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Population Dynamics of Nile Tilapia (*Oreochromis niloticus*, L. 1758) in Lake Nubia, Sudan

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

This study aims to investigate the population dynamics of Nile tilapia (*Oreochromis niloticus*, Linnaeus, 1758) in Lake Nubia, Sudan. Monthly samples were collected from fishermen from January to December 2021, and recorded total lengths (TL) of 996 specimens nearest to 1.0 mm using a standardized measuring board; the lengths (TL) exhibited a range from 5.2 to 41.3 cm. Population parameters were assessed using the ELEFAN I routine within FiSAT II software, which produced von Bertalanffy growth parameters as follows: an asymptotic length (L_∞) of 43.05 cm, a growth curvature (K) of 0.230 yr^{-1}, and a theoretical length at age zero (t_0) of -0.1816. The growth performance index (Φ') was calculated to be 2.639. The instantaneous mortality rates were evaluated, revealing total mortality (Z) at 0.65 yr^{-1}, natural mortality (M) at 0.63 yr^{-1}, and fishing mortality (F) at 0.02 $year^{-1}$; While the exploitation rate (E) was determined to be 0.04 yr^{-1}. The size at first capture (L_c) was obtained as 5.2 cm, while L_{50} was estimated at 10.07 cm, both being below

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the size at first maturity (L_m) of 13.5 cm, and the longevity (T_{max}) was noted to be 12.86 years. The results indicated poor utilization of the Nile tilapia population in Lake Nubia, and its size at first capture and L_{50} was below the size at first maturity. This situation is an indication of the need for a continuous process of monitoring and managing to reduce the harvesting of smaller individuals and to improve productivity toward achieving levels that optimize sustainable yield.

Keywords: Lake Nubia; population dynamic; nile tilapia; FiSAT; mortality; exploitation.

1. INTRODUCTION

Sudan, one of the largest countries in Africa, has a rich diversity of water resources, including the Nile River and its tributaries, artificial reservoirs, irrigation canals, and haffirs (water harvesting basins); inland fish species have been documented in Sudan; Notably, Lake Nubia is recognized for its high species richness, accounting for 41% of the total fish species reported within the Nile system within Sudan (Abdalla and Adam 2024, Mahmoud et al. 2024, Neumann 2016).

Nile tilapia (*O. niloticus*) is an omnivorous species, that consumes a diverse diet (Tesfahun et al. 2018). This species exhibits high reproductive rates, spawning two times annually (Abdalla, 2018 and Bwanika et. al., 2007). and a life-span exceeding ten years (Mayank and Dwivedi, 2016). in freshwater ecosystems, tilapia ranks as the most economically significant fish (El-Sayed et. al. 2023). Tilapia is now cultivated in over 140 countries worldwide, with most of its production sourced from aquaculture. In 2017, aquaculture accounted for approximately 6.5 million metric tonnes of tilapia, while capture fisheries contributed less than 1 million tonnes, (FAO 2018).

To assess fish population dynamics, various methodologies have been employed; traditional techniques often utilize hard structures such as scales and otoliths to study the age and growth patterns of temperate fish; however, these methods are less frequently applied to tropical fish due to challenges such as high costs, time constraints, and limited access to advanced aging technologies (El-Sayed et al. 2023, FAO 2018, Assefa et al. 20019). Additionally, the formation of unclear growth rings in tropical environments complicates age estimation (Beaune et al. 2021, McConnell et al. 1987).

Globally, tilapia, encompassing all species, ranks as the second most significant group of farmed fish after Carp’s and is the most widely cultivated fish species (Abdelhadi 2011) Inadequate monitoring of commercially important fish stocks can result in population collapse, threatening food security and commercial fisheries (Worm et al. 2006). Effective stock assessments provide essential baseline data for evaluating these fish populations' status and implementing sustainable management practices (Ecoutin et al. 2005).

The primary aim of this study is to estimate population parameters of *Oreochromis niloticus*, including growth, and mortality rates, recruitment patterns, and exploitation rates, utilizing length-frequency distribution data; This analysis will contribute to the development of effective fisheries management strategies for *O. niloticus* in Sudan, and in Lake Nubia particularly, which has recently experienced significant climate changes.

