INTRODUCTION

The current Ethiopian fish production potential estimates using empirical models from its inland fisheries is about 94,500 t per year, of which 73,100 t from lentic (lakes, reservoirs and ponds) and about 21,400 t from lotic (rivers) ecosystems[1]. The majority of the Ethiopian lakes are confined within the rift valley that extends from the Kenyan border in the south to the Afar depressions in the north, with the major lakes including Abaya, Chamo, Ziway, Shala, Langeno, Abijata Hawassa and Beseka/Matahara[2]. Fish productions in the country are mainly artisanal and commercial fisheries are concentrated to Lakes Tana, Chamo, Hawassa, Ziway and Turkana[1]; where all these lakes except Tana are found in the rift valley.

Nile tilapia (*Oreochromis niloticus)* is among the commercially important indigenous fish species in Ethiopia and constituted over 50% of the annual average catch of the country's fish production during 1998-2010[1,3], but recently declining according to the national report in 2015. The fish contributes from 61-90% of the total landings in the rift valley lakes[4]. The tilapia fish is among the most studied group of fish in the country due to its economic importance and its different biological properties in different natural and manmade environments. The studies so far undertaken covered their length weight relationship, reproductive and feeding biology[4-11], gear selectivity against maturity[12] and their maximum sustainable yield in fishery stock assessment[13]. However, a comprehensive investigation regarding reproductive characters of the populations was not conducted in detail so as to use the information for proper fishery management and also as basic information for genetic improvement in aquaculture development.

Environmental factors affect growth performances and reproductive characters of *O. niloticus* populations in the process of adapting to different environments[14-16], though the *O. niloticus* tend to breed throughout the year in tropical region. Aquatic environments of the three rift valley lakes (Chamo, Koka and Ziway) in terms of their basic morphometric features, altitude, water quality parameters and fish species diversity are different[2,17]. Under these different environmental conditions of the three lakes, their *O. niloticus* populations are expected to develop different phenotypic and genetic characters. Phenotypic variation is wide in organisms spread in different geographical locations and often involves ecologically relevant behavioral, physiological, morphological and life-history traits. Phenotypic character differences were observed between the *O. niloticus* populations of Chamo, Koka and Ziway in a study made parallel to this one (unpublished data).

In an effort to develop the aquaculture sector in Ethiopia, seeds of *O. niloticus* were collected from natural environments, especially from the Ethiopian rift valley lakes to stock aquaculture ponds. Moreover, in an attempt to select better-performing strains for aquaculture, tilapia populations from different Ethiopian rift valley lakes were evaluated for their growth performances. The tilapia populations from different Ethiopian rift valley lakes: Chamo, Hawassa, Hora, Koka, Matahara and Ziway showed different growth performances in pond culture[18,19] whereby the Chamo, Koka and Ziway strains were reported to have performed better. Investigations on biological parameters such as length-weight relationship, condition factor and size at first sexual maturity are the easiest means of determining the stress of fishing pressure and water pollution on fish populations[20]. Studies on breeding season and associated factors are needed to protect new recruits and predict recruitment variability. Number of recruitment in fish stock depends on availability of sexually mature fishes in the water bodies[21].

Characterization of the *O. niloticus* population helps in utilization of the resource in aquaculture and further contributes to protect the population in their natural environments. Hence, the aim of the present study was to investigate the reproductive characteristics of the *O. niloticus* of rift valley lakes with specific objective of investigating sex ratios, breeding season, size at first sexual maturity and fecundity of the *O. niloticus* populations of Lakes Chamo, Koka and Ziway as an input for proper fishery management and indication of their reproductive quality in aquaculture development.

MATERIALS AND METHODS

Study areas: This study was conducted in three Ethiopian Rift Valley lakes: Chamo, Koka and Ziway (Fig. 1) from May, 2018 to April, 2020. The lakes were selected for their significant contribution in the fishery production and Nile tilapia (*O. niloticus*) populations were targeted as these are candidate fish species in the development of aquaculture in Ethiopia. The lakes are found in different water basins; Koka having largest watershed area followed by Ziway while Chamo (with no visible outlet) has the lowest watershed area. In morphometry, Ziway is the widest and the shallowest Lake of the three[22-24]. Sites for data collection and fish landing from each lake were purposely selected to represent the fish catches from inlet region, middle of the lake and outlet region.

