

Original Article

Salinity tolerance of Nile tilapia (*Oreochromis niloticus*) to seawater and growth responses to different feeds and culture systems

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Western Indian Ocean
JOURNAL OF
Marine Science

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Open access

Citation:

Mirera DO, Okemwa D (2023) Salinity tolerance of Nile tilapia (*Oreochromis niloticus*) to seawater and growth responses to different feeds and culture systems. Western Indian Ocean Journal of Marine Science 22(2): 75-85 [doi: 10.4314/wiojms.v22i2.6]

Received:

November 17, 2022

Accepted:

August 24, 2023

Published:

November 28, 2023

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Abstract

The inability to acclimatise, feed and grow Nile tilapia (*Oreochromis niloticus*) in full seawater salinity has been a major obstacle to farming in marine waters. We investigated the salinity tolerance of *O. niloticus* and growth responses to different feeds and culture systems. Fish were first acclimatised to different salinities in laboratory aquaria, and the survival and growth performance in sea water were then assessed in aquaria, cages and ponds. Acclimatization to seawater salinity (5 – 30) took place at a rate of 5 every 9 days. Fish were stocked at densities of 5 fish/20 L in aquaria, 5 fish/m³ in cages and 3 fish/m² in ponds. Replicates of 5, 3 and 3 were performed in aquaria, cages and ponds, respectively. Fish were fed on commercial (1 and 2) and locally formulated (30 % crude protein) diets. Mortality rates were higher in aquaria, when fish were introduced to salinities between 5 and 30 over 24 hours. Gradual salinity adjustments attained a stable survival rate of 78 % at salinities above 30. Aquarium experiments indicated significant negative correlation between salinity and survival ($p < 0.001$, $r = 0.387$) and daily growth rates varied with diet (0.01 – 0.05 g/day). Acclimatized fish showed minimal mortality in ponds and cages. Daily growth rates varied with diet and culture system; 0.54 - 2.48 g/day in cages and 1.1 - 2.5 g/day in ponds. Fish fed on commercial feed 2 showed significant growth rates for all culture methods ($p < 0.05$). *O. niloticus* could be fully acclimatised to seawater and attained promising growth rates when subjected to different commercial diets indicating potential of farming the species in marine waters.

Keywords: *Oreochromis niloticus*, salinity, survival, growth, feed

Introduction

Tilapia are tropical freshwater fish native to Africa but introduced to different global destinations for commercial production (Pillay & Kutty, 2005; Lutz *et al.*, 2010; Ninh *et al.*, 2014; Ridha, 2014). Currently, tilapia are farmed in 124 countries and ranked the fifth highly farmed species, with an annual production of 6.1 million tonnes (FAO, 2021). Farming of tilapia has been successful because of its fast growth, higher reproduction, feeding on low trophic levels, euryhaline characteristics and tolerance to adverse environmental conditions (Suresh & Lin, 1992; Morgan *et al.*, 1997; Ridha, 2004; Liti *et al.*, 2005). Furthermore, tilapia breeding

innovations have been undertaken to increase economic production. These innovations include production of genetically improved male tilapia (GMT) and genetically improved farmed tilapia (GIFT), as well as attempts to farm tilapia in brackish and marine waters though still not fully developed in sub Saharan Africa (El-Sayed, 2006; Cnaani *et al.*, 2011; Ninh *et al.*, 2014 FAO, 2020).

Marine water aquaculture in sub Saharan Africa has been impacted by a lack of hatchery infrastructure which is the backbone of seed production, resulting in low fish production and increased poverty

levels (Ridha, 2004; World Bank, 2016). Many authors reported that hatchery and breeding technologies for tilapia are simple and well developed globally for adoption and use in seawater (Jalabert & Zohar, 1982; Little *et al.*, 1993; Brummett, 1995; Ridha and Cruz, 1998; Bhujel, 2000). Farming of Nile tilapia (*Oreochromis niloticus*) in marine waters will maximise the use of currently underutilised ocean space for increased fish production and ensure food sufficiency to the more than 690 million people going without food daily (Editorials Nature, 2020).

Most tilapia utilised for commercial production are derived from *O. niloticus* or its hybrids and have been observed to exhibit limited salinity tolerance. The only strain that has been observed to withstand high salinities is Mozambique tilapia although its growth rates are economically not viable and its size at maturity is small (Lothian, 1960; Mateo *et al.*, 2004, Kamal & Mair, 2005). According to Watanabe *et al.* (1985b), McGeachin *et al.* (1987) and Perschbacher & McGeachin (1988), *O. niloticus* mortalities progressively increase with increasing salinities. Other studies have established that a progressive increase in daily salinities (6 g/l) tends to minimise mortalities of *O. niloticus* (Mateo *et al.*, 2004). Further studies by Lemarie *et al.* (2004) established that daily salinity increases of 2-8 g/l increased survival of *O. niloticus* while that above 8 g/l decreased survival significantly.

Over the years, farming of *O. niloticus* in brackish water systems has attained some level of success globally, while hybrids are being trialled in full seawater salinity with limited success (Stickney, 1986; Suresh & Lin, 1992; Lutz *et al.*, 2010; Ridha, 2014). The current study builds on the successes made in farming *O. niloticus* in seawater to establish a full seawater tolerant strain for marine aquaculture. A series of experiments were conducted with two objectives (1) To establish an optimal salinity acclimatization strategy based on progressive incremental salinity to support the

farming of *O. niloticus* in full seawater; (2) To assess the growth response of *O. niloticus* to different diets during the acclimatization process in aquaria, net cages and intertidal earthen ponds. We discuss the results of the experiments undertaken at the laboratory (aquaria) and at the field (net cages and intertidal earthen ponds). The study provides information that will contribute towards farming *O. niloticus* in full seawater thus contributing to utilization of the ocean potential.