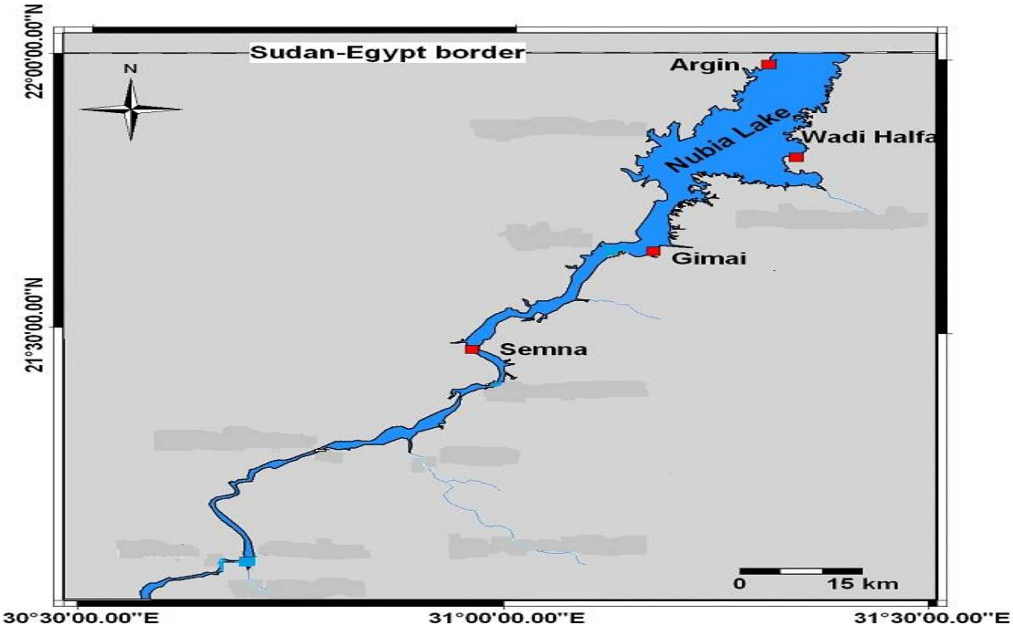
2. MATERIALS AND METHODS

2.1 Study Area

Lake Nubia, located within the northern border of Sudan, is part of the artificial reservoir created by the Aswan High Dam's construction in 1961 in Egypt. The lake extends approximately 180 km in length, averages 10 km in width, and has an average depth of 25 m, covering a total surface area of around 1,000 km² at maximum storage level (Ali, 1984) as shown in the Picture 1.

2.2 Data Collection

Specimens were collected monthly from fishermen at four sites: Argin, Semna, Wadi Halfa, and Gimai as illustrated in Pic. (1); from January to December 2021, samples were identified at the species level (Neumann et al. 2016). The total length (TL) of 996 specimens was recorded in the field from the tip of the snout to the tip of the upper lobe of the caudal fin, using a standard measuring board, (Karrar et al. 2016).



Picture 1. A map of Lake Nubia

2.3 Growth

The von Bertalanffy growth function (vBGF) growth parameters were estimated using FiSAT II software (version 1.2.2); (Gayanilo et al. 2005).

$$L_t = L_\infty [1-e^{-k(t-t0)}].$$

Where L_t (cm) is the length at a given time t, L_∞ (cm) is the asymptotic length, K is the rate at which L_∞ approached the asymptote; t_0 (yr) is not a direct output of FiSAT II from length-frequency data, an estimate was made independently using (Pauly and Gill 2005) empirical formula:

$$\text{Log}(-t_0) = -0.3922 - 0.2758 \times \log L_\infty - 1.038 \times \log K.$$

The growth performance index (Φ') was estimated using the formula proposed by (Munro and Pauly 1983).

$$\Phi' = 2\log L_\infty + \log K.$$

where K and L_∞ are growth parameters of the von Bertalanffy growth equation.

The longevity (also called maximum age, T_{max}) was obtained from (Pauly 1983) equation:

$$T_{max} = 3/K + t_0$$

2.4 Mortality Rates

Total mortality (Z): The instantaneous rate of total mortality (Z) was estimated using the length-converted catch curve method outlined by (Pauly 1983) as follows:

$$Z = \ln(dni/dti) = a + bti.$$

Where Z is the total mortality, *ni* is the number of fish in length class *i*, *dt* is the time needed for the fish to grow through length class *i*, *ti* is the age (or the relative age, computed with t_0 = 0) corresponding to the mid-length of class *i*, and *b* is the slope of the regression, with the sign changed, which provides an estimate of Z.

Natural mortality (M): The instantaneous rate of natural mortality (M) was calculated using (Pauly 1980) empirical formula using vBGF Parameters, L_∞ and K as mentioned above, and the mean annual surface water temperature of 25 °C, as follows:

$$\text{Log } M = 0.0066 - 0.27 \log L_\infty + 0.6543 \log K + 0.434 \log T.$$

Fishing mortality (F): The instantaneous rate of fishing mortality (F) was calculated as follows:

$$F = Z – M \text{ (Beverton and Holt 1957)}$$

Exploitation rate (E): The exploitation rate was calculated from the ratio between fishing mortality and total mortality, according to (Pauly 1983) as follows:

$$E = F/Z = F/M+F.$$

Maximum fishing effort (F_{max}) was determined as:

$0.67 \times K / 0.67 - L_c$ (Hoggarth et al. 2006).

The precautionary limit reference point (F_{limit}) was determined as:

⅔×M (Patterson 1982)

The precautionary target reference point (F_{opt}) was calculated as:

0.4×M (Pauly 1984)

2.5 First Maturity

First maturity (L_m or L_{50}) is defined as the length at which 50% of the population attains sexual maturity; To estimate L_m from maturity stage data, only individuals classified as maturity stages III and above were considered mature. The proportion of mature fish within each length class was calculated, and L_m was estimated following the methods outlined by (Gunderson et al. 1980). The relationship between the percentage of mature fish across length classes and fish length was modeled using a logistic curve:

$$P = 1/1+e^{(b\,L + a)}$$

Where P is the proportion of mature fish at length class x, *a* and *b* are model parameters (*a*, intercept and *b*, slope of the logistic regression) estimated by the regression, and L is the length of fish. The L_{m50} was then derived from the relationship of *a* and *b*.

$$L_m = -a/b.$$

2.6 Length at First Maturity (L_m)

The estimates described above were utilized to calculate the numerical percentage of specimens in the catches that exceeded the length at maturity (L_m). Additionally, the percentage of fish within the range between L_m and 10% of the length corresponding to optimum cohort biomass (L_{opt}) was determined, referred to as the L_{opt} range. Furthermore, the percentage of fish exceeding this L_{opt} range was assessed, termed mega-spawners (Froese 2004). These size-based indicators were employed to evaluate the status of the stock.

2.7 Length at First Capture (L_c)

The probability of capture was estimated according to (Gayanilo et al. 2005). The length at first capture (L_c) is defined as the length at which 50% of the fish become vulnerable to capture; It is estimated using the (Beverton and Holt 1957) equation, which incorporates the growth constants of the von Bertalanffy growth function (vBGF), the mean length of the fish catch (ȴ), and the total mortality parameter (Z):

$$L_c = ȴ - K \times (L_\infty - ȴ) \div Z.$$

Estimation of age at first capture (tc_{50}) was according to (Beverton and Holt 1957).

