Reproductive biology of *Heteropneustes fossilis* in a wetland ecosystem (Gajner Beel, Bangladesh) in relation to eco-climatic factors: Suggesting a sustainable policy for aquaculture, management and conservation

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**Abstract**

The stinging catfish, *Heteropneustes fossilis* (Bloch, 1794) is a commercially important fish species in Asia. This is an important food fish as it is enriched with high amounts of protein, iron and calcium. The current research demonstrates the population structure, size at sexual maturity, spawning- and peak-spawning season and fecundity of *H. fossilis* in an important wetland ecosystem - Gajner Beel in northwestern Bangladesh with an aim of its sustainable conservation through induced breeding and aquaculture practices. A total of 426 stinging catfish captured from the Gajner Beel through monthly sampling from January to December 2019 used in the study. Total length (TL), standard length (SL) and body weight (BW) of individual fishes were measured. The size ranges were with 6.70–24.10 cm TL, 1.37–83.94 g BW. Gonads were removed carefully through ventral dissection and weighted. Lm was 14.02, 13.5, 13.0 and 15.0 cm based on maximum length (*L*max), TL vs. GSI (%), TL vs. SL and logistic model, respectively. Monthly variations of GSI and maturation stages were confirmed in April to August as spawning season and June as peak spawning month. Fulton’s condition factor (*K*) was found to be with significant relations with GSI values. Fecundity was 1,730 to 23,870 and significantly correlated with both TL and BW. Temperature has been increasing 0.029 °C/year with the falling of rainfall at 2.96 mm/year in the study area. Environmental factors -Temperature, rainfall, dissolved oxygen and pH were found to be significantly correlated with GSI. We found the optimal range of temperature (29–31 °C), rainfall (350–380 mm), dissolved oxygen (5.0–6.0 mg/l) and pH (7.1-7.5) for spawning of *H. fossilis*. The paper recommended the policy guidelines to pave the ways of the aquaculture, conservation and management of *H. fossilis* in the changing eco-climatic events through specific management measures.

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**1. Introduction**

The Order Siluriformes (catfish) comprises 4,100 species, which constitute 6.3% of all vertebrate species and 12% of all fish species. Catfish have long been playing key role in biological research, as they are similar to a common fishery parent than most bony fish (infraclase Teleostei) because of their phylogenetic position. Nutritionally, catfish are well-known as a valuable source of dietary protein worldwide (Liu et al., 2016). The stinging catfish *Heteropneustes fossilis* (Bloch, 1794), under the Family Heteropneustidae is generally known as the ‘Shingi or Singhee’ among Bengali speaking people in Bangladesh and India and diaspora living in other parts of the world (Rahman et al., 2019). The benthopelagic catfish is widely distributed in Bangladesh, India, Laos, Myanmar, Nepal, Sri Lanka, and Thailand (Talwar and Jhingran, 1991). It inhabits mainly in slow and shallow water bodies - ponds, ditches, swamps, marshlands, and sometimes in muddy rivers. As it provides large concentrations of protein, iron (226 mg/100 g) and calcium the fish is dubbed as an essential food fish (Saha and Guha, 1939) and occupy high price in the markets (Alok et al., 1993). IUCN Bangladesh (2015) and IUCN (2000) declared the fish as least concern (LC) in Bangladesh and the world, respectively.

Fruitful fisheries management largely depends on exact assessment of biological parameters, such as reproduction, growth and
assessment of stock (Tracey et al., 2007). Understanding of reproductive biology of fish species is vital and a prerequisite for conservation and relevant management approaches (Brewer et al., 2008; Grandcourt et al., 2009; Muchlisin et al., 2010). Besides, conscientious evaluations of reproductive behavior unearth dynamic causes that may influence survival in addition to recruitment of different fish species (Khatun et al., 2019). Fish population replenishment as well as individual potency is mostly dependent on fruitful reproduction (Hossain et al., 2017a). Subsequently, the knowledge of gonadosomatic index, maturation size and spawning period are considered as a key element for the biological researches in fishes (Hossain et al., 2012).

$L_m$ of fish is important in exploring the causes of variations in the length of maturation (Templeman, 1987). In addition, maturation size of fishes is broadly used as a sign of minimum-allowable capture size (Lucifora et al., 1999; Hasan et al., 2021). Estimation of spawning/breeding season in fish is essential mainly for the conservation of adult or mature individuals from heavy fishing pressure (Templeman, 1987; Mawa et al., 2021). The condition factor indicates the level of wellness of the fish in their natural environment. It is an essential measure of different ecological and biological variables such as the degree of fitness, the production of gonads and the suitability of the atmosphere with respect to the feeding state (Mac Gregor, 1959).

Fecundity is a vital element of fish biology that must be recognized to understand variations in population levels and to make attempts to raise the high amount of harvest capability. (Akter et al., 2007). The fecundity referred the total number of eggs that is produced by a female during the usual life-span. The number of ripening eggs in female ovaries before spawning can also be recognized (Shrivastava, 1999; Hossain et al., 2021). It must be known to assess the reproductive potentials of a fish stock (Lagler, 1956) and to understand of reproductive strategy (Nazari et al., 2003).

The reproductive cycle is an equitable mechanism related to the environmentally regulated routine of organisms living in different aquatic environments. Therefore, the normal breeding mechanism of the fish community may be influenced by some unfavorable environmental factors and may eventually inhibit the process of recruiting into the stock by spawning and hampering the migration process. Environmental factors (e.g. rainfall, temperature) and changes in water hydrological parameters (e.g. DO, pH, and alkalinity) have effects on fishes especially in their ecology and growth (Lappalainen et al., 2008; Britton et al., 2013; Hossain et al., 2021). In addition, temperature is a fundamental physical regulator in fish life, and its influence is strongly embodied in the management of all reproductive processes, from gamete growth and maturation, ovulation and permeation, breeding, embryonic development and laying eggs, to larval and juvenile growth and survival (Pankhurst and Munday, 2011). Water temperature is also known as a major element of fish growth i.e. the growth rate of aquatic organism is reduced with the decrease of water temperature (Blanck and Lamouroux, 2007; Lappalainen et al., 2008).

