases (Khan *et al.* 2022; Ray *et al.* 2023). The declining biomass-per-recruit trend observed in this study highlights the necessity of maintaining exploitation near precautionary biological reference points (Sparre and Venema 1998; Froese *et al.* 2016).

Virtual Population Analysis demonstrated increasing fishing mortality toward larger size classes, indicating selective removal of mature individuals. Because fecundity in cyprinid fishes increases exponentially with body size, removal of large breeders may significantly reduce reproductive output and recruitment success (Ricker 1975; King 2007; Winker *et al.* 2012). Similar patterns of size-selective exploitation have been reported from the Ganga River, where heavy fishing pressure disproportionately removes spawning adults (Dwivedi *et al.* 2026). Protection of larger individuals through gear regulation or size limits is therefore critical for sustaining spawning stock biomass. However, fishing mortality estimates should be interpreted cautiously, as length-based methods are influenced by assumptions regarding growth, recruitment, and gear selectivity (Taylor *et al.* 2005; García-García *et al.* 2026).

## 5 | CONCLUSIONS

The present study provides the first comprehensive eval-

uation of the population and exploitation parameters of the *C. reba* in the Saryu River using length-based stock assessment approaches. The study points towards gradual increase of fishing pressure on the stock. Therefore, management measures like greater mesh size and reduced fishing pressure are crucial in ensuring the sustainability of the stocks in the long-term. Although the population remains productive at present, the results indicate that the fishery is approaching full exploitation and may become overexploited if fishing intensity continues to increase. Early management intervention is therefore essential to prevent long-term stock decline. Adoption of ecosystem-based fisheries management measures, including regulation of fishing effort, enforcement of appropriate mesh sizes and protection of spawning seasons and critical habitats, is recommended to maintain spawning stock biomass and ensure sustainable yield. Overall, the findings provide important baseline information for science-based management of minor carp fisheries in the middle Ganga basin and contribute to the sustainable conservation and utilization of *C. reba* resources in riverine ecosystems.

#### ETHICAL APPROVAL

Fish sampling was conducted following standard fisheries research ethical guidelines with the cooperation of local fishing communities and without involvement of endangered species handling procedures requiring institutional animal ethics approval.

#### CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

#### AUTHORS' CONTRIBUTION

Lavkush: Conceptualization, investigation, field sampling, data curation, formal analysis, visualization and writing original draft preparation. Radhakrishnan K.V.: Methodology development, supervision, validation and writing review and editing. C.P. Singh and Pullagura Siva Nagenra: Statistical analysis, data validation and interpretation of results. Sunil Kant Verma and Puneet K Patel: Investigation, field data collection and resource support. Moira G. Momin and Abhisek Gharai: Visualization, critical review and manuscript editing.

#### DATA AVAILABILITY STATEMENT

The datasets generated during the current study are available from the corresponding author upon reasonable request.

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
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- Lavkush  <https://orcid.org/0009-0000-1808-0238>
- Radhakrishnan KV  <https://orcid.org/0000-0002-4407-6125>
- CP Singh  <https://orcid.org/0000-0001-6305-5496>
- SK Verma  <https://orcid.org/0009-0007-0873-8752>
- PK Patel  <https://orcid.org/0009-0007-4845-6479>
- PS Nagendra  <https://orcid.org/0009-0002-5354-379X>
- MG Momin  <https://orcid.org/0009-0003-8624-5884>
- A Gharai  <https://orcid.org/0009-0002-4668-2142>