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Reproductive Biology of Bombay Duck *(Harpadon nehereus)* as a Basis for Sustainable Management in the Malacca Strait

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ABSTRACT

The Bombay duck (Harpadon nehereus), a common bycatch species found in various coastal fisheries, has experienced a global population decline. Studies on its reproductive biology, distinguishing between males and females, are still limited, particularly in the Strait of Malacca. This study aimed to investigate sexual dimorphism in the reproductive biology of H. nehereus, including body length distribution, length-weight relationship, growth pattern and coefficient, condition factor (K), hepatosomatic index (HSI), sex ratio, and gonadal maturity stage (GMS). Each specimen was morphometrically measured and dissected to collect data on total length, body weight, growth pattern, condition factor (K), hepatosomatic index (HSI), and gonadal maturity stage (GMS). Linear regression analysis was performed to examine the length frequency distribution, length-weight relationship, and growth pattern, as well as to evaluate the condition factor, hepatosomatic index, sex ratio, and gonadal maturity stage. The results showed that the total length of males ranged from 150 to 309 mm, and that of females from 198 to 309 mm. The length-weight relationship of both sexes showed a positive correlation, indicating positive allometric growth. The condition factor (K_1=3.2753% and K_2=2.9142%) and hepatosomatic index (HSI= 0.00717%) indicated that the physiological status of H. nehereus was generally healthy, with a condition factor value of 1-3. The sex ratio showed a higher number of males than females, with an average ratio of approximately 2.10:1. Analysis of gonadal maturity stages showed that most males were at stage I (immature), while most females were at stage IV (mature).

Keywords: bombay duck, condition factors, hepatosomatic, length-weight

INTRODUCTION

The issue of changing fisheries resource status, as assessed under the International Union for Conservation of Nature (IUCN) criteria, has gained increasing attention in recent years. The Bombay duck *(Harpadon nehereus)* is currently classified as Near Threatened (NT) by the IUCN, primarily due to an estimated 30% global decline in its catch and landing records over the past decade (Russell *et al.* 2019). In the Malacca Strait, Bombay duck *(Harpadon nehereus)* is typically regarded as a low-value bycatch species, and comprehensive assessments of its exploitation status remain limited. Declining fish stocks can often be inferred indirectly through indicators of exploitation level and biological characteristics, including growth patterns, reproductive performance, and mortality rates. Among various approaches, the analysis of length-frequency distribution provides crucial insights into the population dynamics and structure of fish species (Alam *et al.* 2022). Moreover, length-based data are relatively more straightforward to obtain compared to age structure or abundance indices, making them a practical and effective tool for preliminary stock assessments (Dai 2021).

Extensive research has been conducted on various biological aspects of Bombay duck *(Harpadon nehereus)* across different geographic regions and methodological approaches. For instance, He *et al.* (2019) examined the length–weight relationship of the Bombay duck *(Harpadon nehereus)* in the coastal waters of the South China Sea, while Kalhoro *et al.* (2020) analyzed its growth patterns in Bangladesh. Similarly, Sultana *et al.* (2020) investigated the growth dynamics of this species along the coast of Pakistan, and Taqwa *et al.* (2020) emphasized its reproductive biology in the waters of Tarakan, Indonesia. According to Jisr *et al.* (2018) and Oliveira *et al.* (2020), the length–weight relationship provides essential information for assessing the sustainability of fisheries and serves as an indicator of the physiological condition (viability) of fish, as well as the environmental suitability of their habitat. This relationship is frequently employed to estimate growth rates, gonadal development, and maturity stages in fish populations. Moreover, the condition factor (K) offers valuable insights into the overall well-being of fish and the

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degree to which environmental conditions support species growth and reproduction. Together, these parameters constitute essential indicators for understanding population dynamics and for developing sustainable fisheries management strategies.

The length–weight relationship (LWR) is widely utilized to estimate fish growth rates, gonadal development, and reproductive maturity stages. According to Ghosh (2014), the LWR of Bombay duck *(Harpadon nehereus)* along the Saurashtra coast exhibits sexual dimorphism, where males demonstrate nearly isometric growth, while females display allometric growth patterns. Such differences are often attributed to variations in energy allocation between somatic and reproductive development. In addition, condition indices, particularly the condition factor (K), provide critical insights into the physical well-being of fish and the suitability of their surrounding environment to support growth and reproduction. These indices are considered valuable tools for assessing environmental fitness and habitat-specific adaptation in aquatic species, offering a basis for evaluating population health and ecological sustainability.

Despite its ecological and economic significance, studies on the reproductive biology of the Bombay duck *(Harpadon nehereus)* in the Malacca Strait remain limited, particularly concerning the biological differences between males and females. Sexual dimorphism is a fundamental factor influencing various biological aspects of fish, including body size, growth patterns, and the size at which they reach first sexual maturity. Understanding these differences is therefore essential for elucidating species-specific reproductive strategies and their adaptive responses to environmental conditions. The present study aims to examine and compare the reproductive biology of male and female Bombay duck *(Harpadon nehereus)* in the Malacca Strait. The analysis encompasses length–frequency distribution, length–weight relationship, growth patterns and coefficients, condition factor (K), hepatosomatic index (HSI), sex ratio, and gonadal maturity stages (GMS). The outcomes of this research are expected to provide a scientific basis for the sustainable management of Bombay duck *(Harpadon nehereus)* resources in the Malacca Strait, and to contribute to the advancement of fisheries technology as well as broader marine biological studies.