Materials and methods

Experimental fish and diet

The experimental fish were hatched from the broodstock collected from the National Aquaculture Research Development and Training Centre (NARDTC) in central Kenya where selective breeding is undertaken to attain fast growing freshwater *O. niloticus*. The fish were hatched in borehole water of salinity 0.63 from a coastal hatchery, and acclimated to salinities of 30 ± 5 in laboratory aquaria. The acclimated fish were later used in laboratory aquaria, cages and pond growth experiments. Three diets comprising of commercial feed 1, 2 and a locally formulated diet both with 30% crude protein content were used in the experiments (Table 1). According to Simon *et al.* (2019), commercial feed 2 had a marine bacteria biomass unlike commercial feed 1. Locally formulated feed was formulated with local ingredients like coconut husks, fishmeal (*Rastroneobola agentii* "Omena"/"daggaa"), maize bran and cassava flour.

Experimental design

Salinity tolerance and growth of *O. niloticus* in seawater was assessed in laboratory aquaria, cages and intertidal earthen ponds. Treatments were based on three feed diets; commercial feed 1, 2 and locally formulated feed. The level of replication varied between the different culture systems (5 for aquaria, 3 for cages and 3 for intertidal earthen ponds). Aquaria experiments were conducted in the laboratory at the Kenya Marine and Fisheries Research Institute (KMFRI) Mombasa

Table 1. Proximate composition of the three feed diets used in the *O. niloticus* experimental trials

Proximate composition	Diet treatments		
	Commercial feed 1	Commercial feed 2	Local formulated feed
Crude protein (%)	30	30	30
Fat (%)	7	7	4
Fibre (%)	9	9	3
Ash (%)	12	12	4
Moisture (%)	11	11	14
Marine bacterial biomass	Absent	Present	Absent

while cage and pond experiments at Kibokoni, Umoja self-help group mariculture farm, Kilifi creek, Kilifi County. All the fish used in field experiments (cages and ponds) were first taken through the laboratory aquaria and acclimatised to salinities of more than 30.

Experiment 1: Laboratory aquaria

Experiments were performed in 20 L glass aquaria with gentle aeration. The experimental fish varied in weight between 1.2 and 2.0 g. They were first acclimatized for two days at 0.63 salinity, room temperature (25 - 26 °C) and fed to satiation twice a day at mid-morning and mid-afternoon. Fish were randomly stocked at 5 fish/L before subjection to different salinity levels (5, 10, 15, 20, 25 and 30) with a replication of five for each salinity level. Baseline salinity was established by subjecting all the fish directly to different salinity levels for a period of 24 hours and survival elimination was done. Subsequent experiments monitored survival and feeding at different salinity levels/gradients over a period of 216 hours at each level. During acclimatization period, slow and consistent adjustments of salinity (10 – 30‰) was employed as detailed by Perschbacher (1992) and Yao et al. (2008). Attainment of full seawater stability was alluded to when (1) there was a reduction in mortality, (2) fish were observed to feed normally and attained weight as a sign of growth. Fully modified laboratory experimental fish were retained for an extra 336 hours at full seawater salinity (30 ± 5) before use in laboratory aquaria growth experiments and transportation for use in field (cage and pond) experiments. To assess the growth of fully acclimatized seawater *O. niloticus* in the laboratory, fish of weight 2.2 g – 4.7 g were used. Experiments were set and monitored over a period of 7 days at stocking densities of 5 fish/20 L at a replication of 5 for the different feed diets. The growth of fish was monitored by measuring individual weight using a digital balance of precision 0.01 g at the start and at the end of the experiment. Mortality was monitored frequently and dead fish were removed and record documented. The behaviour and response of fish to feed were observed and recorded for different salinity levels.

Experiment 2: Field cages

Cage trials were used to assess the stability of laboratory seawater acclimatized *O. niloticus*. The cages were installed in intertidal earthen ponds (120 m²) constructed in mangrove open flats at Kibokoni Umoja fish farm, Kilifi creek. The size of experimental cages was 1 m width, x 1 m length x 2 m height. The fish

with an average weight of 3.5-14.0 g were cultured at a stocking density of 3 fish/m² for a period of 32 days. The experimental fish were fed twice a day (mid-morning and mid-afternoon) at 5% of their body weight. The weight of fish was measured using a digital balance (precision of 0.01) and length using a measuring board to assess growth bi-weekly. Survival was estimated by checking the nets daily for dead fish, recording the number and removing them. The final number was calculated by subtracting the number of dead fish from the initial number stocked. Survival percentage was calculated as;

$$\% \text{ Survival} = (\text{No. of fish at termination of experiment} / \text{Initial No. stocked}) * 100.$$

Experiment 3: Intertidal earthen ponds

Experimental ponds were constructed along the open mangrove intertidal flats and measured 10 m x 12 m (120 m²). The intertidal earthen ponds are designed to allow free flushing at spring high tides to self-regulate water volume, salinity and quality (Mirera, 2011). Full seawater laboratory aquaria acclimatized fish with an average weight of 1.8 – 2.6 g were stocked at densities of 3 fish/m² for a period of 123 culture days. The fish were fed twice a day (mid-morning and mid-afternoon) at 5% of their body weight. The growth performance of fish was monitored by measuring weight and total length using a digital balance and measuring board respectively once a month. At the end of the experiment, all fish were retrieved from pond through seining and finally draining all the water from the ponds. Fish recovery estimates were made by counting all the retrieved after emptying the pond. Survival was calculated as;

$$\% \text{ Survival} = (\text{No. of fish retrieved} / \text{No. of fish stocked}) * 100$$

Water quality monitoring

Experimental aquaria water management involved siphoning 80% of the dirt water and replacing with clean filtered water of same salinity level. Water quality parameters like salinity, temperature, pH and dissolved oxygen in laboratory aquaria were monitored daily, while in cages and intertidal ponds quality parameters were monitored bi-weekly using water quality meter.