Fisheries management is sometimes regarded as a reaction to 'common failure,' in which the lack of exclusive property rights means that fish are overfished and resources and labor are wasted (Wilson and McCay, 2001). Aquaculture, or water farming, is the rearing, breeding, and cultivation of fish, shellfish, and aquatic plants. It has been considered as an effective and environmental friendly form of production of food and commercial goods, ensures ecosystem sustainability and restores threatened or endangered organisms (NOAA, 2020).

H. fossils has immense aquaculture potential and may easily be farmed in ponds and shallow ditches. The culture of this fish is yet to flourish in Bangladesh owing to a lack of effective culture technologies (Roy et al., 2019). Most of the Beels are dried out during half of pre-monsoon and post monsoon period due to the increasing temperature and decreasing rainfall. In addition, lacks of good

| Table 1 | Available works on different aspects of Heteromeustes fossils world wide. |
| Aspects | Water body/Country | References |
| --- | --- | --- |
| **Biometrics relationships** | | |
| Length-weight relationships | Ganga River | Khan et al. (2012) |
| Length-weight relationship and conditions | Ramsar site, Assam, India | Das et al. (2015) |
| length-length, length-weight relationship and conditions | Nageshwar, Bangalore | Ferdausy and Alam (2015) |
| Length-weight relationships | Indus River, Pakistan | Hossain et al. (2017b) |
| length-weight relationship and conditions | Atrai and Brahmaputra Rivers | Islam et al. (2017) |
| Morphometrics and meristics | Gajner Beel | Rahman et al. (2019) |
| **Reproduction** | | |
| Spawning season | Bangladesh | Shafig and Quddus (1982) |
| Induced spawning of the Indian catfish | India | Joy and Tharakan (1999) |
| Fisheries of Bangladesh | Bangladesh | Saud et al. (2015) |
| Fecundity of the freshwater catfishes | India | Bhatt et al. (1977) |
| Freshwater fishes of Bangladesh | Bangladesh | Rahman (1989) |
| Fisheries of Bangladesh | Bangladesh | Shafig and Quddus (2001) |
| Gonado-somatic index and fecundity | Brahmaputra River, Assam, India | Saud et al. (2015) |
| **Growth** | Bangladesh | De Graaf (2003) |
| Impact of eco-hydrological factor on growth | Gajner beel | Hasan et al. (2020) |
| Age and Growth | Medei beel, Netrokona District | Mustafa and De Graaf (2008) |
| Population parameters | | |
| **Aquaculture and Hatchery** | | |
| Water quality, growth and production performance | Bangladesh | Roy et al. (2019) |
| Effect of stocking density on growth, survival and production | Bangladesh | Monir and Rahman (2015) |
| Induced Breeding | Bangladesh | Rahman et al. (2013) |
| Induced spawning of catfish | Alok et al. (1993) | |
| Biochemical impacts of salinity | Bangladesh | Ahmed et al. (2017) |
| Culture potentials | Bangladesh | Rahman et al. (2014) |
| Effect of feeding frequency on surfaceing activity | India | Marian et al. (1982) |
| Effects of dietary proteins levels | India | Siddiqui and Khan (2009) |
| Comparative growth performance assessment | Bangladesh | Nushaj et al. (2020) |
| Impacts of different diets on growth | Bangladesh | Ahmed et al. (2016) |
| Optimum ration level for better growth | India | Khan and Abidi (2010) |
| Seed Production an Urgent Need | India | Haniffa et al. (2017) |
quality seed is also an obstacle in the way of developing aquaculture of *H. fossilis*. For the profitable and sustainable fish farming, seed is very important. Fish seeds (fertilized eggs, spawns, fry and fingerlings) collected from open water bodies are preferred by the fish farmers over the seed produced in the hatchery.

There are a few studies conducted on *H. fossilis* reproduction (Table 1) including the study on reproductive biology (Talwar and Jhingran, 1991; Joy and Tharakan, 1999) and on fecundity (Bhatt et al., 1977). However to date no study explored the reproductive biology and its relation with eco-climatic factors for this important fish species. The present study was the first attempt that covered the key aspects of reproduction, including length at first sexual maturity and spawning seasons, and fecundity using various models considering the changes in climatic factors as well as the aquaculture, conservation and management aspects of *H. fossilis* in the wetland ecosystem of Bangladesh.

2. Materials and methods

2.1. Sampling site and fish measurement

Monthly samplings were done from the Gajner Beel wetland ecosystems, northwestern Bangladesh during the January to December 2019 (Fig. 1). Cast net (1.5–2.5 cm, day time: 8.30 to 9.30 am) was used to collect the samples with the help of local fishers. Specimens were immediately preserved in ice and transported to the laboratory and preserved in a deep freezer until further analysis. Before taking measurements, each specimen was dipped with water, washed, and taken on a tray. Then lengths were measured (TL, and SL, to closest 0.1 cm) by a measuring board and total weight was taken (BW, to nearest 0.01 g) by an electronic balance. Sex identification was done through observing gonads under a microscope and by evaluating the meristic and morphometric characters of fishes. Length frequency distribution for *H. fossilis* was calculated individually with 1 cm intermissions of TL.

