



# Reproductive potential and stock status of the anadromous shad, *Tenulosa ilisha* (Hamilton, 1822): Implications for managing its declining fisheries in northern Bay of Bengal bordering India

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## ABSTRACT

The anadromous shad, *Tenulosa ilisha* is a fish of high economic importance in countries flanking the Bay of Bengal (BoB). Its fishery in the northern BoB bordering India and the associated Bhagirathi–Hooghly river system has been declining. Scientific explanations on the existing fishery management recommendations, especially the length at first maturity ( $L_{m50}$ ), minimum legal size (MLS), minimum mesh size for fishing nets and stock status were limited, raising serious concerns on the sustainability of its fisheries. Through the examination of its reproductive cycle, using histological maturity identifiers, the  $L_{m50}$  of males and females were redefined at 265 mm TL/ 1.0 year age and 305 mm TL/ 1.2 year age, respectively. The size-based fecundity, sex ratio and abundance revealed that females of 281–360 mm TL/ 1.0–1.6 year of age have maximum reproductive potential. In the catch, 45%–65% of males and females were below  $L_{m50}$ . The temporal progression of mean length in the catch (MLC) and female length at maturity showed declining trend. Application of length-based indicators (LBI) and stock assessment models showed the fishery in near full exploitation, less optimal and undergoing multi-generation, indiscriminate, size-selective overfishing. The spawning stock biomass (SSB) has declined to 26.8% of the virgin SSB, while the yearly spawning potential ratio (SPR) ranged from 0.04 to 0.29, which is lower than the SPR threshold (0.3) suggested for sustaining a fishery. The species is both growth and recruitment overfished. Though the mean annual catch is marginally lower than the estimated maximum sustainable yield (MSY) of 32,953 t, any increase in fishing effort would further impact the SSB. Based on the results, a MLS of 360 mm TL, minimum mesh size of 110 mm for fishing gear and a precautionary annual catch limit of 30,000 t suggested for management, and the potential impact of implementing these on fishers' catches discussed.

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## 1. Introduction

Capture fisheries provide food, nutrition and livelihood to billions of people globally, and is hugely significant in the present, and coming days as the number of the undernourished and malnourished population are growing. The overall status of the

world's capture fisheries is much discussed, although the majority remain formally un-assessed (Costello et al., 2012). Hilborn and Ovando (2014) indicated that assessed and managed fish stocks were improving and asserted that there is a greater need for actively managing the un-assessed fisheries of the world for sustaining their benefits to humanity. The sustainability of fisheries is essential for supporting the livelihoods of billions of people in coastal communities around the world, especially in developing countries, where 97% of fishers live (Kituyi, 2018). Several natural fisheries resources around the world have suffered decline in yields due to fishing pressure (Pauly et al., 2002). Studies also highlighted fishing-induced changes in intensively exploited stocks, manifesting decrease in body sizes (Beverton

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and Holt, 1957; Kuparinen et al., 2016), early maturation (Jorgensen, 1990; Lappalainen et al., 2016; Heino et al., 2015) and possible fisheries-induced evolution (FIE) (Olsen et al., 2004). Age truncation caused by selective removal of larger individuals in a population is also a direct impact of fishing (Berkeley et al., 2004). The implications of these population alterations and their consequences on the sustainability of fish stocks need to be addressed through science-based assessment and management. Though management strategies, including size or age limits in the capture, declaration of no-fishing areas or seasons, catch quotas, etc., are being implemented to protect the natural fisheries resources, the information available for determining such management strategies are highly inadequate in most tropical fisheries (Hoggarth et al., 2006) or often based on conflicting database leading to ineffective management decisions. Convenience overfishing, as coined by Froese (2004), also occurs in waters of most developing nations, as it is more convenient to risk the health of fish stocks than to risk social or political conflicts. Therefore, fisheries managers are giving greater consideration to generating empirical data to establish biological and fishing target reference points to enable surveillance, monitoring, policy decisions and managing poorly managed fisheries resources.

Clupeoids or fishes under the order Clupeiformes, are an important group of food fishes across the globe, hence are highly lucrative and heavily exploited. The majority of the tropical clupeid fish species are anadromous, un-domesticated and caught from the wild (Milton, 2009). *Tenualosa ilisha* is one of the most studied and economically important anadromous clupeids. The species belonging to the sub-family Alosinae of the family Clupeidae, mainly inhabit the marine waters and migrate to low saline and freshwater stretches of rivers for breeding. The juveniles migrate back to the sea for growth and maturation. The species occurs in waters of Bangladesh, India, Myanmar, Kuwait, Iraq, Iran, Bahrain, Qatar, Oman, United Arab Emirates, Saudi Arabia, Pakistan, Malaysia, Thailand, Viet Nam, and Sri Lanka (Freyhof, 2014), collectively reaching an annual catch of 0.4 million t (Fernandes et al., 2016). It forms a rich fishery worth over US \$ 2.0 billion, in the northern Bay of Bengal (BoB) and associated rivers in Bangladesh, India, and Myanmar (BOBLME, 2012). In India, popularly known as hilsa, the species is the major single-species fishery along the northern BoB and the Bhagirathi–Hooghly river system (Sajina et al., 2019), besides being highly important to the economy and socio-cultural heritage of the people of the entire lower Ganga plains. The IUCN red list shows a decreasing global population trend of the species (IUCN, 2021). Characterized by open access, with crowding fishing effort, its fishery has drastically declined in the BoB bordering India, especially in the estuarine and freshwater zones (Sajina et al., 2019). *T. ilisha* being a trans-boundary species, a collective regional management approach by its fishing nations bordering BoB has been on the cards (BOBLME, 2010). Such actions, however, are yet to take effect. Until then country-specific stock assessment and management efforts were encouraged (BOBLME, 2014). Though, there have been efforts to manage its resources in northern BoB bordering India and the associated Bhagirathi–Hooghly River system through legislated seasonal fishing closures to protect brooders; banning of <90 mm mesh nets and promulgation of minimum legal size (MLS) of 230 mm total length (TL) in catch to protect immature ones (The Kolkata Gazette, 2013). Nevertheless, the species is still being growth and recruitment overfished (Sajina et al., 2019, 2020). The existing management decisions are based on conflicting reports on the length–weight relation, size at first maturity, gear selectivity and population parameters, which are important in setting up yield equations, stock assessment and fishing regulations. The reported sizes at maturity of the species have been inconsistent and varied widely from its fishing regions

in the world (Kuwait: Al-Baz and Grove (1995); Iraq: Hussain et al. (1994), Al-Noor (1998), Mutlak (2012), Mohamed and Qasim (2014), Al-mukhtar et al. (2016); Bangladesh: Shafi et al. (1978), Dunn (1982), Islam et al. (1987), Halder (2002), Amin et al. (2005); Myanmar: Bladon et al. (2019), Merayo et al. (2020); Malaysia: Halim et al. (2020)) and from Indian waters (Chacko and Ganapati, 1949; Chacko and Krishnamurthy, 1950; Jones and Menon, 1951; Pillay, 1958; Mathur, 1964; Banerji and Krishnan, 1973; De, 1980, 1986; Reuben et al., 1992; Bhaumik and Sharma, 2012; BOBLME, 2015). The available stock assessment reports on the species from the study area are that of Reuben et al. (1992), Dutta et al. (2012) and BOBLME (2015), based on highly limited short-term data sets, constraining application of robust stock assessment models, necessitating generation of long-term empirical data-based biological and fisheries reference points. Against this backdrop, the present study aimed to generate long-term data; redefine the size at first maturity, MLS, and minimum mesh size for fishing gear, and assess the status of its stock to aid informed resource management decisions. The study also looked at possible signs of fishing-induced changes in size composition and maturity of the species.

## 2. Materials and methods

### 2.1. Study area and sample collection

The study was carried out in the northern BoB bordering India and the associated Bhagirathi–Hooghly river system (Fig. 1) along the migratory route of the species. The northern BoB and the Bhagirathi–Hooghly River system (an offshoot of river Ganga passing through the Indian territory across West Bengal), supports the largest hilsa fishery in India (Bhaumik and Sharma, 2012). Samples of *T. ilisha* were collected monthly during 2013 to 2017, covering 16 fish landing centres, beginning from Digha (21° 28' 53.10" N; 87° 46' 15.68" E) up to Farakka (24° 47' 35.6" N; 87° 54' 34.4" E), in a stretch of 554 km (Fig. 1). The migratory stretch of the fish along the river ends at Farakka, due to a barrage constructed across the river. Hilsa landing along Digha to Sultanpur comprised estuarine and marine catch, with the marine fishing extends waters up to 140 km offshore. Landing along the Godakhali to Farakka stretch of the river comprised freshwater (inland) catch. For studying the length–frequency distribution in catches, estimating length-based indicators (LBI) as per ICES (2015) and Shephard et al. (2020), population parameters and stock assessment (Sparre and Venema, 1998), the total lengths (TL) of hilsa samples in catches were measured randomly at a monthly interval from all the designated fish landing centres while the catches were brought ashore. Though gill nets of mesh size varying from 50 to 110 mm were the major gears used for commercial hilsa fishing, to ensure sufficient size representation in samples, other minor gears operated by fishers were also targeted for sample collection. The TLs of the samples were measured from the tip of the snout to the tip of the extended caudal fin using a digital calliper. A total of 10171 specimens were thus measured for total lengths during the study period. About 20 to 30 random samples representing small, medium, and large size categories as per Froese (2006), were collected separately from the landing centres on the sampling days and were measured for TL and the respective weights for establishing length–weight relation. Gonads of these specimens were dissected out, weighed, and preserved in 10% neutral buffered formalin for analysis of fecundity, sex ratio and maturity. The total hilsa catch of the landing centres on the sampling days was recorded following (Sekharan, 1962) for application in stock assessment models.

