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Article

Lateral Target Strength (TS) Estimation of Free-Swimming Nile Tilapia (*Oreochromis niloticus*) in Ponds Using a 200 kHz Single-Beam Echosounder

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Abstract

As global aquaculture continues to expand there is an increasing interest for sustainable and non-invasive tools to monitor fish growth. Nile tilapia (*Oreochromis niloticus*) is one of the most farmed species worldwide. Its biomass estimation often relies on manual sampling or stereo-cameras systems limited by water turbidity. This study establishes a robust relationship between lateral Target Strength (TS) and the total length (TL) and weight (W) of Nile tilapia using a cost-effective 201 kHz single-beam echosounder. Measurements were conducted with free-swimming fish in a controlled pond environment (TL range 13–44 cm). The results show a strong linear correlation between acoustic and biometric data. Specifically, the relationship for mean TS was defined as $TS_{mean} = 20.1\log(TL) - 66.7$ ($R^2=0.91$) and $TS_{mean} = 6.3\log(W) - 55.4$ ($R^2=0.96$), proving the system's accuracy for biomass estimation. Furthermore, the Method of Fundamental Solutions (MFS) was employed for numerical validation based on X-ray morphometry of the swim bladder. A very good agreement was observed between experimental data and numerical simulations, reinforcing the validity of the acoustic models despite the inherent complexity of biological targets. These findings demonstrate that calibrated single-beam acoustic systems provide a viable, non-intrusive tool for real-time monitoring in aquaculture ponds.

Keywords: Nile tilapia; target strength; single-beam echosounder; aquaculture monitoring; numerical methods; blue economy

1. Introduction

Aquaculture production reached a record 130.9 million tons in 2022, with a total value of 295.7 billion dollars [1]. Nile tilapia (*Oreochromis niloticus*) is the fourth most farmed species, with a global production of 5.3 million tons in the same year. As fishery resources continue to decline due to over-fishing, pollution, poor management, and other factors, aquaculture is expected to expand to meet the growing demand for food. However, this growth must be achieved sustainably, ensuring ecosystem protection, pollution reduction, biodiversity conservation, and social equity. The concept of Blue Transformation, an international initiative, presents key challenges for fisheries and aquaculture. Within this framework, the expansion of aquaculture aims to be both sustainable and resilient, addressing environmental and social concerns while enhancing global food security [1]. Nile tilapia aquaculture can be developed in cages, ponds, or tanks. This species exhibits rapid growth, with individuals increasing their weight by approximately 50% within 6 to 9 months, making it well-suited for farming. To ensure adequate growth, it is essential to monitor various parameters, such as size, weight, and population density. For this reason, regular sampling must be carried out. Traditionally, aquaculture

production in cages or tanks has been monitored through manual sampling, performed either by farm staff or machinery. However, this method is often invasive to fish. In recent years, video-based systems have been increasingly used to estimate fish length and monitor various procedures in aquaculture. These non-intrusive systems can be mono, stereo, or drone-based, and their data can be processed automatically, often incorporating artificial intelligence [2–4]. However, video systems are limited by factors such as water depth and turbidity. Alternatively, underwater acoustics has been employed to estimate biomass in free water [5]. An increasing number of studies focus on the application of acoustic techniques for monitoring fish growth in cages and tanks [6–9]. In these studies, a relationship between target strength (TS) and fish length was found from different perspectives (ventral and lateral). TS is defined as the acoustic energy backscattered by an individual fish [5]. The TS returned by a fish depends on several factors, with some of the most important being fish size, the presence or absence of a swim bladder, and swimming orientation. Liu et al. (2022) [10] demonstrated that a reliable relationship between target strength (TS) and fish length can be obtained for Nile tilapia using a scientific echosounder. In their study, Nile tilapia of different sizes were anchored and measured in a laboratory tank. Scientific echosounders are commonly used, as they can compensate for TS variations based on the fish’s position within the acoustic beam. Moreover, they provide valuable information about fish swimming trajectories. However, their high cost limits their widespread use as a monitoring tool in aquaculture. On the other hand, Dwinoventy et al. (2023) [11] used a single-beam scientific echosounder (Simrad EK15) and a fish finder (Furuno FCV-628) to establish a relationship between Nile tilapia length and TS in a tank. To achieve this, the fish were anchored to obtain TS-length data. In this study, a strong relationship between TS and the total length of Nile tilapia was found. During the measurements, the fish were swimming freely, making the conditions similar to those in production environments. A single-beam echosounder was used, which, although calibrated, is a cost-effective system when compared to scientific echosounders. Preliminary results were described in [12,13]. Because of this, it has the potential to become a useful non-invasive tool in tilapia aquaculture. Its adoption could help producers align with the Blue Transformation guidelines.