2.2. Size at sexual maturity ($L_m$)

The $L_m$ was estimated using several functions (i) Based on maximum length, $\log(L_m) = -0.1189 + 0.9157* \log(L_{max})$ (Binohlan and Froese, 2009). (ii) The relationship of TL vs. GSI, GSI (%) = (GW/BW) $\times$ 100. (Nikolsky, 1963) (iii) The alteration point of TL value from TL-SL statistics helped to estimate $L_m$ using the equation of Huxley (1932): $y = a + bx$. A discrete linear regression was calculated for each subset of the data and arranged at 0.5 cm intervals of the break point above the total size frequency of females. The calculations were repeated several times. From the minimum residual sum of squares (RSS), the change was identified in the subsequent two subsets of data (Pankhurst and Munday, 2011; Ahamed and Ohtomi, 2014). Furthermore, the growth type was identified by regression analysis from untransformed TL-SL data. For this length-length relationship, significant discrepancy of $b$ values from the hypothetical isometric value ($b = 1$) of growth was either positively ($b > 1$) or negatively allometric ($b < 1$) (Hartnoll, 1982). ANCOVA (analysis of covariance) was used to check for significant deviation in slopes and intercepts between the two subsets of data (Zar, 1984). (iv) A logistic curve was fitted to the maturity information by distributing the percentage of mature individuals (PMI) against TL class. PMI = 100/ [1 + exp{-f(TLm - TL50)}], where $f$ refers to growth coefficient and $TL_m$ is the midpoint of every TL class (King, 2007). PMI never exceeds 100%, even though the biggest TL classes of all mature individuals in a population are simultaneously in a reproductive cycle. Thus, the data were adjusted to overcome an unnecessarily high estimation of $TL_{50}$ according to the method of King (2007).

2.3. Spawning season

Spawning season was estimated using two methods (i) monthly changes in gonadosomatic Index (GSI) (Khatun et al., 2019) and (ii) seasonal progression of gonads (maturation stages of gonad) (Zhang et al., 2009). Gross physical (morphological) analysis of the ovary reported macroscopic determination of gonad maturity and seasonal progression of the gonad. Depending on the macroscopic features, the maturation stage was defined by the opacity of the gonads, the durability and vascularization and the overall coloring of the gonads (Shinkafi et al., 2011; Nath, 2013).

2.4. Condition and prey-predatory status

Fulton’s condition factor (Fulton, 1904) was estimated as a percentage, i.e., $K_F = 100*(W/L^3)$. Relative weight ($W_R$) was
considered through the formula of Froese (2006): \[ W_R = \left( \frac{W}{W_5} \right) \times 100, \quad W_5 = aTL^b \]

2.5. Fecundity

According to Murua et al. (2003) total fecundity (\( F_T \)) was estimated by gravimetric method. The relationships within \( F_T, TL \) and BW were done by, \( F_T = m \times (TL)^a \) (non-linear) and \( F_T = m + n \times (BW) \) (linear regression).

2.6. Eco-climatic factors

Hydrological data were collected in every month from sampling station by HACH (HQ400) digital multi-meter parameter. Monthly dissolved oxygen (mg/l), temperature (°C), pH, total dissolved solids (TDS) mg/l and total alkalinity (mg/l) were assessed. A specific sampling time (9:00–11:00 am) was maintained. Climatological data (rainfall and air temperature) were obtained from the meteorological station of Dhaka, Bangladesh.

2.7. Statistical analyses

All statistical studies were performed by Microsoft® Excel, past 4.03 and GraphPad Prism 6.5 software. Normality of data was confirmed by Shapiro-wilk test. The non-parametric Spearman-rank test examined the relationships between (a) eco-climatic information and GSI and (b) condition factors with GSI at a 5% (\( p < 0.05 \)) significance level. The correlation analysis helped to discern the essential environmental features that induced egg maturity and spawning period.

3. Results

3.1. Population structure

From a total of 845 \( H. fossilis \) individuals, 426 female specimens were analyzed. The total length (TL) of the analyzed female fishes ranged between 6.70 and 24.10 cm TL and body weight (BW) ranged between 1.37 and 83.94 g. Weight of gonad was 0.01–25.90 g. Table 2 represented minimum, maximum, mean and 95% CL of TL, BW, and GW. Length-frequency distribution of \( H. fossilis \) is shown in Fig. 2.

3.2. Sexual maturity

The calculated \( L_m \) of \( H. fossilis \) was 14.02 cm (95% CL = 10.99–17.84 cm) in TL based on maximum length. We also calculated the size at first sexual maturity (\( L_m \)) of \( H. fossilis \) from different worldwide water-bodies based on maximum length which was shown in Table 3. On TL vs. GSI relationship, we found the lowest and highest values of gonadal weight studied of the \( H. fossilis \) were 0.01 g and 25.90 g. The GSI was smaller than 13.50 cm TL was low (<8.80%). The GSI (>8.80%) around 13.50 cm in TL rose sharply for maximum of the female of \( H. fossilis \). Therefore, \( L_m \) may consider being started from 13.50 cm in TL for \( H. fossilis \) in the Gajner Beel, northwestern Bangladesh. The relationship between TL vs. GSI of \( H. fossilis \) are given in Fig. 3. Spearman rank correlation test revealed significant correlation between TL vs. GSI (\( r_s = 0.1172; \quad p = 0.0155 \)) indicating that GSI was dependent on body size. Through regression analysis at 1.0 cm intervals of total size range of females, a break point was found with an individual TL value, depending on the lowest total RSS value and comparative growth of TL-SL of \( H. fossilis \) as distributed into two phases (Table 4). The comparative growth rate of SL was estimated as 13.0 cm TL (Fig. 3). SL rose more promptly than TL after this size and indicated a negative allometric growth pattern (Table 4). ANCOVA showed significant differences in slopes (\( p = 0.01 \)) above by below the alteration point for the observed regression (Table 5). In addition, the logistic equation of mature females for every length class (TL) group was expressed the relations between TL and the mature individuals’ percentage values (Fig. 3). We found that the smallest size of mature female was 12.0 cm and a TL of 15.0 cm corresponded to 50% of sexually mature \( H. fossilis \) females in Gajner Beel. Based on above four models, range of \( L_m \) was 13.50 to 15.00 cm of \( H. fossilis \).