2.8 Recruitment Pattern

The age at first capture (t_c) was determined using the estimated growth parameters (L_∞, K, and t_0) through the ELEFAN I method, which projects and analyzes length-frequency data. This approach identifies the number of seasonal recruitment pulses reflected in the length-frequency data (Gayanilo et al. 2005). To estimate the recruitment pattern, the "Percent of sample total" option in FiSAT was selected, given the variability in sample sizes.

2.9 Relative Yield Per Recruit (Y/R)

Relative yield per recruit (Y/R) and relative biomass per recruit (B/R) values were calculated as a function of exploitation (E), using the estimated growth parameters and probability of capture by length (L_c) (Pauly and Soriano 1986). The calculations were carried out using the FiSAT software package.

2.10 Virtual Population Analysis (VPA)

Estimated length structured (VPA) Analysis was conducted using the FiSAT II routine (Gayanilo et al. 2005). The inputs included the values of L_∞, K, M, F, a (constant), and *b* (exponent). The constants *a* and b were estimated from the length-weight relationship ($W = aL^b$).

The exploitation rates (biological reference points) at the maximum (E_{max}), ($E_{0.1}$), and ($E_{0.5}$) were worked out using Beverton and Holt's model of relative yield per recruit (Y'/R) and relative biomass per recruit (B'/R), utilizing the knife-edge selection (Ts) procedure as a function of exploitation rate (E), incorporated into the FiSAT II software (Gayanilo et al. 2005). The length at optimum cohort biomass or yield pre-recruitment (L_{opt}) was estimated from L_∞, K, and M, using the (Beverton 1992) formula:

$L_{opt} = L_\infty * (3/3 + M/K)$.

Where, L_∞, K, and M are as defined above.

3. RESULTS

3.1 Growth Parameters

This study shows that most specimens varied in length between 10 and 28 cm (Fig. 1); The length-frequency data, analyzed using ELEFAN I in FiSAT II, revealed a von Bertalanffy growth curve for Nile tilapia in Lake Nubia, Monthly analyses indicated that the fish lengths exhibiting the highest mode are represented by black bars, while those with the lowest mode are indicated by white bars, revealing fourteen cohorts in the population (Fig. 2); The parameters of growth estimated were L_∞ = 43.05 cm, K = 0.230 year^{-1} and t_0 = -0.1816 (Fig. 2 and Table 1); Moreover, the growth performance index (Φ') was calculated to be 2.639, with a potential longevity of 12.86 years (Table 1); The von Bertalanffy growth equation is expressed as:

$$L_t=43.5\times[1-\exp(-0.230\times(t+0.1816))]$$

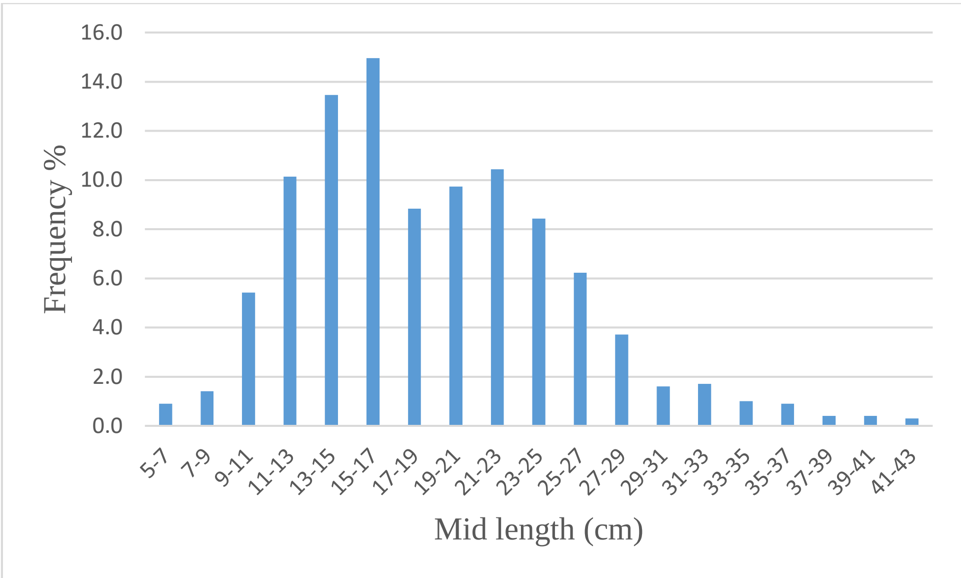


Fig. 1. size spectrum of the Nile tilapia in Lake Nubia (n=996); sizes are represented by the total length