METHODS

Study Area

The present study on the reproductive biology of the Bombay duck *(Harpadon nehereus)* was conducted at three observation stations located in the Malacca Strait region (Figure 1). Station 1 was situated in the coastal waters of Sinaboi (2°29′12″ N, 100°53′47.68″ E), Station 2 in the central Malacca Strait (2°05′34.06″ N, 101°50′59.16″ E), and Station 3 in the southern part of the Malacca Strait (1°37′58.21″ N, 102°14′48.95″ E). Sampling activities were conducted over five months, from August to December 2023, encompassing both the inter-monsoonal and transitional phases characteristic of this region.

Data Collection Methods

A total of 389 specimens of the Bombay duck *(Harpadon nehereus)* were collected from three sampling stations across the Malacca Strait. The sample distribution consisted of 126 individuals from Station 1, 133 individuals from Station 2, and 130 individuals from Station 3. Sampling was conducted monthly from August to December 2023 using a random sampling approach, in collaboration with local fishermen operating within the study area. All specimens were obtained from the routine catches of artisanal fishing vessels employing conventional fishing gear commonly used in the region. The random sampling procedure was designed to ensure representativeness of the population structure across

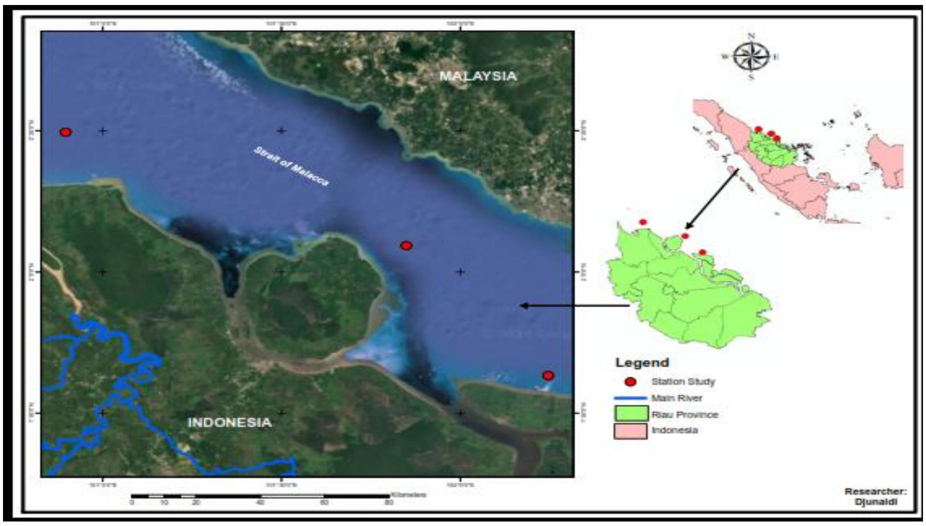

Figure 1 Research location map.

different spatial and temporal scales, while minimizing potential bias related to fishing effort or location. Following collection, all fish specimens were immediately stored in insulated ice boxes to preserve their freshness during transportation to the laboratory. Upon arrival, the samples were thawed to ambient temperature before undergoing morphometric and biological measurements.

Total length (TL) was measured using a digital caliper (accuracy ±0.01 mm), while body weight (BW) was recorded using a precision analytical balance (Kern ABS 220-4, accuracy ±0.01 g). Excess surface moisture was gently removed with absorbent tissue before weighing to ensure measurement accuracy. Each specimen was subsequently dissected along the abdominal cavity using standard dissection tools to determine sex and gonadal maturity stage. The gonads were visually examined and classified macroscopically based on their morphological characteristics, including size, color, and texture, in accordance with established criteria for gonadal maturity.

Length–Frequency Distribution

The length–frequency distribution of Bombay duck *(Harpadon nehereus)* was analyzed by determining the class interval, class width, mid-point of each class, and the frequency of individuals within each length group. The categorized length data were subsequently plotted as histogram distributions to visualize the size composition of the population. The appropriate number of class intervals (K) was determined following the rule proposed by Walpole (1995), expressed by the equation:

$$K = 1 + 3{,}3\, Log\, n$$

Where:
K = Represents the number of class intervals
n = Denotes the total number of observations

The class interval was determined using the following equation:

$$C = \left(\frac{Xn - X1}{K}\right)$$

Where:
C = Denotes the class interval
X_n = Represents the maximum data value
X_1 = Indicates the minimum data value
K = Corresponds to the total number of classes

After determining the class interval, the data were arranged in ascending order and grouped according to their respective class ranges. Subsequently, the frequency of each class was plotted as a histogram to illustrate the distribution pattern of the sample size and to visualize the size composition of Bombay duck *(Harpadon nehereus)* within the study area.

Relationship Between Length and Weight and Growth Pattern

The length–weight relationship and growth pattern of the fish samples were analyzed using a linear regression model. This analysis was conducted based on the conventional length–weight relationship formula as described by Lagler (1970), Ricker (1971), and Effendie (1992), expressed as:

$$W = aL^b$$

Where:
W = Represents the body weight (g)
L = Total length (cm)
a and b = Constants derived from the regression analysis

The exponent b indicates the type of growth pattern exhibited by the fish.

When b = 3, the growth is considered isometric, meaning that body weight and length increase proportionally. Conversely, when b ≠ 3, the relationship is allometric, implying that the rate of weight gain differs from that of length increase. Specifically, b > 3 denotes positive allometric growth, where weight increases at a faster rate than length, whereas b < 3 indicates negative allometric growth, where length increases faster than weight.