3.3. Spawning season

Monthly variations in GSI values are represented in Fig. 4. The ovary started to mature in March and continued until August. The highest GSI values were observed in April to August to define the full reproductive period of \( H. fossilis \). In addition the highest GSI values were observed in the June that defines the peak season for spawning of \( H. fossilis \).

Five maturity phases were identified from macroscopic investigation (Table 6). Temporal variation in gameto genic patterns of females has showed that the developed condition of gonads (Mature) was found in every month. The highest percentage of mature gonads was observed in June and the lowest was in November. Based on macroscopic features, fishes with gonads with mature stages were considered as spawning and peak spawning season of fishes (Fig. 4).

| Characters | \( n \) | Min | Max | Mean ± SD | 95% CI |
| --- | --- | --- | --- | --- | --- |
| Total length TL (cm) | 426 | 6.70 | 24.10 | 14.68 ± 3.88 | 14.31 – 15.05 |
| Standard length SL (cm) | 426 | 6.00 | 21.80 | 13.18 ± 3.57 | 12.84 – 13.52 |
| Body weight BW (g) | 426 | 1.37 | 83.94 | 20.87 ± 17.50 | 19.20 – 22.54 |
| Gonad weight GW (g) | 0.01 | 25.90 | 1.16 ± 3.09 | 0.87 – 1.46 |

\( n \), sample size; Min, minimum; Max, maximum, SD, standard deviation; CI, confidence intervals.
Table 3
The calculated size at first sexual maturity ($L_m$) of *Heteropneustes fossilis* (Bloch, 1794) from worldwide different water-bodies based on maximum length.

| Water body                  | Max TL (cm) | $L_m$   | 95% CI of $L_m$ | References                  |
|-----------------------------|-------------|---------|-----------------|-----------------------------|
| Ganges River, India         | 31.00       | 17.65   | 13.70 – 22.64   | Khan et al. (2012)          |
| Deepar Beel, Assam, India   | 19.10       | 11.33   | 8.96 – 14.31    | Das et al. (2015)           |
| Nageshwari, Bangladesh      | 15.50       | 9.36    | 7.47 – 11.75    | Ferdaushy and Alam (2015)   |
| Gajner Beel, Bangladesh     | 16.50       | 9.91    | 7.89 – 12.46    | Hossain et al. (2017b)      |
| Indus River, Pakistan       | 13.00       | 7.96    | 6.40 – 9.94     | Muhammad et al. (2017)      |
| Atrai and Brahmaputra Rivers| 13.71       | 8.36    | 6.71 – 10.46    | Islam et al. (2017)         |
| Gajner Beel, Bangladesh     | 26.80       | 15.45   | 12.06 – 19.72   | Rahman et al. (2019)        |
| **Gajner Beel, Bangladesh** | **24.10**   | **14.02**| **10.99 – 17.84**| Present Study               |

TL, Total length; $L_m$, Size at first sexual maturity; CI, confidence intervals.

Fig. 3. (i) Relationship between gonadosomatic index (GSI) vs. total length (TL) (ii) total length vs. standard length and (iii) total length (TL) vs. adjusted percentage of *Heteropneustes fossilis* in the Gajner Beel, NW Bangladesh.
Table 4
Estimated slope and intercept of linear equation representing the relationship between total length and standard length of female *Heteropneustes fossilis* in the Gajner Beel, Bangladesh and RSS in different sets of two phases.

| Break point (cm) | Early phase | | | | Late phase | | | | Total RSS | | | |
|-----------------|-------------|-----------------|-------------|-----------------|-------------|-----------------|-------------|-----------------|-------------|-----------------|-------------|
| Slope Intercept | n RSS | Slope Intercept | n RSS | Slope Intercept | n RSS | Slope Intercept | n RSS | Slope Intercept | n RSS | Slope Intercept | n RSS |
| 7.0 | 0.69 | 1.4245 | 5 | 0.020 | 0.92 | 0.3184 | 421 | 24.379 | 24.399 |
| 8.0 | 0.89 | −0.0089 | 19 | 0.191 | 0.92 | −0.3278 | 407 | 24.226 | 24.417 |
| 9.0 | 0.89 | −0.0087 | 41 | 0.767 | 0.92 | −0.3420 | 385 | 23.613 | 24.380 |
| 10.0 | 0.88 | 0.0157 | 71 | 0.898 | 0.92 | −0.3403 | 355 | 23.469 | 24.367 |
| 11.0 | 0.90 | 0.1621 | 116 | 5.394 | 0.92 | −0.3724 | 310 | 18.976 | 24.370 |
| 12.0 | 0.89 | −0.0600 | 160 | 7.170 | 0.91 | −0.3151 | 265 | 17.103 | 24.273 |
| 13.0 | 0.91 | 0.2373 | 204 | 19.240 | 0.92 | 0.3876 | 221 | 4.645 | 23.885 |
| 14.0 | 0.91 | 0.2190 | 256 | 11.900 | 0.92 | −0.3548 | 170 | 12.495 | 24.395 |
| 15.0 | 0.92 | 0.2678 | 287 | 14.597 | 0.93 | −0.4620 | 139 | 9.818 | 24.415 |
| 16.0 | 0.91 | 0.2343 | 303 | 16.999 | 0.92 | −0.4006 | 123 | 7.383 | 24.382 |
| 17.0 | 0.91 | 0.2216 | 323 | 17.708 | 0.91 | −0.3385 | 103 | 6.578 | 24.286 |
| 18.0 | 0.91 | 0.2318 | 341 | 18.110 | 0.89 | 0.2007 | 85 | 6.060 | 24.170 |
| 19.0 | 0.91 | 0.2622 | 371 | 8.655 | 0.84 | 1.3603 | 55 | 15.754 | 24.409 |
| 20.0 | 0.92 | 0.3204 | 390 | 21.632 | 0.81 | 2.0120 | 35 | 2.489 | 24.121 |
| 21.0 | 0.92 | −0.3492 | 409 | 22.699 | 0.91 | −0.3122 | 17 | 1.514 | 24.213 |
| 22.0 | 0.92 | −0.3252 | 420 | 24.129 | 0.83 | 1.7024 | 6 | 0.245 | 24.374 |