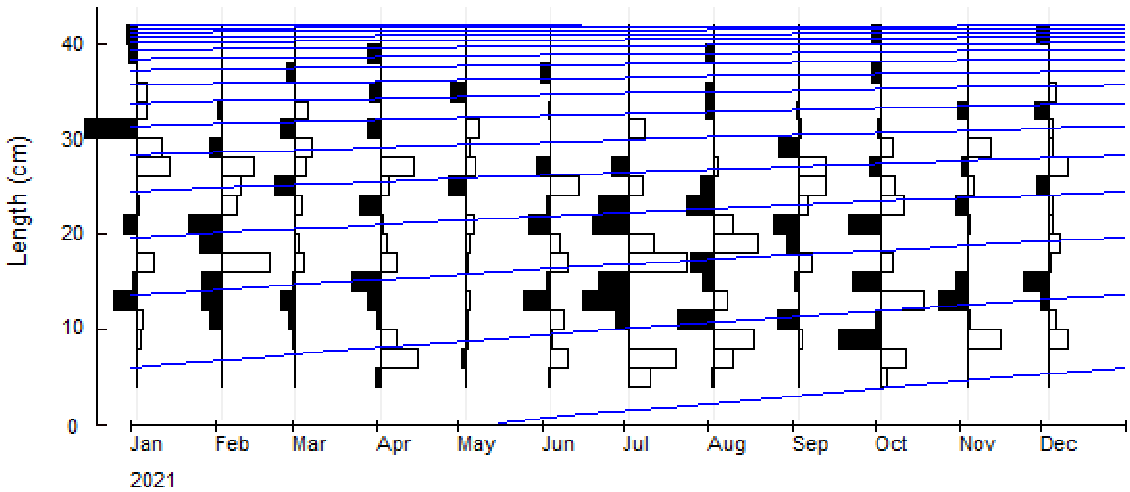


Fig. 2. Von Bertalanffy growth curve of *O. niloticus* via ELEFANI based on the length-frequency distribution (L_∞ 43.05 cm and K 0.230 yr $^{-1}$)

3.2 Mortality Rates

The instantaneous rate of total annual mortality (Z) was calculated from the linearized length-converted curve described by (Pauly 1983) and was determined as 0.65 yr^{-1}; The natural mortality coefficient (M) was calculated at 0.63 yr^{-1}, while the fishing mortality (F) was obtained by subtracting M from Z and found to be 0.02 yr^{-1} (Fig. 3 and Table 1).

3.3 Exploitation Rate

The exploitation rate (E) is the fraction of deaths caused by fishing; (E) was calculated from E= F/Z; E = F/ (F+M), (Gulland 1971) and estimated at 0.04 in this study (Fig. 3 and Table 1).

The probability of capture indicated that the overall length at which 50% of the fish were vulnerable to capture was 10.07 cm TL; the recruitment pattern of *O. niloticus* in Lake Nubia showed two-round of recruitment; with peaks during May/June and August/October; It started to rise in April and reached a peak during May/June, then declined through July, another peak during the period from August to October and witnessed no recruitment through November/December, as shown in (Figs. 4 and 5, and Table 1).

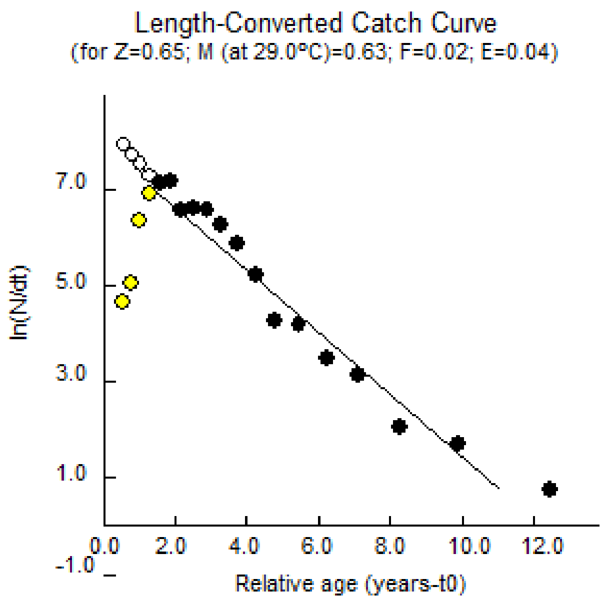


Fig. 3. Von Bertalanffy growth curve (a) (L_∞=43.05 cm; K = 0.230 yr^{-1}; on length-frequency distribution and linearized length-converted catch curve of Nile tilapia in Lake Nubia

Table 1. Fundamental information on the biological parameters of *O. niloticus* population in Lake Nubia during the study period

Parameters	Estimated values	Parameters	Estimated values
L_∞ (cm)	43.05	E ($year^{-1}$)	0.04
K ($year^{-1}$)	0.230	E_{max}	0.421
Phi (Φ')	2.639	E_{01}	0.355
t_0 (year)	-0.1816	E_{05}	0.278
T_{max} (year)	12.86	L_c or (L_{50})	10.07 cm
Z ($year^{-1}$)	0.65	L_{25}	8.49 cm
M ($year^{-1}$)	0.63	L_{75}	11.65 cm
F ($year^{-1}$)	0.02	L_{opt}	22.74 cm
Z/K	2.83	L_m	13.5 cm
L_∞/L_c	0.05	M/K	1
F_{max}	0.18	F_{opt}	0.252
F_{limit}	0.42		

