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Growth Performance and Feed Conversion Efficiency of the Nile Tilapia *(Oreochromis niloticus)* in a Greenhouse Aquaponic System coupled with Lettuce *(Lactuca sativa)* Under Moroccan Conditions

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ABSTRACT

This study evaluates the growth performance and feed conversion efficiency of the Nile tilapia *(Oreochromis niloticus)* cultivated in a greenhouse aquaponic system associated with lettuce *(Lactuca sativa)* under Moroccan climatic conditions. The system consists of an 800L polyethylene fish tank integrated with a dual hydroponic unit (NFT and DWC) operating in a closed recirculating loop. Eighty juvenile tilapias (initial weight = 4.5 ± 0.3g; length = 6.7 ± 0.4cm) were reared for 50 days at an average water temperature of 28.6°C. Results showed a tenfold increase in body weight, reaching 47.4 ± 4.2g and 14.0 ± 1.1cm in length. The specific growth rate (SGR) was 4.71 % day^{-1}, and the feed conversion ratio (FCR) averaged 0.44, indicating excellent feed utilization. The daily weight gain reached 0.86g day^{-1}, and the survival rate was 93.8%. Water quality parameters (DO > 90 %, EC = 1.48 mS cm^{-1}, TDS = 725 ppm) remained within optimal ranges for both fish and plants. These findings confirm the technical feasibility and biological efficiency of integrating tilapia with lettuce in a recirculating greenhouse aquaponic system, supporting its potential as a sustainable food production model for semi-arid urban regions.

INTRODUCTION

Aquaponics represents an emerging form of integrated aquaculture, combining fish production with hydroponic plant cultivation in a recirculating water system where fish waste serves as a nutrient source for plants. This symbiotic relationship not only enhances water use efficiency but also improves nutrient recovery, making it an attractive solution for sustainable food production in water-limited regions (**Buzby & Lin, 2014; Lennard & Goddek, 2019**).

The Nile tilapia *(Oreochromis niloticus)* is the most widely used species in aquaponic systems due to its hardiness, fast growth, and tolerance to suboptimal water conditions **(El-Sayed, 2006)**. Its adaptability to variable oxygen and temperature levels, coupled with its omnivorous diet, makes it particularly suitable for closed recirculating systems. Tilapia also contributes to system stability by providing a steady nitrogen source through excreted ammonia, which supports the growth of nitrifying bacteria and subsequent plant nutrient availability **(Rakocy *et al.,* 2006)**.

In integrated systems, the efficiency of fish growth depends on a delicate balance between feeding rate, water quality, and microbial activity. Excessive accumulation of nitrogenous compounds can impair growth and health, while optimal conditions promote feed conversion efficiency (FCR) and specific growth rate (SGR), as key indicators of aquaculture performance. Evaluating these parameters in coupled aquaponic systems is therefore essential to ensure both biological sustainability and production profitability.

Despite significant advances in aquaponics research globally, studies on fish performance under semi-arid climates remain limited. In Morocco, where water scarcity and rising urban demand threaten traditional aquaculture, integrated aquaponic systems offer a promising pathway toward sustainable food production.

This study aims to evaluate the growth performance, feed conversion efficiency, and survival rate of the Nile tilapia *(Oreochromis niloticus)* cultivated in a greenhouse aquaponic system coupled with lettuce *(Lactuca sativa)* under Moroccan conditions. The findings would provide valuable insight into the technical feasibility and aquacultural productivity of small-scale aquaponic models in resource-constrained environments.

MATERIALS AND METHODS

1. Experimental Site and System Design

The experiment was conducted between June and August 2025 in a glass greenhouse at the Faculty of Sciences, Mohammed V University in Rabat, Morocco. The system operated under natural photoperiod and temperature conditions typical of the local semi-arid climate, with daytime temperatures ranging from 26 to 34°C.

