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# Application of Length-Based Assessment Methods to Elucidate Biological Reference Points of Black Pomfret Stock in the Bay of Bengal, Bangladesh

**Suman Barua [1,2], Qun Liu [1,*], Mohammed Shahidul Alam [1,3], Petra Schneider [4] and Mohammad Mojibul Hoque Mozumder [5]**

[1] College of Fisheries, Ocean University of China, Qingdao 266003, China
[2] Department of Fisheries, Ministry of Fisheries and Livestock, Dhaka 1205, Bangladesh
[3] Department of Fisheries, University of Chittagong, Chattogram 4331, Bangladesh
[4] Department for Water, Environment, Civil Engineering and Safety, University of Applied Sciences Magdeburg-Stendal, Breitscheidstraße 2, D-39114 Magdeburg, Germany
[5] Fisheries and Environmental Management Group, Helsinki Institute of Sustainability Science (HELSUS), Faculty of Biological and Environmental Sciences, University of Helsinki, 00014 Helsinki, Finland
* Correspondence: qunliu@ouc.edu.cn; Tel.: +86-136-8542-621

**Abstract:** The black pomfret (*Parastromateus niger*) is one of the high-income-generating carangid fish species and the only known member of its genus. This study aims to identify existing gaps in stock status and population demography of this species and provide viable management recommendations to enhance the sustainability of this fishery. Therefore, three methodological approaches have been used in this study; TropFishR to present the current exploitation status, the length-based spawning potential ratio (LB-SPR) to quantify stock spawning biomass, and Froese's sustainability indicators (LBI) to establish a basic standard for sustainable management of the fishery. In the length-weight relationship of black pomfret, an allometric growth pattern ($b$ = 2.19) was found. The VBGF life history parameters for black pomfret were $L_\infty$ = 55.25 cm, $K$ = 0.54 year$^{-1}$, and based on LCCC analysis, the total mortality ($Z$ = 1.61 year$^{-1}$), natural mortality ($M$ = 0.69 year$^{-1}$) and fishing mortality ($F$ = 0.91 year$^{-1}$) are calculated. The result reveals that this fishery is currently suffering from overexploitation and the stock's spawning biomass ($SPR$ = 13%) is below the limit reference point because most of the catch (82%) was found to be under the maturity level. Based on the results, this study recommended strictly maintaining the mesh size of the net to ensure not to catch immature fish with a length smaller than 30.63 cm, recommended the length to catch be between 29 and 35 cm, and reducing fishing pressure by one-third to ensure the sustainability of the black pomfret fishery.

**Keywords:** Bay of Bengal; *Parastromateus niger*; spawning potential ratio; length-based indicators; overexploitation; mesh size regulation



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## 1. Introduction

The black pomfret, *Parastromateus niger* (Bloch, 1795), locally known as '*Kalo chanda*' is one of the highly valued commercial fish species belonging to the family Carangidae [1] with a trophic level of 3.0 (primary carnivore) and inhabits the shallower coastal waters of the Indian Ocean to the Western Pacific Ocean [2,3]. It is widely distributed in coastal, estuarine, and marine habitats ranging from the depth of 5 to 105 m in the Bay of Bengal, Bangladesh marine waters [4]. This species is the only known member of its genus. In Bangladesh, black pomfrets are mostly available from November to April, as observed from its mean annual landing [5].

In the absence of age composition data, length composition data is usually applied to estimate stock status and population dynamics, especially in tropical fisheries [6]. Therefore, length-based methods are commonly applied in data-limited fisheries where the determination of age has not been possible [7,8]. Similarly to many world's fish stocks, the black pomfret fishery also lacks substantial data sets such as species-specific landing and catch per unit effort; therefore, it is difficult to assess this fishery with conventional catch-based stock assessment methods [9,10]. With the availability of robust prior information, length-based models showed better performance in many cases than some catch-based models because of the high sensitivity of catch history scenarios and depletion levels [11].

The stock status and population dynamics of black pomfret in the Bay of Bengal Bangladesh waters have not been examined in sufficient detail despite its high commercial value [12–14]. However, some detailed studies have been conducted on the population dynamics of this species in the Bay of Bengal and other waters [15–19]. These previous studies were carried out using length-frequency data only by applying FAO-ICLARM stock assessment tools (FiSAT) to elucidate stock exploitation status but the spawning stock biomass, population percentage related to exploitation, and selectivity pattern were not considered. Moreover, in Bangladesh, commercial marine fisheries are mainly operated by earmarking fishing areas, limiting fishing days, mesh size regulation of gears, closure of spawning grounds, and fishing bans during spawning seasons [14,20–22]. However, the implementation of fishing ban activities only during the propagation period is not as effective [23] as associated with implementing a catch quota for sustainable management of fisheries.

To overcome the limitations of previous studies and to consider data poor condition of the fishery in the Bay of Bengal, this study has been conducted based on three sets of indicators (i.e., i. fishing mortality and exploitation, ii. Spawning potential ratio and iii. Froese's indicators for fisheries sustainability) to rigorously evaluate the current exploitation and biomass status of the fishery. At first, a new procedure based on FAO's traditional stock assessment [6] has been applied using a recently developed R package, "TropFishR" [24–26], to estimate growth, mortality, and fisheries reference points. Secondly, LB-SPR has been used to assess the impact of fishing on the spawning biomass of the stock [27,28]. Finally, another approach of LBI based on catch proportion has been used to curb growth and recruitment overfishing and to identify selectivity patterns of gears used [29]. Therefore, the aims of this study are to pinpoint the current gaps in the stock status and population dynamics of black pomfrets and to present practical management recommendations based on the findings of this study and lessons learned from previous studies.

## 2. Materials and Methods

### *2.1. Study Area*

To elucidate the stock status of black pomfret fishery in Bangladesh marine waters, length data were mainly collected from industrial trawlers and partially from mechanized fishing sectors, which grossly termed here as an artisanal fishery in the country's three main landing stations including Chattogram, Cox'sbazar, and Khulna (Figure 1). Trawl fishing has been restricted by law [30,31] to operate beyond the 40 m depth contour (Figure 1). Industrial trawlers are categorized into the freezer (steel hull) and iced (wooden hull) trawlers [13,14]. Freezer trawlers are mainly of two types such as fish trawlers and shrimp trawlers. Fish trawlers are also divided into two categories based on fishing strategy, such as demersal and mid-water trawlers. Wooden hull trawlers have 56 to 148 mt, and steel hull trawlers have 251 to 668 mt of gross tonnage capacity. The former has an overall length (LOA) of 18.50 to 26.50 m and a power of 420–600 HP; the latter has LOA of 18–26 m and a power of 716–1850 HP but mostly falls within 500–1000 HP. Alongside, shrimp trawlers largely catch shrimps as target species with various finfish species. Shrimp trawlers usually have 150–250 mt gross tonnage capacity and a power of 500–900 HP, which allows for 30 days in a trip [32–34]. The smaller wooden trawlers were approved to sail for 14 days, and steel hull trawlers for 30 days in a trip [30,31].