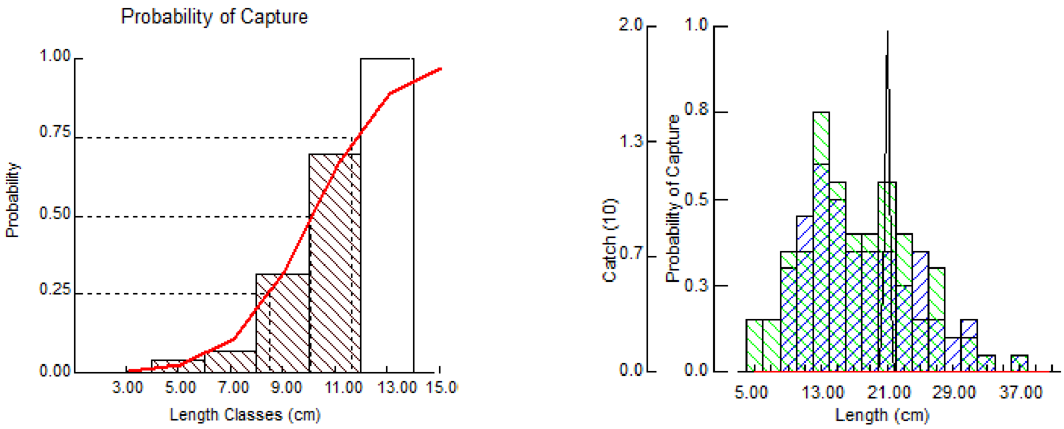


Fig. 4. The selective curve shows the probability of capture

Fig. 6. The maximum relative yield per recruit (Y/R) was obtained for an exploitation rate (E_{max}) at 0.421 as deduced from Fig. (6). The respective exploitation rates which account for 10% and 50% of the maximum Y/R, referred to as E_{01} and E_{05}, were estimated at 0.355 and 0.278, respectively, assuming L_c/L_∞ at 0.050 and M/K at 1.00. The calculated length for optimal cohort biomass or yield before recruitment (L_{opt}) was 22.74 cm (TL). This study shows the maximum fishing effort, F_{max}; precautionary limit reference point (F_{limit}), and precautionary target reference point (F_{opt}) for Nile tilapia in Lake Nubia, which were recorded as 0.18, 0.42, and 0.252, respectively, as presented in Table 1.

The length-frequency data analysis showed that the mean ± SD asymptotic length (L_∞) for the Nile tilapia population in Lake Nubia was 30.00 ± 0.2 cm, and the corresponding von Bertalanffy growth rate constant K was 1.5 ± 0.2 yr^{-1}; The maximum reported length was 35.00 cm, while the estimated maximum length was 39.04 cm, with a 95% confidence interval ranging from 33.38 to 44.70 cm.

The observed lengths at percentiles were: L_{25}= 8.49 cm, L_{50}= 10.07 cm, and L_{75}=11.65 cm; Length at first maturity, L_m was estimated at 13.5 cm while the optimum length, L_{opt} was estimated at 22.74 cm, and the length at first capture, L_c was recorded as 5.2 cm. The calculated ratios were: L_c/L_∞=0.050; M/K=1.00, and Z/K=2.83. Whereas the maximum fishing effort (F_{max}) was 0.18, the precautionary limit reference point (F_{limit}) = 0.42, and the precautionary target reference point (F_{opt}) was 0.252.

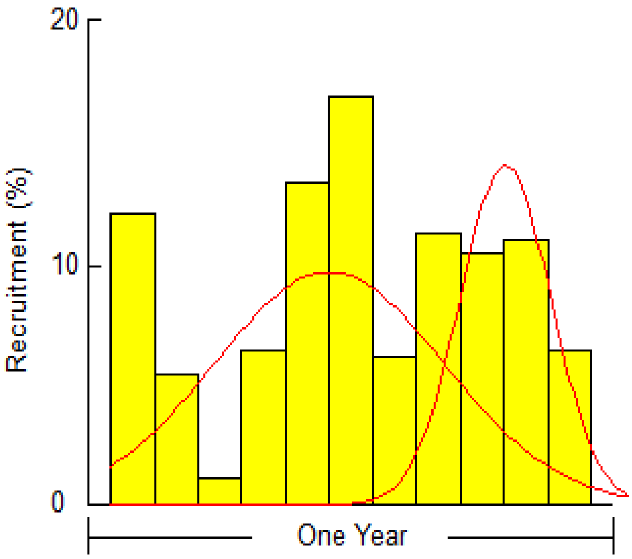


Fig. 5. The seasonal recruitment pattern

Table 2. Estimated growth parameters, mortalities, exploitation rate ($yr.^{-1}$), and growth performance index of *O. niloticus* in various regions obtained from the literature

Location	L_∞ (cm)	K (yr^{-1})	Phi (Φ')	t_0 (yr)	Z	M	F	E	Author
Khashm El-Girba reservoir, Sudan	36.75	0.650	2.943	-0.63	2.38	1.22	1.16	0.49	(Abdalla et al. 2024)
Lake Abaya, Ethiopia	49.35	0.36	3.00	-0.40	1.34	0.34	1.00	0.5	(Shija 1758)
Lake Langeno, Ethiopia	35.70	0.32	2.61	-0.49	2.31	0.82	1.56	0.67	(Tesfaye et al. 2022)
Lake Chamo, Ethiopia	59.4	0.41	3.16	-0.48	2.44	0.57	1.88	0.771	(Tesfaye et al. 2021)
Nam Theun 2 reservoir, Lao PDR	52.5	0.23	2.085		1.41	0.30	1.11	0.79	(Beaune et al. 2021)
Siombak Lake, Indonesia	36.04	0.59		0.087	3.04	1.24		0.59	(Muhtadi et al. 2021)
Halali reservoir, India	46.73	0.63		0.171	1.32	0.60	0.72	0.54	(Johnson et al. 2020)
Manzala Lake, Egypt	34.52	0.38	2.66	-0.39	2.02	0.82	1.20	0.59	(Mehanna et al. 2020)
Garmat Ali River, Iraq	30.45	0.45	2.62	-0.313	3.26	1.03	2.24		(Salman and Mohamed 2020)
Sakumo II, Ghana	19.4	0.54	2.309	-0.34	1.84	1.30	0.54	0.29	(Amponsah et al. 2020)
Lake Naivasha, Kenya	42	0.21	2.57		0.80	0.55	0.26	0.23	(Waithaka et al. 2020)
NT2 reservoir, Lao PDR	65.8	0.08		-0.66					(Tessier et al. 2019)
Lake Tana, Ethiopia	44.1	0.44	2.93	-0.34	2.37	0.98	1.39	0.52	(Assefa et al. 2019)
Lake Chamo, Ethiopia	55	0.37		-0.467	1.509	0.79	0.72	0.48	(Shija et al. 2019)
El-Bahar El-Faraouny, Egypt	37.27	0.294	2.611	-0.089	1.15	0.654	0.496	0.432	(El-Kasheif et al. 2015)
Lake Toho, Benin	41.5	0.33	2.70	-0.75	1.10	0.74	0.36	0.33	(Montcho et al. 2015)
River Nile (Aswan), Egypt	25.73	0.73			3.64	1.44	2.22	0.60	(El-Bokhty et al. 2014)
Lake Victoria, Kenya	53.9	0.50	3.30		2.83	0.91	1.92	0.68	(Njiru et al. 2008)
Nyanza Gulf, Kenya	58.78	0.59	3.31	-0.64	2.16	1.00	1.12	0.48	(Njiru et al. 2007)
Wadi El-Raiyan, Egypt	28.92 - 48.05	0.34 - 0.54	2.59 – 4.44	-0.14 to -0.26	2.59 – 4.44	0.59 – 0.97		0.77 – 0.78	(Mehanna 2005)
Kaptai Reservoir, Bangladesh	55.59	0.39	3.081	-0.13	0.80	0.59	1.39	0.42	(Ahmed et al. 2003)