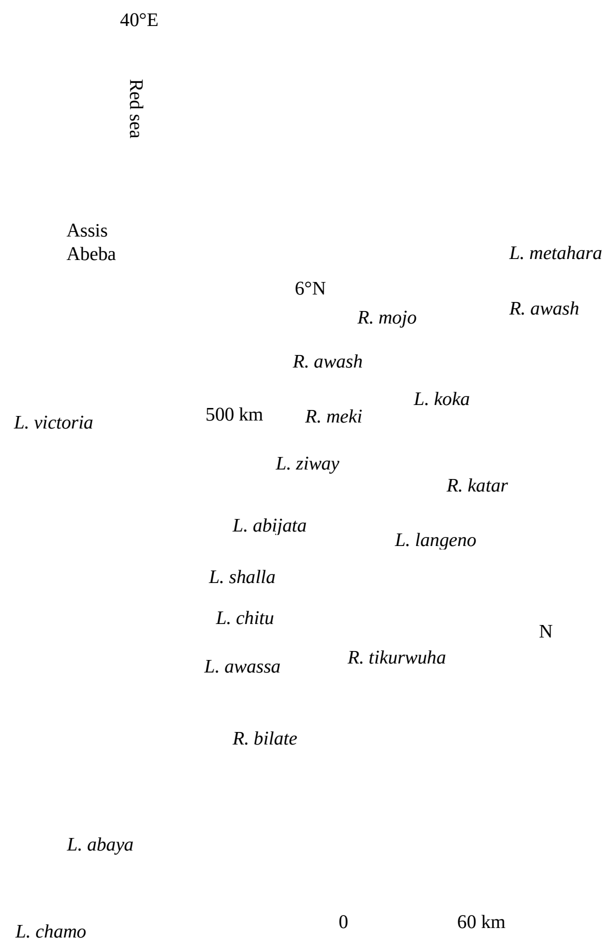

Fig. 1: Location of the Ethiopian rift valley lakes (modified after Kebede *et al.*[25])

Data collection methods: Fish samples were sampled from fishermen at the landing sites on arrival through facilitation of the cooperative chairpersons. The data were collected for two years 'seasonally', from May, 2018-2020. The data collection periods were classified into four 'seasons' in a year as pre-rainy season, main rainy season, post-rainy season and dry season, represented by sampling months of May, July-August, October-November and February-March, respectively for Lakes Koka and Ziway in this study. The rain distribution and season in the three study areas differ; whereby the main rainy season is during the months of June, July and August at Lakes Koka and Ziway while it is during April and May at Chamo Lake. Moreover, October-November months are characterized as season of short rain at Chamo. Accordingly, the data months of May, July-August, October-November and February-March represent the 'seasons' of main rainy season, post-rainy season, short-rain season and dry/pre-rainy season, respectively at Lake Chamo.

Sex ratio determination: A total 1,547 random fish samples from three lakes, Chamo, Koka and Ziway were used in sex ratio determination. At least 30-40 fish samples per landings were sampled every time as a minimal sample size to represent the normally distributed population for statistical computation, except when there was no/less fishing in some landing sites because of 'lake drying' as in Bekele landing site of Lake Koka for the month of May or increasing of Lake level (discouraging the fishermen to set nets) and coinciding with busy crop cultivation period.

The samples were immediately taken to temporary shed or processing shed (at Lakes Chamo and Koka) or to fishery lab in the case of Lake Ziway for data (sex, length, weight) collection. Sex identification of *O. niloticus* was made by visual observation into their genital papilla and observation of gonads after dissecting their abdomen. The proportion of females and males in the samples was calculated[26] after recording the frequencies of the sexes in each of the lakes in every sampling season. Sex ratio was expressed as Female: Male and tested against an expected ratio of 1:1 using the chi-squared test at p-value of 0.05.

Length at first sexual maturity: Lengths of the sampled fish were measured on a portable measuring board of 50 cm length graduated at 0.1 cm level. Total Length (TL) of the fish was measured to the nearest 0.1 cm from all sampled fish. Fish Total Weight (TW) was measured to the nearest 0.1g using a sensitive balance, LD610-2, Max = 610, d = 0.01 g. The L_{50} is the onset of sexual maturity at which 50% of the fish have reached sexual maturity. The female's and male's gonad maturity stages were identified based on macroscopic gonadal maturation stages[27] whereby the female's gonad classified into five maturity stages and that of males into four stages. The five stages in ovaries classified as immature, maturing, ripe, spent or resting. The male's four gonad maturity stages are classified as immature, maturing and ripe or spent.