Data analysis

The proportion of time taken for fish to survive at each salinity gradient without any modification was

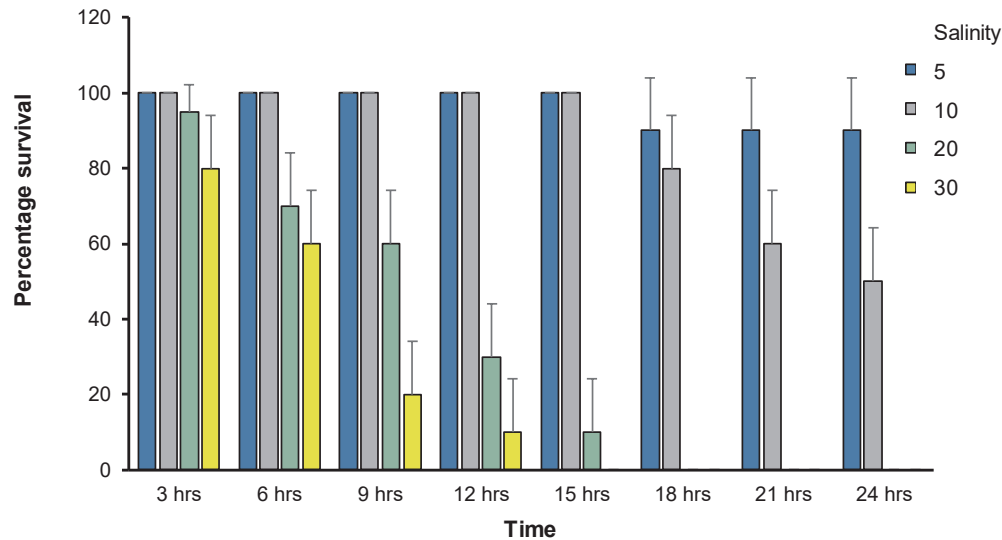


Figure 1. Survival (\pm Stdev) of *O. niloticus* fry to different salinity gradients over a period of 24 hours in the laboratory

estimated and averages were calculated. Fish growth rate in laboratory, cages and ponds was estimated using the formula;

$$\text{Growth rate} = (\text{FW} - \text{IW})/\text{T}$$

Where FW= average final fish weight (g), IW = average initial fish weight (g), T= duration of the experiment (days).

The growth performance data of fish in the laboratory, cage and pond experiments were analysed using one-way Analysis of Variance (ANOVA). Pearson correlation analysis was done to assess the influence of salinity on survival. Statistics were performed using graph pad prism vs 9.0.

Results

Salinity tolerance

A total of 5,330 *O. niloticus* juveniles were used for the salinity tolerance experiments. The direct transfer of fish juvenile to different salinities over a period

of 24 hours indicate a progressive decline in survival to 100% mortality in 18 hours for salinity levels above 20 (Figure 1). Laboratory aquaria experimental units experienced salinity fluctuations ranging between 0.16 and 0.24 per day (Table 2). Overall, during the 216 hours laboratory aquaria experimental cycle, fish survival decreased with increasing salinity levels (Figure 2a). Gradual incremental salinity modifications in the laboratory aquaria experiments attained stable fish survival rates of 78% for salinity levels above 30 (Figure 2b). Correlation analysis established a significant negative correlation between salinity and survival ($p < 0.001$, $r = 0.387$).

Growth performance

Experiment 1: Laboratory

Daily growth rates of 0.01 – 0.05 g/day were attained in laboratory aquaria experiments. Growth rates varied between and within the three feed treatments (Figure 3). A slower daily growth rate (0.01 g/day) was recorded for the locally formulated feed (Table 3). Fish fed on the locally formulated feed grew 33.3%

Table 2. Average daily salinity (\pm Stdev) dynamics in the experimental units at different salinity gradients during the *O. niloticus* laboratory modification

Salinity gradient	Salinity fluctuation (Mean \pm STDEV)
5	0.20 \pm 0.086
10	0.23 \pm 0.092
15	0.16 \pm 0.081
20	0.20 \pm 0.026
25	0.24 \pm 0.035
30	0.18 \pm 0.044