Growth Coefficient

The growth coefficient was analyzed using the Von Bertalanffy Growth Function (VBGF), which describes the relationship between fish length and age. This model is widely applied to characterize the growth dynamics of fish populations and is expressed by the following equation (von Bertalanffy, 1938):

$$TLt = TL1\infty\ X\ (1 - eK\ X\ (t - t_0)$$

Where:
TL = Denotes the total length of the fish at age t (cm)
K = Represents the growth coefficient (year^{-1}) indicating the rate at which the fish approaches its asymptotic length
t_0 = Theoretical age at which the fish length is zero
TL = Asymptotic or theoretical maximum total length (cm)

Condition Factor (K)

The condition factor of the fish was evaluated using Fulton's (K_1) and Clark's (K_2) condition coefficients, as described by Aday *et al.* (2002). These indices were calculated to assess the relative robustness and well-being of individual fish, reflecting the influence of both environmental conditions and physiological status. The equations are expressed as follows:

$$K = \left(\frac{W}{L_3}\right) \times 100$$

Where:
K = Represents the condition factor
K_1 = Calculated based on the total body weight of the fish
K_2 = Calculated using the gutted body weight

W denotes the body weight (g) — either with or without viscera, depending on the coefficient used — and L is the total length of the fish (cm).

Hepatosomatic Index (HSI)

The hepatosomatic index (HSI) was analyzed to evaluate variations in liver condition, which serve as indicators of the fish's physiological and metabolic status. The HSI was determined by measuring the total body weight and the liver weight of each specimen. The calculation followed the method described by Nikolsky (1969) and Lagler (1978), expressed by the following equation:

$$HSI = \left(\frac{LW}{BW}\right) \text{X } 100$$

Where:
HSI = Hepatosomatic index
LW = Represents the liver weight (g)
BW = Total body weight of the fish (g)

Sex Ratio and Gonadal Maturity Stage (GMS)

Estimating the sex ratio is an essential aspect in evaluating fish population dynamics and plays a significant role in both fisheries production and resource conservation. The determination of sex was conducted through direct gonadal observation, including an assessment of gonadal color and structural characteristics. The gonadal maturity stage (GMS) was determined based on the morphological features of the gonads, including color, shape, and size, as described by Taqwa *et al.* (2020). The sex ratio was calculated using the following equation:

$$SR = \frac{\Sigma\, Male}{\Sigma\, Female}\ X\ 100\ \%$$

Where:
SR = Sex ratio
ΣMale = Represents the total number of male individuals
ΣFemale = Refers to the total number of female individuals in the sampled population.

RESULTS AND DISCUSSION

Length Frequency Distribution

The length frequency distribution of male and female Bombay duck *(Harpadon nehereus)* collected from the Malacca Strait indicated a significant variation in length composition between sexes during the sampling period from August to December 2023. The detailed length-frequency data are presented in Table 1.

Table 1 and Table 2 present the length frequency distribution and body length range of male and female Bombay duck *(Harpadon nehereus)* captured from the Malacca Strait during the period from August to December 2023, showing significant size variation between sexes. The total length of male individuals ranged from 150–165.5 mm for the smallest specimens to 294–309 mm for the largest. In contrast, the total length of female individuals ranged from 198–213.5 mm at the smallest size class to 294–309 mm at the largest.

The length distribution of male Bombay duck *(Harpadon nehereus)* showed the highest frequency within the size class interval of 214–229.5 mm, comprising 95 individuals with a relative frequency (FR) of 36.12% (Figure 2). The second most abundant size class was 198–213.5 mm, with 80 individuals and an FR of 30.42%. The lowest frequency was observed in

Table 1 Length frequency distribution of male and female bombay duck *(Harpadon nehereus)* collected from the malacca strait during the period from August to December 2023

Class Interval (mm)	Total Length (mm)	*Harpadon neherus*			
		Male		Female	
		Total	Relative Frequency (FR)	Total	Relative Frequency (FR)
150–165	165.5	5	1,9011	0	0
166–181	181.5	12	4,5627	0	0
182–197	197.5	15	5,7034	0	0
198–213	213.5	80	30,4182	6	4,7619
214–229	229.5	95	36,1216	27	21,4285
230–245	245.0	40	15,2091	40	31,7460
246–261	261.5	10	3,8022	45	35,7142
262–277	277.5	3	1,1406	7	5,5555
278–293	293.5	2	0,7604	0	0
294–309	309.0	1	0,3802	1	0,7936
Total		263	100	126	100

the 294–309 mm size class, represented by only one individual (FR = 0.38%). In contrast, the female specimens exhibited the highest occurrence within the size class interval of 262–277.5 mm, consisting of 45 individuals with an FR of 35.71%, followed by the 230–245.5 mm class with 40 individuals and an FR of 31.75%. Similar to the males, the lowest frequency among females was recorded in the 294–309 mm class, represented by a single individual (FR = 0.79%).

The length frequency distribution of Bombay duck *(Harpadon nehereus)* in the Malacca Strait was influenced by variations in environmental conditions, including weather patterns and water quality, which affected fish migration, mortality rates, and fishing activities, thereby contributing to population dynamics (Barnett *et al.* 2017; Queiros *et al.* 2018; Cresswell *et al.* 2019). During the study period, the sea surface temperature (SST) in the Malacca Strait exhibited pronounced seasonal fluctuations, with the highest recorded temperature of 32 °C in April. From July to December, water temperature gradually decreased to a range of 29–30 °C. These temperature variations were associated with the influence of the southwest and northeast monsoon systems, which play a significant role in shaping hydrological conditions, particularly in the outer region of the Malacca Strait. According to Madalena *et al.* (2024), strong monsoonal winds enhance Ekman transport, vertical mixing, and evaporation during the summer season, leading to a decline in sea surface temperature. Conversely, when wind intensity weakens, vertical mixing and evaporation decrease, leading to an increase in surface water temperature.