Based on the maturity stages, the fish were grouped into immature (maturity stage-I and stage-II) and mature (maturity stage-III and above). The relationship between the percentage of mature fish (P) per length class and fish total length (L in cm) was described with a logistic curve and L_{50} was estimated according to Gunderson *et al.*[28]:

$$P = \frac{1}{1e^{(bL+a)}}$$

where, P is proportion of mature fish at specific length class, L is total length, a and b are model parameters (a, intercept and b, slope of the logistic regression). The L_{50} was derived from the relationship of a and b:

$$L_{50} = -\frac{a}{b}$$

Gonado-Somatic Index (GSI): Data for Gonado-Somatic Index (GSI) of the fish, which helps in determination of the breeding season, were collected by weighing the fish samples, dissecting the sample and taking its gonad weight both for females and males in each of the study site. The GSI was analyzed only for mature fish groups after the L_{50} was determined[29] for each sex for all the three lakes.

Gonado Somatic Index (GSI) of each fish was computed as the weight of the gonads as the percentage of the total body weight as follows:

$$GSI = \frac{GW\ (g)}{TW\ (g)} \times 100$$

Fecundity determination: The data for fecundity was taken from ripe gonads. After taking the ripe females' total length, total weight data, the females were dissected and their gonads weighed. Sub sample taken from the gonad and fecundity was determined by gravimetric method[27] by counting all eggs in the sub samples taken from ripe ovaries. Absolute fecundity was then calculated using the following formula:

$$\text{Fecundity (F)} = \frac{\text{Number of eggs in sub sample} \times \text{Gonad weight}}{\text{Weight of sub sample}}$$

The relationships between absolute fecundity and female's morphometric measurements and Total Length (TL), Total Weight (TW) and Gonad Weight (GW) were determined using least squares regression:

$$F = aTL^b,\ F = aTW^b,\ F = aGW^b$$

where, a and b are parameters of the fitted lines, TL is total length of fish in cm, TW is total weight of fish in gram and GW is gonad weight in gram.

Statistical analysis: One way ANOVA was employed to investigate differences in mean total lengths, mean weights of fishes among the populations and mean Gonado-Somatic Index (GSI) of the fish between sampling months at the three lakes.

RESULTS

Sex ratios: The two years' sampling results were grouped into four seasons, October-November, February-March, May and July-August months for each lake. The sex ratios of *O. niloticus* were expressed as Female: Male = 1 (Table 1).

When the results were tested by Chi-square test, the sex ratios of female: male in all the three lakes in each of the four sampling seasons did not significantly deviate from 1:1 ratio.

Table 1: Sex ratios (female: male) of *O. niloticus* from Chamo, Koka and Ziway lakes

Lakes	F:M	N	Chi-square	p-value
Chamo	1.05:1	361	0.224	0.636
Koka	0.99:1	494	0.008	0.928
Ziway	1.07:1	692	0.576	0.448

