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# Assessment of reproductive potential and spawning patterns of *Barilius bendelisis* (Hamilton, 1807) in tributaries of the Ganga River in the Garhwal Himalayan region

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## Abstract

Understanding reproductive strategies is essential for the biological conservation and management of hill-stream fishes in dynamic freshwater ecosystems. The present study investigated the reproductive biology of *Barilius bendelisis* (Hamilton, 1807), a key cyprinid species inhabiting three different streams and tributaries of the Ganga River *viz.*: the Song River, Sahastradhara, and Henval River in the Garhwal Himalayan region. The study was conducted from September 2023 to May 2025, covering all major seasons. Key reproductive parameters, including sex ratio, gonadosomatic index (GSI), Dobriyal index (DI), fecundity, and sexual dimorphism, were examined to determine spawning periodicity and reproductive potential. A female-biased sex ratio was consistently observed across all sites, with overall sex ratios of 1:1.14, 1:1.1 and 1:1.45 in the Song, Sahastradhara, and Henval Rivers, respectively. Peak GSI and DI values were recorded during the summer and monsoon seasons, indicating these seasons as the primary spawning period, with DI showing greater precision in identifying spawning periods. Fecundity varied among sites and showed a strong positive correlation with gonad weight, reflecting site-specific reproductive investment. Notably, males displayed prominent breeding tubercles during the spawning phase, serving as markers for sexual dimorphism. Overall, the findings reveal spatial variation in reproductive traits and highlight adaptive strategies of *B. bendelisis* in Himalayan hill-stream ecosystems. These insights offer a scientific foundation for developing season-specific conservation strategies, regulating fishing pressure during peak breeding periods, promoting the sustainable management of freshwater biodiversity in the Garhwal Himalayas.

## Introduction

*Barilius bendelisis* (Hamilton, 1807), commonly known as the Indian hill trout, is a small bodied cyprinid fish inhabiting the fast flowing streams and rivers of the Himalayan foothills. Locally referred to as "Chilwa" in Dehradun and "Jaapki" in Tehri Garhwal, Uttarakhand, the species is characterised by a compressed, moderately elongated body with dark blue spots or bars on the body, and a dorsal fin inserted behind the pelvic fin origin (Mahanta *et al*., 2011). Hill trouts are known for their ecological, economic and conservation significance, particularly in the ornamental fish trade (Gurung *et al*., 2005; Jayaram, 2010). Earlier investigations on the systematics and osteology of the genus *Barilius* have further highlighted its ecological relevance (Howes, 1980).

Fisheries population dynamics and management models require the determination of maturity stages, reproductive indices such as Gonadosomatic index (GSI) and Dobriyal index (DI), as well as reproductive capacity, among other parameters (Rayal *et al.,* 2021 b). Fecundity is a critical parameter for understanding the dynamics of ripe ova and the life history traits of fish populations (Kapoor and Khanna, 2004), as it plays a key role in maintaining population structure and maturity size. Fecundity refers to the number of ripening eggs present in females before spawning (Bagenal, 1978). An individual female's fecundity is influenced by factors such as age, size, food availability, space, climatic conditions, seasons, environmental aspects, habitat, nutritional status, and genetic potential (Doha and Hye, 1970). Understanding the breeding capacity of a fish, largely influenced by the riverine habitat ecology, is essential for evaluating its commercial potential, comprehending its life history, optimising its cultivation and ensuring its effective fishery management. Given that the temperature of snow-fed water is lower than that of spring-fed water, fecundity may vary depending on the habitat niche to which the fish species is adapted. Previous studies have reported habitat-related variation in fecundity of *B. bendelisis*, with comparatively lower fecundity observed in colder snow-fed systems (Rayal *et al.,* 2021a). The availability of natural food and moderate temperature ranges creates an excellent breeding environment for fish in spring-fed rivers. The dynamics of reproductive traits, such as spawning, ova diameter, fecundity, and GSI, are likely influenced by climatic and ecological factors. Several research studies have previously examined the reproductive biology of *Barilius* species in Uttarakhand (Dobriyal and Singh, 1987; Gaur and Pathani, 1996; Nautiyal and Negi, 2004; Bahuguna *et al.,* 2009, 2010, 2020, 2021; Saxena *et al.,* 2016; Rayal *et al.,* 2021a). Despite these regional studies, comparative research on the fecundity patterns of *B. bendelisis* across multiple locations within the Garhwal Himalayan region remains limited.

The present study aims to address this gap by evaluating the fecundity of *B. bendelisis* across three distinct tributaries of the Ganga River, namely the Song River, Sahastradhara, and Henval River in the Garhwal Himalayan region. By examining the reproductive potential, specifically the fecundity, the study provides insights into the reproductive biology of *B. bendelisis* under varying environmental contexts, thereby contributing to the sustainable management and conservation of this valuable species in the endemic hill streams of the Himalayan region.