n, Number of individuals; TL, Total length; RSS, Residual sum of square; SL, Standard length.

Table 5
Allometric coefficients measured as slope for linear regressions (by least square estimate, with log-transformed data) between TL and SL of *Heteropneustes fossilis*.

| Relationship | n | Allometric coefficient | $r^2$ | Significance level |
|--------------|---|-----------------------|-------|-------------------|
| TL vs. SL    | Early phase | 179 | 0.91 | 0.88–0.92 | 0.979 | $p = 0.01$ |
|              | Late phase  | 247 | 0.92 | 0.91–0.93 | 0.989 |

$^*$ Allometric coefficient significantly ($p = 0.05$) different from 1.0, TL, Total length, SL, Standard length; n, Sample size; b, Slopes; 95% CI, Confidence interval, $r^2$, Coefficient of determination.

Fig. 4. Monthly variations of gonadosomatic index (GSI) and maturation stage based on colour with maximum and minimum values of female *Heteropneustes fossilis* in the Gajner Beel, NW Bangladesh.
Macroscopic and description of gonad maturation stages of *Heteropneustes fossilis* in the Gajner Beel, northwestern Bangladesh.

| Stages        | Brief description of gonad                                      |
|---------------|----------------------------------------------------------------|
| Stage 1: Immature | Ovary cord like, ova invisible to the necked eye, thick membrane. |
| Stage 2: Maturing    | Greenish, more than two and half quarter of body cavity, opaque ova, granular appearance, lobular. |
| Stage 3: Mature      | Green, large occupies all the body cavity, delicate ovary membrane. Ova flow out with gentle pressure. |
| Stage 4: Ripe        | Deep green to blackish, large occupies all the body cavity, delicate ovary membrane. Ova flow out with gentle pressure. |
| Stage 5: Spent       | Flaccid empty sac, reddish bloody with many tiny opaque green residual ova. |

3.5. Fecundity

The mean total fecundity was $11897.78 \pm 5027.28$ and ranged between 5942 and 49852. Significant correlation was observed between TL and $F_T$ ($r_s = 0.967$ and $p < 0.0001$) and between BW and $F_T$ ($r_s = 0.923$ and $p < 0.0001$). Significant linear relationships were also found for natural log (In) transferred TL vs. $F_T$ ($r_s = 0.967$ and $p < 0.0001$) and BW vs. $F_T$ ($r_s = 0.965$ and $p < 0.0001$). The relationships were shown in Fig. 8.

3.6. Eco-climatic factors

In our study, several environmental parameters were inspected for their influences on gonadal development and spawning of *H. fossilis*. Temperature, total alkalinity, pH and dissolved oxygen were found to be correlated with GSI (Table 7). The relationships between GSI and water quality factors are shown in Figs. 9 and 10.

The optimal hydrological and physicochemical factors for the spawning of *H. fossilis* as observed in the current study are – temperature $-$ 29 to 31 °C, rainfall $-$ 350 to 380 mm, dissolve oxygen $-$ 5 to 6 mg/l and pH $-$ 7.1 to 7.5 (Fig. 11). A lengthy time series data over five decades (1971 to 2019) on air temperature and rainfall were evaluated to assess its changing temporal pattern. In the study area, annual air temperature revealed a rising trend of 0.029 °C/year, with the coefficient of determination value ($r^2 = 0.371$) whereas the annual average rainfall indicated a dropping trend of 2.98 mm/year ($r^2 = 0.045$) Fig. 12.

3.7. Seed production and farming for *H. Fossilis* were reviewed from the existing literatures

The seeds of *H. fossilis* should be collected after two to three months of peak spawning season. Based on SGR (%), survival (%) and production, the maximum stocking density of *H. fossilis* in the culture systems should not exceed 250,000/ha for monoculture and 44,000/ha for polyculture with Indian major carp and other farmed fishes (Table 8). The feeding rates and feeding frequency should be 12–5% (from nursery phase to grow-out, rate gradually decreases as the individual weight increases) and twice/day, respectively, to optimize the production and cost of production for the species. Dietary protein should be 40% and optimum ration level should remain 5% BW day$^{-1}$ (Table 8). The suitable range of temperature was 27.4–29.8 °C, pH 6.8–7.8, dissolved oxygen 6.8 to 8.6 mg/l, ammonia (NH3) < 0.1 mg/l for good aquaculture.

A healthy broods produced a healthy offspring. In the hatchery good quality of broods are insufficient so we can easily collect the broods from the spawning season. It’s also help to avoid the cross breeding in hatchery. According to survey results all researchers are agreed that ovaprim are the best hormone for induced breeding.
Fig. 8. Relationships between TL vs. $F_T$ and BW vs. $F_T$ and ln (TL) vs. ln ($F_T$) and ln (BW) vs. ln ($F_T$) of female *Heteropneustes fossilis* in the Gajner Beel, NW Bangladesh.