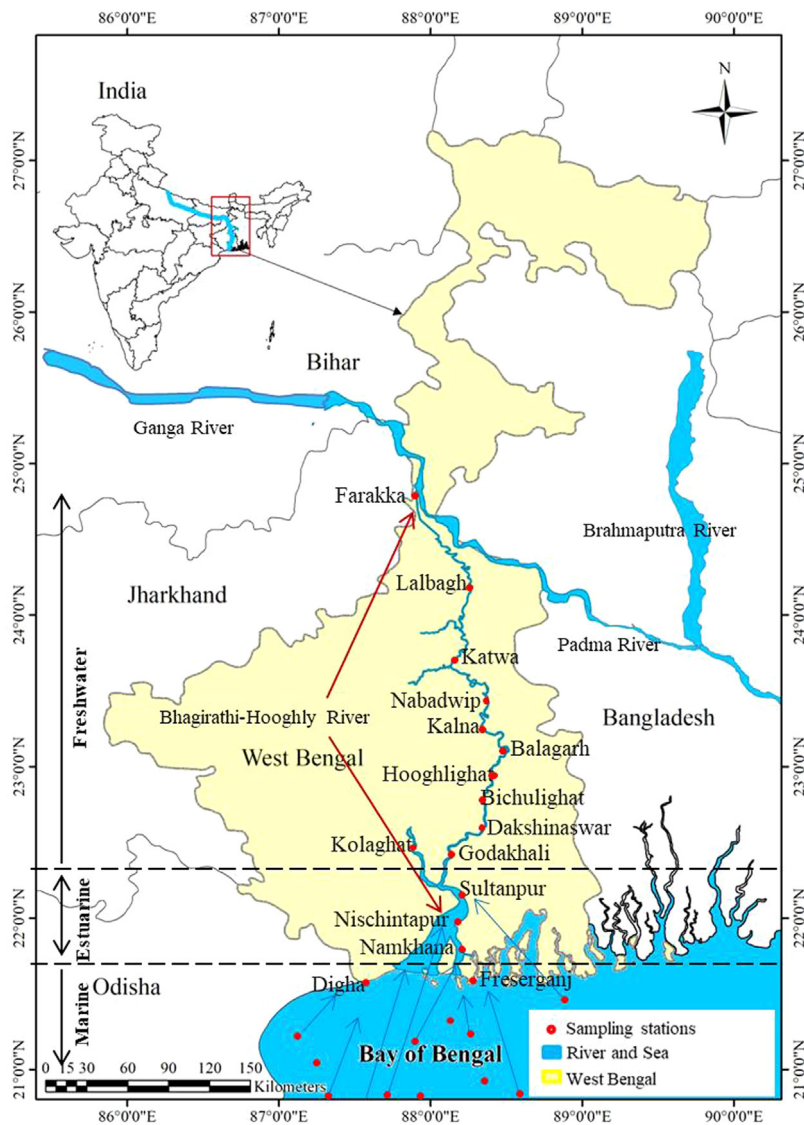


Fig. 1. Sampling stations along the Bhagirathi-Hooghly river and spread of offshore fishing grounds of *T. ilisha* in Indian territory of BoB.

## 2.2. Length–frequency and length–weight relation

The TL data collected monthly were pooled into class intervals of 20 mm and frequency of samples under each of these classes and their cumulative frequencies plotted. The length–weight relation (LWR) of males and females were estimated separately following the equation  $W = aL^b$  (Le Cren, 1951). Chi-square test was used to compare a and b values of each sex to see if there was any significant difference among them. Using the LWR, weights of the specimens were estimated from the lengths and the paired t-test was used to examine if the estimated and actual weights differed significantly or not. The progression of mean length in the catch (MLC) over the years were obtained from available literature (Mitra et al., 1994, 1997; Nath et al., 2004; Bhaumik, 2010; Suresh et al., 2017) for the period prior to 2013, and those for 2013 to 2016 were estimated from the current data.

## 2.3. Reproductive potential

Maturity stages analysed histologically, from subsamples of the neutral buffered formalin-preserved gonads. The subsamples taken from the anterior, middle, and posterior portions of each

lobe of the gonads, were processed for histological examination according to Sonia et al. (2007). The paraffin-embedded samples were sectioned at 0.5  $\mu\text{m}$  thickness and stained with Delafield Haematoxyline and Eosine (Mayer, 1986). The DPX mounted sections were examined under a microscope having a calibrated image processing features. The maturity phases of the samples were classified based on the scheme of Brown-Peterson et al. (2011). For estimating the length at first maturity ( $L_{m50}$ ), the proportion of mature males and females in length classes of 10 mm were fitted to a logistic function and the  $L_{m50}$  was taken as the length at which 50% of the individuals attained maturity (King, 2005).

For estimation of absolute fecundity, sub-samples were sourced from the anterior, middle, and posterior portions of both lobes of the ovaries during spawning season and weighed to the nearest 0.001 g. The total number of yolked or vitellogenic oocytes, including hydrated oocytes, were counted and the absolute and relative fecundity estimated as per Maura et al. (2003). The sexes were pooled into different size class drawn for length–frequency analysis and the sex ratio (number of males per female) in each length class was calculated using the Binomial Proportion test (Snedecor and Cochran, 1967). The frequency (%)

of females in each length class was taken as the length-wise female abundance. The females of the species being generally larger in size (Pillay, 1958; Pillay and Rao, 1963) are prone to overfishing and gravid females being more prone to fishing than the smaller males, the temporal progression of female length at maturity was assessed for possible indications of fishing-induced early maturity. For this, the historical metadata available for females from the study region, irrespective of the methods used, were plotted on the Generalized Linear Model (GLM) using the ggplot2 package in 'R' (R Core Team, 2020).

## 2.4. Stock assessment

### 2.4.1. Population parameters

The length–frequency data were raised to the sampling day's catch and then to the corresponding month considering the fishing days in each month (Sekharan, 1962). The  $L_{\infty}$  (asymptotic length) and  $K$  (growth coefficient) were calculated using the length–frequency (sexes pooled) data on ELEFAN-II (Gayaniilo Jr et al., 2005). The  $t_0$  was estimated from the empirical equation,  $\text{Log}_{10}(-t_0) = -0.3922 - 0.2752 \text{Log}_{10}(L_{\infty}) - 1.038 \text{Log}_{10}(K)$  of Pauly (1979). Using  $L_{\infty}$ ,  $K$  and  $t_0$ , the age at lengths were estimated as  $\text{age}(t) = t_0 - \text{LN}(1 - L/L_{\infty})/K$  and weights at different ages were calculated as  $Wt = W_{\infty}\{1 - \exp.[-K(t - t_0)]\}^b$ . The total mortality rate ( $Z$ ) was estimated through the 'length-converted catch curve' method (Gayaniilo Jr et al., 2005). The natural mortality rate ( $M$ ) was calculated using Pauly's empirical equation (Pauly, 1980), taking the mean habitat temperature as 28.2 °C. The fishing mortality rate ( $F$ ) was obtained as  $F = Z - M$ . The exploitation ratio ( $E$ ) was estimated as  $E = F/Z$ . The length at first capture  $L_{c50}$  (the length at which 50% of the population become vulnerable to fishing) and  $L_{c95}$  (the length at which 95% of the population become vulnerable to fishing) were estimated using the probability of capture method (Pauly, 1983). These values were used to model the yearly length based selectivity against maturity and length based spawning potential ratio (SPR).

### 2.4.2. Length based indicators

A suite of length-based indicators (LBI) were estimated using the length–frequency data and population parameters and expressed with associated reference points (RPs) for gaining quick insight into the stock status of the species. The indicators and their calculations were based on ICES (2015) and Shephard et al. (2020). The LBIs thus obtained were compared with the expected RPs related to conservation, optimal yield and maximum sustainable yield (MSY) as per ICES (2015), Shephard et al. (2020). The LBIs used and their methods of estimation are given in Table 1.

### 2.4.3. Biomass and yield

The Y/R (relative yield per recruit) and the B/R (relative Biomass per recruit) were estimated through the 'knife-edge selection' method, substituting  $L_{c50}/L_{\infty}$  and  $M/K$  values (Gayaniilo Jr et al., 2005). Using Thompson and Bell (1934) model, the yield and the spawning stock biomass (SSB) at different exploitation levels were estimated based on the Virtual Population Analysis (VPA) routine (Gayaniilo Jr et al., 2005) using the pooled data for the entire study period. The value of  $SSB_0$  was allocated considering the  $L_{m50}$ .

### 2.4.4. Spawning potential ratio

The length-based spawning potential ratio (SPR) estimates the proportion of un-fished spawners in an exploited fish population and has a maximum value of 1.00 when there is no harvest and it

declines towards zero as the fishing mortality increases (Walters and Martell, 2004). The SPR was estimated using the scheme proposed by Hordyk et al. (2020). The population parameters such as  $L_{\infty}$ ,  $K$ ,  $M/K$  (ratio of natural mortality to growth rate),  $L_{m50}$  (the length at which 50% of the population becomes sexually mature), (relative fishing mortality ratio), along with the year-wise length–frequency were the input data. The model estimated the selectivity-at-length and the F/M ratio, which were then used for the estimation of SPR (Hordyk et al., 2020). The SPR values were estimated using the statistical program 'R' (R Core Team, 2020).

