Journal of
Marine Science and Engineering

MDPI

Article

Stock Assessment of Exploited Sardine Populations from Northeastern Bay of Bengal Water, Bangladesh Using the Length-Based Bayesian Biomass (LBB) Method

Partho Protim Barman [1,2], Qun Liu [1,*], Md. Abdullah Al-Mamun [1,3], Petra Schneider [4] and Mohammad Mojibul Hoque Mozumder [5]

1 College of Fisheries, Ocean University of China, Qingdao 266003, China; partho.cmf@sau.ac.bd (P.P.B.); mamunbau09@yahoo.com (M.A.A.-M.)
2 Department of Coastal and Marine Fisheries, Sylhet Agricultural University, Sylhet 3100, Bangladesh
3 Department of Fisheries, Ministry of Fisheries and Livestock, Dhaka 1217, Bangladesh
4 Department for Water, Environment, Civil Engineering and Safety, University of Applied Sciences Magdeburg-Stendal, Breitscheidstraße 2, D-39114 Magdeburg, Germany; petra.schneider@h2.de
5 Fisheries and Environmental Management Group, Helsinki Institute of Sustainability Science (HELSUS), Faculty of Biological and Environmental Sciences, University of Helsinki, 00014 Helsinki, Finland; mohammad.mozumder@helsinki.fi
* Correspondence: qunliu@ouc.edu.cn; Tel.: +86-136-8542-6216

Citation: Barman, P.P.; Liu, Q.; Al-Mamun, M.A.; Schneider, P.; Mozumder, M.M.H. Stock Assessment of Exploited Sardine Populations from Northeastern Bay of Bengal Water, Bangladesh Using the Length-Based Bayesian Biomass (LBB) Method. *J. Mar. Sci. Eng.* **2021**, *9*, 1137. https://doi.org/10.3390/jmse9101137

Academic Editor: Paola Rumolo

Received: 30 August 2021
Accepted: 11 October 2021
Published: 16 October 2021

Abstract: Stock assessment is necessary to understand the status of fishery stocks. However, for the data-poor fishery, it is very challenging to assess the stock status. The length-based Bayesian biomass (LBB) technique is one of the most powerful methods to assess the data-poor fisheries resources that need simple length frequency (LF) data. Addressing the present gap, this study aimed to assess the stock status of three sardines (*Sardinella fimbriata*, *Dussumieria acuta*, and *D. elopsoides*) in the Bay of Bengal (BoB), Bangladesh using the LBB method. The estimated relative biomass for *S. fimbriata* was $B/B_0 < B_{MSY}/B_0$, indicating the overfished biomass, while the assessed $B/B_0 > B_{MSY}/B_0$ for *D. acuta* and *D. elopsoides* indicates healthy biomass. Additionally, for *S. fimbriata*, the length at first landing was smaller than the optimum length at first landing ($Lc < L_{c\_opt}$), indicating an overfishing status, but a safe fishing status was assessed for *D. acuta* and *D. elopsoides* ($Lc > L_{c\_opt}$). Therefore, increasing the mesh size of fishing gears may help to ensure the long-term viability of sardine populations in the BoB, Bangladesh.

Keywords: clupeiformes; size frequency; capture fisheries; stock status; management

1. Introduction

Stock assessment of a fishery is necessary to relieve fishing pressure and ensure the fisheries' sustainability. The fishers and management administrators need to set management actions based on stock assessment information [1–3]. However, most of the world's fish stocks are still unassessed because of data limitations, and a shortage of expertise is a significant constraint in fishery management [3,4]. In affluent nations, the evaluated fish stock's percentage varies between 10% and 50%, whereas in developing countries, the proportion is often 5% to 20% [1,5]. Due to the high cost of data collection and analysis, resource assessment exists for less than 1% of global fish species. As a result, only 12% of fish stocks are managed correctly or have advanced stock assessments [5,6].

Traditional stock assessment techniques are generally based on the target fish's life history data, age-structure data, time series of catch, and effort data that are hard to collect [7]. Mainly, long-term catch effort data are challenging to get, and there may even be no data for non-targeted species [6,8]. To address this problem, the length-based Bayesian biomass (LBB) approach was developed [8]. LBB requires simple length frequency (LF) data, and is often the most suitable method for data deficient fish stock [4,8–11]. LBB can evaluate growth, mortality, and stock information, and the fishery administrator may utilize this information to manage the fishery resource when LF data is suggestive of an exploited stock [4,8,10,11]. Additionally, LBB findings may be utilized as inputs for stock assessment techniques that need an independent estimation of biomass as input in comparison to unfished biomass [8,10,11].

In the Bay of Bengal (BoB) water, several surveys were conducted after 1970 to explore the marine fishery resources, but were paused in 1999 [4]. The BoB is part of the Indian Ocean and is considered one of the most productive ecosystems endowed with a tropical climate and abundant rainfall [12]. In 2016, the *R.V. Meen Sandhani* started survey research and recorded 344 species of fish, 45 species of shellfish, and 14 species of cephalopods within the shelf sea area of Bangladesh [4,13]. Furthermore, some previous studies reported that around 511 marine fishes, including shrimps, exist within the BoB, Bangladesh [4,14,15]. The marine fisheries' resources are harvested from three different depth zones in the BoB, Bangladesh. The artisanal fishing activities are done within 40 m water depth. Industrial mid-water trawlers operate between 40 to 200 m water depth. Beyond the 200 m depth to the edge of the exclusive economic zone (EEZ), long-line fishing and deep water trawling activities operate in the BoB, Bangladesh [16].

Though, in the demersal fishing reported, the pelagic fish is among the major targeted catch group from the marine water of Bangladesh [14]. Sardines comprise one of the largest clupeid groups of fishery targets, in terms of biomass captured from the BoB, Bangladesh [17–20]. Sardines are silver in color, oily, small fish swimming as a school. Sardines mainly graze on plankton and offer themselves as food to support predators, and thus maintain the food cycle and ecosystem, and marine environment [17,21]. A total of 61 species of sardine has been reported globally, and the Indo-Pacific water contains 15 species of sardine, while the BoB is the home of 12 species. *Sardinella fimbriata* (fringe scale sardine), *Dussumieria acuta* (rainbow sardine), *D. elopsoides* (*slender* rainbow sardine), *S. gibbosa* (gold stripe-sardine), and *S. melanura* (black stripe sardine) were reported from the territorial water of Bangladesh. *S. fimbriata*, *D. acuta,* and *D. elopsoides* are the most abundant [13,18,19]. Sardines comprise 4.28% of the total marine production in Bangladesh, where a large portion comes from the industrial catch (97%), and only 3% come from the artisanal catch [22]. Before 2012, the sardine landing was recorded and estimated as "other marine catch", but after recognizing their importance, separate catch statistics of the landed sardine have been started since 2012. The annual landing of sardine was reported at 20,187 metric tons (mt) in 2012. After that, a robust increasing sardine landing trend was reported until 2017 (48,704 mt) [22]. The landing of sardine that was reported almost double in 2018 (41,486 mt), compared to its initial report in 2012, but the decline in sardine landing was reported in 2019 (28,256 mt) [22]. The minimum number of fishing efforts was 183,102 gears/year (g/yr) observed in 2014, while the maximum effort was 242,450 g/yr in 2012 and 2013 [22]. The average landing was 34,135 mt, and the average effort was 200,201 g/yr reported for sardines in Bangladesh [22]. However, the sudden decline in the sardine landing in 2019 has raised questions about its sustainability in the BoB, Bangladesh (Figure 1). Additionally, the changes in the physicochemical parameters of the water strongly influence the biology and abundance of sardines, that ultimately impacts the other marine catches [23]. Therefore, stock assessment is the primary objective for ensuring the sustainability of the fishery stocks in Bangladesh's marine waters.