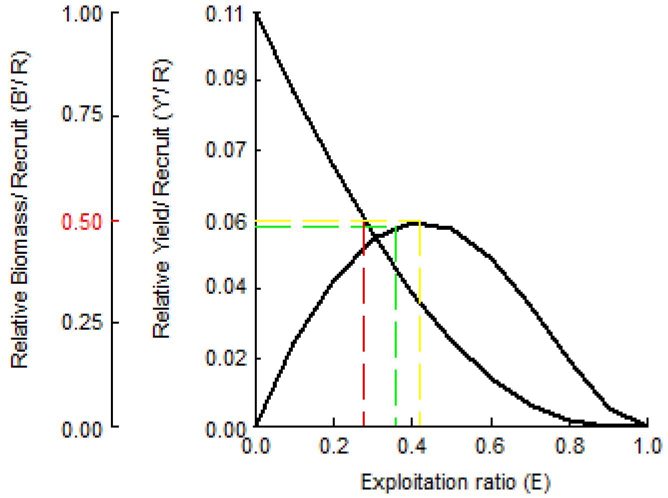


Fig. 6. Beverton and Holt relative yield per recruitment (Y/R) and biomass per recruit (B/R) of the *O. niloticus* in Lake Nubia

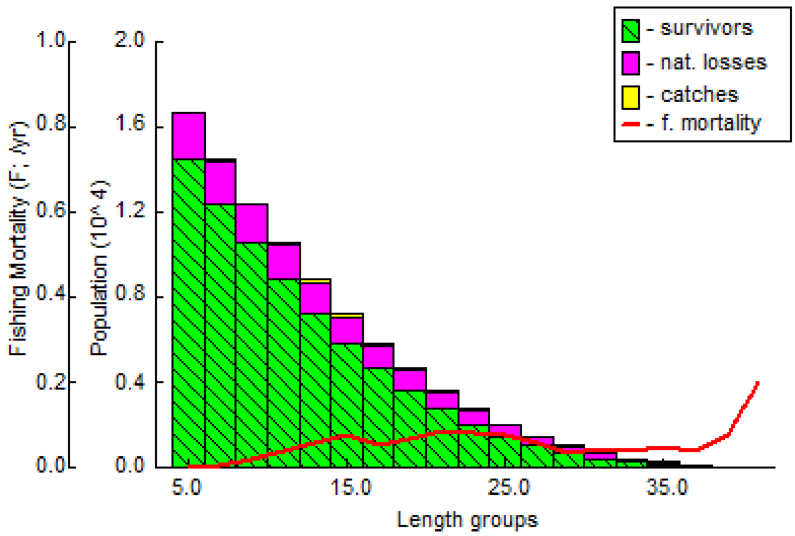


Fig. 7. Length-structured virtual population analysis of *O. niloticus* in Lake Nubia

4. DISCUSSION

The findings of this study reveal that the majority of specimens measured between 10 and 28 cm in total length (Fig. 1), this distribution shows slight variation when compared to the length range of *O. niloticus* reported in Khashm El-Girba (Abdalla et. al., 2024). Length-frequency analysis using the ELEFAN I method in FiSAT II indicated a von Bertalanffy growth curve of Nile tilapia in Lake Nubia; the parameters were as follows: L_∞ = 43.05 cm, K = 0.230 yr.$^{-1}$, and t_0 = -0.1816; as shown in (Fig. 2 & Table 1); several researchers have studied the growth of Nile tilapia, noting an inverse relationship between asymptotic length and growth rate; some of the previous studies indicated that the asymptotic length of Nile tilapia ranged between 19.4 and 65.8 cm in Sakumo II (Ghana) and the NT2 reservoir (Lao PDR) according to (Amponsah et al. 2020 and (Tessier et al. 2019) respectively; the asymptotic length observed in Lake Nubia falls with these results, showing only minor variation when compared to data from Halali Reservoir (India), Lake Naivasha (Kenya), Lake Tana (Ethiopia), Lake Toho