2. Materials and Methods

2.1. Biometric Data Collection

The data were collected at Centro de Investigación Piscícola (CIMPIS) of the Universidad Agraria La Molina (Lima, Perú) (12°05’03" S - 76°56 ’44.8"W) from December 2018 to December 2019. To do it, a pond of 4.0 x 4.0 x 1.5 m was built. Nile tilapia (*Oreochromis niloticus*) with total length (TL) between 13 and 44 cm were selected and divided into 8 groups. The maximum size dispersion for each group was 2.0 cm, with an uncertainty of ±0.5 cm. The number of fish in each group varied between 6 and 20 fish depending on the availability. A description of selected groups is shown in Table 1. To obtain TL of each fish, an ichthyometer (INC Aquatic Eco-Systems) was used. The fish weight (W) was obtained (Figure 1) using a digital precision scale Bondibuy SF-400 (±1g). Morphological data acquisition process is described in [14].

Table 1. Fish group data.

Group	Fish number	Mean TL (cm)	Min TL(cm)	Max TL(cm)	Mean W(g)	std W(g)
1	20	14.1	13.0	15.0	47	10
2	15	17.9	17.0	19.0	99	7
3	14	21.5	21.0	22.0	180	8
4	14	24.6	24.0	25.0	230	16
5	6	30.3	29.0	31.0	540	60
6	6	35.1	34.0	36.0	760	60
7	6	40.8	40.0	41.5	1380	20
8	6	43.7	43.0	44.0	1450	110



Figure 1. In the left digital precision scale during fish measurement (W= 338 g). In the right the ichthyometer (TL= 17.5 cm). Adapted from [14]

2.2. Acoustic Data Collection

Acoustic measurements were performed using a Biosonics DT-X echosounder working with a 201 kHz single beam transducer. The transducer was placed at the end of the pond such the acoustic beam was parallel to the water surface. Thus, lateral point of view of the fish was recorded (Figure 2). Acoustic data were collected during 2 to 5 days for each length group shown in Table 1. During the measurements, fish were swimming freely into the pond. Echosounder measurement settings are presented in Table 2. Data were recorded using Visual Acquisition software from Biosonics®. For ease the analysis, short files were recorded, with maximum duration of 30 minutes.

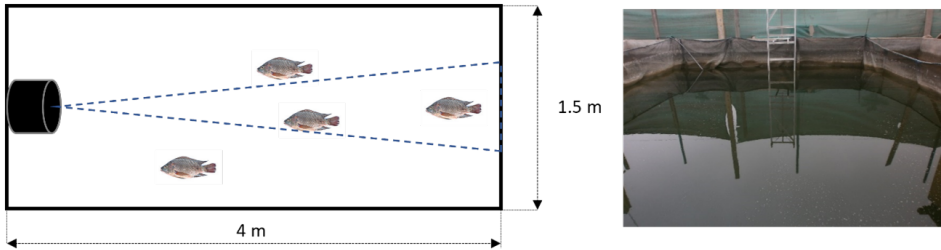


Figure 2. In the left, lateral scheme of the pond with Biosonics 201 kHz transducer and its beam. In the right, picture of real pond used.

Table 2. Selected settings for DT-X Biosonics echosounder.