F: Female, M: Male, n: Number of sample used in the data analysis

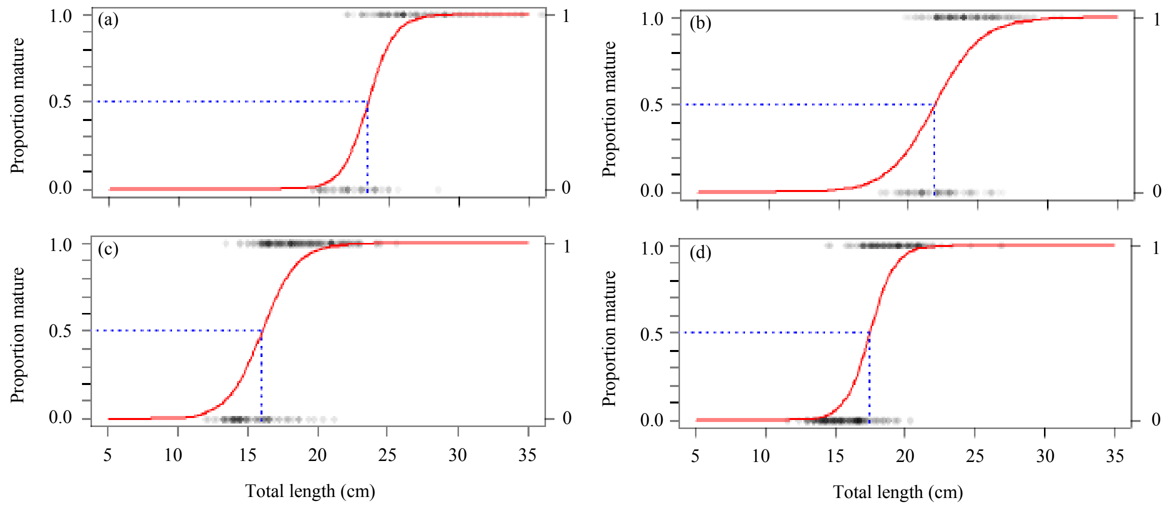

Fig. 2(a-d): Length at first sexual maturity (L_{50}) of *O. niloticus*, (a) Lakes Chamo for mixed sex, (b) Koka for mixed sex, (c) Ziway female and (d) Ziway male

Table 2: L_{50} of *O. niloticus* populations of Chamo, Koka and Ziway with size range at 97.5% CI

	Chamo mixed sex	Koka mixed sex	Ziway female	Ziway male
L_{50} (cm)	23.48	21.91	16.00	17.49
Size range at 97.5% CI	23.08:23.87	21.41:22.35	15.59:16.30	17.14:17.84

L_{50}: Length at 50% of the population reach their first sexual maturity, CI: Confidence interval

Table 3: Absolute fecundity of female *O. niloticus* from Lakes Chamo, Koka and Ziway

Lake	Chamo	Koka	Ziway
Mean±STD	1321.76±342.92	1146.89±115.227	450.07±180.829
Minimum	739	962	209
Maximum	1886	1357	800

Length measurement at first sexual maturity (L_{50}): The length at first sexual maturity (L_{50}) of females and males were not significantly different for the *O. niloticus* populations of Lake Chamo and Lake Koka in which the L_{50} was derived from mixed sexes (Table 2). However, the females and males had exhibited significantly different L_{50} in Lake Ziway. The L_{50} of Nile tilapia for the three lakes differed as illustrated in Table 2.

Length at first sexual maturity (L_{50}) where 50% of the population of Nile tilapia reaches sexually mature for the first time was at Total Length (TL) of 23.48 cm in Lake Chamo (Fig. 2a) for mixed sex; there was no significant difference between males and females. The L_{50} for mixed sex Nile tilapia in Lake Koka was 21.91 cm (Fig. 2b). The L_{50} values for female and male groups were significantly different in Lake Ziway where it was 16.00 cm for females (Fig. 2c) and 17.49 cm for males (Fig. 2d). Distribution pattern of the proportion of mature fishes along the total length of the fishes was different for the populations in the different lakes.

Evaluation of Gonado-Somatic Index (GSI): The gonado-somatic index (GSI) of the *O. niloticus* species from Lakes Chamo, Koka and Ziway was analyzed separately for sexes in the four different sampling seasons. The mean GSI was relatively higher in October-November (short rainy season) and February-March (pre-rainy season) at Chamo Lake for both male and female sexes. The highest mean GSI for the females (Fig. 3a) of Koka population was recorded in May (pre-rainy season) and in July-August (main rainy season) for males (Fig. 3b). The relatively highest mean GSI was recorded both for females and males in February-March (dry season) for tilapias of Ziway population.

Fecundity: Fecundity (number of eggs a female can produce at a time) was calculated based on the egg samples taken from gonads of ripe females following standard procedures and presented in Table 3. The absolute fecundity ranged from 209 at Ziway to 1886 eggs per female at Chamo. The mean absolute fecundity was high for *O. niloticus* of Lake Chamo (1,322 eggs/female) followed by Lake Koka (1,147 eggs/female) and lowest for Lake Ziway (450 eggs/female).