(Benin), and Wadi El-Raiyan (Egypt) respectively, according to (Njiru et al. 2008, Waithaka et al. 2020, FAO 2018, Montcho et al. 2015, Mehanna 2005). However, this study's results disagree with those of other researchers who reported lower symptomatic lengths in various regions, including Khashm El-Girba Reservoir (Sudan), Lake Langeno (Ethiopia), Siombak Lake (Indonesia), Manzala Lake (Egypt), Garmat Ali River (Iraq), and the River Nile (Aswan, Egypt) as recorded by (Abdalla et al. 2004, Tesfaye et al. 2022; Muhtadi et al. 2021; Mehanna et al. 2020; Salman and Mohamed 2020; Amponsah et al. 2020; El-Kasheif et al. 2015, El-Bokhty et al. 2014) the observed differentiation may be associated to variations in fishing methods, sample collection, environmental conditions, and geographic locations. Furthermore, (Shija 2004, Tesfaye et al. 2021, Shija et al. 2019, Tessier et al. 2019, Assefa et al. 2019, Njiru et al. 2007, Njiru et al. 2008, Ahmed et al. 2003) have documented growth functions across various regions including Ethiopia (Lake Abaya and Chamo), Lao PDR (NT2 reservoir), and Kenya (Lake Victoria and Nyanza Gulf), as well as Kaptai Reservoir (Bangladesh); the differences in growth rates may relate to food availability and suitable water conditions, which support higher growth rates.

This study indicates that the growth performance index (Φ') for Nile tilapia from Lake Nubia is 2.639 (Table 1), which is comparable to results documented in Lake Manzala and El-Bahar El-Faraouny (Egypt), Lake Langeno (Ethiopia), Garmat Ali river (Iraq), and Lake Toho (Benin), (Mehanna et al. 2020, El-Kasheif et al. 2015; Tesfaye et al. 2022; Salman and Mohamed 2020, Montcho et al. 2015) it differs from findings reported by several researchers in different locations. For instance, (Abdalla et al. 2024) noted a growth performance index of 2.943 for Nile tilapia in Khashm El-Girba, while (Shija 2024) reported Φ = 3.00 in Lake Abaya (Ethiopia), and (Tesfaye et al. 2021) observed 3.16 in Lake Chamo (Ethiopia); the highest value recorded was 4.44 in Wadi El-Raiyan (Salman et al. 2020) and the lowest, 2.08, was found in the Nam Theun 2 reservoir (Lao PDR) according to (Beaune et al. 2021) The study also reveals that the longevity of Nile tilapia can reach up to 12.9 years as illustrated in (Table 1); in contrast, (Abdalla 2018) found that the lifespan of Nile tilapia in Khashm El-Girba Reservoir and Atbara River averages around 3+ years, while (Mayank and Dwivedi 2016) reported a maximum of 10 years.

This study shows that the total annual mortality rate (Z) for Nile tilapia (*O. niloticus*) was calculated using the linearized length-converted curve (Pauly 1983) resulting in a value of 0.65 yr^{-1}. The natural mortality coefficient (M) was found to be 0.63 yr^{-1}, while fishing mortality (F) was obtained using the equation $F=Z-M$, leading to a fishing mortality rate of 0.02 yr^{-1} (Fig. 3 and Table 1); In comparison to previous studies, total mortality rates for Nile tilapia range from low rate (0.8 yr^{-1}) in Lake Naivasha (Kenya) and Kaptai reservoir (Bangladesh) (Waithaka et al. 2020, Ahmed et al. 2003). to as high as 3.64 yr^{-1} in the Nile River at Aswan (El-Bokhty et al. 2014). Natural mortality has been documented at a low of 0.30 $year^{-1}$ in Nam Theun 2 reservoir (Lao PDR) (Beaune et al. 2021) and a high of 1.44 $year^{-1}$ in Aswan, Egypt (El-Bokhty et al. 2014 additionally, (Waithaka et al. 2020) reported a low fishing mortality rate of 0.26 $year^{-1}$ in Lake Naivasha, while [38] found a natural mortality rate of 2.24 $year^{-1}$ in Garmat Ali River, Iraq. The findings from this study demonstrate that the total, natural, and fishing mortality rates differ significantly from those reported for the Khashm El-Girba reservoir (Abdalla et al. 2024) which indicated total, natural, and fishing mortality rates of 2.38, 1.22, and 1.16 yr^{-1}, respectively; These higher rates in Khashm El-Girba can be attributed to its smaller area than Lake Nubia and differences in annual flushing, geographical factors, fishing activities, and equipment utilized; A similar situation is observed in the Nile River at Aswan (Egypt) (El-Bokhty etbn al. 2014) and Lake Tana in Ethiopia (Assefa et al. 2019) where total, natural, and fishing mortality rates are higher than those in Lake Nubia due to varying fishing pressures; However, mortality rates from El-Bahar El-Faraouny (Egypt) align more closely with the findings of (El-Kasheif et al. 2015).

The exploitation rate (E), which indicates the proportion of total mortality assigned to fishing, was calculated using the formulas $E=F/Z$ or $E=F/(F+M)$ (Gulland 1971) resulting in an estimate of 0.04 (Fig. 3 and Table 1); This suggests a low level of exploitation for Nile tilapia in Lake Nubia, which does not approach the sustainable yield edge of 0.5; Comparatively, (Abdalla et al. 2024) reported an exploitation rate of 0.49 for Nile tilapia in the Khashm El-Girba reservoir, highlighting a significant difference in fishing intensity. Some Nile tilapia fisheries remain below optimal exploitation levels (E =