### 2.4.5. Spawner recruit relation

The spawner recruit relationship was studied using Ricker (1975) as  $R = aS \exp(-bS)$ , where  $R$  is the number of recruits,  $S$  is the number of individuals in the spawning stock;  $a$  and  $b$  are parameters of the curve. Through VPA, the number of spawning stock existing was estimated using the monthly raised length–frequency data for sizes above  $L_{m50}$  (spawning stock). The values in numbers were then converted to equivalent weights based on the weights of the midsize of each SSB class.

## 2.5. Gear selectivity

To study the length range of specimens that would be caught in gill nets of different mesh sizes, the relation between the TL and girth of the species was used. Depending on the size, the fish was caught in the gill nets along the region extending from their opercula to the broadest portion of the body just before the origin of the dorsal fin. The maximum girth ( $G_{max}$ ) of the fish was measured to the nearest millimetre, as the circumference of the fish at the broadest part of the body at the origin of the dorsal fin, using a narrow graduated measuring tape. The relation between TL and  $G_{max}$  was established based on the best fit (maximum  $R^2$ ). The number, TL and corresponding weight of the specimens caught in gill nets of mesh sizes ranging from 50 to 110 mm, operated by fishers' were recorded from important hilsa fishing locations covering all seasons. Specimens caught entangled in the nets were not considered. The  $G_{max}$  and TL of these specimens estimated from the length girth model were compared with the actual TL of the specimens using the t-test.

## 3. Results

### 3.1. Length–frequency and length–weight relation

The size ranges of specimens sampled were 23 mm/ 0.179 g to 618 mm/ 2635 g with a modal length class of 261–280 mm TL. The unsexed length–frequency ( $n = 10171$ ) at class intervals of 20 mm, using the pooled data for the entire study period, is shown in Fig. 2. The cumulative frequency showed that the size groups >40 to <100 mm TL and >240 to <320 mm TL formed the maximum percentage in the catch (21.04 and 31.60%, respectively) and length groups in between were comparatively low in catches. The LWR established for males is  $W = 0.000005L^{3.1206}$ , females  $W = 0.000005L^{3.1275}$  and for sexes pooled  $W = 0.000005L^{3.1192}$  are shown in Fig. 3a. The t-test showed that the slope of the relation for males, females, and sexes pooled did not vary significantly ( $P < 0.01$ ) and actual weights and the weights estimated from LWR did not vary significantly ( $t = -0.47578$ ,  $df = 5994$ ,  $p = 0.6342$ ). The MLC data available from 1962 to 2016 showed a significant ( $P = 0.0068$ ) progressive decline over the years. The MLC was 356 mm TL in 1962, which declined to 263 mm TL in 2016, with an overall decline of 93 mm; the lowest value was in 2013 (250 mm TL) (Fig. 4).

**Table 1**  
Length-based indicators and maximum sustainable yield proxy reference points.

Indicator	Calculation	Reference point	Indicator ratio <sup>a</sup>	Expected value <sup>a</sup>	Property <sup>a</sup>	Observed value <sup>b</sup>	Inference <sup>b</sup>
$L_{\max 5\%}$	Mean length of largest 5%	$L_{\infty}$	$L_{\max 5\%}/L_{\infty}$	> 0.8		0.6537	
$L_{95\%}$	95th percentile	$L_{\infty}$	$L_{95\%}/L_{\infty}$	> 0.8	Conservation of large individuals	0.6096	Recruitment overfishing; large individuals to be conserved
$P_{\text{mega}}$	Individuals above $L_{\text{opt}}+10\%$	0.3–0.4	$P_{\text{mega}}$	> 0.3		0.0005	
$L_{25\%}$	25th percentile of length distribution	$L_{m50}$	$L_{25\%}/L_{m50}$	> 1	Conservation of immature individuals	0.3279	Growth overfishing; juveniles to be conserved
$L_c$	Length at first catch (length at 50% of mode)	$L_{m50}$	$L_c / L_{m50}$	> 1		0.9836	
$L_{\text{mean}}$	Mean length of individuals larger $L_c$	$L_{\text{opt}} = 2/3L_{\infty}$	$L_{\text{mean}}/ L_{\text{opt}}$	$\approx 1$	Optimal yield	0.7334	Less optimal exploitation and yield
$L_{\text{mean}}$	Mean length of individuals larger $L_c$	$LF=M = (0.75L_c + 0.25 L_{\infty})$	$L_{\text{mean}}/L_{F=M}$	$\geq 1$	Maximum sustainable yield	0.9209	Yield slightly less than MSY
$P_{\text{obj}}$	Sum of catch based length proportions, $P_{m50}, P_{\text{opt}}$ and $P_{\text{mega}}$	$1 < P_{\text{obj}} < 2$	$P_{\text{obj}} = P_{m50} + P_{\text{opt}} + P_{\text{mega}}$	$\geq 1$	Sustainable selection	0.3024	Selectivity not following sustainability recommendations (Froese, 2004)

<sup>a</sup>ICES (2015) and Shephard et al. (2020).

<sup>b</sup>Present study.

### 3.2. Reproductive potential

The different maturity phases of ovaries and testes and the histological identifiers for each of these phases are given in Table 2. The corresponding histo-micrographs are shown in Fig. 5. The lengths at which 50% of the males and females in the population attained maturity ( $L_{m50}$ ) were 265 mm TL and 305 mm TL, respectively (Fig. 6), while the lowest lengths at which males and females with mature testes and ovaries recorded were 180 mm and 213 mm TL, respectively. The historical metadata on length at maturity of male and female hilsa, from different regions of the world, ranged from 160 to 400 mm for males and 186 to 430 mm for females (Table 3). Though the reported length at maturity of the females of the species from the study region varied considerably over the years (Table 3), the GLM plot of the temporal progression showed a declining trend (Fig. 7). The mean absolute and relative fecundity, sex ratio, and abundance in the catch for different length classes are shown in Fig. 8. The absolute fecundity range was 0.06 million for the specimen of 213 mm TL and 125.4 g weight to 2.13 million for the specimen of 573 mm TL and 2480 g weight, while the relative fecundity ranged from 0.048 million/g body to 0.086 million/g body. The mean absolute fecundity increased with the length of the fish, while the relative fecundity increased with length up to 360 mm TL; it then declined as the length further increased. The sex ratio ranged from 0.2 to 3.7 with an overall mean sex ratio of 2.1 males for every female. The abundance range of females in each length class in catches was 1.5–15% with maximum abundance for 300–360 mm TL length class.

### 3.3. Stock assessment

#### 3.3.1. Population parameters

The estimated Von Bertalanffy Growth Function (VBGF) parameters ( $L_{\infty}$ ,  $K$  and  $t_0$ ) were 648 mm, 0.46/year, and  $-0.15$  year, respectively. The reconstructed monthly length-frequencies on which the population parameters were estimated are given in Fig. 9, with overlaid VBGF curves. The corresponding growth curve showing length and weight of the species at different ages are plotted in Fig. 3b. The fish grew to 267, 407, 496, 552, 588, 610 mm in the 1st, 2nd, 3rd, 4th, 5th and 6th year of age, respectively with corresponding weights (g) of 209, 785, 1460, 2043, 2492 and 2655, respectively. The parameter estimates for total mortality  $Z$  was 1.25/year, natural mortality  $M$  was 0.46/year, and fishing mortality  $F$  was 0.79/year. The exploitation ratio  $E$  was 0.63/year. The estimated  $L_{c50}$  and  $L_{c95}$  were 300 mm TL and 350 mm TL.

#### 3.3.2. Length-based indicators

Results of the analysis of the LBI are shown in Table 1. The observed indicator ratios were  $L_{max5\%}/L_{\infty} = 0.6537$ ,  $L_{95\%}/L_{\infty} = 0.6096$ ,  $P_{mega} = 0.0005$ ,  $L_{25\%}/L_{m50} = 0.3279$ ,  $L_c/L_{m50} = 0.9836$ ,  $L_{mean}/L_{opt} = 0.7334$ ,  $L_{mean}/L_{F=M} = 0.9209$  and  $P_{obj} = 0.3024$ . For all the eight indicators, the observed values were lower than the expected values (Table 1).

#### 3.3.3. Biomass and yield

The B/R and Y/R of the species, estimated using  $L_{c50}/L_{\infty}$  (0.46) and  $M/K$  (1.0), showed an exploitation rate that maximized the Y/R ( $E_{max}$ ) at 0.64 (Fig. 10). The exploitation that resulted in a 10% decline in biomass from the virgin stock biomass ( $E_{10}$ ) was 0.561 and that resulted in a 50% decline ( $E_{50}$ ) was 0.36. The yield and SSB against different  $f$ -factors are shown in Fig. 11. At  $f$ -factor = 1 (current exploitation), the yield is 31,369 t; the corresponding SSB is 37,151 t. Thus, SSB at  $f$ -factor 1 is 26.8% of the SSB<sub>0</sub> (virgin spawning stock biomass). The yield reached a maximum at  $f$ -factor 1.6 (Fig. 11), and declined with further increase in  $f$ -factor, indicating attainment of MSY (32,953 t) at  $f$ -factor 1.6.

#### 3.3.4. Spawning potential ratio

The simulation of the year-wise proportion of selectivity at different lengths of maturities of females is shown in Fig. 12a and the year-wise length at 50% and 95% selectivity, relative fishing mortality ( $F/M$ ), and SPR are shown in Fig. 12b for 2013 to 2017. Fig. 12a showed that 50% of the females became vulnerable to fishing before reaching  $L_{m50}$ , and the selectivity varied year wise. The  $F/M$  declined from 2013 to 2017, while the SPR increased correspondingly (Fig. 12b). The SPR for the study period ranged from 0.04 to 0.29.