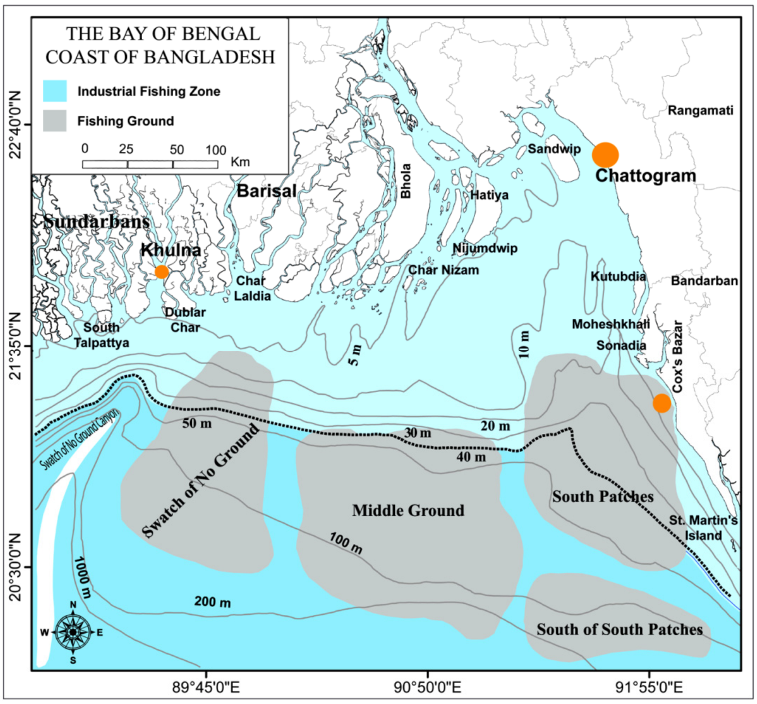


**Figure 1.** Map of the Bay of Bengal Bangladesh marine waters showing industrial fishing zone beyond 40 m depth contour (deep sky) and the location of sampling sites (brown) [22].

## 2.2. Data Source

Length and weight data of black pomfret (Figure 2) were collected monthly from July 2021 to May 2022, except in June due to the annual fishing ban from 20 May to 23 July [20]. The total number of individuals was 2701, comprised of both sexes. Sampling was conducted from onboard after hauling and from the unloading state of trawlers and partially from artisanal landing stations. Data collection by crews during onboard conditions measured the specimens. In some cases, we took 100% of fish for measurement as low landings. However, in some cases, the catch of black pomfret was plentiful as it moved on to form a school [35]; care was taken to ensure that the random samples were measured in that case. The total length (TL) of all collected individuals was measured to the nearest 0.1 cm and weighed to the nearest 1 gm.

**Figure 2.** Data collection on black pomfret from an industrial fishing vessel during unloading at Karnafuly River, Chattogram, Bangladesh.

## 2.3. Length Distribution

The collection of the total length (TL) of 2701 individuals for 11 months is arranged in Table 1. The minimum and maximum lengths were 5 cm and 53.5 cm, respectively. The minimum and maximum lengths were recorded in March and November to December, respectively. The observed length frequency distribution had a modal size range from 17 to 33 cm (Figure 3). The mean length of the collected samples was 31.75 cm. Though there was no spatial and temporal size difference observed, very young individuals (5 to 11 cm) were observed to be caught from February to April.

**Table 1.** The number of samples collected monthly from July 2021 to May 2022.

| Month | 21 July | 21 August | 21 September | 21 October | 21 November | 21 December | 22 January | 22 February | 22 March | 22 April | 22 May |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of Individuals | 94 | 98 | 124 | 380 | 264 | 304 | 277 | 382 | 198 | 279 | 301 |

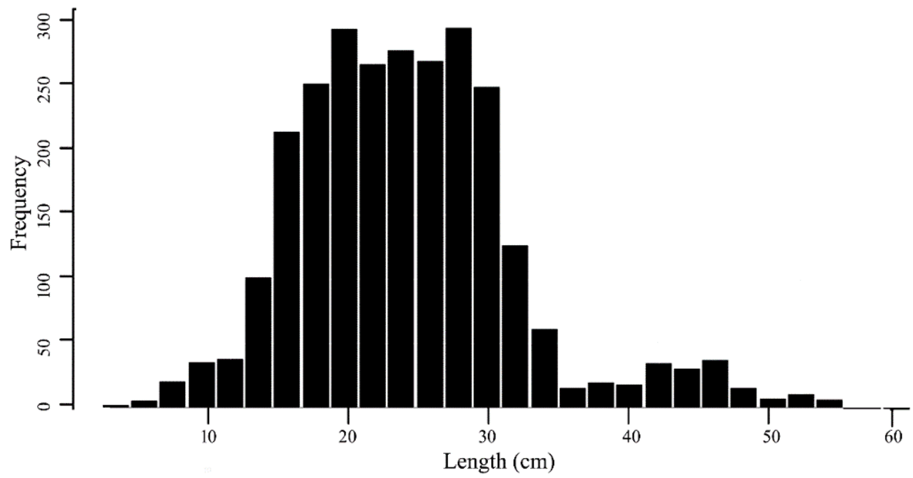


**Figure 3.** The bar chart illustrates the length-frequency distribution of black pomfret based on month-wise data collection from July 2021 to May 2022.

## 2.4. Length-Weight Relationship

This model is often referred to as an allometric growth model. The length-weight parameters '*a*' and '*b*' were estimated using the following equation [36]:

$$W = aL^b \tag{1}$$

where $W$ is body weight in gm, $L$ is the total length in cm, $a$ and $b$ are parameters.

## 2.5. Stock Assessment Indicators

At first, we used a newly developed R package (TropFishR) based on FAO traditional stock assessment methods [6,25] for stock assessment of black pomfret to estimate the stock's biological characteristics, exploitation, and fishery selectivity. Secondly, we used another R package, LB-SPR (Length-based Spawning Potential Ratio), developed by Hordyk et al. 2015 [27] to calculate the Stock Potential Ratio (*SPR*) as a function of relative fishing mortality (*F/M*). The *SPR* is the proportion of unfished reproductive potential that remains in the stock under the present degree of exploitation [28]. This well-established biological reference point for medium to long-lived species has been reviewed in the scientific literature to estimate the influence of current fishing pressure on the stock's reproductive capacity [27,28]. As an estimated value, 40% *SPR* is overwhelmingly treated as the standard of sustainability of a fishery and, therefore, considered the target referent point. On the other hand, 20% as the limit reference point [37] and *SPR* < 20% indicates the necessity of immediate management action to protect the fishery. Finally, we used Froese's (2004) length-based sustainability indicators to assess our collected length composition data to length reference points [36,38], an easy and practical management prescription to diagnose and overcome both growth and recruitment overfishing [29].

### 2.5.1. Estimation of Growth Parameter

Monthly length-frequency data were pooled and synced from January 2021 to December 2021 in order to estimate growth parameters using TropFishR. In the TropFishR package (v1.2) [26], the von Bertalanffy (1938) [39] growth parameters ($k$, $L_\infty$, and $t_0$) were estimated by applying the VBGF to the length frequency data [40]:

$$L_t = L_\infty \left(1 - e^{-k(t-t_0)}\right) \tag{2}$$

where $L_t$ is the length of the fish at a particular age $t$, $L_\infty$ is the asymptotic length in cm, $k$ is the growth rate coefficient in year$^{-1,}$ and $t_0$ is the theoretical age of a fish at which length is zero.