# Materials and methods

## Study area and sample collection

In the present study, fish samples were collected from different streams and tributaries of the Ganga River *i.e.*, Song (30° 12' 14.148" N; 78° 7' 58.584" E), Sahastradhara (30° 23' 17.88" N; 78° 7' 53.364" E), and Henval River (30° 15' 14.004" N; 78° 22' 33.132" E), during September, 2023 to May, 2025 (Fig. 1). Samples were procured with the assistance of local fishermen using cast net (mesh size: 2 x 2 cm) and the thali method during experimental fishing. The sampled specimens were identified to species level following Hamilton (1822) and Day (1873) and after examination most of the fish were released back into their respective streams. Selected specimens were photographed in fresh condition, preserved immediately in 10% formalin and transported to the laboratory for further analysis. Total length and body weight were measured using a scale and digital balance nearest to 0.1 cm and 0.001 g, respectively.

## Identity of sex and sex ratio

The male and female *B. bendelisis* were identified after dissecting the fish, and analysing the reproductive organs (Figs. 2, 3 ). The sex ratio was calculated using the formula:

$$X = \frac{M}{F}$$

where X is the sex ratio, M and F are the number of male and female fish, respectively. The overall sex ratio was expressed as male: female (M: F), and significant deviation from the expected 1:1 ratio was tested using the chi-square test ($\chi^2$) proposed by Fisher (1930):

$$X^2 = \sum \frac{(O - E)^2}{E}$$

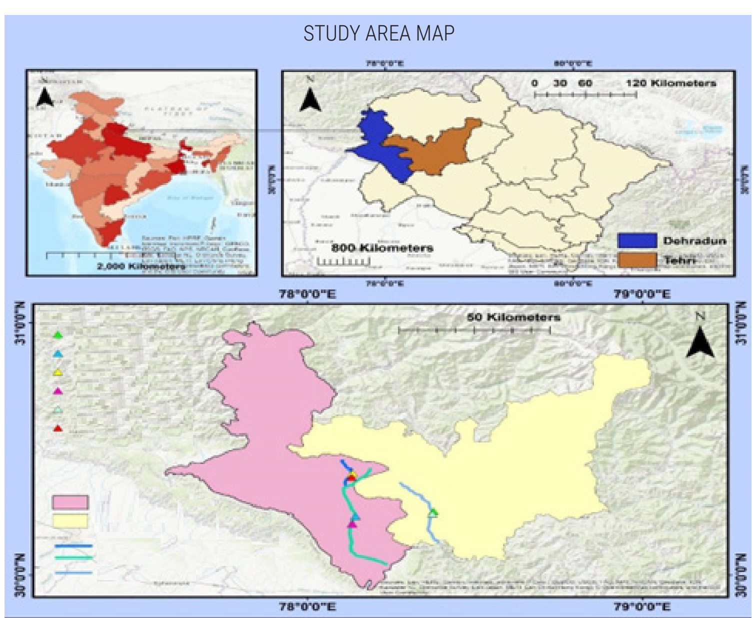



Fig. 1. Study area map

## Gonadosomatic index and Dobriyal index

Mature specimens were selected for gonad analysis. Ovary length was measured with the help of a scale nearest to 0.1 cm (Fig. 2), and ovary weight was taken with the help of an electronic balance nearest to 0.001 g and later preserved in 10% formalin for further analysis. The morphometric measurements of fish were recorded in fresh condition. Gonadosomatic index (GSI) and Dobriyal index were calculated seasonally for both sexes using the formula:

Gonadosomatic index (GSI.) = Weight of gonads/Weight of fish×100 (Nikolskii, 1963)

Dobriyal index (DI) = $\sqrt[3]{GW}$ (Cube root of average gonad weight) (Dobriyal *et al.*, 1999)

## Fecundity

Fecundity was estimated from stage IV mature ova using the gravimetric method (Lagler, 1956). Mature ovaries were excised; length and weight were measured, before being preserved in Gilson's solution. Subsamples of 0.1 g, were taken separately from the anterior, middle and posterior regions of each ovarian lobe. The eggs in each subsample were counted, and the mean number of eggs was calculated. Absolute fecundity was then calculated following Bagenal (1978):

$$\text{Absalute fecundity} = \frac{\text{No.of ova in the subsample} \times \text{Total ovary weight}}{\text{Weight of subsample}}$$

## Data analysis

The experimental data collected were statistically analysed using Microsoft Excel (2021). Regression analysis was used to examine the relationships among fecundity, ovary length (cm), and ovary weight (g) (Fig .3).