#### 3.3.5. Spawner recruit relation

The spawner recruit relationship showed that the mean annual SSB fished was  $2692 \times 10^5$  numbers, which is about 37,151 t, based on the mean weight of specimens in the catch (138 g) during the period of study. The number of recruits declined once the capture of spawners (SSB) exceeded  $2000 \times 10^5$  numbers, which is about 27,600 t.

### 3.4. Gear selectivity

The TL, weight and  $G_{max}$  of 1154 unsexed specimens ranged from 192 to 496 mm, 73 to 1280 g and 79 to 288 mm, respectively. The relation between  $G_{max}$  and TL of the samples is shown in Fig. 13. The regression model resulted from the relation is  $G_{max} = 0.70415 * TL^{0.972543}$ . Using the model, the TL corresponding to each  $G_{max}$  estimated as  $TL = \exp\{[\log(G_{max}) + 0.35076] / 0.972543\}$ . The number of samples caught in nets of each mesh size, the actual TL and weight range along with the modelled  $G_{max}$  and TL are shown in Table 4. The t-test revealed no significant difference between the modelled TL and the actual TL ( $P = 0.44$ ).

## 4. Discussion

Increasing demand for human consumption, owing to taste and high nutritional value (De et al., 2019), subjects the species to intensive fishing in northern BoB, and the associated Bhagirathi–Hooghly river in West Bengal (Sajina et al., 2019). Length–frequency in catches revealed that the species is fished at sizes as low as 23 mm/ 0.179 g; often as by catch in small meshed shore seines, bag nets and lift nets. The length group 101 to 239 mm were relatively low in catches as they mostly remain in marine areas for growth and maturation and less frequently caught in gill nets of mesh sizes larger than 50 mm, commonly used for hilsa fishing in marine areas. However, the length groups up to  $\approx 100$  mm are prevalent in freshwater and tidal zones of the Bhagirathi–Hooghly river system and get caught in smaller meshed (<50 mm) nets. Maximum length ( $L_{max} = 618$  mm TL) and weight ( $W_{max} = 2635$  g) recorded in this study are new size records for the species from this study area as the previous size record was 573 mm TL and 2480 g weight (Sandhya et al., 2016). Knowing the LWR of exploited fish populations is important in setting up yield equations in stock assessment (Beverton and Holt, 1957; Ricker, 1958). Pillay (1958), Swarup (1966), Ramakrishnaiah (1972), De and Datta (1990), Reuben et al. (1992), Bhaumik et al. (2011), Dutta et al. (2012), BOBLME (2015), Mandal et al. (2018), Dutta et al. (2019) reported length–weight relation of *T. ilisha* from Indian waters. Islam et al. (1987), Amin et al. (2004), Amin et al. (2005), Flura et al. (2015) reported it from Bangladesh; Narejo et al. (2008) from Pakistan and Al-Baz and Grove (1995) from Kuwait. A comprehensive account of the LWR reported by various workers for the species is available in Suresh et al. (2017). These reports however, showed wide variations in  $a$  and  $b$  values, even within the same study region. As the  $a$  and  $b$  values are important parameters for stock assessment, a fresh attempt for assessment of these parameters was made following

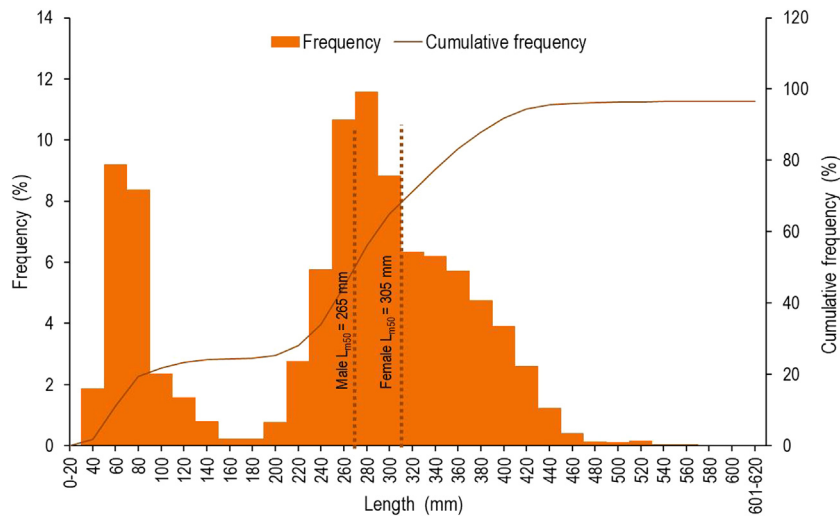


Fig. 2. Length–frequency distribution of *T. ilisha* and their cumulative frequency in catches (n = 10171).

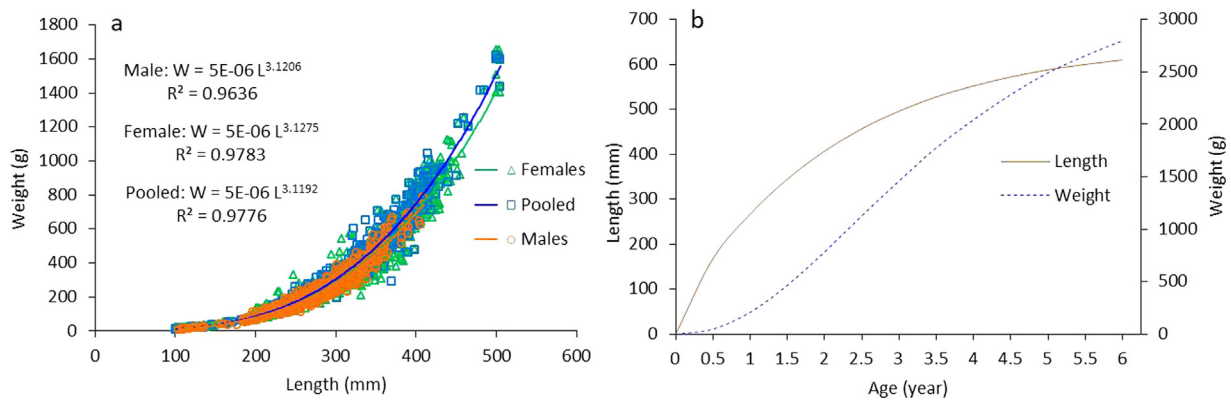


Fig. 3. (a) Length–weight relation of *T. ilisha* for male, female, and sexes pooled and (b) length and weight progression of *T. ilisha* at different ages.

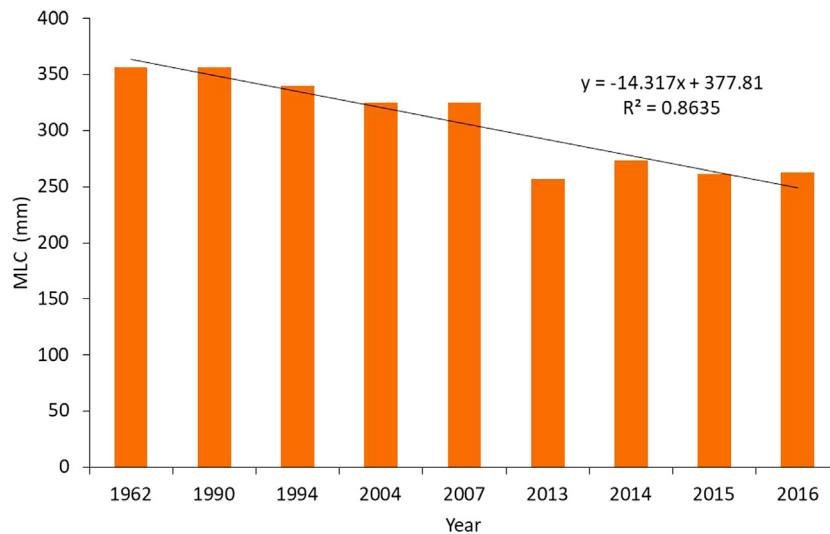


Fig. 4. The progression of the mean length of *T. ilisha* in catches in the study area showing significant temporal decline of MLC (P= 0.0068).

the sample collection procedure of Froese (2006). Though the LWR might vary across locations due to local environmental and fishery factors (Froese, 2006), the a and b values obtained in the current study are comparable with the reports of De and Datta

(1990) from India; Islam et al. (1987) and Narejo et al. (2008) from Bangladesh and Al-Baz and Grove (1995) from Kuwait for males and females and BOBLME (2015) for sexes combined from India.