Winter–summer differences are generally too low to mark seasonal growth oscillations of fish in tropical waters [41,42], such as the black pomfret in the Bay of Bengal, and thus no such term was included in Equation (2).

A bootstrapped version of the Electronic Length Frequency Analysis (ELEFAN) [43] was used in the TropFishR for the fitting function. The parameter $t_{anchor}$ in ELEFAN within TropFishR is used to define the fraction of the year where the von Bertalanffy growth curve crosses length zero for a given cohort [40]. The range of initial seed values for $t_{anchor}$ was 0 to 1 [25].

The growth parameter index ($\Phi'$) was also estimated from the following formula given by Pauly and Munro 1984 [44]:

$$\Phi' = \log k + 2 \log L_\infty \tag{3}$$

Priors of $L_\infty$ and $k$ are required by TropFishR, the initial value for $L_\infty$ was calculated from the following formula proposed by Pauly (1984) [45]:

$$L_\infty = \frac{L_{max}}{0.95} \tag{4}$$

where, $L_{max}$ is the observed maximum length of the fish, which was estimated from the mean of 1% of large fish present in the sample. Then we set the initial seed value for $L_\infty$ as $L_\infty \pm 20\%$, and the $k$ ranged between 0.01 and 3. Finally, a suitable moving average (MA = 7) was computed by restructuring the data based on tuning MA values and the rule of thumb described in Taylor & Mildenberger (2017) [40], indicating the number of bins to remain in the youngest cohorts.

### 2.5.2. Exploitation Rate and Fishing Mortality

For the estimation of fishing mortality, a linearized length-converted catch curve (LCCC) was produced from the length data and growth parameters. Then the instantaneous mortality rate ($Z$) was calculated from the slope of the regression line of the descending part of the catch curve [32]. The natural mortality ($M$) was then calculated using the following formula proposed by Then et al. (2015) [46]:

$$M = 4.118 \times k^{0.73} \times L_\infty{}^{-0.33} \tag{5}$$

This formula was selected among available empirical formulas because of its better prediction power when the precise estimation of maximum age is not available [27].

Fishing mortality ($F$) and exploitation rate ($E$) were then calculated using the following formulas:

$$F = Z - M \tag{6}$$

$$E = \frac{F}{Z} \tag{7}$$

The current exploitation rate was then compared to the threshold level of 0.5 proposed by Gulland (1971) [47]. The estimated fishing mortality and exploitation rate were also compared to the following reference points obtained from Beverton & Holts (1956) Yield Per Recruit (YPR) model [48]:

A. Fishing mortality and exploitation at maximum yield per recruit ($F_{max}$ and $E_{max}$),
B. Fishing mortality and exploitation reduce the population to 50% of unfished spawning biomass ($F_{0.5}$ and $E_{\ 0.5}$),
C. Fishing mortality and exploitation reduce the marginal gain in yield per recruit to an arbitrary 10% of that at F = 0 ($F_{0.1}$ and $E_{0.1}$).

2.5.3. Length-Based Spawning Potential Ratio (LB-SPR)

LB-SPR [27,28] is a widely accepted data-limited stock assessment method. It estimates a reference point of stock status (spawning Potential ratio-SPR), which has been meticulously bench-marked in the literature and has a strong theoretical foundation [11,27,37,49,50], and has been widely tested. The assumption of the LB-SPR methodology is the length composition of an exploited population, and the *SPR* is a function of relative fishing pressure (*F/M*) and two life history ratios, *M/k* and $L_m/L_\infty$, where $L_\infty$, *M*, and *k* are previously mentioned and $L_m$ is the length at which 50% of a size class is mature [46]. The LB-SPR model requires the following input parameters: (i) the M/K ratio, (ii) the asymptotic length ($L_\infty$), and (iii) the variability of length-at-age (CV $L_\infty$), which is likely assumed to be around 50% ($L_{50\%}$) and 95% ($L_{95\%}$) of a fish population are mature [37]. In this study, $L_{50\%}$ is considered. Practically, it is likely to be impossible to estimate $L_\infty$ in a data-poor fishery. However, $L_m$ is more easily estimated, and an estimate of $L_m/L_\infty$ can be used to estimate $L_\infty$. The assessment model uses the maximum likelihood method to estimate the length at 50% ($SL_{50\%}$) and 95% ($SL_{95\%}$) selectivity of the population and relative fishing mortality (*F/M*), which are then used to compute the *SPR* [37].

The equilibrium-based LB-SPR model runs the assessment procedure based on the following assumptions: (i) asymptotic selectivity; (ii) growth accurately described by the von Bertalanffy equation; (iii) length-at-age is normally distributed; (iv) natural mortality rates constant over adult age classes and (v) constant growth rate throughout the cohorts of stock [37].

2.5.4. Input Parameters of LB-SPR

The calculated value of $L_\infty$, *M*, and *k* of TropFishR were used as input parameters for LBSPR in this study. The length at 50% sexual maturity ($L_{50\%}$) was then estimated from the following empirical equation proposed by Froese and Binohlan (2000) [51];

$$\log L_{50} = 0.8979 \log L_\infty, - 0.0782 \quad (8)$$

The length at 95% sexual maturity was estimated from the equation proposed by Prince et al. (2015) [37];

$$L_{95} = 1.1 \times L_{50} \quad (9)$$

The LB-SPR analysis was accomplished using the LB-SPR R package [52], available at https://www.CRAN.R-project.org/package=LB-SPR (accessed on 8 July 2022).

2.5.5. Froese's Length-Based Indicator

To keep the assessment of fish stock simple, Froese (2004) introduced three length-based reference points (i.e., $P_{mat}$, $P_{opt}$ and $P_{mega}$) based on the principles "Let them spawn, let them grow, and let the mega spawners live" in such a straightforward manner that everyone—from decision-makers to fishers—can follow it and take part in the process. [29]. $P_{mat}$ defines as the proportion of mature fish present in the catch and the management target should be 100% and can be estimated as the percentage of fish in the catch having a length greater than its sexual maturity ($L_m$) [24,41]. The target set by Froese (2004) for this indicator is to let all (100%) fish spawn at least once in their life span before they are caught, which will rebuild and keep the spawning biomass healthy [29].

$P_{opt}$ refers to the percentage of optimally sized fishes. This is a range and the target is to catch all fish (100%) having length within this range. $P_{opt}$ can be expressed as [36]

$$P_{opt} = \text{Percentage of fish between } 0.9 \times L_{opt} \text{ and } 1.1 \times L_{opt}$$

where, $\log L_{opt} = 1.053 \times \log(L_m) - 0.0565$ [51].

$P_{mega}$ refers to the percentage of fish in the catch having a length greater than the optimum length plus 10% of the optimum length ($\geq$1.1 $L_{opt}$) [29]. They are also terms as mega-spawner due to their high spawning capability (41). The target of the management is to keep the mega-spawners out of the catch (target = 0%). If there is no such strategy in place, about 30–40% of mega-spawner in the catch should be allowed, whereas less than 20% will be desirable [29]. The three LBIs are finally summarized below:

$$P_{mat} = \sum_{Lmat}^{Lmax} (P_L) \tag{10}$$

$$P_{opt} = \sum_{L0.9Lopt}^{1.1Lopt} (P_L) \tag{11}$$

$$P_{mega} = \sum_{1.1Lopt}^{Lmax} (P_L) \tag{12}$$

where, $P_L$ is the percentage of fish in the catch in the length interval $L$.