Parameter	Value
Frequency	201 kHz
Beam width	9.9°
Pulse length	0.1 ms
Ping rate	5 pings·s ⁻¹
Source level	202.3 dB rel. 1μPa @ 1m
Receiver Sensitivity	−64.9 dB

2.3. Acoustic Data Analysis

Acoustic data were collected and analysed using Sonar 5-Pro [15]. Echograms were transformed and a threshold of 95 dB was used to obtain higher quality images. Due to a single beam transducer was used, 2D Single Echo Detector (SED) algorithm was applied. Traces were isolated manually, and they be ranked in terms of quality. To do it, TS profile of each trace was analysed. If the trace had the typical “v” shape, it was stored otherwise it was rejected. Two examples of selected traces are shown in Figure 3. For each trace maximum TS, mean TS and distance from the centre of gravity of the trace were calculated. When de distance from the centre of gravity was lower than 1 meter, traces were discarded. Data obtained from Sonar5-Pro were transferred to Statgraphics Centurion XIX software for statistical analysis. Mean and maximum TS versus fish length relationships were obtained. The linearized equation (1) was used

$$TS = a \log(TL) + b \tag{1}$$

where a is the slope and b is the intercept and TL is expressed in centimetres. In fisheries, a fixed slope $a=20$ has been extensively used [16]. Nevertheless, McClatchie et al., 2003 [17] shown that, when information related to a wide range of fish size is available, a free slope provides better TS vs TL fits. In this study both, a and b , were obtained from lateral TS measurements and fish sampling for each group.

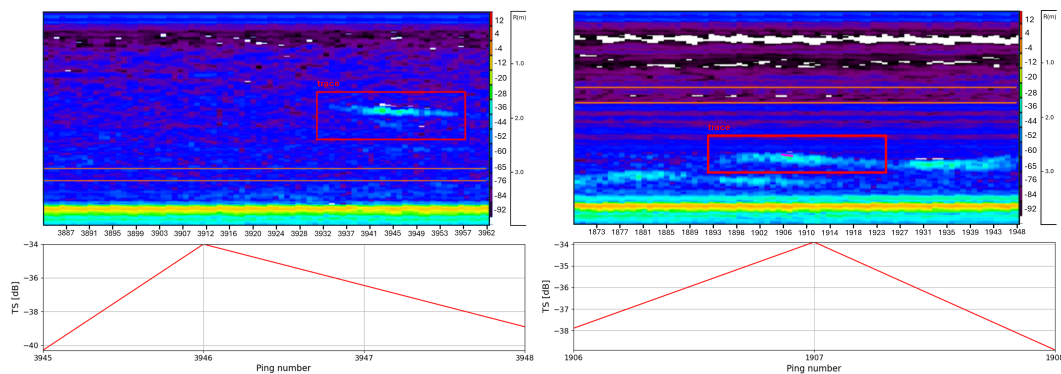


Figure 3. In the left, echogram and TS profile of one trace belonging to group 7. In the right, echogram and TS profile of one trace belonging to group 8. All images were obtained from Sonar5-Pro software.

2.4. Numerical Simulations of TS from Nile Tilapia

For the numerical estimation of TS, the Method of Fundamental Solutions (MFS) was selected. MFS is a non-mesh simulation method based on reproducing the field through a linear combination of a set of virtual sources located outside the domain of interest [18]. A determinant advantage of the MFS is its capability to evaluate the acoustic backscattered field at any working distance between the fish and the echosounder, but, being a meshless method, avoiding the high computational costs associated with the use of other numerical methods with a mesh, as it is the case of boundary element method or finite element method [19]. The propagation of sound within a homogeneous acoustic space can be described mathematically in the frequency domain by using the Helmholtz differential equation (2):

$$\nabla^2 p + k^2 p = 0 \quad (2)$$

where

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \quad (3)$$

in the case of 3D problem, p [Pa] is the acoustic pressure, $k = \omega/c$ the wave number, $\omega = 2\pi f$ the angular frequency, f [Hz] the frequency and c [m/s] the sound propagation velocity within the acoustic medium. For the 3D case, assuming a point source placed within the propagation domain, at point x_0 with coordinates (x_0, y_0, z_0) [m], it is possible to establish fundamental solution G , for the sound pressure, and H , for the particle velocity [m/s], at a point with coordinates x [m], which can be written respectively as:

$$G^{3D}(x, x_0, k) = \frac{e^{-ikr}}{r} \quad (4)$$

$$H^{3D}(x, x_0, k, \vec{n}) = \frac{1}{-i\rho\omega} \frac{(-ikr - 1)e^{-ikr}}{r^2} \frac{\partial r}{\partial \vec{n}} \quad (5)$$