# Results and discussion

In the present study, 247 specimens (137 females and 110 males) were collected from various tributaries and streams of the Ganga River, namely the Song, Sahastradhara, and Henval Rivers, between September 2023 and May 2025. The number of males and females shows considerable variation across different seasons (Fig. 4), with females outnumbering males at all sites, yielding sex ratios of 1:1.14, 1:1.1, and 1:1.45 in the Song, Sahastradhara, and Henval Rivers, respectively (Table 1). These findings are consistent with earlier observations by Wootton and Smith (2014), who reported that wild fish populations often exhibit female-biased sex ratios due to favourable environmental conditions such as moderate temperatures, neutral to basic pH and lower population densities. The dominance of females in the present study suggests that such conditions likely prevailed in these rivers during the study period. However, occasional seasonal shifts toward a male bias in Sahastradhara and the Henval River may reflect short-term environmental fluctuations, such as increased temperature or decreased pH and dissolved oxygen, which are known to influence sex differentiation. The observed patterns affirm the role of ecological factors in shaping the natural sex ratio in riverine fish populations, as supported by previous literature.

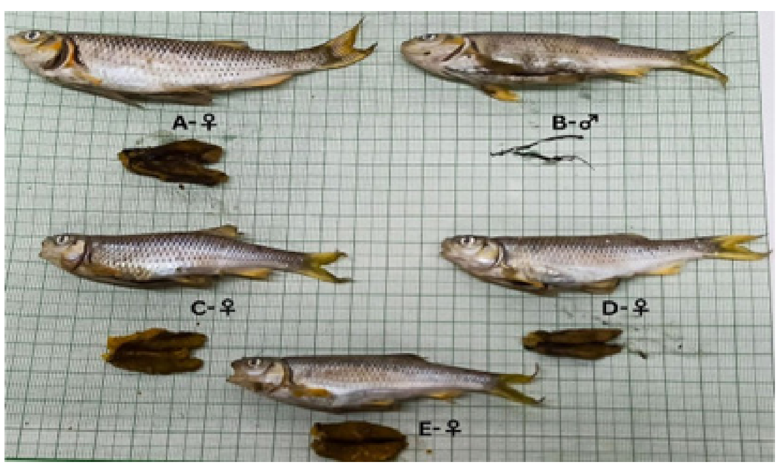



Fig. 2. Variation in length of mature gonads of different sizes of *B. bendelisis* (Male: B and Female: A, C, D, E)


(a) (b)

Fig. 3. Position of gonads in (a) female and (b) male *B. bendelisis*

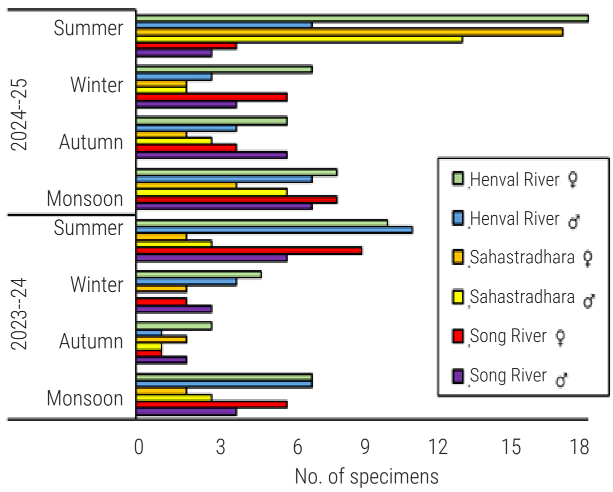



Fig. 4. Seasonal variation in the number of fish specimens captured from various streams and tributaries of the Ganga River

Fecundity in fish is closely linked to morphometric parameters such as gonad weight, body weight, and total length, typically increasing in a linear or curvilinear manner (Jessop, 1993; Dey *et al.*, 2016). The present study confirms this trend, showing a strong positive correlation between fecundity and ovary weight in *B. bendelisis* (Fig. 5), with $R^2$ values of 0.91 and 0.93 from the Song River and Sahastradhara, respectively, which was also reported by Jhingran (1968) in *Catla catla*, Hussain *et al.* (2003) in *Osteobrama cotio cotio*, Bahuguna and Khatri (2009) in *Noemacheilus montanus*, Alam and Pathak (2010) in *Labeo rohita*, and Jan *et al.* (2014) in *Schizothorax plagiostomus*. However, a moderate correlation ($R^2$ = 0.61) was observed in the Henval River, where ovary length and ovary weight were equally related to fecundity. The absolute fecundity of *B. bendelisis* ranged from 359 eggs (6.6 cm, 2 g) to 3458 eggs (13.7 cm, 29 g) in the Song River (Table 2), 694 eggs (7.9 cm, 8 g) to 2007 eggs (12.9 cm, 20 g) in Sahastradhara (Table 3), and 1125 eggs (11.5 cm, 18 g) to 2329 eggs (14.1 cm, 30 g) in the Henval River (Table 4). The fecundity values obtained in the present study fall within the range reported in earlier works. Dobriyal and Singh (1987) recorded a maximum fecundity of 5048 eggs; Jabeen *et al.* (2016)