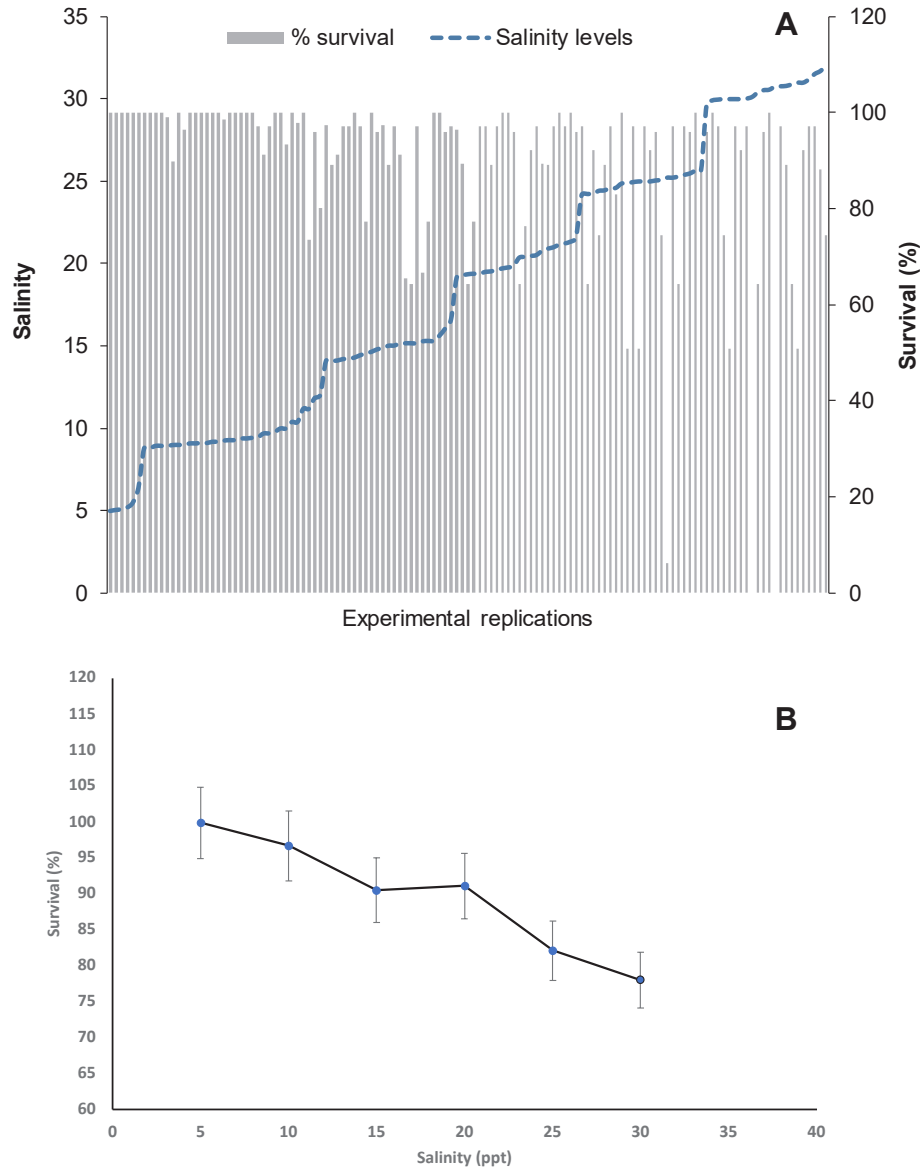


Figure 2. The relationship between survival and salinity levels for *O. niloticus* for the different experimental replicates (A) and average recorded survival at different salinity levels (B) in the laboratory modification experiments.

slower than the mean growth rate for the three feed diets. In treatments where commercial feed 2 was used fish grew 66.7 % more than the mean growth rate of the three feed diets. There was a significant difference in fish growth when all the diets were compared ($p < 0.05$) and commercial feed 2 had the highest growth rate.

Experiment 2: Cage experiments

The weight of fish in all feed experiments increased gradually during the experimental period. On average, the daily fish growth rate of 0.5 g/day, 0.6 g/day and 2.5 g/day was attained for locally formulated feed, commercial feed 1 and 2, respectively (Table 3; Figure 4).

A fish survival of more than 90% was attained in all three feed treatments. Statistical analysis (one-way ANOVA) showed a significant difference ($p < 0.05$) in weight increment for the different feed diets. Commercial feed 2 had a significantly higher weight increment compared to the other two diets.

Experiment 3: Intertidal earthen ponds

There was a steady increase in weight of fish for all the feed treatments throughout the experimental period. Daily growth rates varied between treatments; 1.1 g/day for locally formulated feed, 1.5 g/day for commercial feed 1 and 2.5 g/day for commercial feed 2 (Table 3). Over the 123 days experimental period, fish

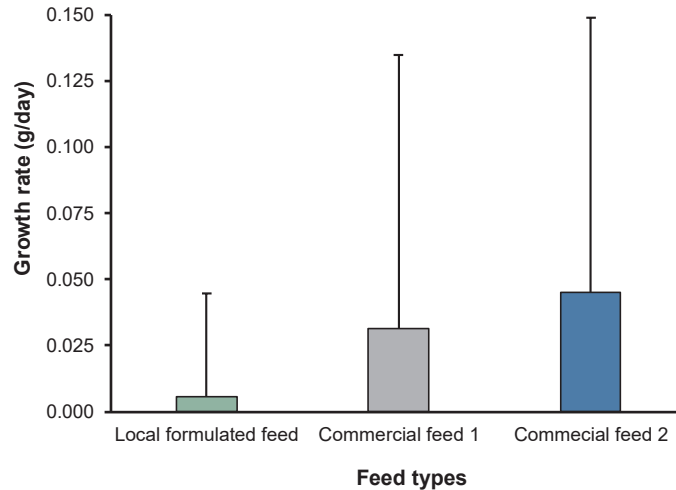


Figure 3. Growth (\pm Stdev) of full seawater salinity transformed *O. niloticus* subjected to different feeds under laboratory conditions over seven-day culture period

attained an average weight of 250 g for commercial feed 2, 200 g for commercial feed 1 and 150 g for the locally formulated feed (Figure 5). Fish survival in the different diet treatments ranged between 60% and 80% with no statistically significant difference. There was an observed decline in fingerling reproduction with only a few produced in the ponds. Fish colour was more clear and morphological features were well identified. The study established that the fish mucus layer was available and consistent in all treatments.

Water quality

In the laboratory growth experiments, water quality was maintained at a salinity of 30.0 ± 5.1 , pH of 7.8 ± 0.2 and temperature of 26.4 ± 0.5 °C. Water quality in cage experimental facilities was documented as DO 4.85 ± 0.25 , pH 7.71 ± 0.32 , salinity 31.65 ± 5.52 and temperature 29.68 ± 2.85 °C. The salinity of water in

experimental ponds varied between 30 and 34 (average of 32.99), pH between 7.5 and 8.6 (average of 7.9) and dissolved oxygen 2.3 – 8.7 mg/l depending on time of day and an average of 7.26 mg/l in mid-morning (Table 4).