The salinity levels observed in the study area ranged from 25 to 28 ppt, with an average value of 26.33 ppt. This value is relatively lower than the optimal salinity range for marine biota growth, which generally falls between 29 and 34 ppt. Spatially, salinity gradients may develop both vertically and horizontally, while temporally, salinity values are influenced by seasonal variations and tidal cycles. According to Rajaa *et al.* (2024), salinity tends to increase with water depth due to stratification and reduced freshwater input in deeper layers. The relatively low salinity recorded in the present study is likely associated with high precipitation in the study area, which contributes to freshwater influx and dilution of surface salinity. Conversely, elevated salinity conditions are typically linked to intense evaporation and limited freshwater discharge into coastal waters (Sujie *et al.* 2024).

The dissolved oxygen (DO) concentration in the waters of the Malacca Strait ranged from 4.16 to 5.49 mg/L, with an average value of 4.92 mg/L. These DO levels, together with the measured pH, remain within the optimal range that supports the survival and physiological functions of marine biota, including fish species. Higher DO concentrations generally indicate more favorable environmental conditions for sustaining aquatic life within the ecosystem (Yuhan *et al.* 2024). Temporal fluctuations in DO concentrations were observed, likely driven by diurnal and seasonal variations associated with water mass movement, vertical mixing, photosynthetic activity, respiration, and the input of organic and inorganic matter into the aquatic system (Effendi, 2002). Furthermore, DO concentration is closely associated with Total Suspended Solids (TSS), Biological Oxygen Demand (BOD), and Chemical Oxygen Demand (COD). Increased TSS levels may elevate water turbidity, reducing light penetration and subsequently limiting photosynthetic processes, which ultimately lead to a decline in DO concentration within the water column.

The pH measurements obtained from the sampling stations in the Malacca Strait ranged from 6.4 to 7.2,

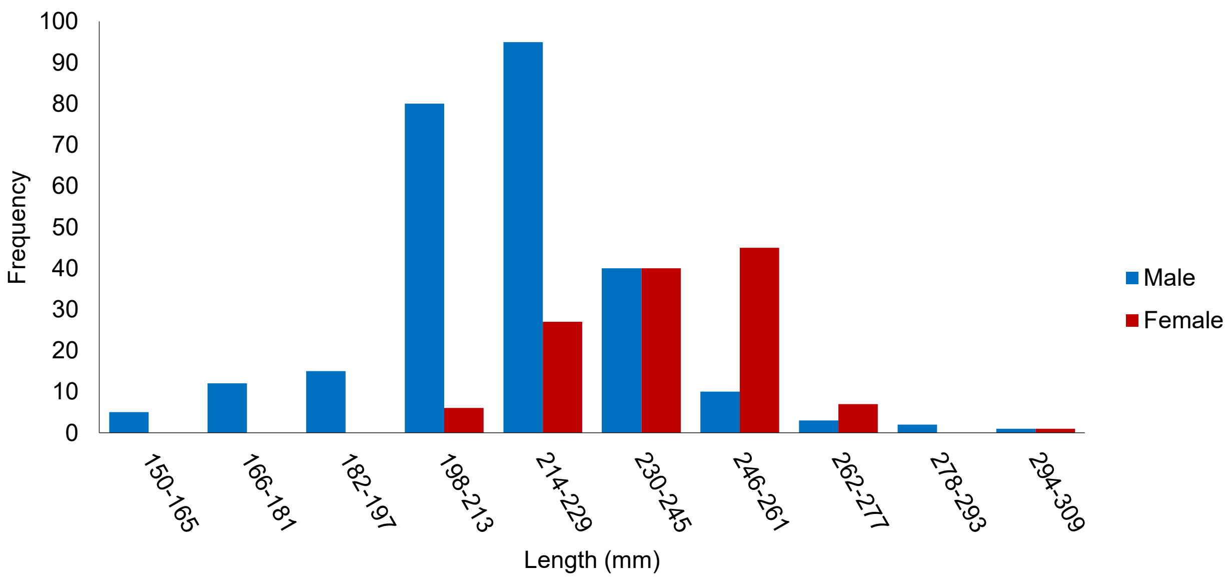

Figure 2 Length distribution of male and female bombay duck *(Harpadon nehereus)* collected from the malacca strait.

with a mean value of 6.9. This range is generally considered normal for marine and estuarine ecosystems and remains within the optimal conditions to sustain marine biota. According to Effendi and Hefni (2003), most aquatic organisms are sensitive to pH fluctuations, typically exhibiting optimal physiological performance within a range of 7.0–8.5. Deviations toward more acidic or alkaline conditions may adversely affect aquatic organisms by disrupting key physiological processes such as metabolism and respiration (Hamuna *et al.* 2018). Furthermore, pH serves as a critical parameter influencing the overall water quality and the adaptive capacity of resident aquatic organisms (Barus *et al.* 2019). Sustained deviations from the optimal range may, therefore, have cascading ecological effects on the structure and functioning of the aquatic community.