The aquaponic prototype functioned as a recirculating coupled system, combining tilapia *(Oreochromis niloticus)* rearing and hydroponic cultivation of lettuce *(Lactuca sativa var. Madrilène).* The setup included an 800L high-density polyethylene (HDPE) fish tank filled to 500L, a dual filtration unit, and a hydroponic section composed of NFT and DWC subsystems connected by gravity flow. It housed 80 juvenile tilapias (*Oreochromis niloticus*) with an average initial weight of 4.5 g and an average length of 6.66 cm. Optimal growth conditions were maintained by a submersible water heater (thermoregulator) that ensured stable water temperature, and an aeration system composed of two air pumps, each with a flow rate of 1.5 $L \cdot min^{-1}$, providing adequate oxygenation of the aquatic environment. The filtration system consisted of two barrels: a mechanical filter containing wool materials to trap suspended solids, and a biological filter filled with Sera Siporax, providing substrate for nitrifying bacteria.

The filtered water was collected in a slump, from which a submersible pump (3.8 W) recirculated the flow toward the hydroponic unit. The entire water circulation operated under a gravity-assisted loop, minimizing energy consumption, thus maintaining a closed and continuous recirculating loop between all components of the system.

2. Feeding and Management

Fish were fed a commercial floating feed (1.5 mm pellets) containing fishmeal, cereals, and soybean meal, providing a balanced ratio of protein and lipid content, thereby meeting the nutritional requirements of tilapia during the growth phase. Feed was manually distributed twice daily, at 9:00 a.m. and 5:00 p.m.

The daily feeding rate was adjusted based on biomass, representing 5–6 % of the mean body weight, and corrected every 10 days after sampling. Uneaten feed and solid residues were removed daily to maintain water quality.

3. Water Quality Monitoring

Water quality parameters were monitored using a multiparameter probe (HI 9829, Hanna Instruments) and a spectrophotometer for nutrient analyses. Daily measurements included temperature (°C), dissolved oxygen (DO, mg L^{-1}), electrical conductivity (EC, mS cm^{-1}), and total dissolved solids (TDS, ppm). Ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), phosphate (PO_4^{3-}), potassium (K^+), iron (Fe), and copper (Cu) were analyzed two to three times weekly. The average temperature was 28.6°C, EC 1.48mS cm^{-1}, and DO above 90 % saturation, consistent with optimal ranges for tilapias.

4. Data Collection

The monitoring of physico-chemical parameters and nutrient concentrations was carried out using various measuring and analytical instruments:

- **Multiparameter probe (HI 9829, HANNA Instruments):** used for *in situ* measurements of water temperature (°C), dissolved oxygen (DO, mg·L^{-1}), electrical conductivity (µS·cm^{-1}), and total dissolved solids (TDS, ppm). These parameters were monitored daily to ensure the stability of the aquatic environment.
- **Spectrophotometer:** employed for the analysis of dissolved nutrients, including ammonium (NH_4^+), ammonia (NH_3), nitrites (NO_2^-), nitrates (NO_3^-), phosphorus (P), potassium (K), molybdenum (Mo), and copper (Cu). Specific reagents were used in accordance with the manufacturer's protocols, allowing for accurate quantification of nutrient concentrations.
- **Complementary equipment:** precision weighing scales were used for fish sampling and feed ration measurements, a submersible thermoregulator was employed to maintain water temperature in the fish tank, and air pumps provided continuous aeration throughout the experiment.

The frequency of analyses varied according to the experimental phase: measurements were taken daily during the biological start-up period, and subsequently two to three times per week once the system stabilized. These measurements made it possible to characterize the evolution of biogeochemical cycles within the system and to identify potential critical fluctuations affecting the cultured organisms.

5. Growth Performance Evaluation

a. *Fish Growth Assessment*

Fish growth was evaluated through biometric measurements performed at the beginning and end of the experimental period. A representative sample of 50 individuals as minimum was weighed and measured to monitor growth trends. Individual body weight (g) and total length (cm) were recorded using a precision digital scale and a measuring board, respectively.

From this data, the following performance indicators were calculated:

- **Weight gain (WG, g):** $WG = \frac{W_f - W_i}{t}$, where W_0 and W_t are the initial and final mean weights, respectively, and *t* is the duration of the experimental period (days);
- **Specific growth rate (SGR, %·day⁻¹):** $SGR = \frac{ln(W_f) - ln(W_i)}{t} \times 100$;
- **Feed conversion ratio (FCR):** $FCR = \frac{F}{W_g}$, where *F* represents the total amount of feed administered (g);
- **Survival rate (SR, %):** $\boldsymbol{SR} = \frac{N_f}{N_i} \times 100$, where N_0 and N_t are the initial and final numbers of fish, respectively.