Discussion

Effect of salinity on survival of *O. niloticus*

The pursuit to farm *O. niloticus* in seawater is due to its prolific reproduction, faster growth, market acceptability and simple established breeding technologies. Therefore, seawater tilapia aquaculture will maximise utilization of the ocean space to enhance food security and nutrition for the population. Studies on the salinity tolerance of tilapia have focused on single populations, comparison between varieties and genetic influences (Villegas, 1990; Kamal & Mair, 2005; Lutz *et al.*, 2010). We assessed the tolerance of *O. niloticus* to different salinity levels/gradients over

Table 3. Growth response (\pm Stdev) of *O. niloticus* to different feeds in aquaria, cages and intertidal earthen ponds

Experiment	Local formulated feed	Commercial feed 1	Commercial feed 2
Laboratory aquaria			
Stocking density (fish/L)	5	5	5
Average weight at stocking (g)	2.2 ± 0.4	4.2 ± 1.2	4.7 ± 0.1
Growth rate (g/day)	0.01 ± 0.03	0.03 ± 0.2	0.05 ± 0.1
Cages			
Stocking density (fish/m ²)	5	5	5
Average weight at stocking (g)	5.5 ± 1.4	3.5 ± 1.1	14.0 ± 4.9
Growth rate (g/day)	0.5 ± 0.0	0.6 ± 0.1	2.5 ± 0.0
Intertidal earthen ponds			
Stocking density (fish/m ²)	3	3	3
Average weight at stocking (g)	2.3 ± 0.6	2.6 ± 1.3	1.8 ± 0.0
Growth rate (g/day)	1.1 ± 0.0	1.5 ± 0.6	2.5 ± 0.6

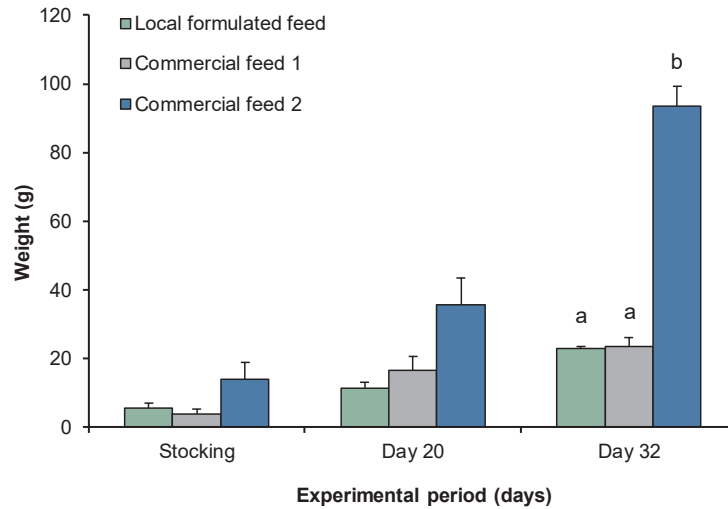


Figure 4. Growth (\pm Stdev) response of *O. niloticus* to different feeds in fish cages held in intertidal earthen ponds over the culture period (different super scripts indicate significant different)

time. Taking cognizance of gaps from previous studies, we employed a three prolonged approach (1) Establishment of a salinity level at which higher survival could be attained over a short time period as a modification baseline, (2) Establishment of a constant gradual salinity gradient increment and time lapse to full seawater salinity tolerance, (3) Assessing the performance of transformed tilapia in laboratory and field conditions.

In this study, laboratory experiments involved the use of juvenile/fry *O. niloticus* for the salinity trials based on previously documented studies where earlier exposure of eggs and fry to high salinity conditions helped to attain higher tolerance to salinity (Al Asghar,

1984; Watanabe *et al.*, 1985b). According to Watanabe *et al.* (1985a), *O. niloticus* fry (60 days after hatching) could withstand salinity of up to 25 when transferred directly from freshwater. Also, the method of such transformation/acclimatization has been underscored as one of the factors influencing salinity tolerance of tilapia (Suresh & Lin, 1992). We found that all fish transferred directly from a salinity of 0.63 to 30 and 25 died within 18 hours of the experiment due to inability to withstand drastic salinity change. Al-Amoudi (1987), argued that direct transfer of *Oreochromis* species to different salinity levels led to low survival compared to gradual increment of salinity thus supporting the findings of this study. Studies by Villegas (1990) and Fineman-Kalio (1988) found that

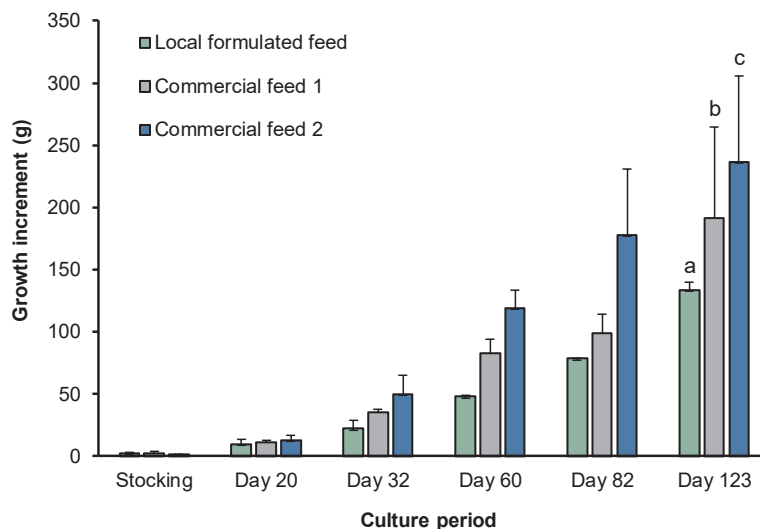


Figure 5. Growth (\pm Stdev) response of *O. niloticus* to different feeds in intertidal earthen ponds over the culture period (different super scripts indicate significant different)

Table 4. Average (Mean \pm STDEV) water quality parameters in the *O. niloticus* experimental intertidal ponds and net cages

Parameter and unit	Ponds	Cages
Dissolved oxygen (mg/l)	7.26 \pm 0.21	4.85 \pm 0.25
pH	7.90 \pm 0.90	7.71 \pm 0.32
Salinity	32.99 \pm 2.99	31.65 \pm 5.52
Total dissolved solids (mg/l)	30.33 \pm 1.15	27.07 \pm 0.44
Temperature ($^{\circ}$ C)	25.12 \pm 0.49	29.68 \pm 2.85

O. niloticus survived direct salinity transfers to 15 – 17.7 by 87%, above 15 led to more than 50% mortality, and to 20 and 32 salinity resulted in complete mortality. Even for the higher salinity tolerant tilapia species like blue tilapia, direct transfer to seawater could result in almost complete mortality compared to gradual transfer (Villegas, 1990; Phillippart & Ruwet, 1982; Lotan, 1960). We attained an *O. niloticus* salinity tolerance of 78% at 30 salinity in a progressive 9-day salinity increment which is comparatively higher than previous studies (Kirk, 1972; Watanabe *et al.*, 1985a). Fineman- Kalio (1988) observed that *O. niloticus* could gradually acclimatize to salinities of 20 – 50 with an average survival of 93.8%. Similarly, we established that there was higher salinity fluctuations in the intertidal earthen ponds ranging between 30 and 40 based on tidal changes and seasonality and the transformed *O. niloticus* was resilient to the higher levels.