In multi-gear fisheries, where the assumption of trawl-like selectivity is frequently not realized, $P_{obj}$, a combined indicator that may be used, was created by adding the three proportions of LBI. $P_{obj}$ was then followed by a Cope and Punt decision tree (2009) [38]. The purpose of this decision tree is to examine the effects of different patterns of fisheries selectivity, recruitment compensation rates, and life history attributes on the outputs of the LBI proposed by Froese (2004). It is based on the results of a deterministic population dynamics model [29]. The authors discovered that $P_{obj}$ had a larger link with spawning biomass (*SB*) than any of the LBI individuals ($P_{mat}$, $P_{opt}$, or $P_{mega}$), and that different selectivity patterns in the fishery were connected to a range of values for $P_{obj}$. After a selectivity pattern based on $P_{obj}$ is developed, threshold values of $P_{mat}$, $P_{obj}$, and/or the $L_{opt}/L_m$ ratio indicate an estimated chance that the stock spawning biomass (*SB*) will be below specified reference points, either 40% or 20% of the unfished spawning biomass (0.4 *SB* or 0.2 *SB*).

## 3. Results

### 3.1. Length-Weight Relationship

The estimated length (TL)-weight relationship is $W = 0.267L^{2.19}$ ($R^2 = 0.8735$) (Figure 4). The estimated '*b*' value indicates the negative allometric growth pattern of the species.

### 3.2. Growth Parameters and Mortality Estimation

#### 3.2.1. Growth Parameters

The growth parameters were calculated using the von Bertalanffy growth equation through the Electronic Length Frequency Analysis (ELEFAN) within the R package TropFishR (Table 2 and Figure 5). The mean estimated growth parameters were 55.25 cm for $L_\infty$ and 0.54 year$^{-1}$ for the growth coefficient, which is a medium growth rate. The growth performance index ($\Phi'$) was 3.22 with a goodness of fit value (Rn) of 0.28.

#### 3.2.2. Fishing Mortality and Exploitation

The calculated value of total mortality (*Z*) based on a linearized length converted catch curve using TropFishR is 1.61 year$^{-1}$. The natural mortality rate (*M*) was calculated as 0.69 year$^{-1}$ by the method introduced by Then et al. (2015) [46]. The fishing mortality rate was estimated as 0.91 by subtracting *M* from *Z*. The biological reference points of fishing mortality and exploitation were then estimated and summarized in Table 2. The graphical outputs of the catch curve and YPR model are illustrated in Figure 5B–D. The calculated present fishing mortality ($F_{current}$ = 0.91) maintains a reasonable distance between the maximum reference fishing mortality ($F_{max}$ = 1.30 year$^{-1}$) and proxy $F_{msy}$ ($F_{0.1}$ = 0.63). The estimated present exploitation rate ($E_{current}$ = 0.56) is higher than threshold $E_{opt}$ = 0.5 [36], and less than the maximum estimated exploitation ($E_{max}$ = 0.73), indicating overexploitation is going on over the stock. Under the present level of gear selectivity when the total mortality ($Z$) is 1.61 year$^{-1}$, the mean length at first capture ($L_c$) was calculated as 17.52 cm, and 22.95 cm refers to this length class has a 50% and 95% respective probability of being captured. Maximum yield could be obtained from the YPR model when the $F_{max}$ and $E_{max}$ values are at 1.18 year$^{-1}$ and 0.73, respectively. Half of the stock biomass likewise could be obtained as the annual yield when $F_{0.5}$ and $E_{0.5}$ are at 0.42 year$^{-1}$ and 0.26 year$^{-1}$, respectively. The biologically optimum yield could be obtained when $F_{0.1}$ = 0.63 year$^{-1}$ and $E_{0.1}$ = 0.39, respectively. The mean stock biomass was calculated as 1800 mt, where the mean weight of matured individuals was estimated as 519 gm.

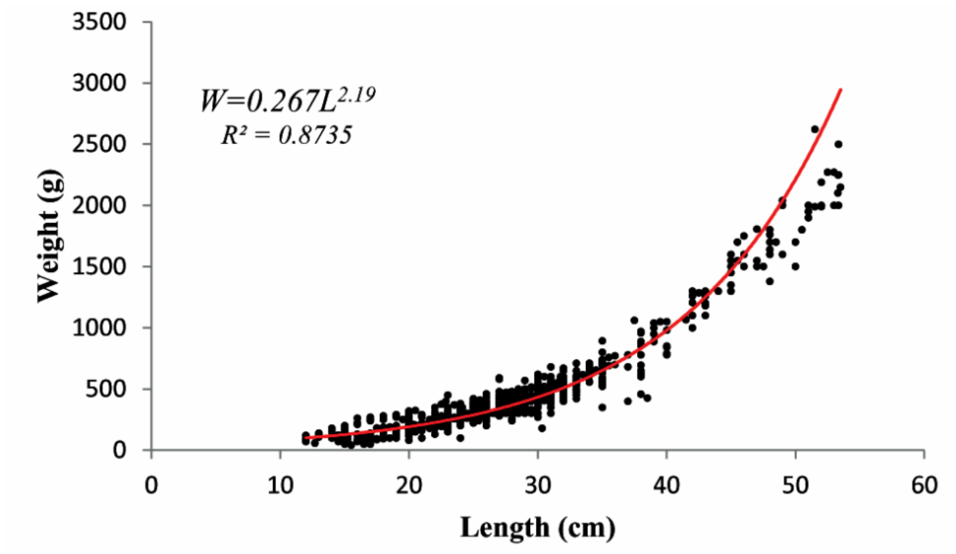


**Figure 4.** Length-weight relationship of black pomfret from Bangladesh marine waters.

### *3.3. Length-Based Spawning Potential Ratio (LB-SPR)*

#### 3.3.1. Estimation of Life History Ratio (LHR) and Size of Maturity

The outputs of TropFishR analysis, such as two LHR including $L_\infty$ and $M/k$ used here as input parameters for LB-SPR analysis. We then estimated the size at which 50% ($L_{50\%}$) and 95% ($L_{95\%}$) maturity were realized (Table 3).

#### 3.3.2. Model Fitting to the Length Distribution Data

The estimated mean length for the collected length-frequency data is 30.63 cm. The estimated growth curve by LB-SPR fits well with the distribution of our data (Figure 6A) and is skewed towards the length classes of small-sized fish.

#### 3.3.3. Length Selectivity and Maturity

The mean estimates of 50% ($SL_{50\%}$) and 95% ($SL_{95\%}$) selectivity are 18.44 cm and 25.63 cm, respectively, indicating small meshed nets are being currently used in fishing (Table 4). The mean estimate of $F/M$ is 1.72, which is above to threshold of $F/M$ = 1. The mean length at first capture was found to be very lower than the mean length of maturity in the ogive curve (Figure 6B).