**Table 2**  
Gonad maturity phases of male and female *T. ilisha*.

Maturity phase*	Maturity phase identifiers	
	Ovary	Testes
Immature	Only oogonia (Og) and primary growth (PG) oocytes present. Mean oocyte diameter 0.08mm or lower (Fig. 5a)	Mostly primary and secondary spermatogonia (Sg) present (Fig. 5f)
Developing	Presence of PG, cortical alveoli (CA), primary vitellogenic (Vtg-1), and secondary vitellogenic (Vtg-2) oocytes (Fig. 5b). Mean oocyte diameter 0.2 mm or lower.	Presence of Sg, spermatocyte (Sc), spermatid (St) and the lumen of lobules clearly visible (Fig. 5g).
Spawning capable	Dominance of Vtg-2 and tertiary vitellogenic (Vtg-3) oocytes along with early oocyte maturation (OM) stages and few PG, and CA oocytes also visible (Fig. 5c). More than 70% of the oocytes are at Vtg-3 or above stages and the mean oocyte diameter is 0.5mm or higher	The lumen of the lobules filled with spermatozoa (Sz) and clumps of St along the periphery of the lobules (Fig. 5h).
Actively spawning (a sub-phase of spawning capable phase)	Dominance of OM oocytes in germinal vesicle migration (GVM) and germinal vesicle breakdown (GVBD) stages. The frequency of OM oocytes is 90% or higher. Few Vtg-3, PG, and CA oocytes also visible (Fig. 5d). Mean oocyte diameter 0.6mm or higher.	Applying gentle pressure on the abdomen release milt in fresh or immediately dead specimens (Fig. 5i)
Regressing	Atresia of oocytes visible, presence of post-ovulatory follicles (POFs), few CA, GVBD oocytes present (Fig. 5e)	Residual Sz present in the lumen of lobules and scattered Sc along with St (Fig. 5j)

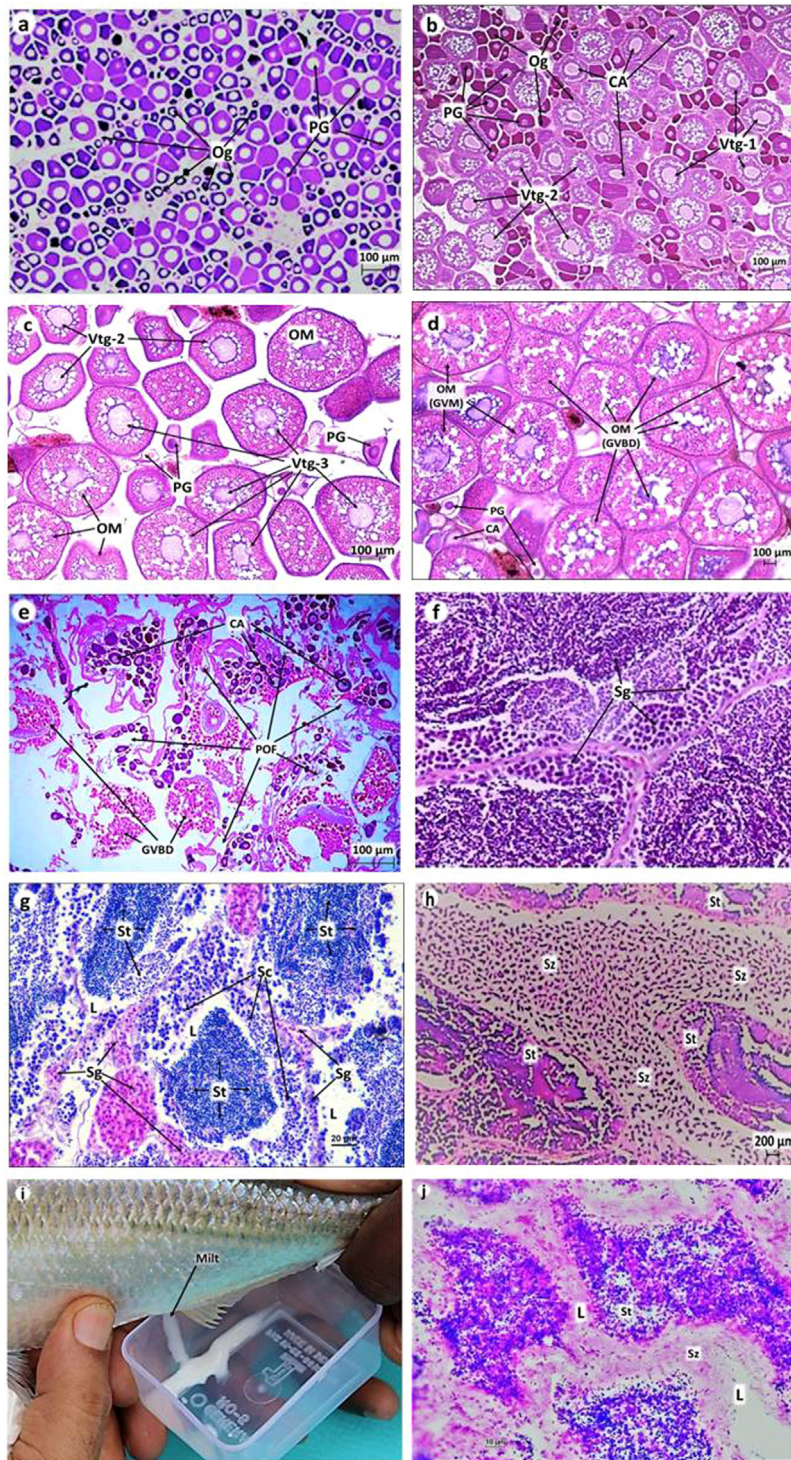
\*Based on the scheme of Brown-Peterson et al. (2011).

**Table 3**  
Length at maturity of *T. ilisha* from different hilsa fishing regions.

Male (mm)	Female (mm)	Location	Author(s)
300	356	Godavari river, India	Chacko and Ganapati (1949)
280	382	Godavari river, India	Chacko and Krishnamurthy (1950)
216–254	267–305	Hooghly and Mahanadi rivers, Chilika lake, India	Jones and Menon (1951)
160–170	190–200	Hooghly estuary, India	Pillay (1958)
	266	Narmada river, India	Karamchandani (1961)
256	370	Godavari river, India	Pillay and Rao (1963)
200	350	Ganga river, India	Mathur (1964)
	330	Ganga at Allahabad, India	Mathur (1964)
	310	Ganga at Varanasi, India	Mathur (1964)
175–300	200–300	Chilika lake, India	Jhingran and Natarajan (1969)
172	186	Chilika lake, India	Ramakrishnaiah (1972)
360	420–430	Godavari river, India	Rajyalakshmi (1973)
	190	Mandapam, India	Banerji and Krishnan (1973)
210	320	Meghna river, Bangladesh	Shafi et al. (1978)
	320	Bhagirathi–Hooghly river, India	De (1980)
400	400	Bangladesh waters	Dunn (1982)
	341	Hooghly estuary, India	De (1980, 1986)
260–290	310–330	Bangladesh waters	Islam et al. (1987)
370	370	Bay of Bengal marine, India	Reuben et al. (1992)
250	330	Shatt Al-Arab river, Iraq	Hussain et al. (1994)
	415	Kuwait waters	Al-Baz and Grove (1995)
250	378	Shatt Al-Arab river, Iraq	Al-Noor (1998)
	190	Bangladesh waters	Haldar (2002)
250–340	280–300	Bangladesh waters	Amin et al. (2005)
170	208	Hooghly–Bhagirathi river, India	Bhaumik and Sharma (2012)
193	207	Ukai reservoir, India	Bhaumik et al. (2012)
242	256	Al-Hammar, Iraq	Mutlak (2012)
200	220	Marine waters, Iraq	Mohamed and Qasim (2014)
322		Bhagirathi–Hooghly river, India	BOBLME (2015)
170	210	Shatt Al Arab River, Iraq	Almukhtar et al. (2016)
273		North-western Persian Gulf	Koochaknejad et al. (2018)
274	285	Myanmar	Bladon et al. (2019)
340	345	Myanmar	Merayo et al. (2020)
273	300	Perak waters, Malaysia	Halim et al. (2020)
265	305	Bhagirathi–Hooghly river, India	Present study

Empirical indicator based RPs are increasingly being evolved and used, especially for managing data-poor fisheries for surveillance and or assessment (Shephard et al., 2020). These early warning signals can support science-based management decisions (Shephard et al., 2015). Currently, a suite of LBIs are available for assessing changes in fish populations due to fishing (Rochet and Trenkel, 2003; Shin et al., 2005). The application of such indicators could provide the status of several fish stocks, which concurred with the estimates emanated from model-based

assessments (Shephard et al., 2020). Application of eight such LBIs, based on ICES (2015), Shephard et al. (2020) in the current study indicated that hilsa is being both recruitment and growth overfished; the fishery is less optimum, yielding lower than MSY and the sizes being fished may not help sustain its fisheries in the long run. Though empirical methods provide valuable insights into the stock status, they may not provide objective or quantifiable indicators (Shephard et al., 2020) that can be used for implementable management actions. The advantage of



**Fig. 5.** Histological growth phases of ovaries of *T. ilisha* at (a) Immature phase, (b) Developing phase, (c) spawning capable phase, (d) actively spawning and (e) Regressing phase [Og= Oogonia, PG= primary growth stage, CA= cortical alveolar oocyte, Vtg-1= primary vitellogenic oocyte, Vtg-2= secondary vitellogenic oocyte, Vtg-3= tertiary vitellogenic oocyte, OM= oocyte maturation (with germinal vesicle migration (GVM), germinal vesicle breakdown (GVBD), the post-ovulatory follicle (POV)] and f, g, h, i and j are the same phases, respectively of the testes (Sg = spermatogonia, Sc = spermatocyte, St = spermatid, Sz = spermatozoa, L = lumen of lobules).

model-based methods is their potential to obtain objective RPs (Shephard et al., 2020). Hence, to gather objective and implementable RPs, we examined the important life history parameters and incorporated these into stock assessment models.