Table 7
Relationship between hydrological parameters with GSI of *Heteropneustes fossilis* (Bloch, 1794) in the Gajner Beel of northwestern Bangladesh during January to December 2019.

| Relationship               | $r_s$ value | 95% CL of $r_s$ | $p$ values | Significance |
|----------------------------|-------------|-----------------|------------|--------------|
| Temperature vs. GSI        | 0.8182      | 0.4450 to 0.9492| 0.0019     | *            |
| DO vs. GSI                 | 0.8392      | -0.9555 to -0.4972| 0.0011     | *            |
| pH vs. GSI                 | 0.9231      | -0.2794 to 0.7337| <0.0001    | *            |
| TDS vs. GSI                | -0.5068     | -0.8351 to 0.1399| 0.1075     | ns           |
| Total alkalinity vs. GSI   | -0.5231     | -0.9794 to -0.7337| 0.0015     | *            |

GSI, Gonadosomatic index; DO, Dissolved Oxygen; TDS, Total Dissolved Solids; $r_s$, Spearman rank correlation values; CL, confidence limit; $p$, shows the level of significance; ns, not significant; * significant ($p \leq 0.05$).
of *H. fossilis* than other hormones. But different researcher used different dose of ovaprim among them we recommend 0.7 ml/kg body weight is best dose for induced breeding of *H. fossilis* fish based on highest fertilizing and hatching rate (Table 8). Reproductive performance, development, feed efficiency and feed intake of fish, normally regulated by a few environmental variables. Here we detected optimum range of some environmental factors (temp was 29 to 31 °C, DO was 5.0 to 6.0 mg/l, and pH was 7.1 to 7.5) which can be applying in hatchery for artificial breeding and also can be used in nursery pond for better growth of fingerlings. Mixed diet (commercial feed and snail meat) is the best for highest growth of *H. fossilis* larvae.

4. Discussion

The study exposes the reproductive feature (sexual maturity, spawning season and fecundity) condition, prey predator status and described the relation within reproductive features and eco-climatic factors. It also deals with the optimum range of
eco-climatic factors in relation to reproduction of *H. fossilis* using multiple indices. As a widely used tool for fisheries biologists and managers, careful estimation of the maturity status of fish, helps to ensure proper assessment and management of exploited stocks (Rahman et al., 2018). Nevertheless, the size at sexual maturity and spawning season of fish were estimated by several models including brooding of eggs over time, appearance of ovary and maturation stages over time (King, 2007), relative weight of gonad (TL vs. gonadosomatic index, modified gonadosomatic index and doibriyal index) over time (Hossain et al., 2017a; Ahamed et al., 2018; Khatun et al., 2019) and histological analyses (Chelemal et al., 2009; Lucano-Ramírez et al., 2019; Jan and Ahmed, 2019). Though histological analyses of gonads is the best way of assessing maturity, where the facilities are lacking, other biotic parameters can easily be measured as indicators of maturity status, (West, 1990; Lowerre-Barbieri et al., 2011; Khatun et al., 2019). GSI was used effectively by a good number of researchers to assess the maturity status of fish (Fontoura et al., 2009; Khatun et al., 2019). A significant population parameter in the fisheries management of exploited stocks is the size at maturity (Jennings et al., 2001). It is vital for fisheries biologists to manage and conserve a particular fish population in any aquatic ecosystem (Lucifora et al., 1999). In our study, the size at first sexual maturity for *H. fossilis* was estimated by four models. On the basis of observed maximum length *L*<sub>m</sub>, which was 14.02 cm. TL vs. GSI relationship also provides an efficient maturity assessment (Ahamed et al., 2018; Hossain et al., 2019). Results of our study estimated *L*<sub>m</sub> of female *H. fossilis* as 13.5 cm TL based on GSI in the Gajner Beel. Several studies have described the comparative growth of TL and SL, wherever an unexpected intensification in one of these length sections is indicative of sexual development (Yamada et al., 2007; Khatun et al., 2019). The comparative growth frequency of SL changed at 13.0 cm TL in our study which may suggest gonadal maturity. Based on the comparative growth of different body parts, the variation point could generally represent sexual maturity (Gab-Alla et al., 1990; Cha et al., 2004). Finally, we used a logistic model to assess *L*<sub>m</sub> of *H. fossilis*. GSI information for a logistic function is attributed to sampling (variation in sample sizes or shrinking body size with formalin preservation) or ecologic differences in population densities, food availability or water temperature (Khatun et al., 2019). This study provides comprehensive information about the length at first sexual maturity of *H. fossilis* by four reliable models. The finding can be useful in selecting mesh size of nets and avoid catching smaller fish thus allowing them to spawn (Khatun et al., 2019).

Spawning season is crucial to assess spawning time and migration of a fish population for breeding purpose (Wilding et al., 2000; Khatun et al., 2019). The maximum values of GSI as an indication of spawning season were determined during April to August in our study. Besides, highest GSI values were observed in June that suggests peak spawning for *H. fossilis* in the Gajner Beel. We found same results, based on monthly changes of maturation stages. A number of other studies observed the spawning season of *H. fossilis* in different months - May and August (Shaif and Quddus, 1982), July to August (Joy and Tharakan, 1999) and April to May and peak in April (Saud et al., 2015). Variation among studies may be ascribed to geographic area, fish population densities, environmental parameters (especially water temperature and rainfall), and/or food availability.

Condition factor as an indicator of success of development, reproduction and survival is a quantitative parameter of the well-being of fish that assesses the performance of the present and future populations (Richter, 2007). Fulton’s condition factor (*K*<sub>f</sub>) is an index illustrating correlations between biotic and abiotic factors in fish physiological conditions. It indicates the well-being of the population at different points of the development cycle (Angelescu et al., 1958). In the current study, *K*<sub>f</sub> ranged from 0.33 to 0.72 for female *H. fossilis*. Ferdaushy and Alam (2015) and Muhammad et al. (2017) reported that the *K*<sub>f</sub> of this species was 0.96 and 0.48, respectively. In our study, *K*<sub>f</sub> was found to be significantly related with monthly GSI values. The study revealed that the spawning period of *H. fossilis* began in April with a peak in June and ended in August when the upper values of *K*<sub>f</sub> represented their recovery in the Gajner Beel, NW Bangladesh.