Despite the scarcity of data and expertise, Bangladesh has conducted stock assessments on a few commercial marine fish species, using different stock assessment techniques [4,12,24] without a sardine assessment. Moreover, many studies and investigations on sardines' reproductive morphology, biology, and abundance have been conducted [17–19]. However, there is still a dearth of complete stock assessment information for sardines in Bangladesh. Therefore, the LBB technique was used in this study on three sardine populations (*S. fimbriata, D. acuta*, and *D. elopsoides*) exploited from the BoB, Bangladesh, to evaluate life history characteristics and determine the biomass depletion level.

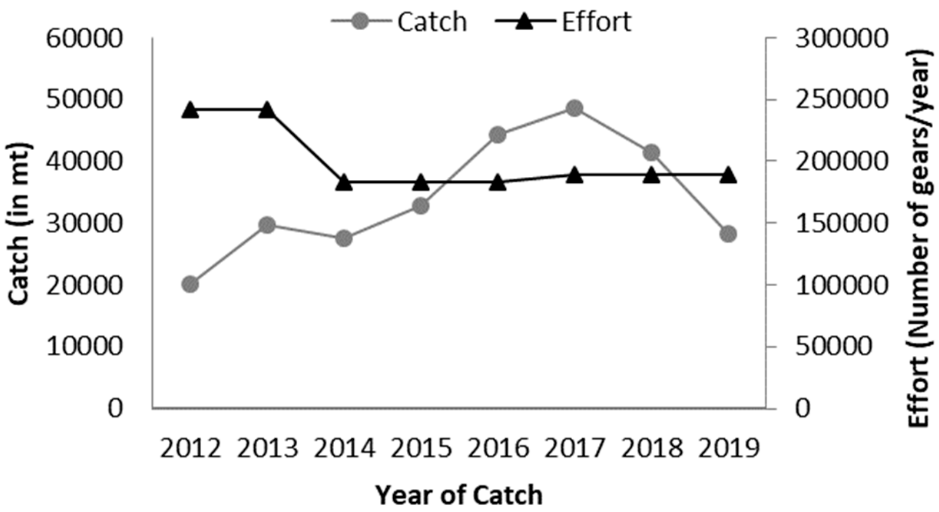


Figure 1. Catch effort data of sardine in the BoB, Bangladesh.

2. Materials and Methods

2.1. Data Source and Sampling Procedure

The coastal and marine fisheries of Bangladesh are broadly categorized as industrial and artisanal sectors. The industrial trawlers are typically 20–40 m long with 350–1450 horsepower (HP) marine diesel engines, and artisanal fishing boats 20–75 HP. Mostly the sardine groups were reported to be captured by the industrial trawlers (>97%), with a few (<3%) captured by the artisanal boats [22]. Landings of *S. fimbriata*, *D. acuta,* and *D. elopsoides* was reported from industrial trawlers, but few landings of *S. fimbriata* were reported from artisanal gill nets. The monthly LF data for these three species were collected from January 2018 to December 2018. Usually, above 90% of industrial trawlers landed their catch in a single landing center called "Fishery Ghat" in Chattogram (22°19′42″N, 91°50′48″E) (Figure 2). In addition, few LF data of *S. fimbriata* were collected from the artisanal gill net catch from two fish landing centers named Teknaf Fishery Ghat in Teknaf Sadar (20°52′0.12″N, 92°17′60″E) and BFDC fish harbor in Cox's Bazar (21°27′06″N, 91°58′05″E), where artisanal fishing vessels landed their catches (Figure 2).

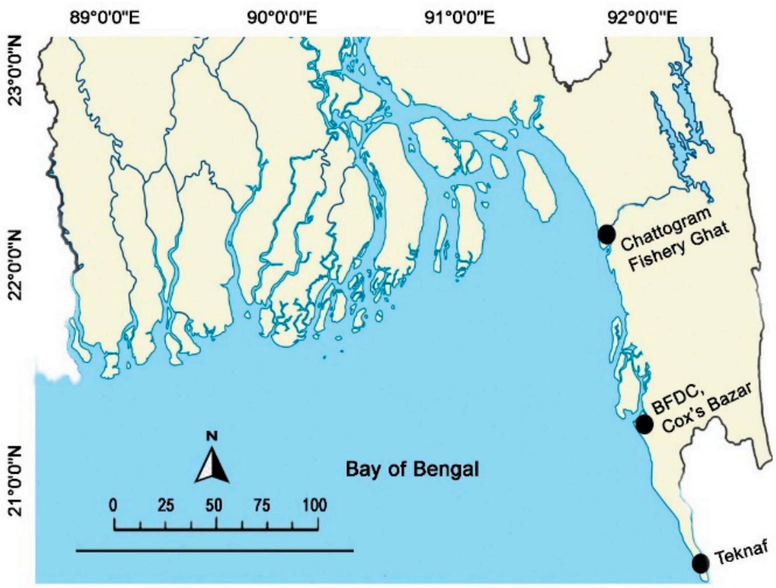


Figure 2. Map of the Bay of Bengal, Bangladesh. Black circles in the map indicate the sampling stations used in this study.

The central industrial landing of *S. fimbriata* was exploited in the southern part of the south patches and south of south patches (N: 20°09′22″, E: 92°04′07″ to N: 20°45′25″, E: 92°18′56″), and north-west to north-east of middle ground areas (N: 21°36′23″, E: 90°06′43″ to N: 21°18′18″, E: 91°17′57″) of the BoB, Bangladesh. The industrial catch of *D. acuta* and *D. elopsoides* were harvested within the north-west to north-east of middle ground areas (N: 21°36′23″, E: 90°06′43″ to N: 21°18′18″ E: 91°17′57″), and south-west to the south-east of middle ground areas (N: 20°17′29″, E: 90°15′21″ to N: 20°29′56″, E: 91°24′22″) in the BoB. However, the artisanal catch of *S. fimbriata* was reported from the shallow coastal and estuarine water of Teknaf and Cox's Bazar area in Bangladesh. To ensure the better representation and good quality of the LF data, trawlers were frequently visited. LF data were randomly collected as mixed fish samples from the trawler owners when their catches were on board the vessels during the landing. The total length (TL) and fork length (FL) for each specimen were measured in millimeters (mm) using a measuring tape. Collected samples were taken to the wet laboratory of the marine fishery survey management unit, Department of Fisheries (DoF), Chattogram, for taxonomic identification, and species names were used following FishBase [25]. Obtained samples were categorized according to species, and the total number was determined based on 10 mm (1.0 cm) class intervals (CL) for each species. The LF data of three sardine populations from the BoB, Bangladesh (Table 1) were analyzed in R using the R-code (LBB_33 a.R) created in the original article [8] and obtained from http://oceanrep.geomar.de/44832/ (accessed on 10 July 2021).