Fecundity has a direct curvilinear relationship with the females' Total Length (TL), Total Weight (TW) and Gonad Weight (GW). Figures 4-6 display fecundity of female

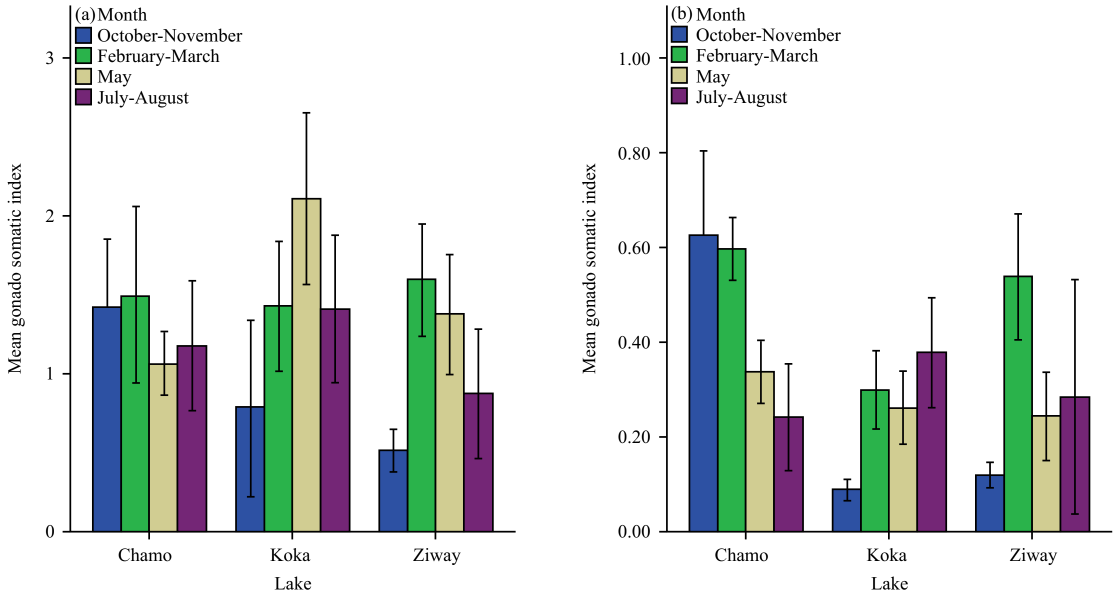

Fig. 3(a-b): Mean GSI (Gonado Somatic Index) of *O. niloticus* by lake (Chamo, Koka, Ziway) and 'season' (Oct-Nov, Feb-March, May, July-Aug) for (a) Female and (b) Male groups
Error bars represent the 95%, CI: Confidence interval

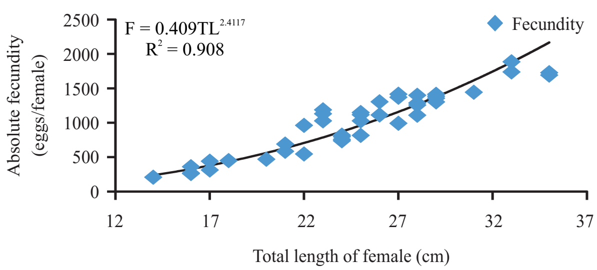

Fig. 4: Relationship between fecundity and total length of *O. niloticus* pooled for Chamo, Koka and Ziway populations

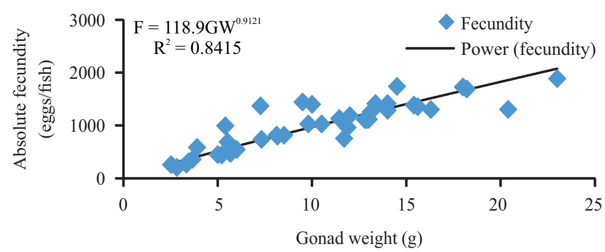

Fig. 6: Relationship between fecundity and gonad weight of *O. niloticus* pooled for Chamo, Koka and Ziway populations

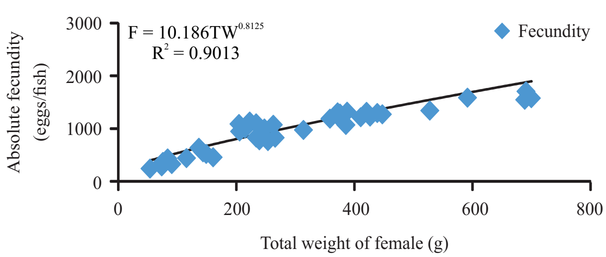

Fig. 5: Relationship between fecundity and total weight of *O. niloticus* pooled for Chamo, Koka and Ziway populations

O. niloticus pooled from Lakes Chamo, Koka and Ziway. The relationship between absolute fecundity (F in eggs/female) and TL in cm was $F = 0.409TL^{2.4117}$, $R^2 = 0.908$ (Fig. 4), F and TW in gram (g) was $F = 10.186TW^{0.8125}$, $R^2 = 0.9013$ (Fig. 5) and between F and GW (g) was $F = 118.9GW^{0.9121}$, $R^2 = 0.8415$ (Fig. 6).