In these equations, r [m] corresponds to the distance between the source point and the domain point given; $\vec{n}$ represents the direction along which the particle velocity is calculated and ρ [kg/m³] the medium density. Being the swimbladder responsible for the most significant contribution of the acoustic dispersion [20], the Nile tilapia TS was evaluated considering the acoustic backscattering from the swimbladder. A characterization of the swimbladder of the species was conducted during the experiment extracting individuals from the same tanks used in the acoustic measurements. A set

of 25 individuals were x-ray scanned to obtain the morphometry of the swimbladder and flesh. The aim was to obtain the allometric relations relating to the swimbladder length and the total fish length, which allow to develop geometrical models for TS estimation. From the X-Ray set, 6 individuals were selected, by visual inspection, to develop the swimbladder model shape. The procedure was as following: for each individual, two orthogonal 2D images of the inflated swimbladder were extracted, which allows to reconstruct a 3D swimbladder model. The 2D images were processed by using our own developed code and the Image Processing App in Matlab®. The masks for the fish flesh and swimbladder were extracted, smoothed and processed to characterize the best elliptic fit for both xy and xz planes, being x defined as the fish axis direction. The two orthogonal 2D ellipses were combined for constructing the best 3D prolate ellipsoid for modelling the swimbladder. This process (Figure 4) was conducted for every fish and considered to perform the numerical estimations. The individuals were preserved in ice and scanned immediately after being extracted from the tank. The size distribution was selected to be distributed along the size range of the experiment.

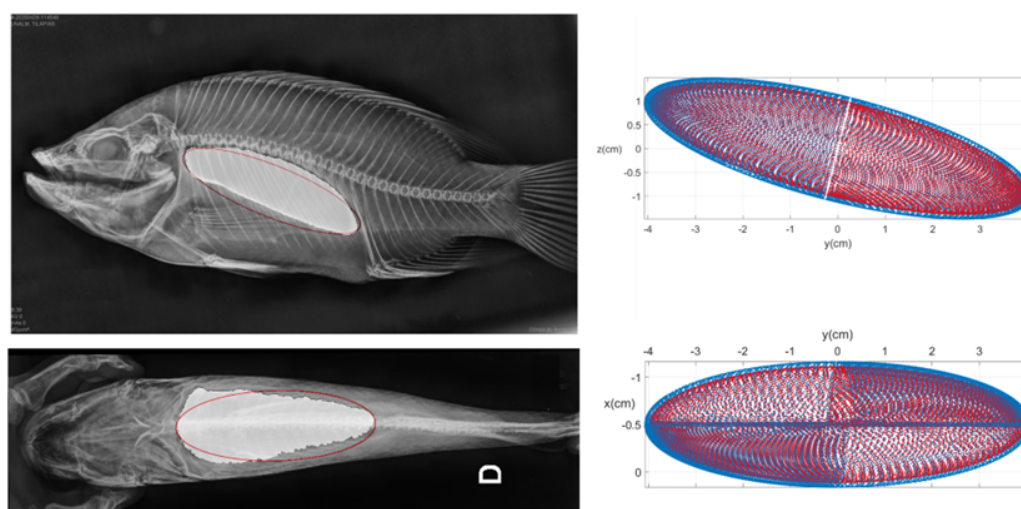


Figure 4. Left: X-ray of a tilapia with total length 27 cm in lateral (up) and dorsal view (bottom). Grey shadows correspond to the extracted 2D orthogonal masks of the swimbladder, red lines mark the best elliptic fitting for the swimbladder masks in the two aspects. Right: Virtual sources (red) and collocation points (blue) in the MFS numerical model for calculating the acoustic backscattering of the Nile tilapia's swimbladder, lateral (up) and dorsal (bottom) views.