Furthermore, food availability represents another crucial factor influencing the length-frequency distribution and population structure of Bombay duck *(Harpadon nehereus)* in the Malacca Strait. Variations in prey abundance can modulate population dynamics through mechanisms such as selective feeding behavior, interspecific competition, and trophic interactions (Knutsen, 2019; Hussein *et al.* 2019). Dietary analysis of Bombay duck *(Harpadon nehereus)* revealed that these species primarily feed on phytoplankton, zooplankton, and other partially digested organisms. The relative abundance of phytoplankton in the study area was higher than that of zooplankton, which is consistent with their trophic positioning, as phytoplankton constitute the primary producers forming the base of the aquatic food web. The lower abundance of zooplankton can be attributed to predation pressure from omnivorous and carnivorous fish species inhabiting the same environment (Serena *et al.* 2024; Anouk *et al.* 2024; Huichao Jiang *et al.* 2024). As noted by Nurruhwati *et al.* (2017), fluctuations in zooplankton density are strongly influenced by the presence of predators and predation intensity within aquatic ecosystems. Such trophic interactions highlight the ecological linkage between primary production, prey availability, and fish population dynamics in the Malacca Strait.

Length–Weight Relationship and Growth Pattern

The length–weight relationship of male and female Bombay duck *(Harpadon nehereus)* collected from the Malacca Strait is presented in Table 2.

Table 2 and Figure 3 present the length–weight relationships of male and female Bombay duck *(Harpadon nehereus)* collected from the Malacca Strait. The results indicate a positive correlation between total length and body weight, showing that heavier individuals tend to exhibit greater body length. The regression equations derived from the empirical data are expressed as follows: for males, W=10−6.8517 L 3.6502 W=10−6.8517 L 3.6502 (r = 0.8124), and for females, W=10−7.7311 L 4.0171 W=10−7.7311 L 4.0171 (r = 0.8156). The estimated exponent values (b) for both sexes were greater than 3. Statistical testing at a significance level of α = 0.05 confirmed that the b values for males and females were significantly different from 3, indicating a positive allometric growth pattern. This finding suggests that weight increases at a faster rate than length, implying that Bombay duck *(Harpadon nehereus)* tends to exhibit body mass accumulation more dominantly than linear growth in length.

The graphical representation further corroborates that the increase in body weight is more pronounced than the increase in total length, indicating a growth pattern that reflects favorable environmental conditions supporting enhanced biomass accumulation. These

Table 2 Regression parameters of the length–weight relationship for male and female bombay duck *(Harpadon nehereus)* from the malacca strait

Harpadon nehereus	N	Coefficient of Determinant (R^2)	Exponential Value (b)	$W = aL^b$
Male	263	0.6599	3,6502	6,8517
Famale	126	0.6653	4,0171	7,7311

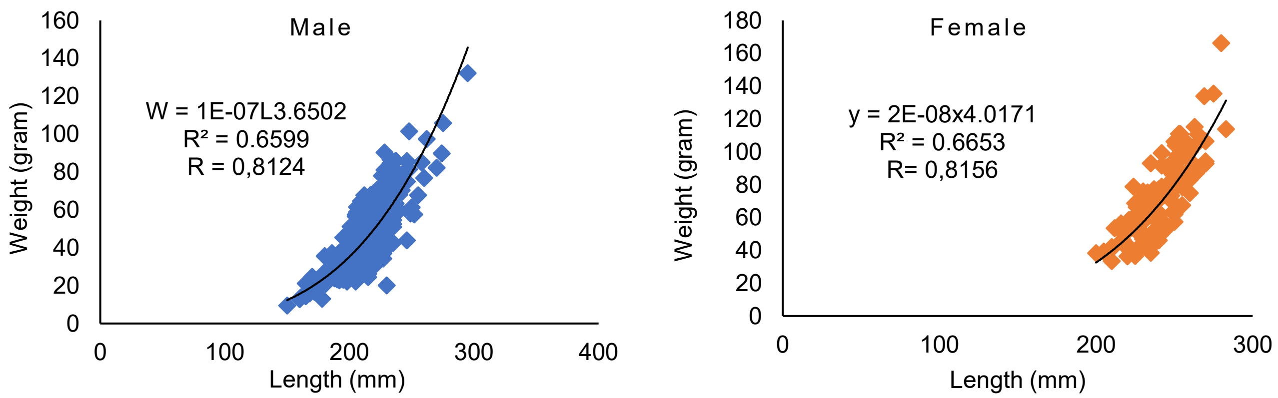

Figure 3 Length–weight relationship of male and female bombay duck *(Harpadon nehereus)* from the malacca strait.

findings are consistent with previous studies conducted in the coastal waters of China, Bangladesh, and Pakistan, which reported a similar positive allometric growth pattern in Bombay duck *(Harpadon nehereus)* irrespective of sex (He *et al.* 2019; Kalhoro *et al.* 2020; Sultana *et al.* 2020).

The length–weight relationship analysis of Bombay duck *(Harpadon nehereus)* conducted between August and December 2023 revealed that the regression exponent (b) values exceeded 3 for both males and females, indicating a positive allometric growth pattern throughout the sampling period. The hypothesis testing results further supported this finding, where the calculated t-statistic (T_{stat}) exceeded the critical value (T_{inv}), confirming that b ≠ 3. This suggests that Bombay duck *(Harpadon nehereus)* in the Malacca Strait exhibits a growth trend in which body weight increases at a faster rate than body length. The detailed results of the length–weight relationship analysis and the corresponding hypothesis testing, which confirmed the positive allometric growth pattern of Bombay duck *(Harpadon nehereus)* during the study period, are presented in Table 3. These findings offer valuable insights for fisheries management strategies, as the observed growth pattern reflects essential biological characteristics closely linked to population dynamics and ecosystem health within the Malacca Strait.