These indices provided an accurate estimation of growth performance, feed efficiency, and survival rate under aquaponic conditions.

6. Statistical Analysis

All analyses were performed using RStudio (version 4.4.2, R Core Team). Descriptive statistics (mean, SD, minimum, maximum) were calculated for growth and water parameters. Growth trends were modeled using linear and polynomial regression to describe temporal patterns. Correlations between fish growth and water quality parameters were assessed using the Kendall rank coefficient (τ), suitable for non-parametric data. Graphs were generated with the ggplot2 package for visual representation of growth, FCR, and survival trends.

RESULTS AND DISCUSSION

1. Descriptive Growth Analysis

Table (1) presents the evolution of tilapia growth parameters during the experiment. The mean body weight increased from 4.48 to 47.39g, corresponding to a net biomass gain of +42.9g over 50 days. Similarly, the average length rose from 6.66 to 14.01cm, representing an increase of +7.35cm. The standard deviation remained low, indicating homogeneous growth among individuals.

Table 1. Summary of growth performance results of *Oreochromis niloticus*

Date	Mean weight (g) ± SD	Min–Max (g)	Mean length (cm) ± SD	Min–Max (cm)	n
2025-06-26	4.48 ± 1.72	1.40 - 10.96	6.66 ± 0.94	4.8 - 10	104
2025-07-06	9.35 ± 3.14	2.90 - 17.00	8.0 ± 0.95	5.8 - 10	59

2025-07-16	16.85 ± 5.40	5.50 - 29.50	9.89 ± 1.35	6.5 - 12.5	58
2025-07-26	22.14 ± 6.41	7.37 - 35.47	10.84 ± 1.22	7.3 - 13	52
2025-08-15	47.39 ± 14.17	20.00 - 80.00	14.01 ± 1.51	10.5 - 17.5	75

This rapid development is typical of the early growth phase of tilapia (and comparable species) in aquaponic systems, where high nutrient availability and stable environmental conditions support efficient biomass accumulation.

The increase in inter-individual variability (standard deviation and Min–Max range) reflects behavioral differences, notably feeding competition among individuals. Overall, the results demonstrate that the system ensured efficient and consistent growth. Fig. (1) illustrates the simultaneous evolution of mean weight (left) and mean length (right) of *Oreochromis niloticus* from late June to mid-August 2025. The growth trend was clear and continuous, with a noticeable acceleration from late July onward.

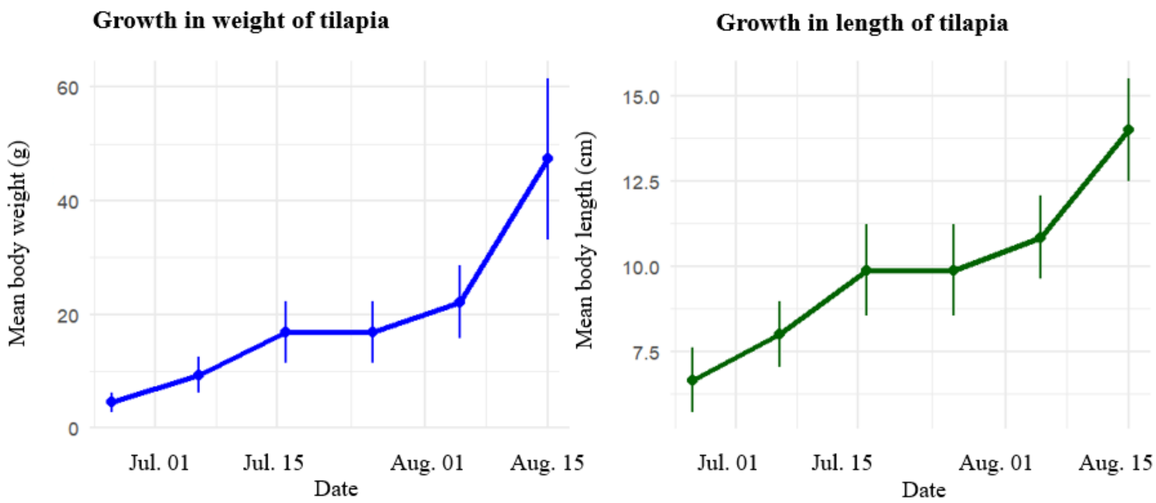

Fig. 1. Growth of Nile tilapia *(Oreochromis niloticus)* in the greenhouse aquaponic system