Table 1. Sex ratio of *B. bendelisis* (male and female) from various streams and tributaries of the Ganga River

| Year | Seasons | Study area | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Song River | | | | Sahastradhara | | | | Henval River | | | |
| | | No. | M | F | M:F | No. | M | F | M:F | No. | M | F | M:F |
| 2023-24 | Monsoon | 10 | 4 | 6 | 1:1.5 | 5 | 3 | 2 | 1:0.7 | 14 | 7 | 7 | 1:1 |
| | Autumn | 3 | 2 | 1 | 1:0.5 | 3 | 1 | 2 | 1:2 | 4 | 1 | 3 | 1:3 |
| | Winter | 5 | 3 | 2 | 1:0.7 | 2 | 0 | 2 | 0:2 | 9 | 4 | 5 | 1:1.25 |
| | Summer | 15 | 6 | 9 | 1:1.5 | 5 | 3 | 2 | 1:0.7 | 21 | 11 | 10 | 1:0.9 |
| 2024-25 | Monsoon | 15 | 7 | 8 | 1:1.14 | 10 | 6 | 4 | 1:0.7 | 15 | 7 | 8 | 1:1.14 |
| | Autumn | 10 | 6 | 4 | 1:0.7 | 5 | 3 | 2 | 1:0.7 | 10 | 4 | 6 | 1:1.5 |
| | Winter | 10 | 4 | 6 | 1:1.5 | 4 | 2 | 2 | 1:1 | 10 | 3 | 7 | 1:2.3 |
| | Summer | 7 | 3 | 4 | 1:1.3 | 30 | 13 | 17 | 1:1.3 | 25 | 7 | 18 | 1:2.6 |
| | Total | 75 | 35 | 40 | 1:1.14 | 64 | 31 | 33 | 1:1.1 | 108 | 44 | 64 | 1:1.45 |

Table 2. Fecundity of *B. bendelisis* from the Song River

| Class interval | Total length (cm) | Body weight (g) | Gondad length (cm) | Gondal weight (g) | No. of eggs | Weight of eggs (g) | Absolute fecundity |
|---|---|---|---|---|---|---|---|
| 6.1-7.0 | 6.6-6.7* (6.65±0.07) | 2.0 | 2.0 | 0.1 | 1150 | 0.32 | 359.375 |
| 7.1-8.0 | 7.6 | 3.0 | 2.2 | 0.15 | 1175 | 0.34 | 518.38 |
| 8.1-9.0 | 8.6-8.8 (8.7±0.14) | 7.0-8.0 (7.5±0.70) | 2.4-2.5 (2.45±0.07) | 0.25-0.4 (0.32±0.10) | 1190-1200 (1195±7.07) | 0.35-0.5 (0.42±0.10) | 850-960 (905±77.78) |
| 9.1-10.0 | 9.7 | 8.5 | 2.6 | 0.4 | 1230 | 0.5 | 984 |
| 10.1-11.0 | 10.1-11.0 (10.56±0.34) | 11.0-15.0 (12.53±1.56) | 2.1-3.0 (2.60±0.27) | 0.3-1.2 (0.81±0.24) | 1450-1650 (1525±66.29) | 0.62-1.0 (0.71±0.09) | 1746-2121.42 (1953.75±118.30) |
| 11.1-12.0 | 11.2-11.9 (11.67±0.24) | 14.0-18.0 (16.4±1.50) | 2.8-3.3 (2.94±0.17) | 0.9-1.45 (1.10±0.20) | 1460-1750 (1612±82.56) | 0.7-1.22 (0.87±0.20) | 1659.09-2121.42 (1980.44±146.53) |
| 12.1-13.0 | 12.3-12.9 (12.62±0.26) | 14.0-20.0 (17.8±2.48) | 2.6-3.1 (2.9±0.2) | 0.5-1.2 (0.88±0.35) | 1650-1750 (1700±50) | 0.8-1.0 (0.93±0.11) | 1980-2125 (2068.33±77.51) |
| 13.1-14.0 | 13.4-14.0 (13.78±0.24) | 22.0-29.0 (26.2±3.11) | 3.1-3.6 (3.32±0.21) | 1.1-1.9 (1.48±0.28) | 1800-1900 (1838±38.98) | 1.0-1.3 (1.21±0.11) | 1672-3458 (2301.36±675.95) |

*Data expressed as Lower limit - Upper limit (Mean±SD)