**Table 2.** Growth parameters, mortality, and exploitation rates of black pomfret calculated by using TropFishR.

| Parameters | Value | Comments |
|---|---|---|
| **Growth Parameters** | | |
| Asymptotic length ($L_\infty$) | 55.25 cm | Without any impediments, black pomfret would gain this length. |
| Growth coefficient ($k$) | 0.54 year$^{-1}$ | Medium growth rate |
| $t_{anchor}$ | 0.75 year | Growth curves when approaching length zero on 7 September. |
| Growth performance index ($\Phi'$) | 3.22 | Medium |
| $R_n$ value | 0.28 | Medium |
| **Mortality and Exploitation** | | |
| Natural Mortality ($M$) | 0.69 year$^{-1}$ | Medium |
| Total Mortality ($Z$) | 1.61 year$^{-1}$ | Comparatively medium |
| Fishing Mortality ($F_{current}$) | 0.91 year$^{-1}$ | Higher than natural mortality |
| $F_{max}$ | 1.18 year$^{-1}$ | Fishing mortality at maximum yield per recruit |
| $F_{0.1}$ | 0.63 year$^{-1}$ | Biologically optimum yield could be obtained at $F_{0.1}$ |
| $F_{0.5}$ | 0.42 year$^{-1}$ | Unfished spawning biomass reduce to 50% at $F_{0.5}$ |
| Current Exploitation ($E_{current}$) | 0.56 | 12% higher than the threshold level, indicating overexploitation. |
| $E_{max}$ | 0.73 | Maximum exploitation level to obtain optimum yield. |
| $E_{0.1}$ | 0.39 | Exploitation level to obtain biologically optimum yield. |
| $E_{0.5}$ | 0.26 | Exploitation level to obtain 50% of the biomass. |
| Length at first capture ($L_{C50}$) | 17.50 cm | The length class at which 50% probability of being first captured. |
| **Stock size** | | |
| Mean Stock Biomass | 1800 mt | Estimated current biomass |

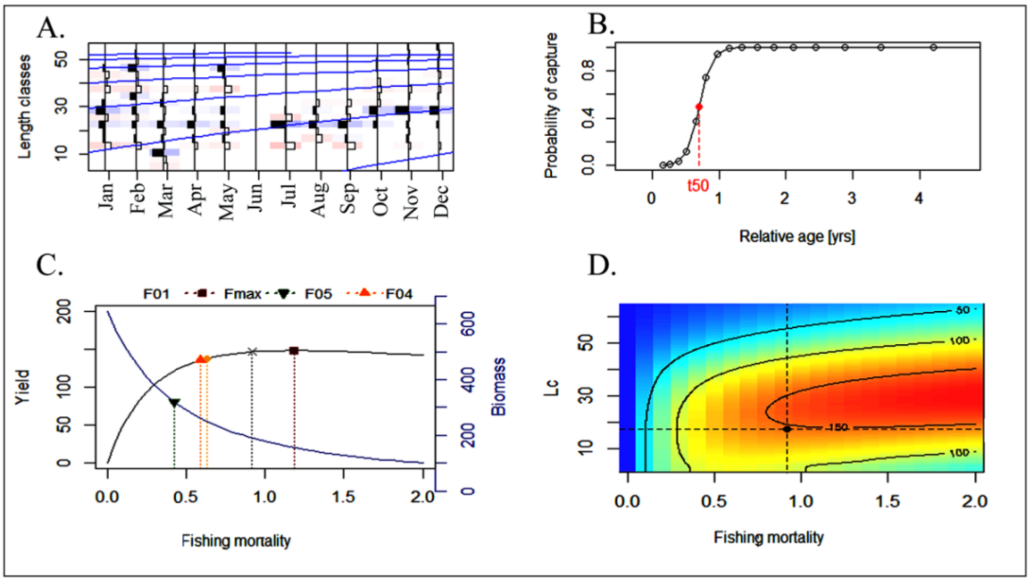


**Figure 5.** The result of TropFishR shows: (**A**) the von Bertalanffy growth curve and length-frequency distribution of the black pomfret ($L_\infty$ = 55.25 cm, $k$ = 0.54 year$^{-1}$); (**B**) the selectivity function of the catch curve estimated as length at first capture ($L_c$) of 17.52 cm; (**C**) yield and biomass per recruit analysis when $L_c$ = 17.52 cm-the green, black, yellow and blue dashed lines represent $F_{0.5}$ = 0.42 year$^{-1}$, $F_{max}$ = 1.18 year$^{-1}$, $F_{0.1}$ = 0.63 year$^{-1}$ and $F_{current}$ = 0.91 year$^{-1}$ respectively; (**D**) relative YPR contour map in response to different fishing mortality and different length at first capture ($L_c$).

**Table 3.** Input parameters for LB-SPR analysis.

| Parameters | Value |
|---|---|
| $L\infty$ | 55.25 cm |
| $K$ | 0.54 year$^{-1}$ |
| $M$ | 0.69 year$^{-1}$ |
| $M/k$ | 1.28 |
| Length at 50% maturity ($L_{50\%}$) | 30.63 cm |
| Length at 95% maturity ($L_{95\%}$) | 33.70 cm |