Table 1. Prior and basic information of three sardine populations in BoB, Bangladesh.

Scientific Name	Min (cm)	Max (cm)	Class Interval (cm)	Individual Number	L_{inf} Prior (cm)	Z/K Prior	M/K Prior	F/K Prior	L_c Prior	Alpha Prior
Sardinella fimbriata	7.0	19.0	1.0	1749	22.8	2.7	1.5	1.21	11.2	38.5
Dussumieria acuta	9.0	19.0	1.0	1145	19.1	1.8	1.5	0.31	14.8	40.0
Dussumieria elopsoides	7.0	18.0	1.0	705	18.0	1.4	1.5	0.3	13.8	22.6

2.2. State of the Sardine Fisheries

A total of 3599 specimens were collected, where 1749 individuals for *S. fimbriata*, 1145 individuals for *D. acuta*, and 705 individuals for *D. elopsoides* specimens were identified during the study period. The minimum length was 70 mm, and the maximum length was 190 mm recorded for *S. fimbriata*. For *D. acuta*, the minimum length was 90 mm, and the maximum length was 190 mm; and for *D. elopsoides*, the minimum length was 70 mm and the maximum length was 180 mm. During this study, the average length of *S. fimbriata*, *D. acuta*, and *D. elopsoides* were reported as 130 mm, 140 mm, and 125 mm, respectively (Figure 3). Mostly sardines were reported to be harvested from the 10 m to 60 m depth, but rarely harvested from 90 m depth. In most cases, the code end mesh size for industrial fish trawler was reported below 60 mm. In the artisanal sector, the sardines were mainly caught by Rog jal (monofilament gill net) having 30 mm, and Bata jal (gill net) having 20 mm mesh size.

D. acuta and *D. elopsoides* were recorded as by-catch from industrial fish trawlers, whereas the midwater trawler accounted for most of the catch. *S. fimbriata* was the target species, whereas industrial fishing from Bangladesh's off-shore waters harvested all three species. The landing of sardines was observed around the year. *S. fimbriata* was exploited mainly in June to August, October to November, and March to April from the artisanal sector. However, this species was exploited mainly in late November to December and late February to the first of April from the industrial sector. The peak landing of *S. fimbriata* was reported from November to December, while January to February was reported as the peak landing period for *D. acuta* and *D. elopsoides*.

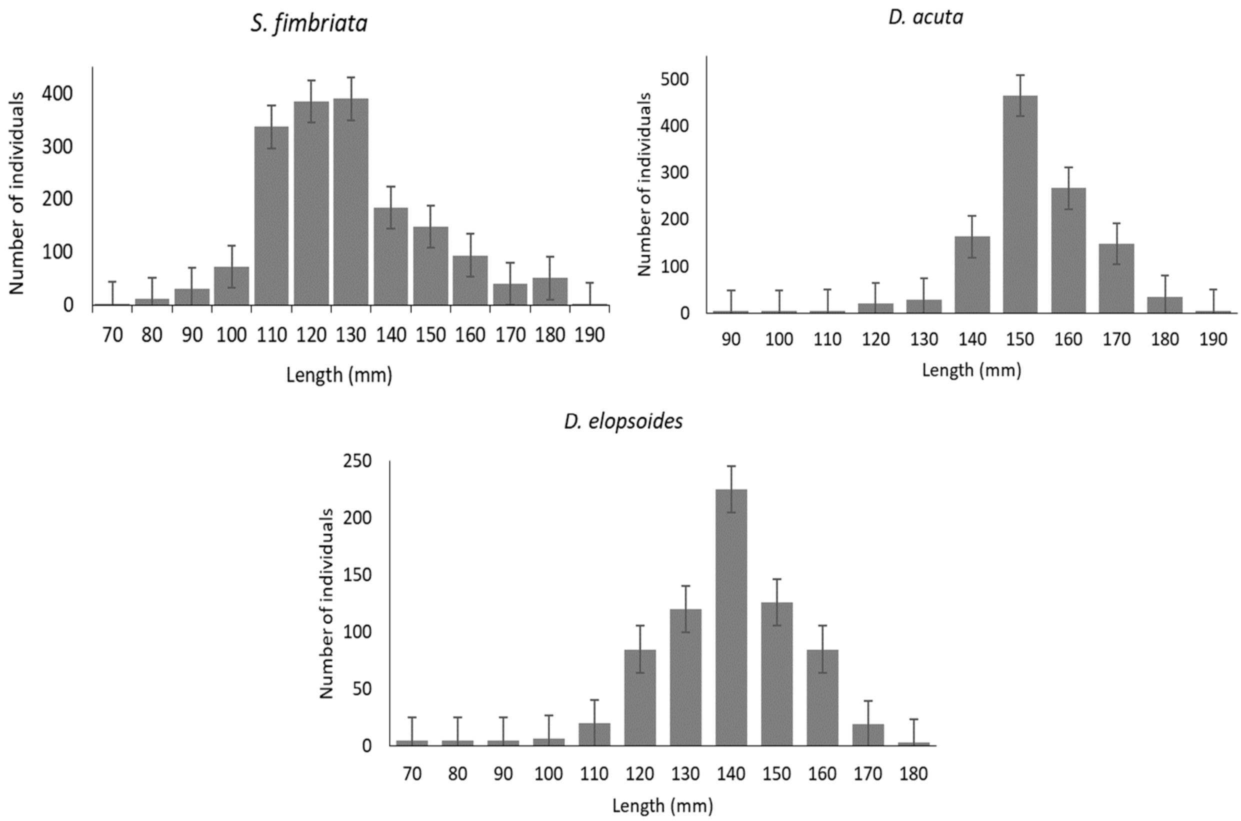


Figure 3. Length frequency data of three sardine populations.

2.3. Description of the LBB Method

LBB is an innovative and powerful method that can estimate the stock status of an exploited fishery using LF data [8,10,11,26]. LBB incorporates a Bayesian Monte Carlo Markov Chain (MCMC) to assess relevant population parameters of an exploited fishery, such as relative fishing mortality (*F/M*), relative natural mortality (*M/K*), average length at first capture (L_c), and asymptotic length (L_{inf}), over the age range described in the LF survey [8]. The LBB is a valid method for species that can grow throughout their lives, such as most commercially harvested fish and invertebrates [4,8,10,11]. Therefore, only the basic formulas for LBB are provided here, while the details are explained by Froese et al., 2018 [8].