Higher *O. niloticus* survival attained at full seawater salinity could be associated with the prolonged transformation/acclimatization period in the laboratory running for days before scaling up to higher salinity levels and progressively advancing to full seawater salinity. According to Al-AMoudi (1987), *O. niloticus* require a longer acclimatization period (8 days) compared to other species like *O. mossambicus* which required less periods (4 days). The current study findings correlated positively to the fact that gradual acclimatization is sufficient to transform salt tolerant tilapia successfully (Villegas, 1990; Phillippart & Ruwet, 1982; Lotan, 1960). Some studies have used a shorter acclimatization period for *O. niloticus* (5 salinity per 45 hrs) and experienced mortalities of all fish before reaching 28 salinity (Villegas, 1990; Lotan, 1960). However, other studies have used prolonged acclimatization periods running to even weeks and obtained minimal survival above 28 salinity (Al Asgah, 1984). Gradual salinity acclimatization is preferred because it takes advantage of the previous level adaptation to facilitate the subsequent adaptation in the next level with less energy cost.

Increased survival at higher salinities can be associated with natural selection due to long-term population adaptation to saline waters (Watanabe *et al.*, 1989). Furthermore, genetic selection was observed to improve the salinity tolerance of *O. niloticus* to survival rate of 75.3 – 91.9% when cultured (1-2 fish/m²) in earthen ponds with salinities of 15 – 20 (Ninh *et al.*, 2014). We did not use genetic selection in the current study but it's an indication of a potential research gap required to enhance the performance of full seawater acclimatized *O. niloticus*.

Growth performance of *O. niloticus* in different culture systems

Throughout the experimental period, dissolved oxygen, temperatures, pH and other physicochemical parameters in the pond, cage and laboratory conditions were within levels suitable for the growth of tilapia. Growth rates were assessed at a salinity range of 30– 34. In laboratory aquaria experiments, commercial feed 2 had a higher growth than the other two diet formulations. Fish fed on the locally formulated diet grew 4.8 times lower than commercial feed 2 in cages and 2.3 times lower than commercial feed 2 in earthen ponds. Growth variations in cage and pond results for the same feed treatment could be associated with restricted movement in cages that does not allow access to planktonic and benthic feed communities that were available in intertidal earthen ponds (Yi *et al.*, 1996; 2002).

The growth results obtained in the current study for *O. niloticus* are not comparable to any in literature due to the previous inability to acclimatize and stabilize the species to full seawater salinity (Watanabe *et al.*, 1985a; Woessner *et al.*, 1991). However, the current growth results are comparable to those of hybrid tilapia grown in freshwater and full seawater with growth rates of 1.4 g/day and 0.73 g/day respectively. The hybrid were cultured in a circulatory system for 180 days at stocking densities of 150 fish/m³ and fed on sea bream feed pellets (Ridha, 2014). We also got results

that resonate well with findings of Thai red tilapia grown in cages placed in earthen ponds and Florida tilapia grown in marine cages with growth rates of 1.17 g/day and 1.82 g/day respectively (Clark *et al.*, 1990; Yi *et al.*, 2002). Also, Basiao *et al.* (2005) observed that *O. niloticus* hybrids mixed with *O. mossambicus* attained a higher daily growth rate (1.58 g/day) compared to other hybrids (1.2 g/day) due to tolerance to saline environments (Liao & Chang, 1983).

A consistent trend of fish growth rate was observed for commercial feed 2, commercial feed 1 and locally formulated feed in all culture systems. This implies that feed formulations will to a larger extent influence the growth rate of fish irrespective of the farming system. The current results support the findings by Simon *et al.* (2019) where Gift tilapia fed on commercial feed 2 increased weight with the inclusion of the marine microbial biomass. In the study, a 10% inclusion of the microbial biomass led to 19.5% weight gain in fish compared to 5% weight gain when fish meal was used in the feed. Unlike in other previous studies where hybrids have attained smaller terminal size or slow growth rate (Lutz, 2001), performance of gift tilapia (Simon *et al.* 2019) supports the significance of feed formulations in enhancing production of *O. niloticus* in full seawater salinity. Therefore, the need for research to establish a suitable feed formulation for full seawater *O. niloticus*.

Conclusions

The findings elucidate the viability of optimal salinity acclimatization of *O. niloticus* to full seawater using gradual salinity increment. The seawater salinity transformed tilapia was able to withstand environmental variabilities in intertidal earthen ponds and attain competitive growth rates thus providing hope for aquaculture investors along the coastal areas. Full seawater transformed *O. niloticus* responded well to different feed formulations. However, varied growth rates were attained for different feed formulations weighing unto the need for quality affordable feeds for the farmers.

This study is the first to demonstrate survival and growth of *O. niloticus* in full seawater and forms a baseline for research on the species to enhance food and nutritional security in Sub-Saharan Africa. Research is needed to assess breeding and reproduction potential of *O. niloticus* in seawater, diseases resistance, and selective breeding to inform farming of the species. Also, there is need for research to assess the ecological

impact of *O. niloticus* in the ocean to guide management of coastal farms.