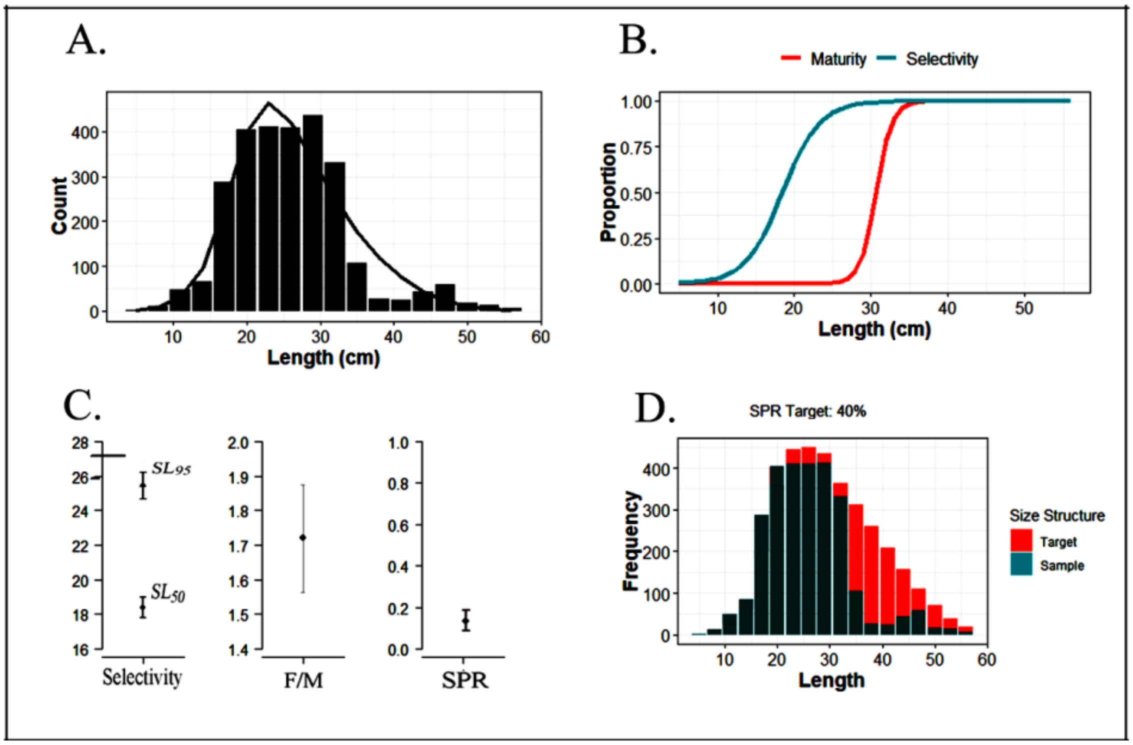


**Figure 6.** The result of the LB-SPR model shows: (**A**) length–frequency distribution of the observed fished population, and the solid black line show the predicted fished size composition from the fitted LB-SPR model; (**B**) maturity and selectivity curve from the fitted LB-SPR model when $L_{50\%}$ = 30.63 cm and $L_{95\%}$ = 33.70 cm; (**C**) shows the distribution of mean selectivity parameters ($SL_{50\%}$ and $SL_{95\%}$), fishing mortality to natural mortality ($F/M$), and spawning potential ratio, $SPR$; (**D**) observed size data against an expected size composition at a target $SPR$ (0.4).

**Table 4.** Outputs from LBSPR analysis.

| Parameters | Value |
|---|---|
| $SL_{50\%}$ | 18.44 cm |
| $SL_{95\%}$ | 25.63 cm |
| $F/M$ | 1.72 |
| $SPR$ | 0.13 |

### 3.3.4. Spawning Potential Ratio (SPR)

The length composition data used in this study is assumed to be a steady-state [27,28]; the *SPR* for the year 2021–2022 was at 13% revealed by this study, which is well below the limit reference point (*LRP*) of 20% (Figure 6C and Table 4).

3.3.5. Comparison with Target *SPR* (0.40)

The current fishing strategy is to have on-target lower length classes than those expected size classes. Though, it shows a clear picture of the target length class that should be maintained to achieve the threshold level (*SPR* = 40%) in Figure 6D.

### *3.4. Results from Length-Based Indicators*

To evaluate the current stock status of the black pomfret fishery in the Bay of Bengal off Bangladesh, a straightforward set of indicators, known as LBI, was also employed. The length at first sexual maturity value ($L_m$) was necessary for LBI estimation. The analysis of catch composition data shows that the calculated length at which 50% of fish are matured ($L_m$) was 30.64 cm, where both sexes are included in the length frequency data used in this investigation. The estimated values of $P_{mat}$, $P_{opt}$, and $P_{mega}$ for the catch-based composition of black pomfret using the calculated $L_m$ value of this study are shown in Table 5. We cannot confidently endorse the individual reference target values proposed by Froese (2004) [29] because of the insufficiency of the calculated values of catch-based length percentage ($P_{mat}$, $P_{opt}$, and $P_{mega}$). Only seventeen percent of black pomfret caught were sexually mature, meaning that roughly eighty-three percent of the population was unable to reproduce. Subsequently, the proportion of optimally sized fish at which the overall biomass of a given year class reaches a maximum is 20.65%, indicating the target length classes for capture only contribute one-fifth of the total catch composition. Older, larger fish, known as mega-spawners ($P_{mega}$), made up a much smaller percentage of the catch (7.06%) (Table 5). The black pomfret fishery's selectivity should focus on the length classes ($L_{opt} \pm 10\%$ of $L_{opt}$) between 29.04 cm and 35.44 cm for the highest yield (Figure 7).

**Table 5.** The result of LBI based on the indicators and a decision tree proposed by Froese (2004) and Cope and Punt (2009), respectively.

| $L_m$ | $L_{opt}$ | $P_{mat}$ | $P_{opt}$ | $P_{mega}$ | $P_{obj}$ | Stock Condition | Probability of Being *SB* < *RP* |
|---|---|---|---|---|---|---|---|
| 30.63 | 32.24 | 17.46 | 20.65 | 7.06 | 0.45 | *SB* < *RP* | 37% for *TRP*, and 22% for *LRP* |

Note: *TRP* is the target reference point, *LRP* is the limit reference point, and *RP* is the reference point.

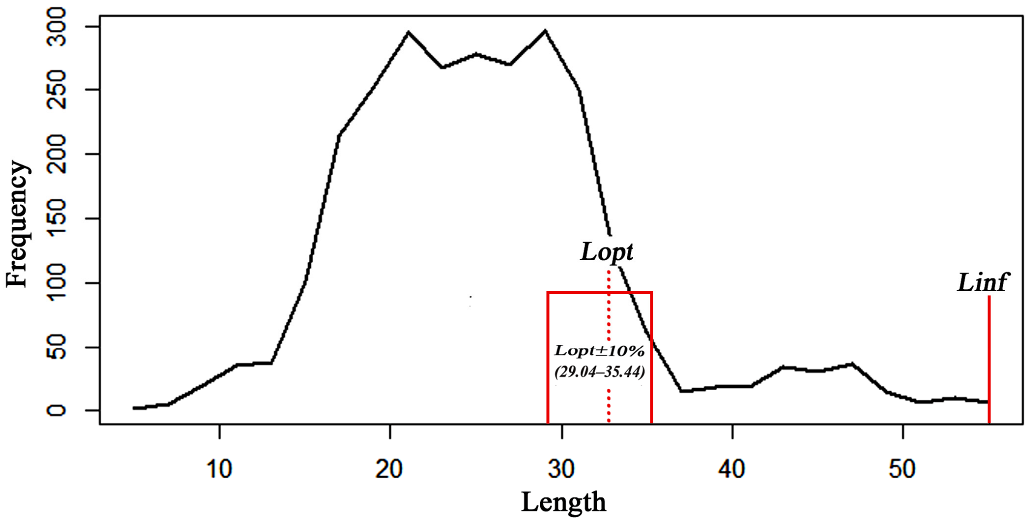


**Figure 7.** Length frequency distribution of the black pomfret shows the $L_\infty$, $L_{opt}$, and $L_{opt} \pm 10\%$ of $L_{opt}$.

The total of the three proportions ($P_{mat}$, $P_{opt}$, and $P_{mega}$) referred to as $P_{obj}$ in the decision tree gives comprehensive information for discerning selectivity patterns. For the estimated length-based indicators, however, the application of the decision tree yielded results indicating that the black pomfret stock is likely to be overfished (probabilities of being overfished were 37 and 22%) for the $L_m$ values with stock biomass below the target reference point (*TRP*) of *RP* = 0.4 *SB* and the limit reference point (*LRP*) of *RP* = 0.25 *SB* as well.

## 4. Discussion

Three length-based methodological approaches have been applied to this study to estimate the reference points of black pomfret in the marine waters of Bangladesh (Table 6).