The length–weight relationship of Bombay duck *(Harpadon nehereus)* males and females is influenced not only by physiological conditions and environmental factors but also by gonadal maturity stages and individual growth variability (Stergiou, 2012; Yilmaz *et al.* 2012; El-Nasr, 2017; Eudriano *et al.* 2020). The size at first sexual maturity was analyzed to estimate the length at which individuals attain reproductive capability. According to Gandhi *et al.* (2014) and Joyanta *et al.* (2024), such analysis is essential for preventing the overexploitation of immature fish populations. Similarly, Hossain *et al.* (2012) emphasized that the size at first maturity can serve as a biological reference for establishing the minimum legal catch size in fisheries management. The present study revealed that Bombay duck *(Harpadon nehereus)* attains first sexual maturity at a total length ranging from 229 to 236 mm. The observed variation in the size at first maturity may be attributed to differences in individual growth parameters within the population. As noted by Udupa (1986), individuals of identical total length within a single population do not necessarily reach gonadal maturity at the same size, as intra-specific variation can occur even among fish of similar morphometric characteristics. Moreover, Zenty (2018) suggested that both internal and external factors affect the size at first sexual maturity in fish. Internal factors include species-specific traits, age, body size, and physiological characteristics such as adaptive capacity and sexual dimorphism. External factors are primarily related to environmental variability and habitat conditions.

Table 3 presents the growth pattern of Bombay duck *(Harpadon nehereus)* (commonly known as Lomek) during the observation period from August to December, indicating a consistent positive allometric growth pattern. No significant differences in growth patterns were observed between sampling months or between sexes. This stability suggests that the environmental conditions in the Malacca Strait remained relatively constant throughout the five-month sampling period. Previous research by Laga *et al.* (2015) on Bombay duck *(Harpadon nehereus)* from the coastal waters of Tarakan Island, North Kalimantan, reported spatial variations in growth patterns among different sampling stations, indicating that environmental heterogeneity can influence fish growth dynamics across locations. According to Evelyn R. (2016), fish growth patterns are influenced by biometric factors, such as length and weight, as well as environmental parameters, including population density and predation pressure. Moreover, fishing methods can also affect growth patterns, as different gear types may influence individual selection and consequently alter the population's overall health and structure.

Furthermore, studies conducted by Chantelle C. *et al.* (2023), Schemmel *et al.* (2022), and Yi M. R. *et al.* (2022) have demonstrated that water temperature represents one of the most influential environmental factors affecting fish growth patterns, with distinct differences observed between species inhabiting tropical waters and those residing in cooler temperate regions of southeastern Australia. In a related investigation, Xing-Yi W. *et al.* (2023) identified that environmental variables and community assembly processes jointly contribute to shaping fish growth dynamics. Environmental factors such as water quality, dissolved oxygen concentration, and both spatial and temporal variability—particularly seasonal fluctuations in hydrographic conditions, species migration, and the introduction of new taxa—collectively influence

Table 3 Growth Pattern of Bombay duck *(Harpadon nehereus)* in the Malacca Strait Waters

Sampling Time	Growth Pattern*	
	Male	Female
Agustus 2023	allometric positive	allometric positive
September 2023	allometric positive	allometric positive
Oktober 2023	allometric positive	allometric positive
November 2023	allometric positive	allometric positive
Desember 2023	allometric positive	allometric positive

Remaks: *Tstat > Tinv; α = 0.05.

interspecific and intraspecific growth responses. The Growth-Level Index (GLI), applied in various reservoir systems, has been used to evaluate fish adaptability, indicating that the complex interactions between environmental drivers and community structural dynamics determine growth performance.

Condition Factor and Hepatosomatic Index

Table 4 presents the values of the condition factors (K_1 and K_2) and the hepatosomatic index (HSI) of Bombay duck *(Harpadon nehereus)* collected from the Malacca Strait. The mean value of the condition factor with viscera (K_1) was 3.2753%, while the condition factor without viscera (K_2) averaged 2.9142%. The hepatosomatic index (HSI) recorded a value of 0.00717%, indicating that the physiological condition of Bombay duck *(Harpadon nehereus)* in the present study was within a healthy range. According to the obtained K values, which ranged from 1 to 3, Bombay duck *(Harpadon nehereus)* exhibited a relatively robust and well-proportioned body form, rather than the laterally compressed morphology previously reported by Febrianti *et al.* (2013). These findings suggest that the sampled population maintained favorable somatic conditions, reflecting optimal environmental and nutritional status within the Malacca Strait ecosystem during the sampling period.

Variations in the condition factor and hepatosomatic index (HSI) of Bombay duck *(Harpadon nehereus)* may be attributed to a range of environmental and biological factors, including diet composition, age, sex, gonadal maturation stage, and spawning season (Sapounidis *et al.* 2015; Uckun & Gokce, 2015). These parameters reflect the influence of reproductive cycles, food availability, and surrounding habitat conditions on the overall health and physiological status of the fish (Morato *et al.* 2001; Lizama & Ambrosio, 2002; Hanjavanit *et al.* 2013; De Giosa *et al.* 2014).

Studies conducted by Xiuxia M. *et al.* (2021) and Roghaieh A. *et al.* (2024) demonstrated that both the condition factor and hepatosomatic index (HSI) in fish are influenced by short-term environmental fluctuations as well as long-term climatic trends, which can directly affect fish physiology and subsequently impact their somatic condition and reproductive capacity. Consequently, individuals in good physical condition tend to have a higher survival potential and reproductive success. In contrast, those experiencing a decline in condition at the onset of the spawning season may face limitations in their reproductive performance.