In terms of weight, individuals increased from 4.5g (June 26) to 47.4g (August 15), which is more than tenfold gain in approximately 50 days. Growth was not strictly linear, showing a pronounced acceleration during early August. The widening standard deviation indicates growing dispersion between individuals, a typical phenomenon in aquaculture linked to competition and inherent growth variability. Length followed a similar pattern, doubling from 6.7 to 14.0cm over the same period, with a brief slowdown in late July followed by renewed acceleration in August. Variability in length remained lower than in weight, consistent with the less sensitive morphological variation of this parameter.

Overall, these findings confirm that tilapia exhibited rapid and sustained growth within the aquaponic system, characteristic of the juvenile phase, where metabolic activity and feed conversion efficiency are the highest. The late-summer acceleration suggests that experimental conditions, including water quality, nutrient availability, and feeding management, were optimal for maximizing development.

2. Zootechnical Indices

To assess the growth performance and feed efficiency of the Nile tilapia in the aquaponic system, several zootechnical indices were calculated: daily weight gain (DWG), specific growth rate (SGR), feed conversion ratio (FCR), and survival rate (SR) (Table 2).

Table 2. Zootechnical indices of *Oreochromis niloticus* cultivated in the greenhouse aquaponic system

Index	Formula	Result	Interpretation
GMQ (g/day)	$FCR = \frac{47.39 - 4.48}{50}$	0.85 g/j	Average daily growth rate
SGR (%/day)	$SGR = \frac{ln(47.39)\ -\ ln(4.48)}{50} \times 100$	4.71 %/j	Relative daily growth rate
FCR	$FCR = \frac{1400}{3195}$	0,44	Excellent feed efficiency
Survival rate (%)	$SR = \frac{75}{80} \times 100$	93,8 %	Good acclimation, low mortality

Tilapia exhibited a mean daily weight gain (DWG) of 0.86g/ day, indicating sustained biomass accumulation throughout the experiment. This rate is typical of the juvenile growth phase, characterized by a high metabolic rate and optimal feed utilization. The specific growth rate (SGR) reached 4.71%/ day, confirming the rapid development observed in the weight and length curves, and suggesting that the water quality and feeding regime were well suited to the species' requirements. The feed conversion ratio (FCR) of 0.44 reflects exceptional feed efficiency, with less than half a gram of feed required to produce one gram of biomass. Out of the 104 individuals initially sampled, only 80 juveniles were introduced into the aquaponic system. At the end of the experiment, 75 fish remained, yielding a survival rate of 93.8 %. The recorded losses were attributed to sampling stress, not to disease or system failure, confirming excellent acclimation and overall fish health during the experimental period.

3. Growth Modeling

a. Polynomial Regression Model

The results of the adjusted regression models are presented in Table (3), while Fig. (2) shows the graphical representation of the weight and length evolution of *Oreochromis niloticus* during the experimental period.

Table (3) indicates that weight growth is best described by a second-degree polynomial model, which explains nearly 93% of the total variability (R^2adj= 0.93, *P*= 0.036). The linear term is statistically significant (*P*= 0.020), confirming a consistent increase in mean body weight over time, whereas the quadratic term is not significant (*P*= 0.149), suggesting only a slight tendency toward accelerated growth at the end of the period.

Table 3. Polynomial regression (2nd degree) and linear model results describing the relationship between growth parameters of *Oreochromis niloticus* and time (days)

Model	Parametr	Estimate	Std. Error	t-value	P-value	R^2 adj
Weight (g) – polynomial (DAY²)	Intercept	20,042	2,011	9,97	0,0099 **	0,928
	Jour (linéaire)	31,183	4,497	6,93	0,0202 *	
	Jour² (quad.)	10,303	4,497	2,29	0,149	
Length (cm) – linear	Intercept	6,372	0,473	13,49	0,0009 ***	0,953
	Jour	1,754	0,193	9,09	0,0028 **	

In contrast, length growth follows a strictly linear relationship, with a highly significant slope (P= 0.0028) and an adjusted coefficient of determination of 0.95, indicating an almost perfect correlation between time and fish elongation.