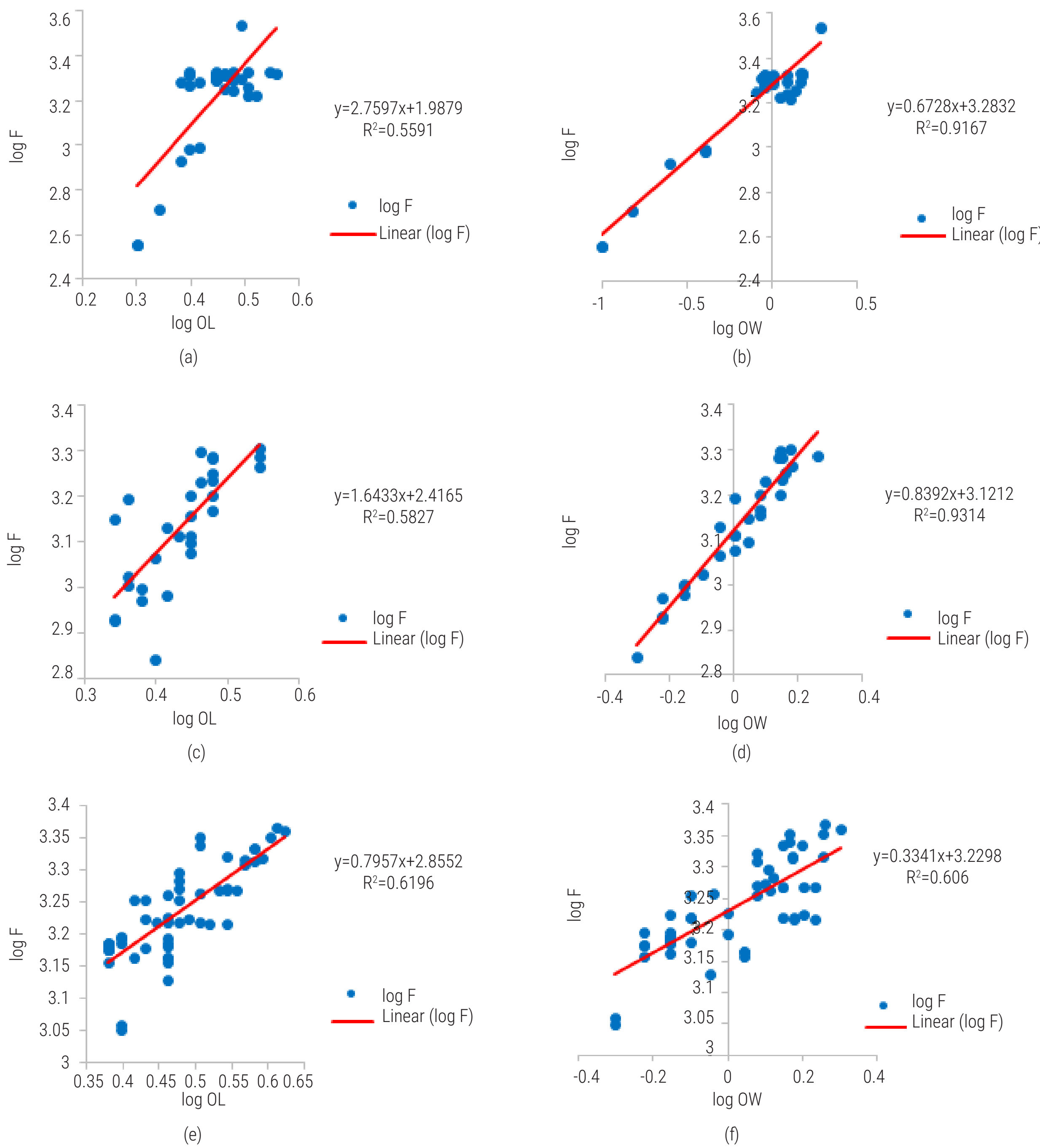



Fig. 5. Relationship of fecundity with ovary length and ovary weight from Song River (a and b); Sahastradhara (c and d); and Henval River (e and f)

found a range of 440 - 2652 eggs; Saxena *et al.* (2017) reported 320-4000 eggs; Bahuguna *et al.* (2010) observed 192-4317 eggs; and Rayal *et al.* (2021a) reported a range of 162-4203 eggs. Considerable variation in fecundity among fish of similar size and weight, especially observed in the Henval River population, may be attributed to environmental factors such as temperature and food availability, as well as genetic differences (Blaxter, 1969; Gibson and Ezzi, 1978; Hoda and Akhtar, 1985). The fecundity of coldwater fish is often observed to be low due to specific ecological factors in hill streams, including decreased food supply and a narrow thermal range (Bahuguna *et al.*, 2007). Bagenal (1957, 1978) and Bagenal and Braum (1978) also emphasised that fecundity might vary among fish individuals of the same size and age, influenced by seasonal and environmental factors. Thus, the present findings not only reinforce the influence of morphometric traits on fecundity but also highlight the role of habitat-specific ecological conditions in shaping the reproductive potential of *B. bendelisis*.