**Table 6.** Methodological approaches used in this study.

| Methods | Application |
|---|---|
| TropFishR | Estimation of growth and mortality from length-frequency data. |
| LB-SPR | Calculation of spawning potential ratio (SPR) for sustainable fishing. |
| LBI | Examine the current status of stock biomass (*SB*) in relation to the target and limit reference points (TRPs and LRPs). |

Besides, the length-weight parameters '*a*' and '*b*' were calculated before running the TropFishR because these are the input parameters for YPR analysis within the package. The exponent '*b*' value indicates the species' negative allometric growth (*b* = 2.19) as of its compressed deep body with dorsal and ventral profiles being equally convexed [53]. Most of the studies are found near this study (>2) for the estimation of slope '*b*' (Table 7). Though LWR parameter '*a*' may change daily, seasonally, or by type of habitat but not 'b,' which does not have significant variation over the year [54]. Spatial variation may alter the parameters of LWR [55] due to the influence of water quality and food availability on fish growth.

**Table 7.** Estimates of LWR parameters of black pomfret from studies in different regions.

| Location | Slope '*b*' | Source |
|---|---|---|
| Bay of Bengal, Bangladesh | 2.113 | Karim et al., 2019 [19] |
| | 2.19 | Present study |
| Kerala, India | 2.792 | Khan, 2000 [16] |
| Taiwan strait | 2.98 | Tao et al., 2012 [18] |

The maximum and minimum lengths recorded in this study were 53.5 cm and 5 cm, respectively. The size distribution shows that the mean length of the collected specimens is 29.5 cm, and 70% of the collected individuals are below this length displaying more juveniles in the catch. However, the percentage of larger sizes (36 to 53.5 cm) in the study was only 7% of the total catch implying that either growth overfishing is going on or the current selectivity pattern of the fishery that excluded the stock's largest size classes. If the latter is true, this encourages more recruitment into fishery by buffering unhealthy competition of population in the ecosystem [29,41] and can intensify fluctuation of abundance. Though, it is beyond imagination to release larger sized fish after being caught by trawl net in the perspective of practicality where IUU fishing is a harsh reality that undermines national and regional efforts to conserve and manage fish stocks [56].

### *4.1. Growth and Mortality Parameters*

In the absence of age-structured data, length composition data were commonly used for assessing any stock and dynamics of the existing population [6]. Von Bertalanffy Growth Function (VBGF) model draws a growth curve using length composition data where the model follows the assumption [57].

A clear understanding of the species' life history parameters [9] is recommended for effective fisheries management. A remarkable variation among the growth parameters has been observed in different studies that assessed the stock status of black pomfret (Table 8).

**Table 8.** Summary of estimated population parameters in different water bodies of the world.

| Location | $L\infty$ | $k$ | $M$ | $Z$ | $F$ | $E$ | Ref. |
|---|---|---|---|---|---|---|---|
| Bay of Bengal, Bangladesh | 57.75 | 0.94 | 1.276 | 2.89 | 1.614 | 0.55 | Karim et al., 2019 [19] |
| | 41 | 0.59 | 1.16 | 2.42 | 1.26 | | Mustafa, 1999 [15] |
| | 55.25 | 0.54 | 0.69 | 1.61 | 0.91 | 0.56 | Present Study |
| West Bengal, India | 63.13 | 0.72 | 1.39 | 2.48 | 1.09 | 0.44 | Mazumdar et al., 2012 [17] |
| Kerala, India | 56 | 0.73 | 0.88 | 4.4 | 3.52 | | Khan 2000 [16] |
| Taiwan Strait | 34.11 | 0.31 | 0.74 | 1.82 | 1.09 | | Tao et al., 2012 [18] |

As per the equation, the calculated asymptotic length, $L_\infty$ = 55.25 cm, was observed in the present study, which is within the acceptable range in comparison to the maximum length of 53.50 cm. This study was found to be a lower value of growth coefficient ($k$) than other studies carried out at home and abroad. Though the $L_\infty$ shows proximity to other regional studies (Table 8), the lower result of the '$k$' value entails comparatively taking more time than that of the above studies to realize the asymptotic length and increase the life span as well [58]. Accordingly, the life span of black pomfret would be 5.5 years which is consistent with the work of age determination of black pomfret (the oldest age = 6 years) based on otolith cross-section in the Iranian coast of the Oman sea [59].

The growth performance index (GPI) denoted by $\Phi'$ shows a value of 3.22, which is considered to be comparatively slow growth that is nearly correspondent to the previous study (3.49) [19]. GPI compares the growth performance of the fish species within inter and intra-populations and higher growth indicated by higher values [44]. Though, a remarkable variation was noticed among the population parameters of this study from other studies (Table 8) because length-derived growth parameters depend substantially on the selectivity of the fisheries [24], the productivity of the ecosystem, and the difference of the genetic structure [47].

Natural mortality mostly depends on some factors such as predation, old age, environmental stress, pollution, and parasitic effects or diseases [60] is an important determiner in calculating fishing mortality. The lowest natural mortality was estimated by the present study in comparison to other studies (Table 8). The ratio of $M/k$ in this estimation was 1.28, which is within the range from 1.12 to 2.50 in most of the fish species [61].

Fishing mortality and exploitation are important parameter estimates of the TropFishR package, which gives a comparative output of the recommended and current level of fishing mortality and exploitation. Among many estimates, these two parameters are widely accepted to develop a suitable management strategy for an exploited stock by keeping the fishing pressure at a sustainable level [62].

The result of the high fishing pressure, $F$ = 0.91 year$^{-1}$, and high exploitation rate, $E$ = 0.56 year$^{-1}$ that observed to catch more fish than recommended ($F_{0.1}$ = 0.63) (Table 1). When the exploitation ratio is above 0.5, then the stock is overfished [47], and accordingly, this study suggests that the industrial stock of black pomfret is overexploited. Moreover, the mean length at first capture ($L_{c50}$ = 17.50 cm) indicates the removal of juvenile fishes from the stock. Commonly, it is recommended to let new spawners at least breed once to ensure a sustainable fishery [63].

*4.2. Stock Condition Analysis Based on LB-SPR*

Length-based assessment does not give effective information on length composition in the condition of fishing not visibly well until fishing mortality is very high and stocks are highly depleted. LB-SPR is an ideal method for assessment of the stock that has higher fishing mortality and exploitation [27]. To assess the spawning biomass of the black pomfret fishery, the LB-SPR method showed its robustness for the scenario with $M/k > 0.53$ and length composition data with uni or bimodal distribution [27,28]. One of the assumptions of LB-SPR, where catch data cannot be categorized by sex, is that a single growth curve can be used to describe both sexes, which have equal catchability [37]. In this study, a single growth curve has been used for both male and female black pomfret. The result of the study is likely to have captured the scenario of the present status of black pomfret stock in the Bay of Bengal Bangladesh waters and is comparable to the findings of other studies from home and abroad. So, it can be said that LB-SPR reasonably well estimated the parameters of black pomfret stock.

The output of TropFishR in this study is hereafter used as input parameters for LB-SPR analysis. The reason behind that the LB-SPR method is highly sensitive to input parameters ($L_\infty$, $k$, $M$, $L_{50}$, $L_{95}$). It is common to notice variations of the above parameters among previous studies. Therefore, input parameters from the same study are likely to be more reliable than that from previous studies [50]. The life history ratio (LHR) of $M$ and $k$ is 1.28, which denotes a moderately high growth rate of black pomfret to reach their maximum length.