Fig. (2) illustrates these trends: the polynomial curve for weight shows an initially steady increase followed by an acceleration toward the end of the experiment, reflecting greater variability between individuals. Conversely, the linear regression of mean length depicts continuous and homogeneous progression throughout the experimental period.

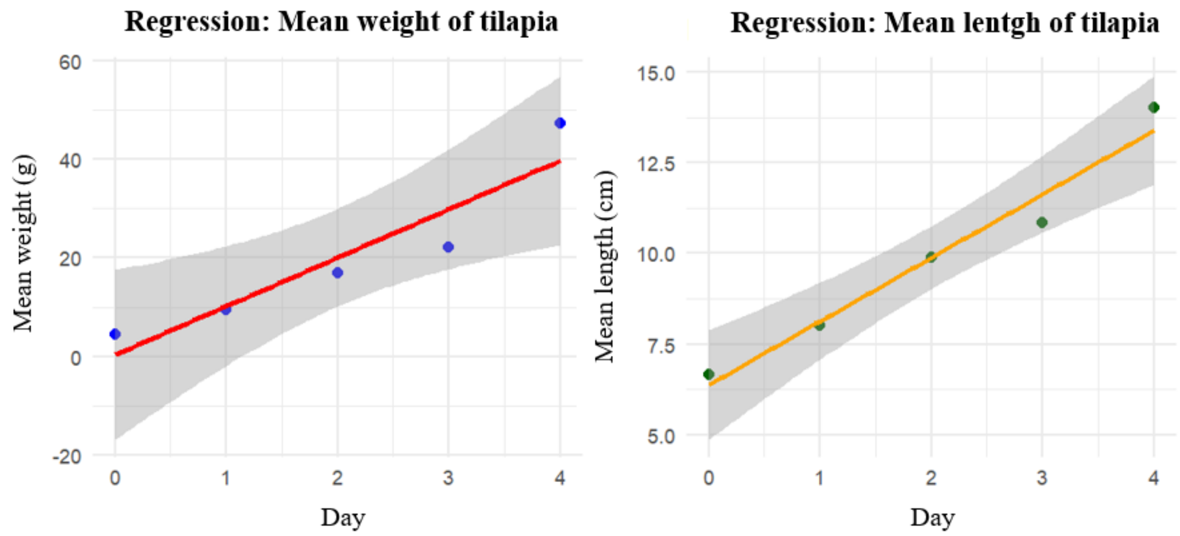

Fig. 2. Modeled growth of the Nile tilapia (*Oreochromis niloticus*) in the greenhouse aquaponic system

These findings confirm that length is a more stable indicator of overall batch growth, whereas weight reflects both elongation and body condition, making it more sensitive to inter-individual variability.

b. Linear Mixed Model

The results of the linear mixed-effects models (Table 4) show that tilapia growth is strongly and linearly related to time, both for weight and length.

Table 4. Results of the linear mixed-effects models (LMM) describing the relationship between growth parameters of *Oreochromis niloticus* and time (days)

Variable	Parameter	Estimate	Std. Error	t value	Random Variance (Fish_ID)	Residual (σ)	Interpretative R^2 *
Weight (g)	Intercept	1,99	0,73	2,71	0,00 (σ = 0,00)	9,26 g	High (Time as explanatory)
	Day	7,37	0,25	29,47			
Length (cm)	Intercept	6,63	0,11	60,54	0,06 (σ = 0,24 cm)	1,34 cm	High (Time as explanatory)
	Day	1.33	0.09	14.78	—	—	—

Interpretative R^2 refers to the proportion of variance in growth explained by time (Day) in the fixed effect structure.

For weight, the estimated slope is +7.37g day^{-1}, indicating a marked and consistent increase in individual biomass throughout the experimental period. In contrast, length growth follows a more regular and homogeneous pattern, with a mean gain of approximately +1.33cm day^{-1}.