Von Bertalanffy Growth Function (VBGF) is essential in the LBB method to predict the fish growth in length [Beverton and Holt 1957; von-Bertalanffy 1938] (Equation (1)). When the fishery becomes completely specialized in particular fishing gear, total mortality (Z) = $M + F$ relative to K is oriented toward the right section of the curve in the catch samples, and is represented by Equation (2). Usually, fishing gears have characteristic selection curves that are assumed (i.e., avoiding capturing extremely young fish) by the ogive distribution of the LBB search (Equation (3)) [8]. The combining and rearrangement of Equations (1)–(3) results in the following equations (Equations (4) and (5)), which may simultaneously calculate *M/K*, *F/K*, L_c, L_{inf}, and α (alpha). Equations below explain the outline to approximate the stock information from *F/K*, *M/K*, L_{inf}, and L_c. The L_{opt} (size of fish at which cohort biomass becomes the maximum) was estimated from the given L_{inf} and *M/K* using Equation (6) [2]. Finally, equation seven was used to calculate the maximum catch and biomass ($L_{c\_opt)}$ based on Equation (6) and *F/M*.

$$L_t = L_{inf}\left[1 - e^{-k(t-t_0)}\right] \tag{1}$$

$$N_L = N_{L_{start}} \left(\frac{L_{inf} - L}{L_{inf} - L_{start}} \right)^{z/k} \quad (2)$$

$$S_L = \frac{1}{\left[1 + e^{-\alpha(L - L_c)} \right]} \quad (3)$$

$$N_{L_i} = N_{L_{i-1}} \left(\frac{L_{inf} - L_i}{L_{inf} - L_{i-1}} \right)^{\frac{M}{K} + \frac{F}{K} S_{L_i}} \quad (4)$$

$$C_{L_i} = N_{L_i} S_{L_i} \quad (5)$$

$$L_{opt} = L_{inf} \left(\frac{3}{3 + \frac{M}{K}} \right) \quad (6)$$

$$L_{c\_opt} = \frac{L_{inf} \left(2 + 3\frac{F}{M} \right)}{\left(1 + \frac{F}{M} \right) \left(3 + \frac{M}{K} \right)} \quad (7)$$

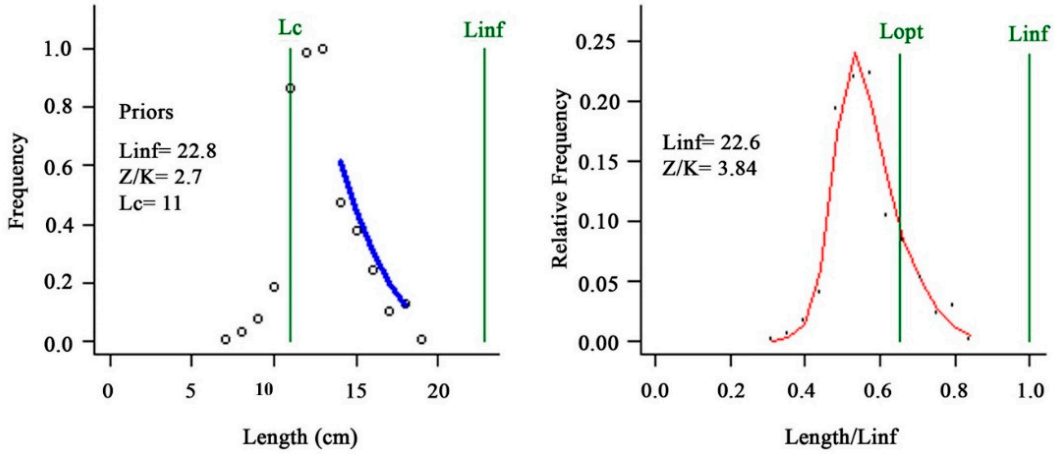
where length at t age is denoted by L_t, L_{inf} signifies asymptotic length, K stands for growth coefficient (year^{-1}), hypothetical age at zero length was indicated by t_0, N_L denotes the number of individuals that survive at L length, the number of individuals at length L_{start} is signified by N_{Lstart}, the fraction of an individual fish at L length captured by fishing gear was symbolized by S_L, α is the gradient of the ogive that determines the length-based selection of gear, L_i is the number of individuals at the length i, L_{i-1} refers the number at the previous length, and C is the number of individuals vulnerable to fishing gear [8].

For the unfinished state of a fishery, the Z/K and M/K are equal, where N_{Lstart} should be set as 1, L_{start} as 0. Further, the result of L_{c_opt} was used for relative biomass to produce maximum sustainable yield (MSY) [8]. The calculated result for F/M > 1 indicates the overfished condition, and F/M <1 indicates the underfished condition. The current relative stock size (B/B_{MSY}) and relative stock size or currently exploited biomass relative to unexploited biomass (B/B_0) were evaluated and converted by the LBB method to explain the fishery stock status. The stock were further classified based on the B/B_{MSY} values [7] and explained as healthy stock (B/B_{MSY} > 1.1); slightly overfished (0.8 < $B/B_{MSY} \leq$ 1.1); overfished (0.8 $\leq B/B_{MSY} \leq$ 0.5); grossly overfished (0.5 < $B/B_{MSY} \leq$ 0.2); and collapsed (B/B_{MSY} < 0.2). However, B/B_0 = 0.4–0.5 was defined as the reference limit for stock biomass [8]. The proportions of L_{mean}/L_{opt} and L_c/L_{c_opt} less than unity, accounting for the fishery's capture of too tiny individuals and truncated length structure. Similarly, the ratios of the 95th percentile length and L_{95th}/L_{inf} (asymptotic length) close to unity (>0.9) indicate the minimum presence of the large individuals. The B/B_0 < B_{MSY}/B_0 recommended that the fishing pressure or catch be reduced, while L_c < L_{c_opt} recommended that the first of the fish caught must be bigger sizes [6,8]. Thus, the findings of relative biomass and L_c from the LBB method are very advantageous for the management of data-poor fisheries. Table 1 represents the basic information and priors (L_{inf}, L_c, Z/K, M/K, F/K, and α) for the LBB analysis.