Furthermore, Zhoulin Y. *et al.* (2023) reported that the nutritional quality of the diet plays a critical role in determining the hepatosomatic index (HSI) and overall somatic condition of fish. An imbalanced diet that fails to meet the nutritional requirements of the species may impair hepatic function—an organ essential for immunity, metabolism, and energy regulation. The HSI serves as an indicator of liver health, with recent studies showing that partial replacement of fish meal with black soldier fly larvae (BSFL) in aquafeed formulations significantly reduces HSI values. This finding suggests that a more balanced and sustainable diet composition can alleviate hepatic stress and improve metabolic efficiency in fish.

Environmental conditions are also known to influence the condition factor and hepatosomatic index (HSI) of Bombay duck *(Harpadon nehereus)*. In the present study, the dissolved oxygen (DO) concentration in the sampling area ranged from 4.16 to 5.49 mg/L, with an average value of 4.92 mg/L^{-}. This range indicates that the water quality remains within normal limits, allowing marine life to thrive. According to Sudarja (1987), most marine organisms can tolerate DO concentrations ranging between 1.00 and 3.00 mg/L^{-1}, and higher oxygen availability generally enhances the physiological performance and overall health status of aquatic biota. Low DO concentrations have been shown to adversely affect both the condition factor and HSI of fish, resulting in reduced hepatic energy reserves due to oxygen stress (Qiang Ma *et al.* 2024). Therefore, optimal oxygenation levels in the aquatic environment play a crucial role in maintaining metabolic homeostasis, supporting liver function, and ensuring adequate energy allocation for growth and reproduction in Bombay duck *(Harpadon nehereus)*.

Sex Ratio

The sex ratio of Bombay duck *(Harpadon nehereus)* collected from the Malacca Strait between August and December 2023 is presented in Table 5. The ratio was determined as the proportion of males to females recorded each month during the sampling period. The results indicate that the number of males captured

Table 4 Condition factors and hepatosomatic index of bombay duck *(Harpadon nehereus)* collected from the malacca strait

Parameter	Types of Fish
	Harpadon nehereus
Internal condition factor (K1, %)	3.2753
Condition factor without viscera (K2, %)	2.9142
Hepatosomatic index (HIS, %)	0.00717

Table 5 Sex ratio of male and female Bombay duck *(Harpadon nehereus)* collected from the Malacca Strait from August to December 2023

Sex Ratio	Agustus	September	Oktober	November	Desember
Male : Female	1,54 : 1	1,65 : 1	3,60 : 1	1,60 : 1	2,10 : 1

consistently exceeded that of females, with the highest ratio observed in October (3.60:1). Ideally, a balanced sex ratio of 1:1 is expected in a stable population, as such an equilibrium promotes optimal reproductive success and genetic diversity. However, the observed fluctuations in sex ratio throughout the study period suggest a deviation from this balance. Such an imbalance may have long-term implications for population sustainability, as a skewed ratio can influence reproductive output, recruitment rates, and overall population dynamics of Bombay duck *(Harpadon nehereus)*.

The variation in sex ratio may be influenced by population dynamics factors, including recruitment, mortality, immigration, and emigration (Sapir *et al.* 2008). Additionally, environmental variables, migratory behavior, and sex-specific habitat preferences may also influence the relative abundance of males and females captured. Such imbalances can provide important insights into the population structure and indicate the potential resilience and long-term development of the species.

Variation in sex ratios among fish populations can be influenced by a range of physiological and ecological mechanisms, including temperature, salinity, seasonal fluctuations, interspecific interactions, and predation pressure (Fryxell *et al.* 2015). These factors can either determine sex differentiation or modulate the proportion of males and females within a population. Temperature is considered the most common environmental cue affecting sex determination; however, population density, pH, and hypoxic conditions have also been shown to influence sex ratios across diverse fish taxa (Baroiller *et al.* 2009; Alejandro *et al.* 2022). Furthermore, exposure to endocrine-disrupting compounds (EDCs) such as polychlorinated biphenyls (PCBs) and heavy metals has been demonstrated to interfere with reproductive processes and sexual differentiation in fish (ZhiChao & Kienzler, 2019; Roghaieh *et al.* 2024). These contaminants can disrupt hormonal balance and gonadal development, resulting in shifts in population-level sex ratios. The complex interactions between environmental contaminants and gonadal physiology highlight the vulnerability of aquatic organisms to both natural and anthropogenic stressors, which may have long-term implications for reproductive success and population stability.

Recent research by Suprakash C. *et al.* (2024) further emphasizes that multiple biotic and abiotic factors influence sex ratio dynamics in fish populations, including feeding habits, habitat location, food availability, age structure, seasonal variation, and intrinsic sexual dimorphism. Inadequate or imbalanced dietary intake, as well as fluctuations in food resources, can negatively impact overall population health and physiological well-being. Such nutritional stressors may indirectly alter sex ratios by modulating growth patterns, endocrine regulation, and the processes of sexual development.

Gonadal Maturity Stage (GMS)

Each individual of Bombay duck *(Harpadon nehereus)* exhibits varying stages of gonadal maturity, even among those of similar age or total length. This variation was observed in both males and females and is likely influenced by several interacting factors, including physiological condition, habitat quality, and food availability, all of which play critical roles in regulating gonadal development at the individual level. Figure 4 illustrates the distribution of gonadal maturity stages for male and female Bombay duck *(Harpadon nehereus)*, categorized according to body length classes. This graphical representation provides a clear depiction of the relationship between size class and reproductive status, offering valuable insights into the species' reproductive pattern and spawning potential across different length intervals.