The LB-SPR approach to black pomfret fishery entailed that the black pomfret stock is exposed to high exploitation ($F/M = 1.72$), and the reproductive potential thereby left to the stock is very low (0.13). A low *SPR* value indicates a stock having a high percentage of juvenile and immature fish with few mature or large fishes in the catch composition. Though the level of targeted *SPR* is 40% (Figure 5D), empirically, it is not possible in many commercially exploited stock like black pomfret as historical catch driven by indiscriminate fishing ranging from juvenile to brood fishes using different gears from coastal water to the deep sea [33,64]. This led to growth and recruitment overfishing which has continued in the fishery over the last decades. Length data should represent the exploited stock for LB-SPR analysis and be sure to have all length groups in the length composition to avoid biases [65] and here, the sampling has been conducted to follow all the strategies of LB-SPR.

### 4.3. Stock Condition Analysis Based on Length-Based Indicators

Using the sustainability indicators proposed by Froese (2004) [29], we analyzed the catch composition to determine the proportion of mature fish ($P_{mat}$), optimally sized fish ($P_{opt}$), and mega-spawners ($P_{mega}$). To tackle deliberate or convenient overfishing, and to encourage people to make responsible decisions when using aquatic resources, Froese [29] suggests that stock assessment indicators should be written in such a way that is accessible to the general public. These predicted indicators can easily be calculated using length-frequency data.

To avoid growth overfishing, the proportion of mature fish ($P_{mat}$) in the catch should be as much as possible, and all catches should be maintained within the 10% range of optimum length ($L_{opt}$) to prevent growth overfishing [29]. This study's findings, however, show that juvenile and immature fish made up the bulk of the catch ($P_{mat}$ = 17% and $P_{opt}$ = 20.65%), and the number of mega-spawners was low; this is evidence that the stock is being overfished in terms of both recruitment and growth. According to the results of a gonado-somatic index (GSI) investigation [66], males reach maturity at 26.5 cm in length, whereas females reach maturity at 28 cm. However, 50% maturity length ($L_m$) was calculated to be 30.63 cm based on the results from this study's catch composition analysis. To acquire a complete picture of the species stock status, it is helpful to compare the calculated $L_m$ value (30.63 cm) derived from this study with the length range as $L_m$ in the reported GSI analysis (26.5–28 cm). It is likely to be consistent because the length frequency data utilized in this study included both sexes (Table 5 and Figure 6). The general tendency of commercial fishing is to catch fish as much as possible without discarding anything. Skippers and crews of industrial fishing trawlers have expressed their opinion that industrial trawl nets and other forms of active fishing gears capture fish of all sizes, leaving them no hope of survival owing to being injured, even if they manage to escape from the net eventually (Personal interview with skippers and crews). In this view, the stock's potency is thought to have been significantly diminished due to the removal of indiscriminate fishing, including large-size groups [53,67], which have a significant role in recruitment success [68]. Froese advocated not to catch more than 30–40% of mega-spawners to support his credo "Let the mega-spawners survive" [36], even if there is no upper size limit for fish. The calculated value of $P_{mega}$ in this study is (7.06%), and in the absence of size constraints, this low percentage of mega-spawners implies that a large proportion of mega-spawners have already been eliminated from the stock [53]. According to the findings of the LB-SPR, there are extremely few adults reproducing fish in the stock. Hence, the low reproductive potential of the stock is consistent with the findings of the LB-SPR. The black pomfret fishery's spawning stock biomass is below both the target reference point (*TRP*) and the limit reference point (*LRP*), according to the application of the Cope and Punt decision tree based on Froese indicators [29,38]. From the existing catch composition and observation of historical catch quantity, in the eye of the first author, solely responsible for looking after the marine catch for more than a decade as an officer of the Department of Fisheries, Ministry of Fisheries, Bangladesh, there is little doubt that the fishery is overfished due to the existing selective pattern of gears and lack of real-time marine fishery protection.

### 4.4. Management Recommendation

In this study, we applied three different approaches to assess the stock status of black pomfret in Bangladesh's marine waters. All methods provided some recommended reference value with other management information (Table 9).

**Table 9.** Some key reference values are recommended from the above three methods.

| TropFishR | | | LBSPR | | | LBI | | |
|---|---|---|---|---|---|---|---|---|
| **Parameter** | **Value** | **Reference** | **Parameter** | **Value** | **Reference** | **Parameter** | **Value** | **Reference** |
| $F$ | 0.91 | 0.63 ($F_{0.1}$) | $SPR$ | 0.13 | 0.4 (*TRP*)<br>0.2 (*LRP*) | $P_{mat}$ | 17.40% | 100% |
| $E$ | 0.56 | 0.39 ($E_{0.1}$) | $F/M$ | 1.72 | 1.0 | $P_{opt}$ | 20.65% | 100% |
| | | | | | | $P_{mega}$ | 7.06% | 0% |
| $L_{c50}$ (cm) | 17.50 | | $SL_{50}$ (cm) | 18.44 | | $L_m$ (cm) | 30.63 | |
| $L_{c95}$ (cm) | 22.77 | | $SL_{95}$ (cm) | 25.63 | | $L_{opt}$ (cm) | 29.00 to 35.00 | |

All methods provided similar results that this species is currently suffering from growth and recruitment overfishing. The mean length at first capture and selectivity range were found to be lower length-class than the mean length of maturity and optimal length range to capture. Consequently, it is necessary to take management measures to protect the juveniles by regulating the mesh size of trawl nets. In a fish trawl net, the minimum mesh size of the cod-end is 60 mm, as per law [30,31]. This mesh size would not catch fish smaller than 29 cm. However, the reality is different due to the lack of effective monitoring at sea. In the absence of proper fishery protection at sea and fishing grounds, such as insufficient patrolling and monitoring of the area while fishing, it is observed to use the net smaller than the approved mesh size and fishing in a depth zone shallower than the allowable limit especially at night during less monitoring and ascertain of more catch. Therefore, a formal monitoring protocol, such as deploying more patrolling vessels solely engaged for fishery protection, a real-time vessel monitoring system, and proper implementation of existing laws, are recommended to improve the situation. Froese et al. (2018) mentioned that fishing mortality is proportional to fishing effort [65]. Therefore, it is highly recommended to reduce the fishing pressure in terms of both the number and size of trawlers and the number of mechanized fishing boats to bring back the fishing mortality to the threshold level ($F = M$).

## 5. Conclusions

As a growing nation with a large population, Bangladesh relies significantly on marine fisheries to meet its citizen's protein demands, provide money for its subsistence to industrial fishers and generate employment for the unemployed youth and common people. Therefore, a comprehensive marine fisheries strategy should be created with sophisticated legal bindings to guarantee sustainable exploitation and harvest scheme without compromising the conservation of marine fisheries resources. In this study, a complete and rigorous length-based stock assessment has been done using three different approaches. This study concluded with the following recommendations after analyzing the results:

I. No catches of fish at or below first maturity (30.63 cm).

II. To prevent recruitment and growth overfishing, the recommended length should be kept between 29 and 35 cm.

III. Reduce fishing mortality by one-third by controlling fishing efforts by both the number of fishing units and active fishing days;

IV. It is crucial to set up an efficient monitoring system for sea surveillance in order for proper fishery protection and sustainably managing marine fisheries resources.

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