The random effect variance associated with the individual identifier (Fish_ID) was null for weight, reflecting high inter-individual homogeneity once the time effect was accounted for. For length, a very small inter-individual variance was detected (standard deviation ≈ 0.24cm), although the residual variance remained dominant.

Overall, the results indicate that linear growth dynamics were consistent across the population, confirming that individual differences contributed minimally compared with the global time effect.

As illustrated in Fig. (3), the mixed-effects regression applied to weight (left panel) reveals a steady increase over time but with a wider dispersion among individuals, reflected by the greater spread of points around the fitted trend line. In contrast, the regression applied to length (right panel) shows a more homogeneous distribution of data points around the fitted line, indicating that length growth is a more stable and less variable indicator than body mass.

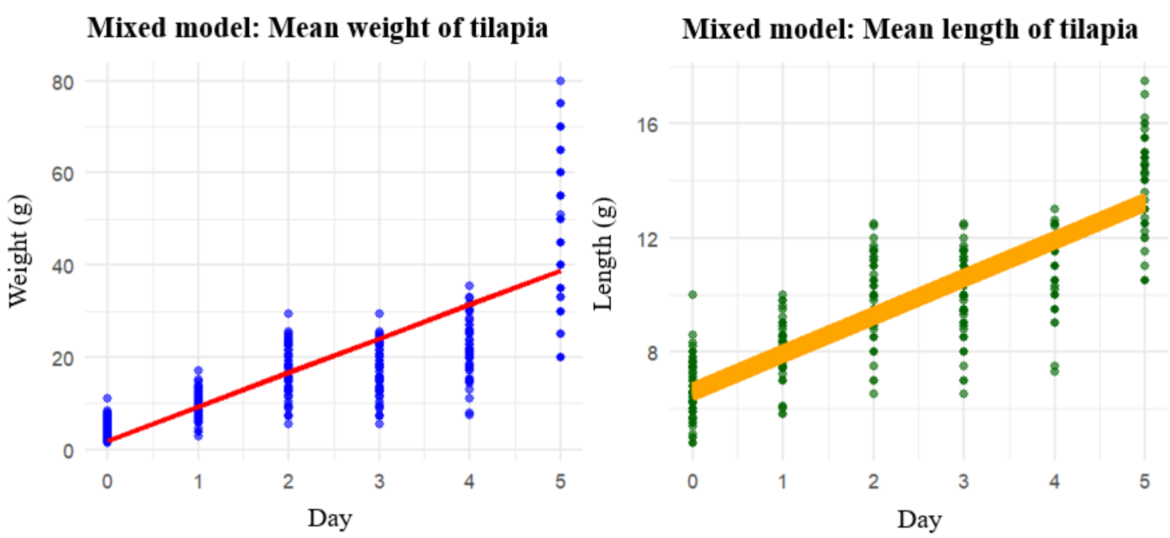

Fig. 3. Linear mixed-model regression of tilapia growth in weight (left) and length (right)

Overall, these findings highlight that weight gain in tilapia is rapid but more heterogeneous, whereas length growth remains steady and uniform, reflecting a developmental pattern consistent with the species' juvenile growth phase biology.

c. Comparison of the Two Models

In the simple regression model (polynomial), a trend curve, either linear or quadratic, is fitted to the mean weight or length values as a function of time. The main advantage of this approach lies in its simplicity of interpretation and ease of visualization (through R^2, slope, and significance levels). However, this type of regression does not account for the repeated-measures structure of the dataset (multiple fish measured at several time points), which can lead to an underestimation of variability.

In contrast, the linear mixed-effects model (LMM) considers both the fixed effect of time (Day) and the random variability among individuals (Fish_ID). This approach is more robust and particularly well suited to longitudinal and correlated data, as it allows the separation of intra- and inter-individual variance components. Its main limitation is that interpretation can be less intuitive, as R^2 values are not directly provided.

For weight, both models indicate a strong relationship with time. Polynomial regression suggests a slight curvature in the growth trajectory, whereas the LMM reveals a predominantly linear and homogeneous increase among individuals (Table 5). Regarding length, both models, simple linear and mixed, converge toward the same conclusion: a regular, time-driven growth pattern, with the LMM further confirming that inter-individual variability remains minimal.