Table 3. Fecundity of *B. bendelisis* from Sahastradhara

| Class interval | Total length (cm) | Body weight (g) | Gonad length (cm) | Gonad weight (g) | No. of eggs | Weight of eggs (g) | Absolute fecundity |
|---|---|---|---|---|---|---|---|
| 7.1-8.0 | 7.4-7.9* (7.64±0.24) | 5.0-8.0 (6.64±1.37) | 2.2-2.5 (2.32±0.11) | 0.5-0.8 (0.64±0.09) | 1130-1250 (1177.85±53.06) | 0.8-0.9 (0.82±0.04) | 694.44-1057.77 (913.17±124.67) |
| 8.1-9.0 | 8.3-8.9 (8.52±0.22) | 7.0-10.0 (8±1.87) | 2.2-2.6 (2.44±0.18) | 0.7-1.1 (2.44±0.18) | 1150-1290 (1224±52.72) | 0.8-1.0 (0.88±0.08) | 956.66-1562.5 (1287.14±233.94) |
| 9.1-10.0 | 9.5-9.6 (9.52±0.05) | 8.0 | 2.7-2.8 (2.77±0.05) | 1.0-1.2 (1.05±0.1) | 1190-1290 (1240±57.73) | 1.0 | 1190-1428 (1299.5±97.78) |
| 10.1-11.0 | 10.1-10.8 (10.44±0.28) | 8.0-15.0 (12.71±3.09) | 2.5-3.0 (2.84±0.17) | 0.9-1.39 (1.23±0.18) | 1250-1650 (1450.83±169.12) | 1.1-1.2 (1.12±0.04) | 1250-1985.71 (1672.15±267.25) |
| 11.1-12.0 | 11.4-11.6 (11.45±0.1) | 11.0-15.8 (13.95±2.1) | 3.0 | 1.2-1.45 (1.35±0.10) | 1465-1600 (1506.25±63.42) | 1.15-1.22 (1.19±0.02) | 1465.57-1920 (1717.74±189.73) |
| 12.1-13.0 | 12.9 | 16.0-20.0 (18.66±2.30) | 3.0-3.5 (3.33±0.28) | 1.1-1.51 (1.37±0.23) | 1600-1740 (1670±98.99) | 1.3-1.32 (1.31±0.01) | 1830.30-2007.69 (1918.99±125.43) |
| 13.1-14.0 | 13.1-14 (13.56±0.45) | 20.0-26.0 (22.66±3.05) | 3.2-3.5 (3.33±0.15) | 1.1-1.82 (1.34±0.41) | 1750 | 1.65 | 1930.3 |

*Data expressed as Lower limit - Upper limit (Mean±SD)

Table 4. Fecundity of *B. bendelisis* from the Henval River

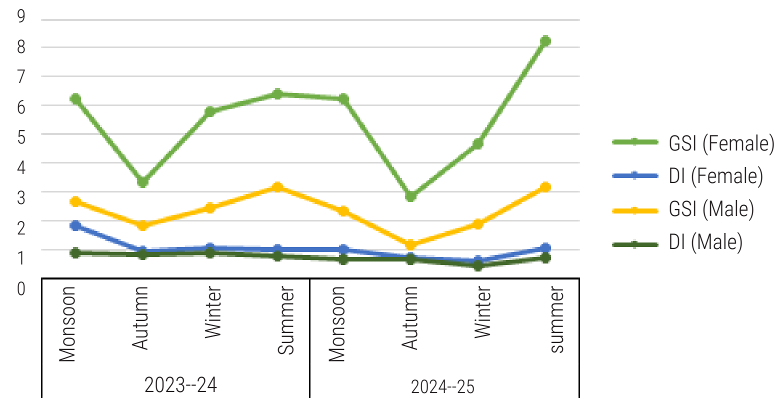
| Class interval | Total length (cm) | Body weight (g) | Gonad length (cm) | Gonad weight (g) | No. of eggs | Weight of eggs (g) | Absolute fecundity |
|---|---|---|---|---|---|---|---|
| 8.1-9.0 | 8.2-8.7* (8.42±0.17) | 6.0-10.0 (6.88±1.76) | 1.6-2.5 (2.24±0.36) | 0.05-0.7 (0.55±0.28) | 1130-1220 (1178.57±34.36) | 0.6-0.7 (0.65±0.05) | 1506.66-1568.57 (1538.63±18.38) |
| 9.1-10.0 | 9.5 | 8.0 | 2.7 | 0.8 | 1210 | 0.8 | 1512.5 |
| 10.1-11.0 | 10.1-10.4 (10.23±0.15) | 10.0 | 2.9 | 1.1 | 1200-1220 (1213.33±11.54) | 1.0 | 1440-1464 (1456±13.85) |
| 11.1-12.0 | 11.1-12.0 (11.56±0.32) | 10.0-19.0 (14.8±4.08) | 2.5-3.0 (2.76±0.24) | 0.5-1.2 (0.8±0.30) | 900-1500 (1204±284.30) | 0.4-1.0 (0.66±0.26) | 1125-1800 (1458.92±305.48) |
| 12.1-13.0 | 12.2-13.0 (12.72±0.26) | 13.0-25.0 (18.85±3.68) | 2.1-3.8 (2.89±0.49) | 0.6-1.58 (0.90±0.42) | 1050-1850 (1461.28±249.82) | 0.4-1.35 (0.82±0.32) | 1440-2190 (1777.80±252.26) |
| 13.1-14.0 | 13.2-13.9 (13.61±0.22) | 18.0-29.0 (22.44±2.53) | 2.5-3.8 (3.11±0.40) | 0.4-1.7 (1.12±0.41) | 1250-1850 (1526.70±184.87) | 0.6-1.2 (0.84±0.19) | 1458.33-2250.83 (1803.07±213.31) |
| 14.1-15.0 | 14.1-14.7 (14.2±0.21) | 24.0-32.0 (26.75±3.16) | 2.9-4.2 (3.72±0.42) | 0.9-2.0 (1.58±0.37) | 1200-2055 (1750±281.25) | 0.8-1.7 (1.25±0.32) | 1350-2329.6 (2017.07±343.24) |