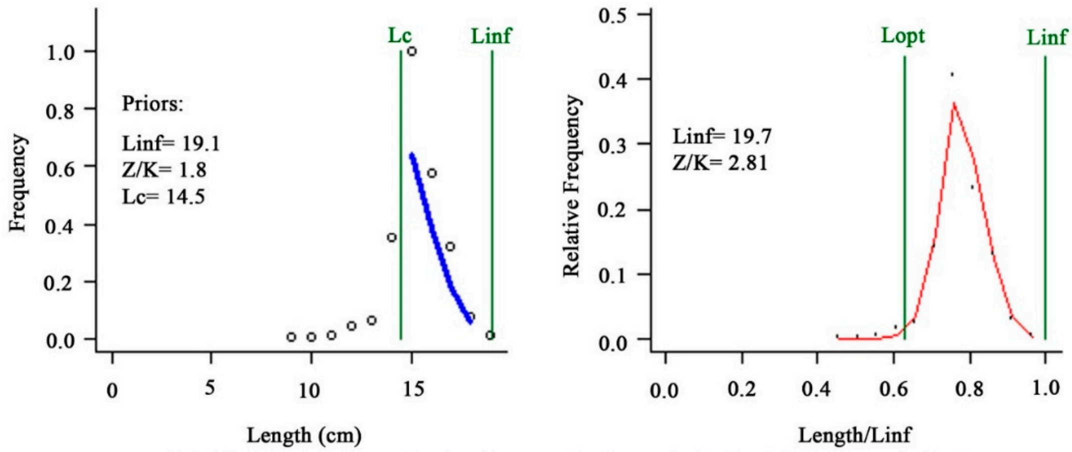
3. Results

3.1. *Sardinella fimbriata (Fringe Scale Sardine)*

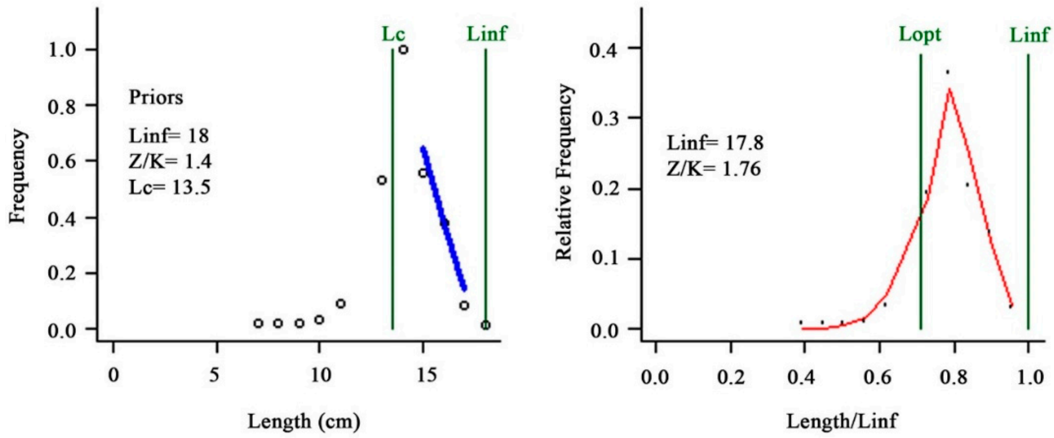
The assessed B/B_{MSY} was 0.70, which denotes an overfished condition for *S. fimbriata* stock, and the current biomass was not enough to produce MSY level (Table 2). The estimated B/B_0 (0.26) was below the reference limit for *S. fimbriata* stock biomass, and denoted that the biomass was in a low condition where the wild stock of this species had been depleted by 74% because of overfishing. The calculated B/B_0 was smaller than B_{MSY}/B_0 (0.37), and F/M was 1.4, which implies the overfishing condition. The estimated L_{mean}/L_{opt} (0.89) and L_c/L_{c_opt} (0.85) were below unity (<0.9), indicating a truncated length structure and overfishing of tiny fishes. The assessed L_{95th}/L_{inf} (0.84) was smaller than the unity (<0.9), indicating insufficient numbers of significant individuals of *S. fimbriata*. In addition, a smaller estimation was observed for L_c (10.6) than L_{c_opt} (13.0), indicating growth in overfishing and recommended that the first fish caught be more extensive. The $B/B_0 < B_{MSY}/B_0$ and $L_c < L_{c\_opt}$ suggested that reducing fishing pressure and increasing gear mesh sizes for fishing might be advantageous for the *S. fimbriata* population in the marine water of Bangladesh (Figure 4A).



(A) LBB derived results for *Sardinella fimbriata* in the BOB, Bangladesh



(B) LBB derived results for *Dussumieria acuta* in the BOB, Bangladesh



(C) LBB derived results for *Dussumieria elopsoides* in the BOB, Bangladesh

Figure 4. Graphical representation of LBB results for three sardine populations in the BoB, Bangladesh. Left curves depict the LBB model's fit to the length data, and right curves depict the LBB method's prediction, where L_c denotes the length of 50% of the individuals caught, L_{inf} indicates the body length limit. L_{opt} signifies the length when the maximum catch is achieved.

Table 2. Estimated results of three sardine species using length frequency (LF) data by LBB method.

Scientific Name	L_c	L_{c_opt}	L_{mean}/L_{opt}	L_c/L_{c_opt}	L_{95th}/L_{inf}	B/B_0	B_{MSY}/B_0	B/B_{MSY}	F/M	Z/K	Assessment
Sardinella fimbriata	10.6	13	0.89	0.85	0.84	0.26	0.37	0.7	1.4	3.8	Overfished
Dussumieria acuta	14.2	9.8	1.3	1.4	0.96	0.57	0.36	1.6	0.59	2.8	Healthy
Dussumieria elopsoides	12.6	9.7	1.1	1.3	0.95	0.63	0.37	1.7	0.44	1.7	Healthy

3.2. *Dussumieria acuta* (Rainbow Sardine)

The estimated B/B_{MSY} was 1.6, which confirmed the healthy condition of *D. acuta* stock and indicated the safe biomass level capable of producing the MSY (Table 2). The calculated B/B_0 (0.57) was above the reference limit for *D. acuta* stock biomass and denoted that the biomass was in the safe condition, whereby 43% of the wild stock of this species had been harvested. The assessed B/B_0 was larger than B_{MSY}/B_0 (0.36), and F/M was 0.59, which indicated an underfishing condition. The output result for L_c/L_{c_opt} and L_{mean}/L_{opt} was 1.4 and 1.3 respectively, which signified the healthy stock with the fishing of prominent individuals. The output result of L_{95th}/L_{inf} (= 0.96) is close to unity (>0.9), indicating the presence of the number of significant individuals in the stock. Furthermore, the L_c (14.2) and L_{c_opt} (9.8) assessment indicated that the current fishing level was in a safe condition. The $B/B_0 > B_{MSY}/B_0$ and $L_c > L_{c\_opt}$ suggested that the existing fishing pressure and mesh sizes may not influence the biomass (Figure 4B). However, it is recommended that maintaining the current fishing pressure and mesh size or slightly increasing the mesh size for fishing may be beneficial for the sustainability of the *D. acuta* population in the BoB, Bangladesh.

3.3. *Dussumieria elopsoides* (Slender Rainbow Sardine)

The calculated B/B_{MSY} of 1.7 denoted the healthy stock condition and safe biomass for this species, enough of which to produce the MSY (Table 2). The assessed B/B_0 (0.63) was above the stock biomass reference limit and denoted that only 37% of the wild stock of this species had been harvested. The F/M was 0.44, and a more significant value of B/B_0 was estimated than B_{MSY}/B_0 (0.37), which indicated the underfished condition for this sardine species. The calculated values for L_{mean}/L_{opt}, and L_c/L_{c_opt} were 1.1 and 1.3, which signified the healthy stock and catching of significant fish individuals for this species. The estimated value of L_{95th}/L_{inf} (=0.95) is near to unity (>0.9), indicating the existence of large size fishes in *D. elopsoides* stock. Moreover, *Lc* (12.6) evaluation was more significant than the assessment of L_{c_opt} (9.7), indicating safe fishing. The calculated values from L_c, L_{c_opt}, and B/B_0, B_{MSY}/B_0 recommended that the current fishing pressure and mesh size of nets do not affect the biomass. So, this research suggested maintaining the current fishing pressure and keeping the present gear mesh size, or even expanding it to ensure the sustainable exploitation of *D. elopsoides* in the BoB, Bangladesh (Figure 4C).