The swimbladder was modeled as a volume with pressure release on its surface [21]. The properties considered for the materials were: $c_{water} = 1500$ [m/s], $\rho_{water} = 1026$ [kg/m³], $c_{air} = 343$ [m/s] and $\rho_{air} = 1.2$ [kg/m³]. The TS was calculated at 3 meters, as was the working length in the experimental tanks. Figure 4 (right) shows the distribution of the boundary points and the virtual sources used in the MFS calculation. To consider the role of the fish orientation, the directivity of the TS was evaluated by rotating the angle α between the fish axis and the beam incidence direction degree by degree from $\alpha = 0^\circ$ -corresponding to incidence from Head to Tail (H2T) orientation- to $\alpha = 180^\circ$ -meaning Tail to Head (T2H) orientation-, being $\alpha = 90^\circ$ the orientation corresponding to the lateral insonification of the fish [9]. In the absence of more accurate information about the swimming orientation distribution of the fish in the tank, to compare with the experimental measurements, we consider a gaussian orientation distribution [22] centered at $\alpha = 90^\circ$ (lateral insonification) and $std = \pm 10^\circ$. To reproduce the realistic experimental situation, the emitter transducer was modeled as a flat piston for the operating frequency of 201 kHz, with a beam angle of 10° at -3 dB.

3. Results

3.1. Experimental Results

Results obtained are presented in Table 3. For each group, the number of manually isolated good quality traces was between 1402 and 8696. The lower number corresponded to the group with smallest size (14.1 cm). However, the largest number of traces come from group 3 with mean TL of 21.5 cm. A mean TS distribution was obtained per group and average value; median and standard deviation were obtained from that. The same applies to maximum TS distribution for each group (Table 3). For TS_{mean} case, average values from -42.2 to -34.8 dB were observed. Average values ranged from -41.0 to -32.0 for TS_{max} . Figure 5 shows the violin plots for each TS distribution. On the top, for maximum TS, TS_{max} , and on the bottom for mean TS. For both, higher length involves higher TS as expected indicating the direct relationship between TL and TS, TS_{mean} . The linear regression fits of average values of TS (mean and maximum) versus TL are also presented in Figure 5, including the results extracted both from experimental measurements and numerical estimations.

Table 3. Average, median and standard deviation values from TS_{mean} and TS_{max} distributions of each Nile tilapia group.

Group	Mean TL (cm)	TS_{mean} (dB)			TS_{max} (dB)			Number of traces
		Avg.	Med.	SD	Avg.	Med.	SD	
1	14.1	-44.2	-44.0	3.4	-41.3	-41.0	3.5	1402
2	17.9	-43.7	-43.5	3.6	-40.8	-40.6	3.8	2240
3	21.5	-41.7	-40.6	5.7	-39.6	-38.6	6.0	8696
4	24.6	-41.5	-41.4	3.4	-36.9	-37.1	3.7	1698
5	30.3	-38.6	-38.7	4.0	-36.4	-36.4	4.0	5088
6	35.1	-38.3	-38.5	3.4	-35.9	-36.3	3.7	2291
7	40.8	-34.9	-34.4	4.5	-32.5	-31.9	4.6	8612
8	43.7	-34.8	-34.7	3.8	-32.1	-32.0	3.8	5400

Two empirical equations (6),(7) were obtained for relating the Nile tilapia length with the measured TS at 200 kHz for TS_{mean} and TS_{max} . In both cases, a good linear correlation was obtained, with R^2 higher than 0.9, bring higher for the TS_{max} .

$$TS_{max} = 19.1 \log(TL) - 62.3; R^2 = 0.94 \tag{6}$$

$$TS_{mean} = 20.1 \log(TL) - 66.7; R^2 = 0.91. \tag{7}$$

Different studies have shown that there is a direct relationship between length and weight of the Nile tilapia [14,23,24]. That means that from measured TS, weight of Nile tilapia could be estimated. For this reason, mean weight presented in Table 1 and average values of TS_{mean} and TS_{max} were fitted to the Total Length. The regression equations obtained are shown below (equations 4 and 5). High R^2 correlation coefficients were achieved, $R^2=0.96$ for W- TS_{mean} and $R^2=0.9$ for W- TS_{max} relationship. That fact implies that using those equations (6)–(9) total length or weight could be converted to TS, and vice versa, in a robust way.