The progression of the MLC of the species from the study area showed a significant temporal decline over the years and is currently lower than the  $L_{m50}$  of both males and females. Removal

of larger individuals through fishing is reflected as changes in mean length (Shin et al., 2005). High fishing pressure often affects the size distribution of the adult stock by reducing the proportion of larger individuals, which generally indicates an unhealthy situation of the stock (Beverton and Holt, 1957; Lappalainen et al., 2016), and is a possible indication of multi-generation, indiscriminate size-selective overfishing (Beverton and Holt, 1957;

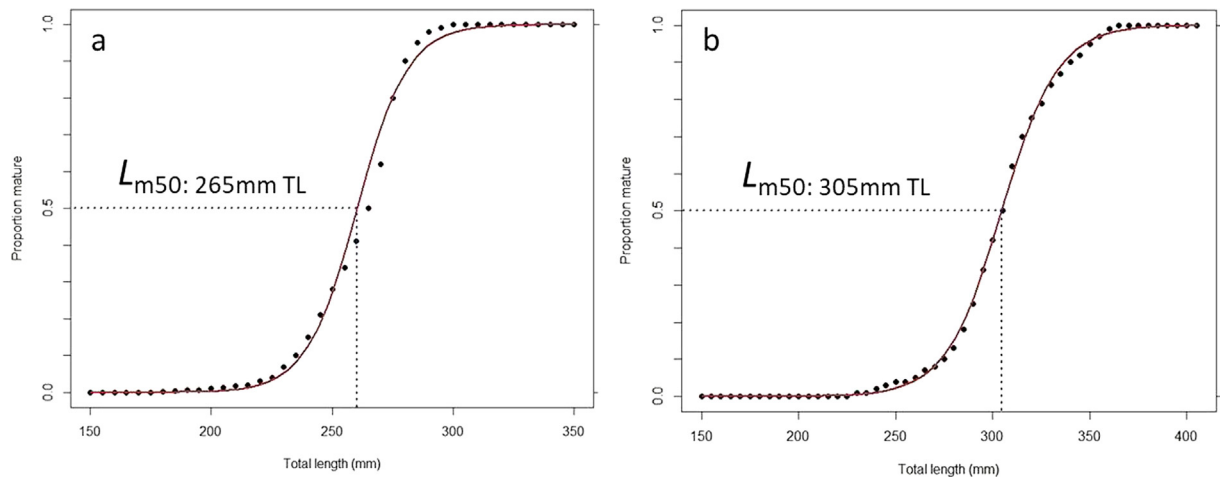


Fig. 6.  $L_{m50}$  of *T. ilisha*; (a) male and (b) female.

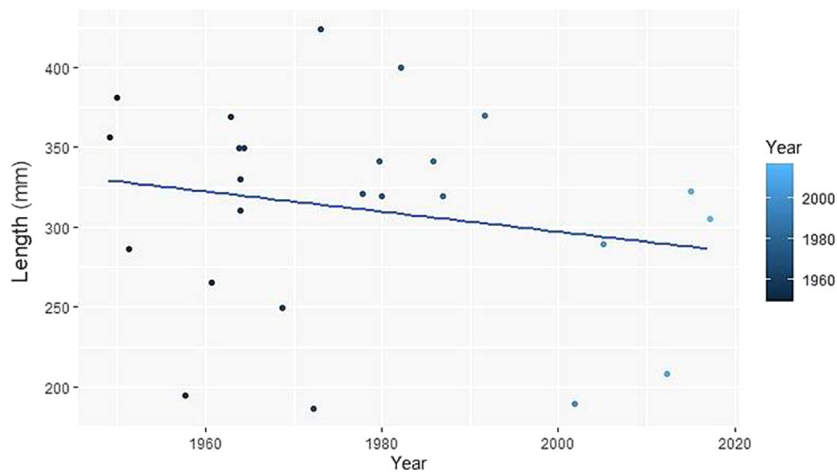


Fig. 7. Temporal progression of the length at maturity of female *T. ilisha* in the study area.

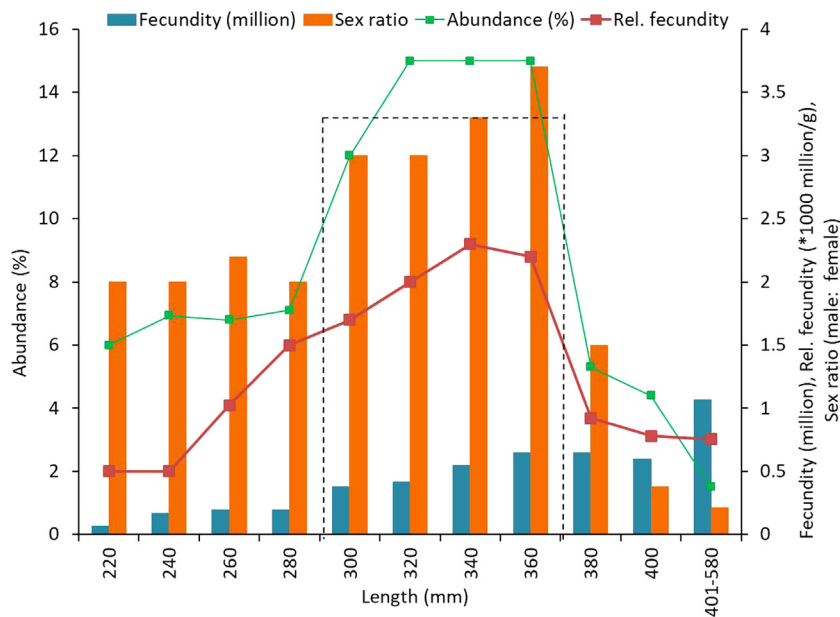
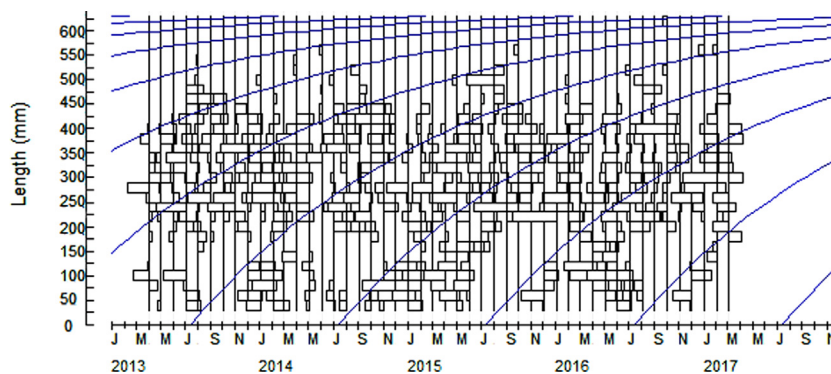


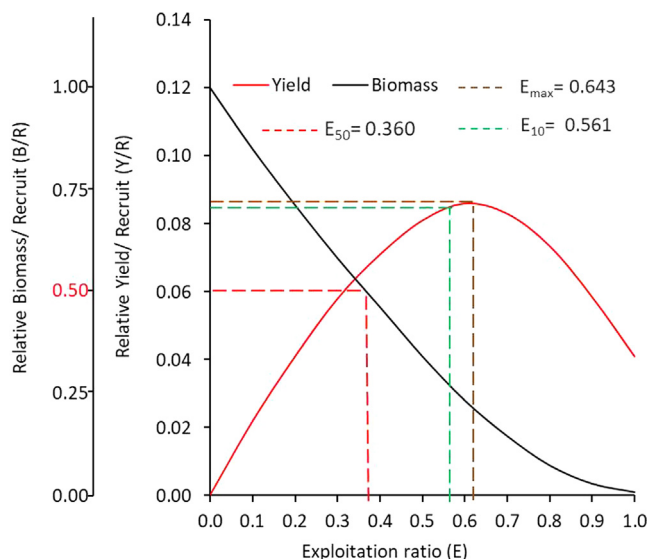
Fig. 8. Lengthwise fecundity, relative fecundity, sex ratio and abundance of *T. ilisha*.

**Table 4**  
The lower and upper length and weight ranges of hilsa caught in experimental fishing using gill nets of various mesh sizes (n = 1154) with their corresponding modelled G max and modelled TL ranges.

Mesh size (mm)	Sample (No.)	Actual length range (mm)	Actual weight range (g)	Modelled $G_{max}$ range (mm)	Modelled length range (mm)
50	92	192–244	73–154	79–134	170–221
55	102	225–311	120–326	86–148	185–245
60	184	227–300	123–356	93–163	201–270
65	388	244–320	154–401	99–175	217–290
70	96	254–337	174–418	107–189	235–315
75	40	268–345	206–492	113–201	250–335
80	93	290–380	307–522	120–214	266–358
90	84	310–420	307–628	134–242	300–405
100	45	351–440	366–797	147–268	330–450
110	30	362–496	470–1280	159–288	360–485



**Fig. 9.** Monthly distribution of restructured length frequencies of *T. ilisha* overlaid by VBGF curves.



**Fig. 10.** Stock status of *T. ilisha* at different exploitation ratios using Beverton and Holt's relative Y/R and B/Y model.  $E_{max}$  = the exploitation level that maximized Y/R,  $E_{50}$  and  $E_{10}$  are exploitation levels that results in 50% and 10% decline in biomass, respectively.

Lappalainen et al., 2016). Rochet and Trenkel (2003) suggested that the MLC may be used as an operational indicator or RP for the potential impact of fishing on the stocks. However, changes in mean length can have different interpretations, pointing to enhanced recruitment or influence of the environment on growth rate (Shin et al., 2005). Hence, there is a need for exploring complementary information obtained through different indicators (Shin et al., 2005) to signal the occurrence of overfishing.