4. Discussion

4.1. Suitability of LBB Method for Data-Poor Sardine Fishery

Sardine is a forage species classified as herring, anchovies, and sardines (HAS). The HAS accounts for 18.6% of the global marine capture production of fish, and is estimated as 15.2 million tons [27–29]. Sardine is considered a commercial fishery harvested from the BoB, Bangladesh [17–19,22,30]. In the past decade, it has been observed that the contribution of sardine landing has increased, which contributed around 4–5% of the total marine harvest in Bangladesh. However, the recent decline in sardine landing was reported in Bangladesh [22], and a similar decline trend was reported in India, Pakistan, and Myanmar waters [21,22,31,32]. However, a wide fluctuation in sardine catch was reported globally and investigated thoroughly [28,29,33]. The Indo-West Pacific (IWP) marine water is the world's biggest tropical area that produced about half of the world's sardines from

2008–2017 [10]. However, the government of Bangladesh recorded sardine's landings from 2012, before it was considered and estimated as "other marine catch" statistics [22]. Still, there is no species-specific landing data record for sardine species, where the reported catch is the cumulative estimation of all species of sardines harvested from BoB. There is no other fishery information available for stock study and management, except for short-term landing data, so sardine can be called a data-poor fishery in Bangladesh. For data-poor fisheries, independent fishery data are usually absent, making it difficult to assess the comprehensive stock status [12,34].

Because of its data-poor nature, this research used one-year LF datasets that represented all potential length classes for three sardine species (*S. fimbriata*, *D. acuta*, and *D. elopsoides*), to evaluate their stock status using the LBB method. The LBB method was applied in this study because of its suitability and reliability to assess the stock status of a data-poor fishery [4,6,8,10,11,26]. This method is appropriate for fish species that can grow continuously through their lifetimes. Additionally, LBB needs no further data beyond simple LF data. Similar to the other methods, this method assumes that the LF data used must reflect the exploited population [8]. The LBB deliberated stock information and exploitation status may directly be used to manage fisheries or as a source of prior information for other assessment techniques [8]. Comparison of the LBB method with classical approach (Pella–Tomlinson Model, Beverton–Holt Y/R analysis) indicated that although available data were rare, the majority could verify the validity of the LBB method [11]. Thus, the LF data of three sardine species used in this study was appropriate, since their resultant fits exhibited asymmetric patterns consistent with the original study [8]

4.2. The Stock Status of Sardine Populations in BoB

This research recorded a total length of 70–190 mm for 1749 individuals of *S. fimbriata*, the size of which was consistent with the previous reports [17,30]. For *D. acuta*, our study recorded the TL 90–190 mm from 1145 individuals, which supports the findings from previous studies [20,35]. Again, the estimated total length of *D. elopsoides* was 70–180 mm for 705 individuals, while a market survey recorded the TL 80–180 mm for this species [13], which supports our length limit findings. However, variations in the minimum length limit for *S. fimbriata* and *D. acuta* were observed compared with previous studies. This variation may happen because of different sample sizes and mesh sizes of nets used in their studies. To avoid the bias results of LBB, we collected possible small size and large size samples from industrial and artisanal catches in BoB, Bangladesh.

The present research identified the overfished condition caused by overfishing and overexploitation of *S. fimbriata*, while the other two sardine species remain in an underfished condition and safe fishing status. Most of the small pelagic fish stock, including sardines, are reported as sustainably fished to underfished conditions in the Indo-Pacific marine water [27]. The LBB-derived parameter results from L_{mean}/L_{opt} and L_c/L_{c_opt} indicated the shortened length structure and capture of very young individuals for *S. fimbriata*, but safe and healthy fishing for both *D. acuta* and *D. elopsoides* species, which was consistent with the previous reports (Table 3). The initial stock assessment of sardine in marine water of Bangladesh was performed using a biomass dynamics model for multispecies of *Sardinella*, and suggested a minor overfished condition [13] that slightly varied from our findings, maybe because of the use of single species (*S. fimbriata*) data and a different assessment method applied in the present study. It was discovered that several studies on the sardine fishery resource assessments had been conducted off the coast of Bangladesh for both *D. acuta* and *D. elopsoides* stock. So far, our research might be the first stock assessment study for these two species in this region.

Table 3. Comparative analysis of the current results in light of other pertinent studies.

Scientific Name	Method of Assessment	Finding	Present Finding	References
Sardinella fimbriata	Length converted catch curve	Overfishing	Overfished	[36]
	Biomass dynamics model	Overfished		[13]
	Length converted catch curve	Overfishing		[37]
	Yield per recruit analysis	Overexploited		[38]
	Length converted catch curve	Overexploited		[17]
Dussumieria acuta	Length converted catch curve	Safe	Healthy	[31]
	Biomass dynamics model	Underfished		[13]
Dussumieria elopsoides	Biomass dynamics model	Underfished	Healthy	[13]

4.3. Ecological Status and Future Research

During the sampling, sardine was reported as one of the most common marine species harvested from the BoB water in Bangladesh. Because of the data deficiency of sardine, no complete stock assessment information is available in this region. Further, a high abundance of sardine in the marine catch indicates a low risk of extinction in the BoB. Presently, the International Union for Conservation of Nature (IUCN, 2021) [39] classifies the sardine species studied in this research as of least concern (LC), despite the potential increases in recent capture [27]. However, the IUCN's designation as LC may be ascribed to the restricted nature of captures, due to a mix of factors including low value, data misrepresenting, and discarding in sampling; a presumed minimal exposure to fishing stress; and species identification problems [6]. Sardines are mostly reported as the non-targeted pelagic species from commercial fishing. However, *S. fimbriata* was reported as a target species during sampling. Our findings were supported by some studies from the onshore areas of Bangladesh, which reported *S. fimbriata* as target species in commercial fishing [13,17,18]. Although concerns have been expressed regarding the significance of non-target species, such as sardines, while most untargeted species are highly productive, many variables contribute to their vulnerability, which may result in population decrease [6].

Furthermore, owing to a deficiency of good quality data, it was unknown if existing levels of sardine fisheries endangered this fish population. Therefore, it is best to use the survey data for LBB analysis to ensure the maximum representation of LF data and minimum data error [8]. Because of funding inefficiency and limited research facilities, the LF data were collected from industrial and artisanal landings for this study. However, the industrial fishing vessel does not maintain the same effort and hauling time, and operates in specific fishing ground areas. Instead, the random operation for sampling may affect the data accuracy and result in the misinterpretation of LF data. The most challenging issue for both commercial and artisanal fishing was the mesh size of nets. According to the Marine Fisheries Ordinance 1983, the industrial fish trawlers can use 60 mm cod-end mesh size in the nets and 45 mm for the shrimp nets; 100 mm for small mesh drift gillnet (Rog jal); and 45 mm for set bag net [22]. However, in practice, the mesh size was not maintained accordingly, so it is difficult to suggest a specific mesh size for the sustainable harvesting of sardine.

Further research on gear selectivity and mesh size selectivity is needed to determine the mesh size, escaping size, and rate of the recapture of sardine. Despite the absence of management and conservation measures to protect this fishery stock, greater emphasis should be paid to improving the sardine stock status. Reduction of fishing pressure or maintaining a balanced effort and increased mesh size of fishing gear might be advantageous to ensure the sustainability of sardine. Furthermore, continuous LF and catch data collection are recommended to observe the overall changes in stock status. Despite many limitations, this research provides baseline information on these three sardine populations that will help the fishery administrator make an effective management policy of sardine and other fisheries in BoB.