In summary, simple regression provides a useful preliminary estimation of growth trends (weight and length over time) and is appropriate for illustrative purposes, while the linear mixed model offers a more robust and accurate framework for repeated-measures data, as it captures the hierarchical structure of observations and isolates individual-level variability.

Table 5. Comparison between simple regression and linear mixed-effects models for tilapia growth

Variable	Simple model (R^2 adj.)	Mixed model (Effect of Day)	Inter-individual Variability
Weight	0,93 (polynomial)	7,37 g/day (t = 29,5)	Null (σ = 0,00)
Length	0,95 (linear)	1,33 cm/day (t = 36,5)	Low (σ = 0,24 cm)

In our case, both modeling approaches led to consistent conclusions: growth was rapid and regular, with greater homogeneity in length than in weight.

4. Modeling and Prediction of Fish Growth

The linear mixed-effects models adjusted between time and the growth parameters of tilapia *(Oreochromis niloticus)* revealed a highly significant and predictive linear relationship (Table 6). Growth in weight was estimated at +7.37g day^{-1}, with an intercept of 1.99g, explaining approximately 68 % of the total variability. This model therefore provides a reliable predictive framework for estimating the future mean weight of fish as a function of culture duration. Similarly, length growth followed a slope of +1.33cm day^{-1} with an intercept of 6.63cm, accounting for roughly 77% of the variability. This model also represents a robust predictive tool for estimating the mean body length of fish over time.

Table 6. Summary of linear mixed-effects models describing fish and plant growth dynamics in the aquaponic system

Variable	Intercept (Estimate)	Slope (Day)	Marginal R^2	Conditional R^2	Random Variance (ID)	Residual (σ)
Weight (g)	1,99 g	+7,37 g/jour	0,68	0,68	0,00 (σ = 0,00)	9,26 g
Length (cm)	6,63 cm	+1,33 cm/jour	0,76	0,77	0,06 (σ = 0,24 cm)	1,34 cm

These results are illustrated in **Fig. (4)**, where grey points represent raw observations, and colored lines correspond to model predictions. The close agreement between observed and fitted data confirms the strong predictive capacity of these models and supports their potential use for forecasting growth performance in the aquaponic system under study.