0.23 – 0.48), as appears in Lake Naivasha (Kenya), Lake Sakumo II (Ghana), Lake Toho (Benin), El-Bahar El-Faraouny (Egypt), Nyanza Gulf (Kenya), and Lake Chamo (Ethiopia) (Waithaka et al. 2020, Amponsah et al. 2020, Montcho et al. 2015, El-Kasheif et al. 2015, Njiru et al. 2007, Shija et al. 2019). Notably, (Shija et al. 2024) indicated that Lake Abaya (Ethiopia) has reached an optimal exploitation level (E = 0.5), while other fisheries such as Lake Tana, Langeno, and Chamo (Ethiopia), the Nile River (Aswan, Egypt), Lake Victoria (Kenya), and Wadi El-Raiyan (Egypt) have exceeded optimal levels, with rates ranging from 0.52 in Lake Tana (Ethiopia) to 0.78 in Wadi El-Raiyan in Egypt (Assefa et al. 2019, Tesfaye et al. 2022, Tesfaye et al. 2021, El-Bokhty et al. 2014, Njiru et al. 2008, Mehanna 2005). The observed differences in exploitation rates may be linked to the specific characteristics of fisheries in Lake Nubia, their distance from consumption centers, high transportation costs, the types of fishing gear employed (such as beach seines), and limited fishing activities in deeper waters. Furthermore, the results indicate that natural mortality (M = 0.63 yr^{-1}) is significantly higher than fishing mortality (F = 0.02 $year^{-1}$), leading to a meager exploitation rate (E = 0.04) for Nile tilapia resources. This finding suggests a pressing need to implement effective management programs for Lake Nubia to enhance productivity and achieve optimal exploitation levels, ultimately ensuring the sustainability of this critical resource.

The capture probability analysis revealed that the length at which 50% of Nile tilapia (*O. niloticus*) are vulnerable to capture is 10.07 cm total length (Fig. 4 and Table 1). In contrast, (Abdalla et al. 2024) reported a capture probability of 15.65 cm for Nile tilapia in the Khashm El-Girba reservoir, additionally, (Amponsah et al. 2020) found a lower capture length of 4.1 cm in Sakumo II, Ghana, while (Assefa et al. 2019) recorded a capture probability of 18.14 cm in Lake Tana (Ethiopia). Recruitment patterns in Lake Nubia showed two distinct peaks for *O. niloticus*, occurring in May/June and August/October, with initial recruitment detected in April. The recruitment peaked in May/June before declining in July and then peaking again from August to October, with no recruitment observed in November/December (Fig. 5 and Table 1); These findings differ with (Abdalla et al. 2024) who reported a single annual recruitment event in Khashm El-Girba during April/May, peaking in June/July; However, the results align with those of (Amponsah et al. 2020) who similarly identified two recruitment peaks in Sakumo II; In contrast, (Assefa et al. 2019) noted a year-round recruitment pattern in Lake Tana, with a peak during May/June. The maximum relative yield per recruit (Y/R) was attained at an exploitation rate (E_{max}) of 0.421; corresponding to virgin fisheries for 10% ($E_{0.1}$) and complete fisheries at 50% ($E_{0.5}$) of maximum Y/R were 0.355 and 0.278, respectively, with L_c/L_∞ = 0.050 and M/K = 1.00. The optimal length for cohort biomass or pre-recruitment yield (L_{opt}) was established at 22.74 cm TL. These results are consistent with those reported by (Abdalla et al. 2024) and (Amponsah et al. 2020) who reported E_{max}, $E_{0.5}$, and $E_{0.1}$ values of 0.48, 0.35, and 0.35, respectively. However, the findings differ from those of (Assefa et al. 2019) in Lake Tana, which reported E_{max}, $E_{0.1}$, and $E_{0.5}$ values of 0.52, 0.45, and 0.32, respectively.

Length-frequency analysis indicated a mean asymptotic length (L_∞) for the Nile tilapia population in Lake Nubia of 30.00 ± 0.2 cm, with a von Bertalanffy growth function (vBGF) growth rate constant (K) of 1.5 ± 0.2 yr^{-1}; The observes maximum length was 35.00 cm, while the predicted maximum reached 39.04 cm, with a 95% confidence interval ranging from 33.38 to 44.70 cm. There is no significant difference in the asymptotic length of *O. niloticus* between the Khashm El-Girba and Lake Nubia fish populations according to results obtained by (Abdalla et al. 2024). Specific length percentiles were as follows: L_{25} = 8.49 cm, L_{50} = 10.07 cm, and L_{75} = 11.65 cm. The size at first maturity (L_m) was determined to be 13.5 cm, with an optimal length (L_{opt}) of 22.74 cm and a first capture length (L_c) of 5.2 cm. Key ratios included L_c/L_∞ = 0.050, M/K = 1.00, and Z/K = 2.83. The exploitation rates were $E_{0.1}$ = 0.355, $E_{0.5}$ = 0.278, and E_{max} = 0.421 $year^{-1}$. For the total population, L_{50} was found to be 9.5 cm, L_{75} was 12 cm, and the maximum fishing mortality (F_{max}) was 0.18. These findings underscore the importance of understanding the dynamics of Nile tilapia populations with fishing pressure and recruitment patterns, which are crucial for effective fishery management.

5. CONCLUSION

This study provides significant insights into the population dynamics of Nile tilapia (*O. niloticus*) in Lake Nubia, indicating a length range of 10 to 28 cm; the estimated growth parameters are L_∞ = 43.05 cm and K = 0.230 $year^{-1}$; The low fishing mortality (F = 0.02 $year^{-1}$) compared to natural mortality (M = 0.63 year⁻¹) and total mortality (Z = 0.63) suggests that fishing pressure is minimal, as reflected in the exploitation rate (E = 0.04), indicating that current fishing practices fall below the optimum sustainable yield; Recruitment patterns revealed two significant peaks in May/June and August/October. Based on the study results, the Lake requires monitoring and adaptive management strategies programs to enhance productivity and optimize the exploitation of Nile tilapia resources to achieve maximum sustainable yields; Additionally, further studies on population dynamics, particularly for commercially important fish, are essential to develop effective management and resource utilization plans that ensure maximum benefits and sustainability.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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