Relative weight (*W*<sub>r</sub>) is the most widely used index for determining the status of fish in the ecosystem (Froese, 2006). *W*<sub>r</sub> values below 100 for individuals or populations suggest problems such as low prey accessibility or high predator density, whereas values above 100 indicate a prey surplus or low predator density (Rypel and Richter, 2008). In our study, monthly deviation of *W*<sub>r</sub> from 100 in female *H. fossilis* populations revealed the disparity in habitat regarding the abundance of food items and the presence of prey and predator organisms (Anderson and Neumann, 1996) in Gajner Beel.

The estimation of the fecundity and explanation of reproductive strategies is essential in fish biology, physiology and population dynamics (Hunter et al., 1992). Fecundity in fishes is a crucial factor to comprehend differences in population size and is very pertinent to fishery management (Rahman et al., 2018; Hossain et al., 2021). In the present study, fecundity of *H. fossilis* was 1730 to 23,870 in the Gajner Beel, NW Bangladesh. In the past, varying numbers of fecundity for this fish were observed by different authors — 1375 to 46,737 (Bhatt et al., 1977), 4200 to 15,750 (Rahman, 1989), 2,843 to 44,724 (Shaif and Quddus, 2001) and 2431 to 23,002 (Saud et al., 2015). The variations in fecundity occurred due to differences in habitat conditions and presence of nutrient and physicochemical factors within, stock variations (Ruzzante et al., 1998) and differences in methodological approaches used for fecundity assessment (Alonso-Fernández, 2009).

Global climate change is impacting the fish and fisheries and will continue to do so in the future (Roesig et al., 2004). Most of the studies into the impact of climate change on fish populations.
have been carried out on pelagic fishes (Loukos et al., 2003; Lloret et al., 2004). Environmental conditions like temperature, DO, pH and total alkalinity affect reproductive migrations of *H. fossilis* in the Gajner Beel wetland ecosystem. The maximum GSI values of females were from March to August, when water temperatures were highest, so GSI may be reacting to water conditions as seen for tropical weather fishes in general (Khatun et al., 2019). The impact of temperature in regulating gonadal development and fish reproduction is corporate by various studies (Ridha et al., 1998; Rideout et al., 2005; Khatun et al., 2019). Hence, alterations in peak spawning behavior may result from increasing global temperatures (Peer and Miller, 2014; Khatun et al., 2019). According to our findings, the lowest temperatures were found in January, and the highest was in June suggesting a substantial connection between water temperature and spawning season. The GSI values were high in April to July when temperatures were 29 to 31 °C. So, 29–31 °C may be best for reproduction. We also found DO, pH and total alkalinity ranges of 5.0–6.0 mg/l, 7.1–7.5 and 90–100 mg/l respectively, from April to July when GSI high. So, these ranges should be optimum for reproduction of *H. fossilis*. No other studies are available for *H. fossilis* to relate to our findings. In contrast, the lowest GSI was found at a water temperature of 25 °C. Primary sex cell and segregation of female gonads stimulated by lower temperature (<20 °C) though Chmilevskiy and Lavrova (1990) is dissimilar to our results. Based on climate data (1971–2019) a thermal increase of 0.029 °C yr⁻¹ temperature is apparent.

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**Fig. 11.** Determination of suitable eco-hydrological parameters by the relationship between temperature, DO, pH and rainfall vs. GSI of *Heteropneustes fossilis* in Gajner Beel, northwestern Bangladesh.
in northwestern Bangladesh. The start of sexual maturity is controlled by environmental and climate driven conditions. Spawning events are normally associated with climatic variability, particularly for rainfall and temperature (Parkinson et al., 1999; Wilding et al., 2000; Khatun et al., 2019; Sabbir et al., 2021). Usually, the annual rainfall sequence of the seasonal tropics is linked to the

![Annual average maximum temperature in Rajshahi region](image1)

![Total rainfall (mm), Rajshahi region](image2)

**Fig. 12.** Annual average maximum temperature (°C) and rainfall (mm) in the Rajshahi region (including Gajner Beel) northwestern Bangladesh during 1971 to 2019.

**Table 8**

Accumulated the optimum parameters from different available works of *Heteropneustes fossilis* on aquaculture aspect.

| Aspect                  | Comparison parameter |Parameter| Parameter| Parameter| Reference                      |
|------------------------|----------------------|---------|----------|----------|---------------------------------|
| Stocking density       | Quantity             | 1.85,000/ha | 1.23 ± 0.021  | 71.61 ± 3.17  | 9708.16 ± 421.40  | Rahman et al. (2014) |
|                        |                      | 1, 25,000/ha | 2.36 ± 0.16  | 87        | 4537.12 ± 227.4  | Roy et al. (2019) |
|                        | 24000/ha (Poly culture) | 1.29 ± 0.02  | 81.78 ± 0.65  | 693.42 ± 3.08  | Hossain et al. (2018) |
| Feeding                | Feeding rate         | 12–4%   | Twice/day | 1.23 ± 0.021  | 2.51 ± 0.04  | Rahman et al. (2014) |
|                        |                      | 12–4%   | Twice/day | 1.23 ± 0.021  | 1.60 ± 0.01  | Nushy et al. (2020) |
| Protein level          | DP (%)               | 40*     | 1.76     | 1.75 | 31.7%  | Siddiqui and Khan (2009) |
|                        | SGR (%)              |          |          |          |                   |                   |
|                        | FCR                  |          |          |          |                   |                   |
| Optimum ration level   | Ration level (BW day ^{-1} ) | 5*     | 1.59 ± 0.03  | 30.8 ± 0.03  | 59.73 ± 0.24  | Khan and Abidi (2010) |
| Induced breeding       | Ovaprim              | 0.5 ml/kg | 10-       | 75.0  | 60     | Haniffa and Sridhar (2002) |
|                        |                      | 0.5 ml/kg | 18-24     | 92.33 | 94.87 | Karl Marx and Chakrabarty (2007) |
|                        |                      | 0.6 ml/kg | 10        | 86.67 | 76.92  | Rahman et al. (2013) |
|                        |                      | 0.7 ml/kg* | –        | 93.6 | 95.5   | Arcockiarraj et al. (2001) |