5. Conclusions

This research assessed three sardine species' stock status (*S. fimbriata*, *D. acuta,* and *D. elopsoides*) in the BoB, Bangladesh. The assessment suggested the healthy stock status for both *D. acuta* and *D. elopsoides*, while an overfished status for the *S. fimbriata*. The calculated L_{c_opt} values by LBB served as a baseline for exploitation and stock rebuilding efforts for the sardine. To aid in the rebuilding of fish populations, fishery policymakers and managers should establish species-specific size restrictions and enforce particular mesh sizes for fishing gear and nets. Nevertheless, management regulations, such as increasing mesh size would be challenging to implement. Thus, the research suggests that decreasing fishing pressure, reducing the number and type of fishing vessels, and restricting harvesting season should be explored to ensure the sustainability of sardine. The present study used all possible size class LF data to avoid biased results generated by the LBB method. Thus, the stock parameters provided by LBB for sardine fisheries are trustworthy and offer information that may be used to manage and conserve these fisheries. These LBB findings can be used as proxies in more complex evaluation models when reliable data is available. Though LBB's stock status estimates are reliable, the validity of LBB output must be shown via further study, as there are limited studies based on it, and the combination of the LBB with additional models may increase the dependability of the actual results.

Author Contributions: P.P.B.: conceptualization, data collection, methodology, data analysis, writing, editing and reviewing, Q.L.: conceptualization, reviewing and editing, M.A.A.-M.: data acquisition, editing and reviewing, P.S.: editing, reviewing and funding, M.M.H.M.: editing, reviewing. The published version of the article has been reviewed and approved by all authors. All authors have read and agreed to the published version of the manuscript.

Funding: The first author wishes to express his gratitude to the Chinese Scholarship Council (CSC) and the SOA (State Oceanic Administration) for their financial support during his doctorate studies. This study is sponsored by the Ocean University of China's fundamental research budget (201562030).

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: Data will be available from the corresponding author by request.

Acknowledgments: The authors want to express their gratitude to the College of Fisheries, Ocean University, China; Department of Coastal and Marine Fisheries, Sylhet Agricultural University, Sylhet; and Department of Fisheries, Government of Bangladesh, for making this study possible.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhang, S.; Wang, Y.; Wang, Y.; Liang, C.; Xian, W. Assessment of 11 Exploited Fish and Invertebrate Populations in the Japan Sea Using the CMSY and BSM Methods. *Front. Mar. Sci.* **2020**, *7*, 1–10. [CrossRef]
2. Froese, R.; Winker, H.; Gascuel, D.; Sumaila, U.R.; Pauly, D. Minimizing the impact of fishing. *Fish Fish.* **2016**, *17*, 785–802. [CrossRef]
3. Froese, R. Keep it simple: Three indicators to deal with overfishing. *Fish Fish.* **2004**, *5*, 86–91. [CrossRef]