*Data expressed as Lower limit - Upper limit (Mean±SD)

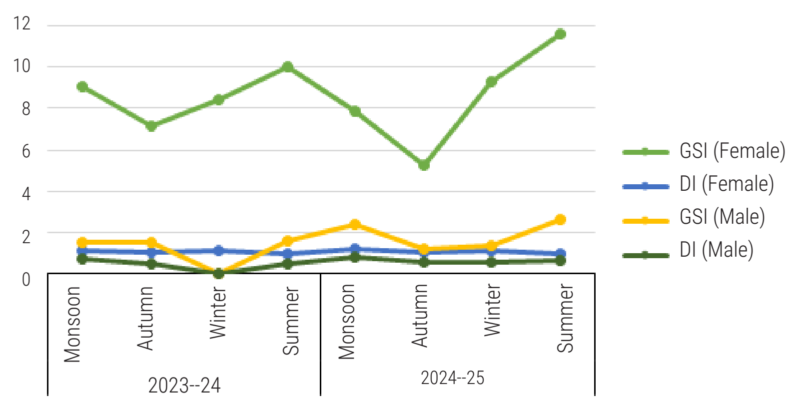
The GSI provides reliable information on fish spawning in temperate and tropical regions (Bouain and Siam, 1983), as gonad weight increases with maturity. In the present study, GSI values increased progressively with gonadal development, peaking during the summer season: 3.19 and 8.26 (Song River), 2.63 and 11.58 (Sahastradhara), and 2.57 and 10.47 (Henval River) for males and females, respectively, indicating an active spawning phase as shown in Fig. 6 (a, b, and c). This was followed by gradually declining values in monsoon and autumn, *i.e.*, 2.85 (Song River), 5.24 (Sahastradhara), 1.11 (Henval River), marking a post-spawning resting phase in the autumn season. After the resting phase, GSI values start to increase in the winter season. This pattern also highlighted prolonged reproductive activity across two seasons. Male fish exhibited a similar seasonal trend. Typically, females display higher GSI values compared to males (Khan, 1945; Ganpati and Chacko, 1954; Pathak and Jhingran, 1977; Piska and Devi, 1993), which was evident in the present study. The observed bimodal peak in GSI, particularly during summer and monsoon, suggests a prolonged and dual spawning strategy. Hill-stream fishes generally reproduce during the monsoon period, with their breeding season typically falling between July and August (Rayal *et al.,* 2022). Grover (1971) reported that *B. bendelisis* spawns during November and December, while Dobriyal and Singh (1987) and Saxena *et al.* (2016) concluded that *B. bendelisis* spawns twice a year, during March to May in summer and August to September during the monsoon season.

Another reproductive index proposed by Dobriyal *et al.* (1999), which is based solely on gonad weight, was applied to assess seasonal reproductive trends in *B. bendelisis* populations from Song River, Sahastradhara, and Henval River during 2023-25 (Fig. 6 a, b, and c). Among females, seasonal trends indicated peak reproductive activity during the monsoon and summer months, while the autumn season consistently represented the spent phase. In the Song River population, the highest DI (1.84) was recorded during the monsoon season in 2023-24, with a notable decline (0.92) in autumn, followed by a moderate increase (1.04) in winter and a slight fluctuation (1.02) in summer. In the subsequent year (2024-25), the peak value (1.04) shifted to summer, with a gradual decline observed in monsoon (1.02), autumn (0.73) and winter (0.61). Similar reproductive trends were observed in Sahastradhara, monsoon DI values being consistently the highest (1.09 and 1.16) in both years, while summer registered the lowest values (0.96). Autumn and winter seasons showed intermediate values, indicating an extended breeding period. The Henval River population had the highest DI (1.17) during summer 2023-24, followed closely by monsoon (1.15), suggesting a protracted spawning window.