DISCUSSION

The sex ratios of the *O. niloticus* in all the sampling seasons at the three lakes did not statistically deviate from the expected 1:1 ratios. The current result of 1:1 sex ratios in the three lakes was attributed to the inclusion of fish samples from all available fishing gears (beach seine, monofilament and multifilament gillnets) and the representativeness of the random samples. Balanced sex ratio is expected in a wild *O. niloticus* population, though environmental sex determination was reported, the case by which the male ratio increases with temperature[30,31]. The current water temperatures in the study areas (28.09±1.48°C at Chamo, 22.77±1.20°C at Koka and 24.24±2.78°C at Ziway during the study time) were not that high to shift the sex ratios[32].

The current sex ratio results agree with the previous report from Lake Chamo[6]. Sex ratios of *O. niloticus* samples can also deviate from the expected 1:1 ratio across seasons due to sexual segregation during spawning, fishing site and gear type[11,33]. Variations in sex ratios were also reported with more females than males at Lake Beseka (because of fish sampling using gillnet, for which females are more vulnerable than males[7], Lake Hayq[8], Lake Ardibo[9] and males predominated over females at Lake Tana[34], Lake Victoria[35], Amerti Reservoir[12], Lake Hayiq[11] because of the above reasons.

The length at first sexual maturity (L_{50}) of the *O. niloticus* populations in the present study were 23.48, 21.91, 17.49 and 16.00 cm (TL) for Lakes Chamo, Koka, Ziway (males) and Ziway (females), respectively (Table 2). The values were different for the three lakes with the highest for population of Lake Chamo and lowest for females of Lake Ziway. The present L_{50} values of the tilapia populations were within the previous L_{50} report ranges from different lakes and reservoirs in the country; 14.0 cm for females and 17.0 for males in Lake Beseka[36], 14.1 and 20.3 cm for females and 17.8 and 20.8 cm for males in Lake Hawassa[37,21], 18.9 cm for females and 21.5 cm for males in Amerti Reservoir[12], 19.5 cm in Lake Langeno[4], 21cm in Lake Tana[38] and 30.81cm for females and 34.5 cm for males in Lake Victoria[35].

The present L_{50} values of all the three *O. niloticus* populations were lower than the previous reports. The L_{50} for Chamo population decreased from 42.0 cm reported by Teferi and Admasu[6] to the present result of 23.48 cm in a period of twenty years. The value for Koka population decreased but slightly, from 23.5 cm to the present value of 21.91 cm in about twelve years[4]. Similarly, the L_{50} of Ziway population decreased from 18.8 cm TL[5] and 19.6 cm for males and 18.1 cm for females[4] to the present value of 17.4 cm for males and 16.00 cm for females. The current decrease in L_{50} of *O. niloticus* populations in Lakes Chamo, Koka and Ziway may be attributed to the fishing pressure[39] and change in the lakes environment (pollution, siltation, fish stock composition)[40].

Size at first sexual maturity is determined both by genetic and environmental factors and it appears to be variable trait that stocks can adjust depending on demographic and environmental conditions[5]. Early sexual maturation negatively affects growth performance of the fish, influencing the quality and quantity of the fish product both in natural environment and in aquaculture productions. The quantity and quality of fish product determines income of the fishermen as well as the profitability of the fish farm. Hence, the decrease in size at first maturation alarms the need for the implementation of proper and effective fishery and environmental management measures to sustain the fishery of the lakes. On the other hand, the Chamo and Koka tilapias, with their relatively higher L_{50} values, become potential populations for further genetic improvement to enhance aquaculture development.