The LBI values for  $L_{max 5\%}$ ,  $L_{95\%}$  and  $P_{mega}$  estimated in the current study indicated size truncation and overexploitation of larger individuals. Hence, size selective overfishing might be the major cause of the declining MLC in the study region (Beverton and Holt, 1957; Lappalainen et al., 2016).

'Reproductive potential' is the capacity of fish populations in producing viable eggs and larvae (Solemdal, 1997; Trippel, 1999). Though the major focus of assessing reproductive potential in fish has been on the reproductively active female proportion in the population (Brown-Peterson et al., 2011), it is also a function of size/ age at maturity, absolute and relative fecundity, sex ratio, and abundance (Konstantinos et al., 2014). Identifying and protecting size/ age groups having maximum reproductive potential is an important step in managing growth and recruitment overfishing. The available data on maturity stages of tropical fishes are majorly based on difficult to distinguish, numbered maturity stages (Brown-Peterson et al., 2011); the case of *T. ilisha* is not different from this. Data on the size at maturity of the species are available from India, Bangladesh, Persian Gulf, Kuwait, Iraq, Iran and Malaysia. A review of the historical metadata available on size at maturity of the species presented conflicting information with wide variation, even within the same study region. The available range of values for males is 160 mm from Hooghly estuary, India (Pillay, 1958) to 400 mm from Bangladesh waters (Dunn, 1982). For females, the range is 186 mm from Chilika lake, India (Ramakrishnaiah, 1972) to 430 mm from the Godavari river, India (Rajyalakshmi, 1973). The maturity size reported from the study region too varied widely. In most of these cases, the maturity stages were decided on macroscopic or basic microscopy observations, categorizing gonads into eight maturity stages, in which Stage I being immature, Stage II to V maturing, Stage VI mature, Stage VII partly spent and Stage VIII spent (Pillay and Rao, 1963), leaving great difficulty in accurately categorizing the stages. The size of the smallest mature individual in sample and the size at first maturity ( $L_{m50}$ ) are other elements of confusion

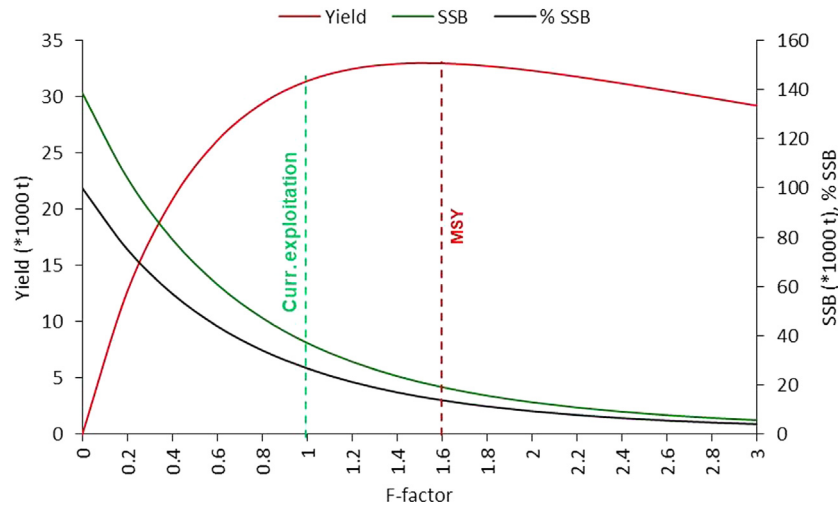


Fig. 11. Thompson and Bell model showing the dynamics of yield and SSB at different f-factors.

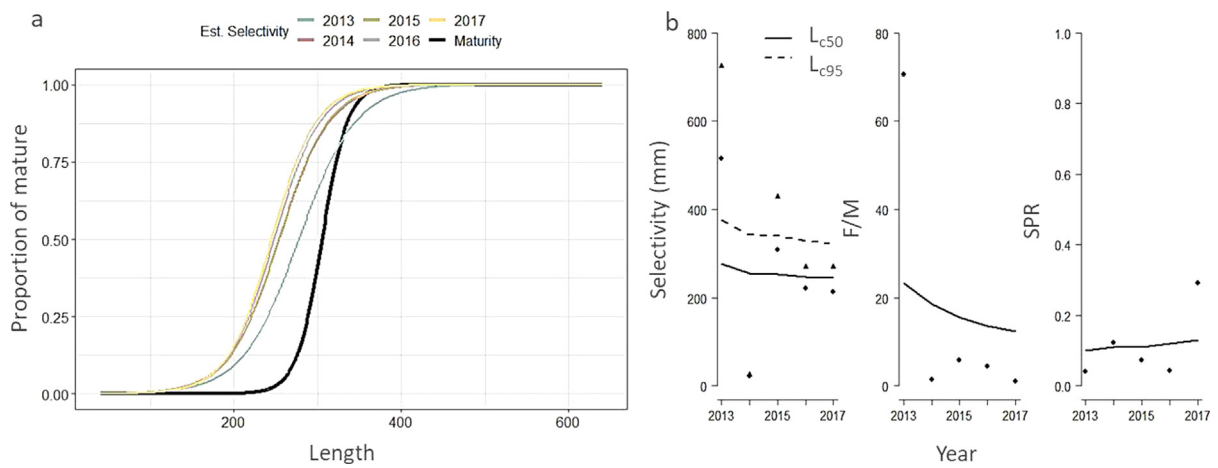


Fig. 12. (a) Year-wise selectivity of females against  $L_{m50}$  and (b) year-wise progression of selectivity at 50% ( $L_{c50}$ ) and 95% ( $L_{c95}$ ), relative fishing mortality ratio (F/M), and spawning potential ratio (SPR).

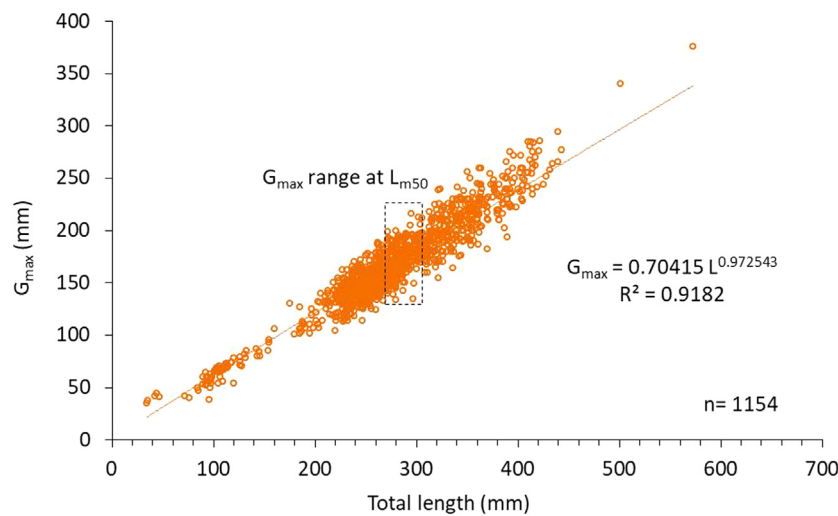


Fig. 13. The relation between TL and maximum girth ( $G_{max}$ ) of *T. ilisha*. The dotted lines box indicate the  $G_{max}$  range at maturity sizes.

in the available literature on the species. Hence, a need for re-defining the size at first maturity of the species arose, as it is an important parameter to decide size based fishing regulations. As the computation of maturity requires accurate maturity staging (Maura et al., 2003), we delineated the maturity stages based on gonad histology. Gonads in 'spawning capable' or higher phases in which ovaries majorly contained vitellogenic oocytes at Vtg-3 or higher stages and males having spermatozoa released into the lumen of testicular lobules were taken as mature. Thus, the  $L_{m50}$  (King, 2005) of males and females were redefined at 265 mm TL and 305 mm TL, which are at 180 g and 280 g weight and 1.0 and 1.2 year of age, respectively. The species is a total spawner with synchronous ovary. Ramakrishnaiah (1972) and De (1980) from river Hooghly; Zohre et al. (2015) from the Persian Gulf also reported similar nature of the ovaries of the species. Though a wide range of maturity sizes are reported for the species, the values obtained in the current study are comparable to the sizes reported by Jones and Menon (1951), Pillay and Rao (1963), Mathur (1964), De (1986) and Bhaumik and Sharma (2011). The lowest length at which males and females with mature testes and ovaries recorded in the present study were 180 mm TL (54 g) and 213 mm TL (92 g), respectively, but by far the lowest size reported is 160–170 mm TL for males and 190–200 mm TL for females from Hooghly estuary (Pillay, 1958).

Analysis of the historical metadata on female length at maturity of the species from the study area showed a declining temporal pattern, indicating manifestation of early maturity. Al-mukhtar et al. (2016) also reported the onset of early maturity of *T. ilisha* from Iraq waters. Fish stocks, which are commercially exploited, most often show early maturation trends (Law, 2000), as a possible outcome of FIE (Rijnsdorp, 1993). Increased mortality at maturity sizes selects for early maturation traits (Reznick et al., 1997; Roff, 2000) as higher mortalities resulting from increased fishing effort favours faster life histories (Jorgensen, 1990; Lappalainen et al., 2016; Heino et al., 2015) and express in FIE of maturation patterns (Olsen et al., 2004). Early maturation might also be due to phenotypic plasticity (Lorenzen and Enberg, 2002) resulting from increased resource availability to the un-fished stock (Alm, 1959). However, disentangling plastic and evolutionary causes of phenotypic changes in exploited fish populations still remains to be fully understood (Law, 2000). Though environmental and climatic factors cannot be ruled out, the complementary information from different indicators such as LBI ( $L_{max5\%}$ ,  $L_{95\%}$  and  $P_{mega}$ ), MLC, SPR and SSB in the present study, reiterated the occurrence of multi-generation, indiscriminate size-selective overfishing, suggesting FIE might be a major cause of onset of early maturity of the species.