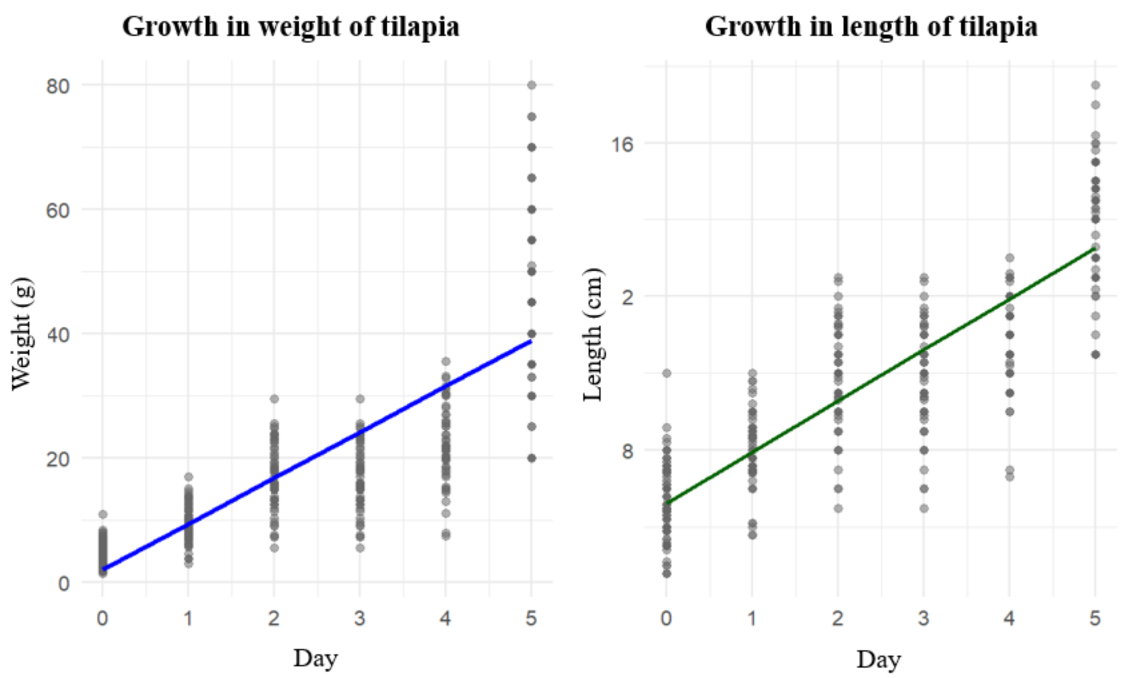

Fig. 4. Growth in weight and length of *Oreochromis niloticus* reared in the greenhouse aquaponic system

The left panel shows the evolution of individual fish weight (g) over time, and the right panel illustrates body length (cm). Grey points represent observed data, while the colored lines (blue for weight, green for length) correspond to the fitted linear mixed-effects models.

DISCUSSION

The present study demonstrates the strong growth performance of *Oreochromis niloticus* reared in a small-scale greenhouse aquaponic system coupled with *Lactuca sativa*. Over a 50-day culture period, tilapia exhibited a tenfold increase in body weight (from 4.5 to 47.4g) and a doubling in length (from 6.7 to 14.0cm). These results are consistent with growth rates reported in recirculating aquaculture systems (RAS) under tropical or subtropical conditions **(El-Sayed, 2006; Buzby & Lin, 2014)**. The daily weight gain (0.86g day^{-1}) and specific growth rate (4.7% day^{-1}) confirm that the physical and chemical conditions of the aquaponic environment were suitable for optimal metabolic activity and feed conversion efficiency.

The low feed conversion ratio (FCR = 0.44) observed in this system reflects excellent feed utilization efficiency. This enhanced performance may be attributed to the nutrient-rich water and balanced microbiological environment typical of aquaponic systems, which promote stable water quality and reduce physiological stress in fish. The constant recirculation and nitrification ensured low concentrations of toxic nitrogen compounds (NH_3 < 1.1 mg L^{-1}; NO_2^- < 2 mg L^{-1}) while providing sufficient nitrate levels to sustain plant uptake. These findings align with the results of **Lennard and Goddek, (2019)**, who reported that efficient microbial nitrification supports both fish health and plant productivity.

The high survival rate (93.8%) indicates successful acclimation and minimal stress within the system. Mortalities were mainly due to sampling losses rather than environmental constraints, highlighting the biological resilience of tilapia to greenhouse aquaponic conditions. The linear mixed-effects models revealed a highly significant and predictive relationship between time and growth for both weight (+7.37g day^{-1}) and length (+1.33cm day^{-1}), confirming homogeneous growth across individuals. The limited random variance observed demonstrates that inter-individual differences were minor once time was accounted for, a trend commonly observed in batch-reared juvenile tilapia **(Hu *et al.*, 2021)**.

These results collectively indicate that the integrated system provided a favorable and stable environment, effectively coupling nutrient cycling, oxygenation, and temperature regulation. The synergy between the fish and lettuce compartments enhanced system efficiency: fish waste served as a continuous nutrient source for plants, while the plants contributed to water purification through nitrate uptake. This mutualistic interaction confirms the ecological and functional complementarity of aquaponics, supporting its potential as a sustainable aquaculture model for urban and peri-urban contexts in Morocco.

CONCLUSION

This study demonstrates the high growth performance and biological efficiency of *Oreochromis niloticus* reared in a small-scale greenhouse aquaponic system coupled with *Lactuca sativa.* The results reveal a rapid and homogeneous growth, with a specific growth rate of 4.7% day^{-1}, a feed conversion ratio of 0.44, and a survival rate exceeding 93%. The linear mixed models confirm a strong predictive relationship between culture time and both weight and length, reflecting optimal system stability.

The integration of fish and plants ensures effective nutrient recycling and water quality maintenance, highlighting the ecological and economic viability of aquaponics as a sustainable production model. These findings support the potential of aquaponic systems as a promising alternative for urban and peri-urban food production in Morocco and similar semi-arid regions.

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