$$TS_{max} = 6.3 \log(W) - 55.4; R^2 = 0.96 \tag{8}$$

$$TS_{mean} = 6.0 \log(W) - 51.9; R^2 = 0.90. \tag{9}$$

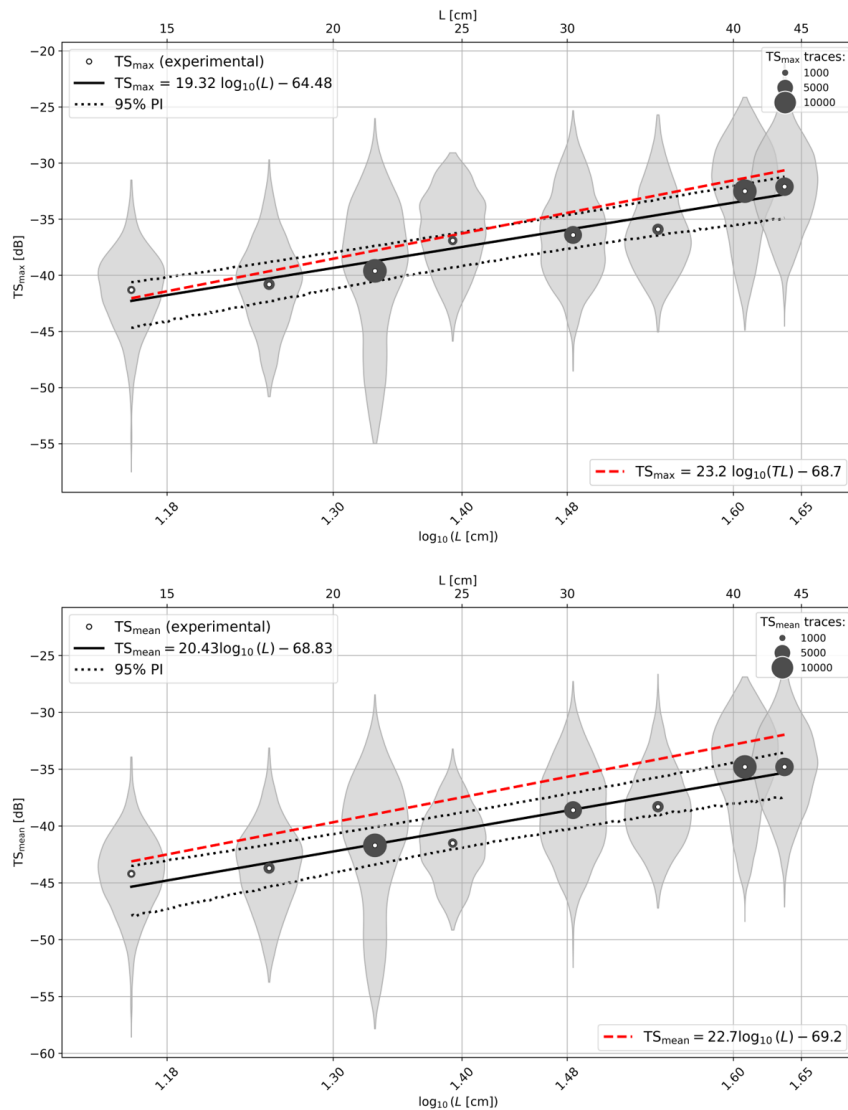


Figure 5. Top: violin plot from T_{max} distributions for the different size groups and linear regression for TS_{max} – TL. Bottom: violin plot from TS_{mean} distributions for the different size groups and linear regression for TS_{mean} – TL linear regression on the bottom. Black continuous line corresponds to the experimental data fit, discontinuous red line to the numerical fitting, and dashed black lines indicate the 95% prediction bounds of the experimental data fit.

3.2. Numerical Simulations of Nile Tilapia Target Strength

Numerical estimates were performed for the range of sizes observed in the tank. The geometric model was developed from the X-ray images, obtaining a relationship between the swimbladder geometrical properties and fish length. Considering the allometry reported for the external morphology of Nile tilapia [14] and for the swimbladder in various species [25], the length (SBL) and volume (SBV) of the swimbladder were related to the total length of the fish according to a functional power relationship. The results of the analysis are illustrated in Figure 6, while the values obtained for the fit parameters are given in Table 4.