4. Al-Mamun, M.A.; Liu, Q.; Chowdhury, S.R.; Uddin, M.S.; Nazrul, K.M.S.; Sultana, R. Stock Assessment for Seven Fish Species Using the LBB Method from the Northeastern Tip of the Bay of Bengal, Bangladesh. *Sustainability* **2021**, *13*, 1561. [CrossRef]
5. Costello, C.; Ovando, D.; Hilborn, R.; Gaines, S.D.; Deschenes, O.; Lester, S.E. Status and Solutions for the World's Unassessed Fisheries. *Science* **2012**, *338*, 517–520. [CrossRef] [PubMed]
6. Kindong, R.; Gao, C.; Pandong, N.A.; Ma, Q.; Tian, S.; Wu, F.; Sarr, O. Stock Status Assessments of Five Small Pelagic Species in the Atlantic and Pacific Oceans Using the Length-Based Bayesian Estimation (LBB) Method. *Front. Mar. Sci.* **2020**, *7*, 1–9. [CrossRef]
7. Palomares, M.L.D.; Froese, R.; Derrick, B.; Nöel, S.; Tsui, G.; Woroniak, J.; Pauly, D. *A Preliminary Global Assessment of the Status of Exploited Marine Fish and Invertebrate Populations*; A Report Prepared by the Sea Around Us for Oceana; Sea Around Us: Vancouver, BC, Canada, 2018; p. 60.
8. Froese, R.; Winker, H.; Coro, G.; Demirel, N.; Tsikliras, A.C.; Dimarchopoulou, D.; Scarcella, G.; Probst, W.N.; Dureuil, M.; Pauly, D. A new approach for estimating stock status from length frequency data. *ICES J. Mar. Sci.* **2018**, *75*, 2004–2015. [CrossRef]
9. Froese, R.; Demirel, N.; Coro, G.; Kleisner, K.M.; Winker, H. Estimating fisheries reference points from catch and resilience. *Fish Fish.* **2017**, *18*, 506–526. [CrossRef]
10. Yue, L.; Wang, Y.; Zhang, H.; Xian, W. Stock Assessment Using the LBB Method for Portunus trituberculatus Collected from the Yangtze Estuary in China. *Appl. Sci.* **2020**, *11*, 342. [CrossRef]
11. Liang, C.; Xian, W.; Liu, S.; Pauly, D. Assessments of 14 Exploited Fish and Invertebrate Stocks in Chinese Waters Using the LBB Method. *Front. Mar. Sci.* **2020**, *7*, 1–8. [CrossRef]
12. Barman, P.P.; Karim, E.; Khatun, M.H.; Rahman, M.F.; Alam, M.S.; Liu, Q. Application of CMSY to estimate biological reference points of Bombay duck (*Harpadon neherus*) from the Bay of Bengal, Bangladesh. *Appl. Ecol. Environ. Res.* **2020**, *18*, 8023–8034. [CrossRef]
13. Fanning, L.P.; Chowdhury, S.R.; Uddin, M.S.; Al-Mamun, M.A. Marine Fisheries Survey Reports and Stock Assessment Bangladesh Marine Fisheries Capacity Building Project; Dhaka. 2019. Available online: http://marine.fisheries.gov.bd/site/notices/081e4467-46b1-4ecd-8116-0deabc750004/Marine-Fisheries-Survey-Reports-and-Stock-Assessment-2019-Based-on-R-V-Meen-Shandhani-surveys-from-2 (accessed on 15 July 2021).
14. Shamsuzzaman, M.M.; Islam, M.M.; Tania, N.J.; Al-Mamun, M.A.; Barman, P.P.; Xu, X. Fisheries resources of Bangladesh: Present status and future direction. *Aquac. Fish.* **2017**, *2*, 145–156. [CrossRef]
15. Murshed-e-Jahan, K.; Belton, B.; Viswanathan, K.K. Communication strategies for managing coastal fisheries conflicts in Bangladesh. *Ocean Coast. Manag.* **2014**, *92*, 65–73. [CrossRef]
16. Islam, M.M.; Shamsuzzaman, M.M.; Mozumder, M.M.H.; Xiangmin, X.; Ming, Y.; Jewel, M.A.S. Exploitation and conservation of coastal and marine fisheries in Bangladesh: Do the fishery laws matter? *Mar. Policy* **2017**, *76*, 143–151. [CrossRef]
17. Ghosh, S.; Hanumantha Rao, M.V.; Sumithrudu, S.; Rohit, P.; Maheswarudu, G. Reproductive biology and population characteristics of Sardinella gibbosa and Sardinella fimbriata from north west Bay of Bengal. *Indian J. Mar. Sci.* **2013**, *42*, 758–769.
18. Jit, R.B.; Singha, N.K.; Ali, S.M.H.; Rhaman, G. Abundance of sardine fish species in Bangladesh. *Basic Res. J. Agric. Sci. Rev.* **2013**, *2*, 111–115.
19. Roy, B.J.; Singha, N.K.; Ali, S.M.H.; Rahman, G. Month wise catch per unit effort of sardine species *Sardinella fimbriata* and *Dussumieria acuta* in Artisanal and Industrial fishing sector. *Glob. Adv. Res. J. Agric. Sci.* **2013**, *2*, 173–179.
20. Roy, B.J.; Singha, N.K.; Haman, G.; Mohanta, S.K.; Officer, S.; Fisheries, M.; Management, S. Abundance Highly Migratory Species in the Bay of Bengal of Bangladesh region. *Int. J. Innov. Food Nutr. Sustain. Agric.* **2018**, *6*, 1–26.
21. Mukhopadhyay, A.; Giri, S.; Hazra, S.; Das, S.; Chanda, A. Influence of Oceanographic Variability on the Life Cycle and Spawning Period of Sardinella fimbriata in the Northern Part of Bay of Bengal. *Proc. Zool. Soc.* **2020**, *73*, 285–295. [CrossRef]
22. DoF. *Yearbook of Fisheries Statistics of Bangladesh, 2018-19*; Fisheries Resources Survey System (FRSS), Department of Fisheries Bangladesh, Ministry of Fisheries and Livestock: Dhaka, Bangladesh, 2019; Volume 36, 135p. Available online: http://fisheries.portal.gov.bd/sites/default/files/files/fisheries.portal.gov.bd/page/4cfbb3cc_c0c4_4f25_be21_b91f84bdc45c/2020-10-20-11-57-8df0b0e26d7d0134ea2c92ac6129702b.pdf (accessed on 15 July 2021).
23. Maravelias, C.D.; Reid, D.G.; Swartzman, G. Modelling Spatio-Temporal Effects of Environment on Atlantic Herring, Clupea harengus. *Environ. Biol. Fishes* **2000**, *58*, 157–172. [CrossRef]
24. Karim, E.; Liu, Q.; Forruq Rahman, M.; Khatun, M.H.; Protim Barman, P.; Shamsuzzaman, M.M.; Mahmud, Y. Comparative assessment of population biology of three popular pomfret species, Pampus argenteus, Pampus chinensis and Parastromateus Niger in the Bay of Bengal, Bangladesh. *Iran. J. Fish. Sci.* **2020**, *19*, 793–813. [CrossRef]
25. FishBase. World Wide Web Electronic Publication. Available online: http://www.fishbase.org (accessed on 10 July 2021).
26. Wang, Y.; Wang, Y.; Liu, S.; Liang, C.; Zhang, H.; Xian, W. Stock Assessment Using LBB Method for Eight Fish Species From the Bohai and Yellow Seas. *Front. Mar. Sci.* **2020**, *7*, 164. [CrossRef]
27. FAO. *The State of World Fisheries and Aquaculture 2018—Meeting the Sustainable Development Goals*; FAO: Rome, Italy, 2018.
28. Al Jufaili, S.M.; Piontkovski, S.A. Seasonal and Interannual Variations of Sardine Catches along the Omani Coast. *Int. J. Ocean. Oceanogr.* **2019**, *14*, 77. [CrossRef]
29. Kripa, V.; Mohamed, K.S.; Koya, K.P.S.; Jeyabaskaran, R.; Prema, D.; Padua, S.; Kuriakose, S.; Anilkumar, P.S.; Nair, P.G.; Ambrose, T.V.; et al. Overfishing and climate drives changes in biology and recruitment of the Indian oil sardine Sardinella longiceps in southeastern Arabian Sea. *Front. Mar. Sci.* **2018**, *5*, 1–20. [CrossRef]

30. Barua, S.; Karim, E.; Humayun, N.M. Present Status and Species Composition of Commercially Important Finfish in Landed Trawl Catch From Bangladesh Marine Waters. *Int. J. Pure Appl. Zool.* **2014**, *2*, 150–159.
31. Abdul, B.; Qun, L.; Baochao, L.; Abdul, W.; Han, Y.; Zhang, Q. Population dynamics of Rainbow Sardines, Dussumieria acuta (Valenciennes, 1847) from Pakistani waters. *Int. J. Aquac. Fish. Sci.* **2020**, *6*, 29–34. [CrossRef]
32. Hosch, G.; Belton, B.; Johnstone, G. Catch and effort trends in Myanmar's offshore fleets operating out of Myeik—2009–2018. *Mar. Policy* **2021**, *123*, 104298. [CrossRef]
33. Schwartzlose, R.A.; Alheit, J.; Bakun, A.; Baumgartner, T.R.; Cloete, R.; Crawford, R.J.M.; Fletcher, W.J.; Hagen, E.; Kawasaki, T.; Maccall, A.D.; et al. Worldwide Large-scale Fluctuations of Sardine and Anchovy Population. *S. Afr. J. Mar. Sci.* **1999**, *21*, 289–347. [CrossRef]
34. Jacquet, J.; Zeller, D.; Pauly, D. Counting fish: A typology for fisheries catch data. *J. Integr. Environ. Sci.* **2010**, *7*, 135–144. [CrossRef]
35. Ahmed, Z.F.; Fatema, M.K.; Habiba, U.; Zohora, A.; Joba, M.A.; Ahamed, F. Coefficient of Algebraic Relationship Between Linear Dimensions as Growth Deduction for Rainbow Sardine *Dussumieria acuta* in the Bay of Bengal. *Res. Agric. Livest. Fish* **2020**, *7*, 545–551. [CrossRef]
36. Bintoro, G.; Lelono, T.D.; Deafatmi, L. Biological aspect and dynamic population of fringescale sardine (*Sardinella fimbriata*: Valenciennes, 1847) in Prigi waters Trenggalek, East Java, Indonesia. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *493*, 012017. [CrossRef]
37. Bintoro, G.; Setyohadi, D.; Djoko Lelono, T.; Maharani, F. Biology and population dynamics analysis of fringescale sardine (*Sardinella fimbriata*) in Bali Strait waters, Indonesia. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *391*, 012024. [CrossRef]
38. Syakila, S. Studi, Dinamika Stok Ikan Tembang (*Sardinella fimbriata*) di Perairan Teluk Palabuhanratu, Kabupaten Sukabumi, Provinsi Jawa Barat. 2009, pp. 4–5. Available online: http://repository.ipb.ac.id/handle/123456789/14154 (accessed on 3 October 2021).
39. IUCN (International Union for Conservation of Nature). Available online: https://www.iucnredlist.org/ (accessed on 10 July 2021).