(a)

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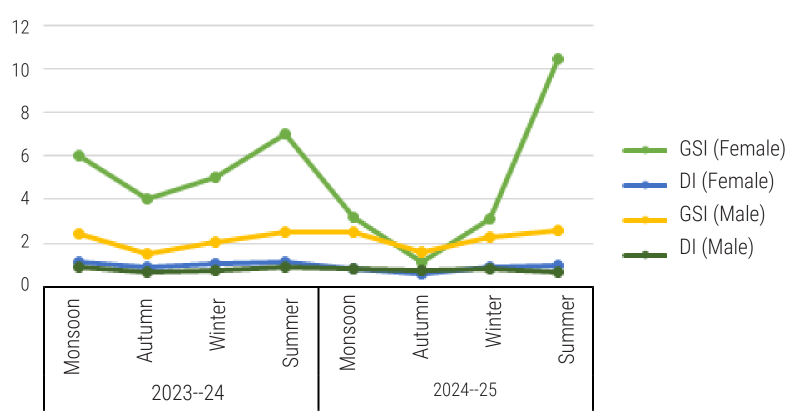


(c)

Fig. 6. GSI and DI of *B. bendelisis* (male and female) (a) from the Song River, (b) Sahastradhara and (c) Henval River

Autumn again reflected the spent phase (0.90), while winter DI (1.03) values rebounded. This seasonal cycle remained consistent across both years in the Henval River.

In males, the DI values were generally lower and displayed more variability than in females, reflecting a greater sensitivity to environmental fluctuations. In the Song River, male DI peaked (0.87) in winter in 2023-24, while in 2024-25, the maximum shifted (0.74) to summer, followed by a decline (0.67) through monsoon, autumn (0.65), and a winter minimum (0.44). Males from Sahastradhara exhibited the highest DI (0.80) in the monsoon in both years, with sharp declines (0.46-0.51) in autumn and summer, suggesting synchronisation of male reproductive effort with the monsoonal cycle. In Henval, the 2023-24 data showed a summer peak (0.91), followed by a decline in monsoon (0.87) and autumn (0.66), with a slight increase in winter (0.78). In contrast, the 2024-25 pattern showed a winter maximum (0.84), a summer decrease (0.66), an increase during monsoon (0.82), and a subsequent decline in autumn (0.72).

The pattern of reproductive indices indicates that the peak season is summer, during which the species reaches full maturity and spawns between the summer and autumn seasons. This data suggests that *B. bendelisis* is a batch spawner, spawning multiple times per year, showing a bimodal pattern of ova laying in the breeding season.

## Sexual dimorphic characters

Sexual dimorphism in *B. bendelisis* is distinctly expressed through both morphological and physiological traits in aquatic habitat niches across geographical regions. One of the most notable features in males is the presence of breeding tubercles on the scales, structures that are absent in juveniles and females. These tubercles serve as protective adaptations against mechanical injury and help maintain close contact during spawning (Hussain and Bordoloi, 2016). Additionally, males possess a more prominently tuberculated snout and exhibit distinct modifications in their pectoral fins, which are broader, thicker, and elongated, often displaying an orange hue compared to the relatively unmodified fins in females. Interestingly, these sexual dimorphic features have remained consistent for nearly four decades. Early observations by Tilak and Jaffer (1982) also documented similar morphological differences in *B. bendelisis*. The sexual dimorphism in pelvic fins and girdles has also been reported in *B. barna* (Tilak and Jaffer, 1982; Tilak *et al.*, 1991). The persistence of these traits over time suggests that such dimorphism is under strong stabilising selection, likely due to its essential role in reproductive success and species-specific mating behaviours.

Physiological differences between sexes further support the presence of sexual dimorphism. Sharma *et al.* (2017) reported significant sex-specific seasonal variations in haematological and serum biochemical indices, with males showing elevated haemoglobin, haematocrit, erythrocyte, and WBC counts in summer, while mean corpuscular volume and haemoglobin were higher in winter. These findings suggest that sex and seasonal environmental factors significantly influence physiological health indicators in *B. bendelisis*.

This study reveals significant spatial variation in the reproductive biology of *B. bendelisis* across three streams and tributaries of the Ganga River in the Garhwal Himalayas. A consistent female-biased sex ratio was observed at all sites. Fecundity exhibited a strong correlation with ovary weight in populations from the Song River and Sahastradhara, while a moderate association with both ovary weight and ovary length was noted in the Henval River population. Absolute fecundity was highest in the Song River, aligning with peak Dobriyal index values, while the highest gonadosomatic index was recorded in Sahastradhara, reflecting larger body sizes despite lower fecundity. The observed discrepancies between GSI and DI underscore the utility of DI as a more reliable indicator of spawning readiness, as it is not influenced by body weight. These findings reinforce the batch spawning strategy of *B. bendelisis*, characterised by two distinct reproductive peaks during the summer and monsoon seasons. Sexual dimorphism was evident during the breeding period, marked by the presence of prominent tubercles, intensified male colouration, and fin modifications. Overall, this study enhances our understanding of reproductive plasticity in hill-stream cyprinids and highlights the importance of site-specific reproductive assessments. From a management perspective, identifying peak spawning periods provides a scientific basis for implementing seasonal fishing restrictions and regulating harvest during critical breeding months. Furthermore, recognising habitat-specific reproductive variation supports the development of localised conservation strategies, habitat protection measures, and long-term monitoring programs to ensure the sustainable management of endemic hill-stream fish populations in the Himalayan riverine ecosystem.

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