Gonado-Somatic Index (GSI) is used to determine the breeding season of the fishes. Females with ripe ovaries and males with ripe (larger, full and white) testes were observed in all the four sampling seasons but with different frequencies in all the three lakes implying that *O. niloticus* is breeding all year round. The mean GSI of *O. niloticus* from Lakes Chamo, Koka and Ziway were different for different sampling seasons (Fig. 3).

For Chamo population, the mean GSI were not statistically different among the four sampling seasons for females ($p>0.05$); however, it was relatively higher (1.42±1.05) in October-November (short rainy season) and 1.50±1.09 in February-March (pre-rainy season) than the other two sampling seasons (1.07±0.58 in May and 1.18±1.02 in July-August). The mean GSI values for males during these two sampling seasons were significantly ($p<0.05$) higher than the mean values recorded during the rainy season and post rainy season (Fig. 3).

For Koka population, the highest mean GSI value (2.11±1.61) for females was recorded in May (pre-rainy season) which was significantly higher ($p<0.05$) than the lowest mean value recorded (0.78±0.88) in October-November (post-rainy season). The lowest mean GSI value for males was also recorded in the October-November sampling season, the value which was significantly lower ($p<0.05$) than that of the other three sampling seasons (Fig. 3).

The relatively highest (mean±standard deviation) GSI value of 1.60±1.28 was recorded in February-March (dry season) and the lowest value of 0.52±0.44 in October-November (post-rainy season) for females of Ziway population. The males have similar peak patterns among the sampling seasons in the lake (Fig. 3). The peak breeding season for Ziway was similar to that of Lake Hawassa[29].

The current result shows that the *O. niloticus* populations of Chamo, Koka and Ziway breed all year round with relatively higher activity in different months in different lakes; peak activity in October-November and February-March in Chamo, in May in Koka and in February-March sampling season in Ziway. The peak spawning usually coincides with the onset of the rainy season[6,34].

The mean absolute fecundity of the *O. niloticus* populations in the present study was higher at Chamo (1,321.76±342.92) followed by Koka (1,146.89±115.23) and significantly lower (p = 0.00) than the two at Ziway (450.07±180.83 eggs/female). The relative fecundity of the females showed positive curvilinear relationship with total length ($F = 0.409TL^{2.4117}$, $R^2 = 0.908$), total weight ($F = 10.186TW^{0.8125}$, $R^2 = 0.901$) and gonad weight ($F = 118.908GW^{0.9121}$, $R^2 = 0.8415$). The higher mean absolute fecundity values of females at Chamo and Koka corresponds to the higher mean total length (28.65±3.72 cm, 25.33±2.19 cm) and total weight (429.41±342.92 g and 282.75±159.52 g) of the females. Similarly, positive relationship of the fecundity with total length, total weight and gonad weight was reported for tilapias in different water bodies[6,16,41].

Generally, the differences observed in L_{50}, breeding season and fecundity of the *O. niloticus* populations were might be attributed to differences in the lakes' environment, sizes, bathymetry, physico-chemical and biological properties and fishing pressure[2,39,40] and perhaps genetic differences between the isolated populations[42,43].

CONCLUSION

Oreochromis niloticus populations of Lakes Chamo, Koka and Ziway have shown similar sex ratios of 1:1 in their natural environments but different sizes at first sexual maturity (L_{50}) and fecundity with Chamo having higher values. All the current L_{50} values of the three populations decreased from previous reports especially in Lake Chamo; signs for increasing fishing pressures and environmental changes. Breeding season of the *O. niloticus* populations was found to happen in all seasons in all the three lakes but season for peak activities were different in the three lakes influenced by onset of rainy season.

SIGNIFICANCE STATEMENT

This study discovered differences in reproductive characters of *Oreochromis niloticus* fish species inhabiting different freshwater lakes in Ethiopian rift valley. It also indicated potential populations for genetic improvement in aquaculture development based on their desired reproductive qualities. The study has shown that some of the reproductive characters of the *O. niloticus* species changed over time because of different environmental and management factors which need corrective measures. The finding can be beneficial for fish breeders, environmental protection authority, the Ethiopian government to enforce lake management policies and researchers. This study will help the researchers to uncover the critical areas of differences in reproductive potentials of *Oreochromis niloticus* populations inhabiting different lakes. Thus a new theory on reproductive potentials of *Oreochromis niloticus* influenced by environmental conditions may be arrived at.

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