The minimum mesh size for hilsa fishing gear and the MLS in catches, as implemented in the study area to protect immature ones from capture, are 90 mm and 230 mm TL, respectively (The Kolkata Gazette, 2013). Our studies on the gill net selectivity based on the  $G_{max}$  and TL model showed that the 90 mm mesh gill nets would exclude sizes up to 310 mm TL, which will indeed exclude the  $L_{m50}$  of both males and females, giving the fish at least one chance to spawn in its lifetime (Beverton and Holt, 1957; Ricker, 1975; Froese, 2004). As the species is both growth and recruitment overfished as reported by Sajina et al. (2019, 2020) and based on the results of the present study, there is a need for simultaneous protection of the spawning stock and the juveniles. However, the existing recommendations on minimum mesh size and MLS will not meet this requirement. Hence we attempted to identify the females sizes having maximum reproductive potential in terms of higher absolute and relative fecundity, sex ratio, and abundance (Konstantinos et al., 2014) and found that the length group 281 to 360 mm TL (294 to 640 g weight) has maximum reproductive potential. Hence, any size based catch

exclusion efforts for managing hilsa fisheries in the region needs to focus on the length up to 360 mm TL. However, currently, about 45 to 65% of the catch constitutes sizes below  $L_{m50}$  of males and females, respectively and about 27% are females with maximum reproductive potential. This needs to be brought down to manage the growth and recruitment overfishing. The length groups >100 to <240 mm TL were comparatively low in catches as they mostly remain in marine areas for growth and maturation and less frequently caught in gill nets of mesh sizes larger than 50 mm commonly used for hilsa fishing in marine areas, thus are protected to some extent. But they become vulnerable to fishing as growth progresses, leading to a decline in spawning stock that migrates to riverine stretches for breeding. There is a scheduled annual fishing ban along the coastline starting from 15<sup>th</sup> April to 14<sup>th</sup> June, under the Marine Fisheries Regulation of West Bengal, to help unhindered breeding of marine fishes. But the ban period is not coinciding with the period of peak breeding migration (September–October) of *T. ilisha*. Due to the crowding of fishing efforts in the marine and coastal areas, once the fishing ban is lifted, there is a rush of thousands of fishing boats. Only those fish escape capture can migrate to riverine stretches for breeding, resulting in low recruitment. Local adjustment of the ban period is not feasible as it is not species-specific. In this backdrop, it was inevitable to assess the current stock status of the fish, using established models to obtain objective RPs for management interventions.

Studies on the population and stock status of *T. ilisha* in Indian waters are that of Reuben et al. (1992), Dutta et al. (2012) and BOBLME (2015), but are based on small data sets of not more than a year, constraining sound management decisions. We collected length–frequency data at a monthly interval from 16 stations along the migratory route of the fish, consecutively from 2013 to 2017, and used it for the length-based stock assessment. The length and weight at age and the estimated age at asymptotic length indicated a relatively slower rate of growth of the fish (Pauly and Munro, 1984). The fishing mortality  $F$  (0.79/year), the total mortality  $Z$  (1.25/year), and the  $Z/K$  (2.72) suggested a mortality dominated fishery (Beverton and Holt, 1956). The  $E$  at 0.63/year showed fishing pressure on the stock as it is higher than the theoretically optimum level of 0.5 (Gulland, 1969). BOBLME (2010), Haldar and Amin (2005), Amin et al. (2008) reported comparable  $E$  values (0.52 to 0.66) from Bangladesh waters. Females are vulnerable to peak fishing below its  $L_{m50}$  as the  $L_{c50}$  is smaller than  $L_{m50}$ . For a sustainable fishery, the  $L_{c50}$  should be larger than the  $L_{m50}$  (Hoggarth et al., 2006), emphasizing the need for control on minimum size at capture by raising the minimum mesh size and MLS.

The Y/R and B/R analysis resulted in an  $E_{max}$  of 0.64 that would maximize yield per recruit from the fishery. The current exploitation ratio ( $E = 0.63$ ) being almost equal to  $E_{max}$ , and higher than 0.5, the exploitation is at maximum possible limits. The Thompson and Bell (1934) model showed the current yield at  $f$ -factor 1 as 31,370 t, and SSB as 37151 t, but the SSB declined to 26.8% of the virgin SSB, which is a bare minimum to sustain the fishery (Rosenberg and Repestro, 1996; Ault et al., 2010). The yield reached a maximum at  $f$ -factor 1.6 (MSY= 32,953 t) and declined with any further increase in  $f$ -factor. However, any increase in the effort to attain MSY would further decline the SSB to critically low levels and badly impact recruitment. The mean annual catch during the study period is 30,761t (Sajina et al., 2019), which is lower than the estimated MSY. However, the annual catch over the years, frequently exceeded the estimated MSY (Sajina et al., 2019), emphasizing the need for limiting annual catch quantity.

Ensuring the survival of adequate spawning stock of fishes is one of the important objectives of managing exploited fisheries

(Mace and Sissenwine, 1993; Caddy and Mahon, 1995). The SPR, an important index of the relative rate of reproduction (Mace and Sissenwine, 1993; Walters and Martell, 2004), has extensively been used for benchmarking spawning stock reference points in fisheries management decisions (Hordyk et al., 2015a,b; Prince et al., 2015; Thorson et al., 2017) and rigorously validated (Hordyk et al., 2015b; Sun et al., 2017; Chong et al., 2020). Though no critical minimum threshold of SPR is set for *T. ilisha*, the SPR range of 0.04 to 0.29 estimated during 2013–2017 are far lower than the range of 0.3 to 0.4 aimed for sustainable management of fisheries, while 0.2 is the minimum limit without seriously risking recruitment (Mace and Sissenwine, 1993; Rosenberg and Repestro, 1996; Ault et al., 2010). This indicated over-exploitation of spawning stock of *T. ilisha* during the study period. The SPR from 2013 to 2016 has been below 0.2 but as the  $F/M$  decreased in 2017, the SPR improved up to 0.29, showing the need for decreasing fishing pressure on spawning stock biomass.

The recruits declined when the capture of SSB exceeded 27,600 t, indicating the need for at least a 26% reduction from the current level of SSB capture. As the fishing effort is likely to increase in future due to increasing demand and declining catches, the fishery management strategies need to be centred on protecting the immature ones and the sizes having maximum reproductive potential by raising the MLS from 230 mm TL to not less than 360 mm TL (470 g of 1.6 year age), along with fixing an annual catch target at a precautionary level. The current mean annual catch of 30,761 t (say 30,000t), is lower than the estimated MSY and estimated catch at the current  $f$ -factor, which may be taken as the precautionary target RP for the annual catch limit. The annual catch limit may be adjusted through regular monitoring of the stock status. Based on the results of the gear selectivity study, for excluding sizes up to 360 mm TL from the catch, the minimum mesh size needs to be raised from the currently recommended 90 mm to 110 mm. This would, however, cause economic loss to fishers as the length groups up to 360 mm TL forms 48% of the current mean annual catch, which is worth INR 3764 million (taking INR 250/kg as the average landing centre price of the fish). Fisheries managers have to take a call on this through generating awareness and willingness among the fishers and consumers on the need for adopting stringent measures for managing the stock of the fish along with suitable livelihood compensations to fishers, at least in the initial years of implementation as the catch is expected to improve with the suggested measures in place. Captive breeding and aquaculture of the species, which are under various stages of standardization in India (example: Chattopadhyay et al., 2018; De et al., 2020) may be fast-tracked to bring in additional biomass for human consumption without further disturbing the natural stocks.

## 5. Conclusions

The stock of *T. ilisha* in the northern BoB bordering India and the associated Bhagirathi–Hooghly river system is in near full exploitation with high growth and recruitment overfishing. Although the current MLS and minimum mesh size recommendations are effective for protecting juveniles, these are inadequate for managing the overexploited spawning stock. Seasonal fishing closure being implemented is less effective in protecting the spawners. To reduce recruitment overfishing there is a need for at least a 26% reduction in current SSB capture. For this, the notified MLS of 230 mm TL needs to be revised to 360 mm TL by raising the currently notified minimum mesh size of 90 mm to 110 mm, which will, however, incur about 48% catch loss to fishers. To avoid over-harvesting, the annual catch quantity needs to be limited at a precautionary level of 30,000 t, which may be adjusted based on stock status monitored regularly.

## CRedit authorship contribution statement

**Vettath Raghavan Suresh:** Conceptualization, Funding acquisition, Project administration, Writing - original draft, Writing - review & editing, Data curation. **Sandhya Kavitha Mandhir:** Supervision, Visualization, Methodology, Investigation, Writing - review & editing. **Aliyamintakath Muhammadali Sajina:** Investigation, Writing - review & editing. **Ranjan Kumar Manna:** Investigation. **Jayanta Mukherjee:** Investigation, Data curation, Formal analysis. **Surajit Kangsa Banik:** Investigation. **Tara Maity:** Investigation. **Rupam Samanta:** Investigation. **Rohan Kumar Raman:** Data curation, Formal analysis. **Jayasankar Jayaraman:** Data curation, Formal analysis. **Bijoy Kumar Behera:** Investigation.

## 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.

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