Figure 4 illustrates the distribution of gonadal maturity stages (TKG) in male and female Bombay duck *(Harpadon nehereus)* from the Malacca Strait. The gonadal development of males was predominantly at Stage I within the length range of 150–261 mm, whereas Stages II and III began to appear between 230–245 mm, and Stage IV was observed at 246–261 mm. In females, Stage IV was most prevalent within the

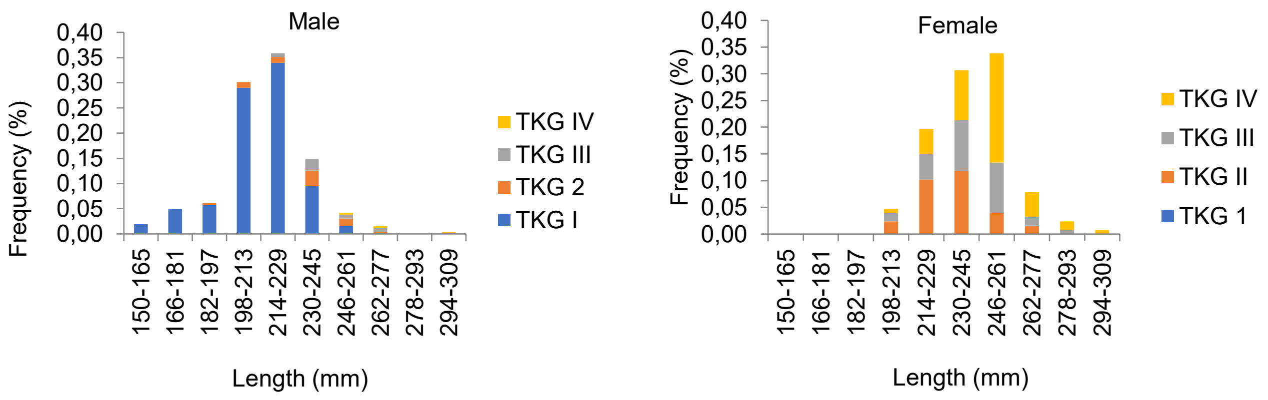

Figure 4 Gonadal maturity stages of male and female lomek fish (Harpadon nehereus) collected from the malacca strait.

length interval of 198–309 mm, while Stages II and III were identified in individuals measuring 198–277 mm. Previous studies, such as that by Taqwa *et al.* (2020), reported that the size at first gonadal maturity for Bombay duck *(Harpadon nehereus)* ranges between 202 and 210 mm, suggesting that multiple external factors, including environmental conditions and nutritional availability, may influence variations in size at maturity.

Environmental factors, including temperature, dissolved oxygen concentration, food type and availability, water quality, light intensity, and meteorological conditions, are key determinants that regulate fish reproductive processes. A reduction in the size at first gonadal maturity may serve as a biological indicator of environmental stress within fish populations (Tu *et al.* 2018). Joyanta *et al.* (2024) further emphasized that gonadal maturation is influenced by a complex interplay of genetic, physiological, and environmental factors, which collectively modulate reproductive development and contribute to population stability under changing environmental conditions.

Another crucial factor influencing gonadal maturation in fish is the concentration of sex steroid hormones, particularly estrogen (E2) and 11-ketotestosterone (11-KT), both of which play essential roles in reproductive regulation. Estrogen (E2) governs vitellogenin synthesis, which is vital for oocyte development in females, whereas 11-KT supports spermatogenesis and modulates reproductive behavior in males. Environmental conditions such as water flow dynamics and climate variability have also been reported to influence gonadal maturation in fish (Vania F. *et al.* 2024). According to Peter A.P. *et al.* (2023), gonadal maturity is further associated with an increase in the Gonadosomatic Index (GSI), which typically peaks during the Ov-2 and Ov-3 stages. At the Ov-3 stage, significant elevations in sex steroid hormones, including E2 and testosterone (T), indicate the physiological readiness of fish for spawning. The complex interaction between hormonal regulation and environmental factors suggests that gonadal development is not solely determined by intrinsic biological cycles but also modulated by external stimuli that trigger adaptive physiological responses to environmental changes.

CONCLUSION

The length-frequency distribution of male and female Bombay duck *(Harpadon nehereus)* in the Malacca Strait during the period of August–December 2023 varied, with male individuals ranging from 150 to 309 mm in total length, and females ranging from 198 to 309 mm. The length–weight relationship of both male and female Bombay duck *(Harpadon nehereus)* exhibited a positive allometric growth pattern, indicating that body weight increased proportionally faster than body length. The condition factor (K_2) was 2.9142%, and (K_1) was 3.2753%. In comparison, the hepatosomatic index (HSI) was 0.00717%, suggesting that the physiological condition of Bombay duck *(Harpadon nehereus)* was generally healthy, with condition factor (K) values ranging from 1 to 3. The sex ratio indicated a higher number of males than females, with an average ratio of 2.098:1, corresponding to gonadal maturity stage I (TKG I) in males and stage IV (TKG IV) in females. These findings provide a scientific basis for the sustainable management of Bombay duck *(Harpadon nehereus)*, including recommendations on fishing seasons, minimum catch size, and appropriate fishing gear types to conserve Bombay duck *(Harpadon nehereus)* stocks and ensure the ecological sustainability of Malacca Strait waters.

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