Acknowledgements

We are grateful to the Indian Ocean Rim Organization (IORA) through which the funding was sourced and the Department of Foreign Affairs and Trade in Australia (DFAT) for providing the funding. Appreciation is to Prof. Nigel Preston and Prof. Greg Coman (Commonwealth Scientific and Industrial Research Organization- CSIRO) for providing inputs to the research design. Further, appreciation is to Kenya Marine and Fisheries Research Institute (KMFRI) for providing research infrastructure where the research was undertaken. Also, recognition is provided to Umoja self-help mariculture farm, Kibokoni village, Kilifi County, Kenya where field experiments were conducted.

References

- Al-AMoudi MM (1987) Acclimation of commercially cultured *Oreochromis* species to seawater – an experimental study. *Aquaculture*, 65: 333-342.
- Al-Asgah NA (1984) The effect of salinity on eggs and larvae of *Oreochromis niloticus* (Linnaeus). *Arab Gulf Journal of Scientific Research* 2:673-681.
- Avella M, Berhaut J, Bornancin M (1993) Salinity tolerance of two tropical fishes, *Oreochromis aureus* and *O. niloticus* .L. Biochemical and morphological changes in the gill epithelium. *Journal of Fish Biology* 42, 243-254.
- Basiao ZU, Eguia RV, Doyle RW (2005) Growth response of Nile tilapia fry to salinity stress in the presence of an 'internal reference' fish. *Aquaculture Research*, 36: 712-720
- Brummett RE (1995) Environmental regulation of sexual maturation and reproduction in tilapia. *Reviews in Fisheries Science* 3: 231-248
- Bhujel RC (2000) A review of strategies for the management of Nile tilapia (*Oreochromis niloticus*) broodfish in seed production systems, especially hapa-based systems. *Aquaculture*, 181: 37-59
- Clark AE, Watanabe WO, Olla BL, Wicklund RI (1990) Growth, feed conversion and protein utilization of Florida red tilapia fed isocaloric diets with different protein levels in seawater pools. *Aquaculture* 88: 75-85.
- Cnaani A, Velan A, Hulata G (2011) Improving salinity tolerance in tilapias: a review. *Proceedings, Ninth International Symposium on Tilapia in Aquaculture*. (ed. by L. Liping & K. Fitzsimmons). pp. 193–201. Shanghai Ocean University, Shanghai, China.

- Editorials Nature (2020) To end hunger, science must change its focus. 336/Nature/Vol 586/ 15 October 2020
- El-Sayed A-FM (2006) Tilapia culture in salt water: Environmental Requirements, Nutritional Implications and Economic Potentials. En: Editors: L. Elizabeth Cruz Suarez, E. C., Marie, D. R., Mireya Tapia Salazar, Martha G. Nierto Lopez, David A. Villarreal Cavazos, Ana C. Puello Cruz Y Armando Garcia Ortega. Anances en Nutricion Acuicola VIII. VIII symposium Internacional de Nutricion Acuicola 15 – 17 Noviembre. Universidad Autonoma de Buevo Leon, Monterrey, Nuevo Leon, Mexico. ISBN 970-694-333-5.
- FAO (2021) Top 10 species groups in global aquaculture 2019. WAPI FACTSHEET. CB5186EN/1/06.21
- FAO (2020) The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome. <https://doi.org/10.4060/ca9229en>
- Fineman- Kalio AS (1988) Preliminary observations on the effect of the effect of salinity on reproduction and growth of freshwater Nile tilapia (*O. niloticus*) cultured in brackish water ponds. Aquaculture and fisheries management. 19: 313-320.
- Jalabert B, Zohar Y (1982) Reproductive physiology in cichlid fishes, with particular references to Tilapia and Sarotherodon. In: The Biology and Culture of Tilapia, ICLARM Conference 7 (ed. by R.S.V. Pullin & R.H. Lowe-McConnell), pp.129-140. Department of Fisheries, Bangkok, Thailand, and International Center for Living Aquatic Resources Management, Manila, Philippines.
- Kamal AHMM, Mair GC (2005) Salinity tolerance in superior genotypes of tilapia, *Oreochromis niloticus*, *Oreochromis mossambicus* and their hybrids. Aquaculture, 247: 189-201.
- Kirk RG (1972) A review of recent developments in Tilapia culture, with special reference to fish farming in the heated effluents of power stations. Aquaculture 1:45-60.
- Liao I.-C, Chang S.-L (1983) "Studies on the feasibility of red tilapia culture in saline water". In: L. Fishelson and Z. Yaron (Compilers), Proceeding of the International Symposium on Tilapia in Aquaculture. Tel Aviv University, Tel Aviv, Israel, pp. 524-533.
- Lemarie G, Baroiller JF, Clota F, Lazard J, Dosdat A (2004) A simple test to estimate the salinity resistance of fish with specific application to *O. niloticus* and *S. melanotheron*. Aquaculture 240,575-587.
- Liti DM, Fulanda B, Munguti JM, Straif M, Waidbacher H, Winkler G (2005) Effects of open-pond density and caged biomass of Nile Tilapia (*Oreochromis niloticus* L.) on growth, feed utilization, economic returns and water quality in fertilized ponds. Aquaculture research, 36: 1535-1543.
- Little DC, Macintosh DJ, Edwards P (1993) Improving spawning synchrony in the Nile tilapia, *Oreochromis niloticus*. Aquaculture and Fisheries Management 24: 399-405
- Lotan R (1960) Adaptability of *Tilapia aurea* to various saline conditions. Bamidgeh 12:96-100.
- Lothian R (1960) Adaptability of *Tilapia nilotica* to various saline conditions. Bamidgeh 12, 96-100.
- Lutz CG, Armas-Rosales AM, Saxton AM (2010) Genetic effects influencing salinity tolerance in six varieties of tilapia (*Oreochromis*) and their reciprocal crosses. Aquaculture Research, 41: 770-780
- Lutz CG (2001) Practical Genetics for Aquaculture. Fishing News Books, Blackwell Sciences, Oxford, United Kingdom.
- Mateo D, Aguilar R, Campos W, Katalbas M, Severa F, San-ares R, Edra R, Chevassus B, Lazard J, Morrisens P, Baroiller JF, Rognon X (2004) Salinity tolerance of *Oreochromis niloticus* and *O. mossambicus* F1 hybrids and their successive backcrosses. In: Proceeding of the Sixth International Symposium on Tilapia Aquaculture (ed. by R. Bolivar, G. Mair & K. Fitzsimmons), pp. 426-438. Bureau of Fisheries and Aquatic Resources, Manila, Philippines.
- McGeachin RB, Wicklund RI, Olla BL, Winton JR (1987) Growth of *Tilapia aurea* in seawater cages. Journal of the World Aquaculture Society 18, 31-34.
- Mirera HOD (2011) Experimental polyculture of milkfish (*Chanos chanos*) and Mullet (*Mugil cephalus*) using earthen ponds in Kenya. WIO Journal of marine science. 10(1): 59-71
- Morgan JD, Sakamoto T, Grau EG, Iwama GK (1997) Physiological and respiratory responses of the Mozambique tilapia (*O. mossambicus*) to salinity acclimation. Comparative Biochemistry and Physiology. 117A: 391-398.
- Ninh NH, Thoa NP, Knibbb W, Nguyen NH (2014) Selection for enhanced growth performance of Nile tilapia (*Oreochromis niloticus*) in brackish water (15-20 ppt) in Vietnam. Aquaculture 428-429: 1-6
- Perschbacher PW, McGeachin RB (1988) Salinity tolerances of red hybrid tilapia fry, juveniles and adults. In: The Second International Symposium on Tilapia Aquaculture, ICLARM Conference Proceedings 15, 623pp, (ed. by R.S.V. Pullin, T. Bhukaswan, K. Tonguthai & J. L. Maclean), pp. 415-419. International Center for Living Aquatic Resources Management, Manila, Philippines.