*Indicated the best. DP, Dietary protein; SGR, Specific growth rate; PER, Protein efficiency ratio; PRE, Protein retention efficiency; FCR, feed conversion ratio; PRE, Protein retention efficiency; ERE, Energy retention efficiency.
timing of spawning for Southeast Asian cyprinids (Rainboth, 1991). The maximum rainfall was perceived in April to July in our study, when GSI value was at apex suggesting a connection between GSI and rainfall. The maximum rainfall was reported in June (380 mm) when GSI was highest. GSI was also lowest when rainfall was lowest in January, when no reproduction was occurring. Fluctuation in the spawning season for *H. fossilis* is predicted by exploration of climate data (1971–2019) which showed that rainfall is decreasing by 2.96 mm/year in northwestern Bangladesh. Absence of information prevents comparisons of our findings. But for a temperate freshwater teleost, Parkinson et al. (1999) reported that the high rainfall and temperature influenced final maturation of gonads and spawning season which is similar to our findings. Also increase of air temperature has impact on ecosystem and catfish fishery such as changes in ecosystem, blockage of migratory route and high turbidity of water (Khatun et al., 2019; Sarkar et al., 2020).

We suggest that stocking density 1, 25,000/ha is the best for *H. fossilis* whereas Rahman et al. (2014) suggested 1, 85,000/ha. We found 0.7 ml/kg ovarprim is the optimum for induced breeding of *H. fossilis*. According to Nayak et al. (2001) the best dose is 0.4 ml/kg. Vijaykumar et al. (1998), Haniffa and Sridhar (2002) and Karl Marx and Chakraborty (2007) revealed 0.5 ml/kg is the best dose for *H. fossilis* induced breeding.

5. Management policies

The management of fisheries is aimed at optimizing the advantages of the unit of output (fish stock) that is being managed. Based on our study outcomes, some management policies are suggested here for the sustainable management of *H. fossilis* in the wetlands of Bangladesh and in the region. For instance, the *Lm* was 13.0 to 15.0 cm of *H. fossilis* in the Gajner Beel, NW Bangladesh that’s mean 50% fishes spawn at this length, so smaller sized fishes than the *Lm* are strongly prohibited to catch and only bigger than 15.0 cm fishes are recommended for exploitation. Banned period should be established based on peak spawning season. In that time fishing would be strictly prohibited. The suitable range of *Kf* (0.33–0.72) should be maintained in hatchery for artificial breeding of this species. Warming temperatures may be causing earlier river flow pulses which may be responsible for the changes in breeding patterns of fishes (Sarkar et al., 2019). We found that temperature was increasing and rainfall was decreasing day by day with an obvious impact on the shifting of the spawning season of *H. fossilis* so, short term management policies should be established for the management and conservation of the wild stock of this species.

6. Conservation strategies

To protect the diversity of catfishes, numerous measures have been implemented, including in situ conservation, habitat fingerprinting, ex-situ conservation, and the development of live gene banks (Sarkar et al., 2012). We should also restore wetlands because they are an important aspect of the riverine ecosystem, and fish survival is largely dependent on the quality of water bodies. Due to extensive siltation, several wetlands have already lost their link to the main waterway. Fishes use wetlands as breeding and rearing grounds so, research efforts should be translated into action in order to restore those crucial habitats.

7. Conclusion

The air-breathing sting catfish (*H. fossilis*) is considered to be highly nourishing, palatable and tasty and well preferred because of its less spine, less fat and high digestibility in many parts of Indian subcontinent. Attempt has been taken to describe the changes in reproductive biology, relation to eco-climatic factors and suggesting a policy for aquaculture, conservation and management of *H. fossilis*. In fine, to conserve the wild stock of *H. fossilis* and to ensure the effective and sustainable management of this important fish, it is essential to set the mesh size of nets and establishment of ban period during peak spawning season through the *Lm* and spawning season, correspondingly. This is vital for the protection of wild stock of *H. fossilis* in the Gajner Beel and other open water bodies. *H. fossilis* seeds can be collected from the natural water bodies, after 2–3 months followed by the peak spawning in June and should be farmed following suggested stocking density, feed, feeding rate, feeding frequency and protein levels ensuring good aquaculture practices. *H. fossilis* broods can be collected during the spawning season and artificially breed in the hatchery using recommended doses of hormone. Analyses of time series data on temperature and rainfall revealed a rising trend of temperature and declining drift in rainfall. These eco-climatic factors play key role in the onset of spawning and entire lifecycle thereafter and are responsible for the shift in the breeding season including spawning peak. Any management policy and conservation guideline such as ban period, gear selectivity, amending or proposing new mesh size of nets – must take into account the impact of the eco-climatic factors to pave the way of successful management of *H. fossilis* in the wetland ecosystem.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The study was carried out with the financial assistance from the Bangladesh Agriculture Research Council (ID: 484) and National Science and Technology, Bangladesh.

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