- Perschbacher PW (1992) A review of seawater acclimation procedures for commercially important euryhaline tilapias. *Asian Fisheries Science*. 5:241-248.
- Pillay TVR, Kutty MN (2005) *Aquaculture: principle and practices*. Second Edition, Blackwell Publishing Ltd. UK
- Phillippart J-Cl, Ruwet J-Cl (1982) Ecology and distribution of tilapias. in R. Pullin and R. Lowe-McConnell, eds. *The biology and culture of tilapias*. International Center for Living Aquatic Resource Management, Manila, Philippines. pages 15-59.
- Ridha MT (2014) Preliminary observations on growth and survival of *Oreochromis spilurus* x GIFT *Oreochromis niloticus* F1 reciprocal hybrids in fresh and seawater. *Aquaculture Research*, 45: 528-536
- Ridha MT (2004) Observations on the reproductive performance of three mouth-brooding tilapia species in low salinity underground water. *Aquaculture research*, 35: 1031-1038
- Ridha MT, Cruz EM (1998) Observations on the seed production of the tilapia *Oreochromis spilurus* (Gunther) under different spawning conditions and with different sex ratios. *Asian Fisheries Science*, 10: 199-208.
- Simon CJ, Blyth D, Ahmad Fatan N, Suri S (2019) Microbial biomass (Novacq™) stimulates feeding and improves the growth performance on extruded low to zero-fish-meal diets in tilapia (GIFT strain). *Aquaculture*. Volume 501: 319-324. <https://doi.org/10.1016/j.aquaculture.2018.11.052>
- Stickney RR (1986) Tilapia tolerance of saline waters: a review. *Progress in Fish Culture*. 48, 161-167.
- Suresh AV, Lin CK (1992) Tilapia cultures in saline waters; a review. *Aquaculture* 106; 201-226.
- Villegas CT (1990) Evaluation of salinity tolerance of *Oreochromis mossambicus*, *O. niloticus*, and their F1 hybrids. *Aquaculture* 85: 281-282.
- Watanabe WO, Kuo CM, Huang MC (1985a) The ontogeny of salinity tolerance in the tilapias *Oreochromis aureus*, *O. niloticus*, and an *O. mossambicus* x *O. niloticus* hybrid, spawned and reared in freshwater. *Aquaculture* 47:353-367.
- Watanabe WO, Kuo CM, Huang MC (1985b) Salinity tolerance of Nile tilapia fry (*O. niloticus*) spawned and hatched at various salinities. *Aquaculture* 48:159-176.
- Watanabe WO, French KE, Ernst DH, Olla BL, Wicklund RI (1989) Salinity during early development influences growth and survival of Florida red tilapia in brackish and seawater. *Journal of the World Aquaculture Society* 20: 134-142.
- Woessner J, Fortes RD, Corre VJr (1991) *Pond Dynamics /Aquaculture Collaborative Research Data Reports, Volume 4, Number 1: Philippines Cycle I of The Global Experiment*. Pond Dynamics/Aquaculture Collaborative Research Support Program, Oregon State University, Corvallis, OR.
- World Bank (2016) *World development indicators (WDI)*. Washington, D.C: World Bank.
- Yao K, Ouattara M, Ahoussi AFA (2008) *Survie du Tilapia du Nil (Oreochromis niloticus) en eaux salées durant un transfert direct et progressif [Survival of the Nile Tilapia (Oreochromis niloticus) in salt water during a direct and progressive transfer]*. *Livestock Research Rural Development*. 20: Article #72. (<http://www.lrrd.org/lrrd20/5/yao20072.htm>; in French with English abstract).
- Yi Y, Lin CK, Diana JS (1996) Influence of Nile tilapia (*Oreochromis niloticus*) stocking density in cages on their growth and yield in cages and in ponds containing the cages. *Aquaculture* 146: 205-215.
- Yi Y, Lin CK, Diana JS (2002) "Supplemental feeding for semi-intensive culture of red tilapia in brackish water ponds". In: K. McElwee, K. Lewis, M. Nidiffer, and P. Buitrago (Eds.), *Nineteenth Annual Technical Report*. Pond Dynamics/Aquaculture CRSP, Oregon State University, Corvallis, Oregon, pp. 97-101.