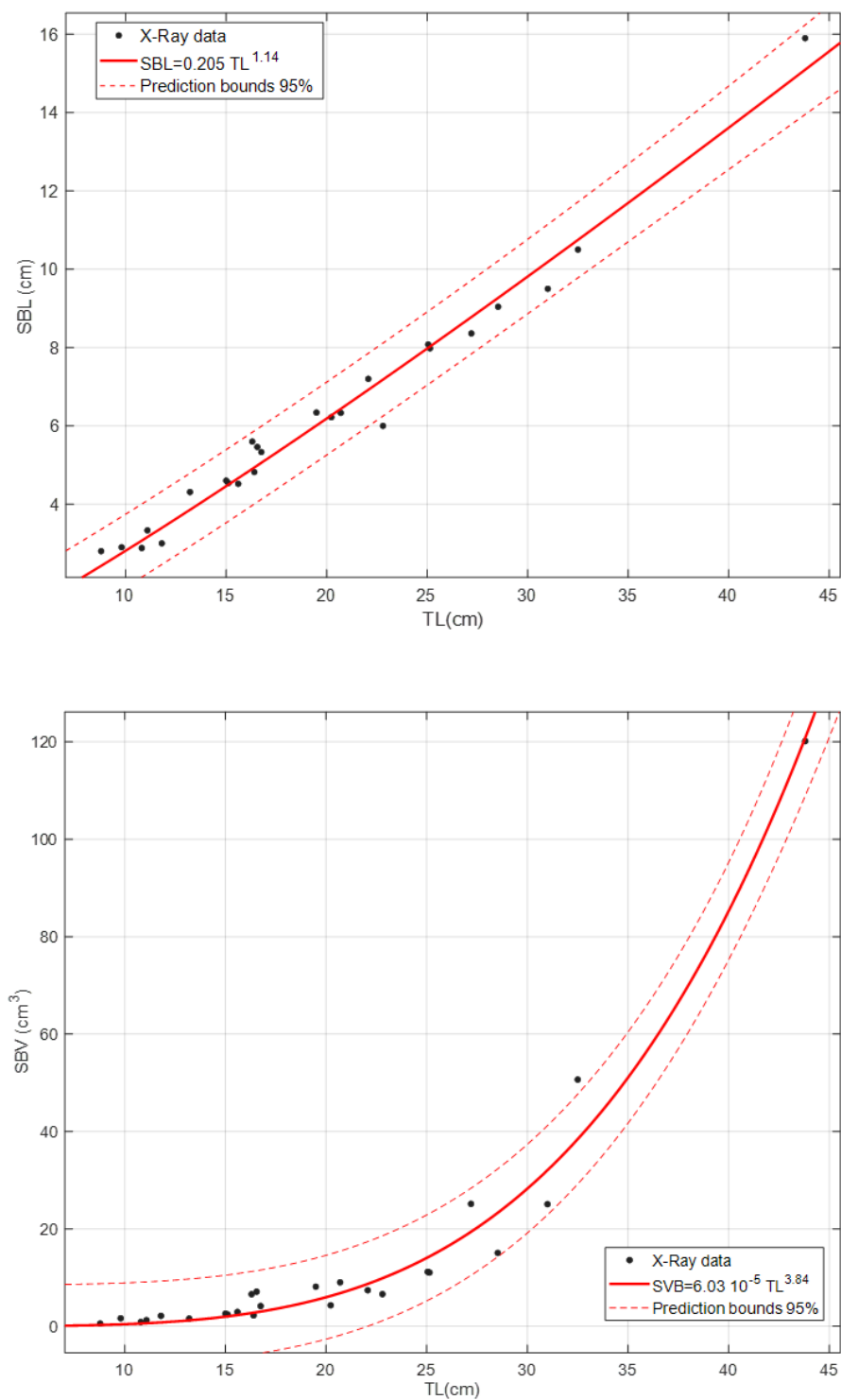


Figure 6. The figure shows the data obtained from X-ray images, the potential fit, and the 95% prediction intervals for swimbladder length (SBL, left) and swimbladder volume (SBV, right) as a function of the total length of the fish (TL).

To evaluate the influence of the swimbladder dimension on the TS, focusing on TS-log(TS) relationship, its maximum lateral cross section (SBCS). Figure 7 shows the relationship between the maximum lateral effective section and the total length of the fish.

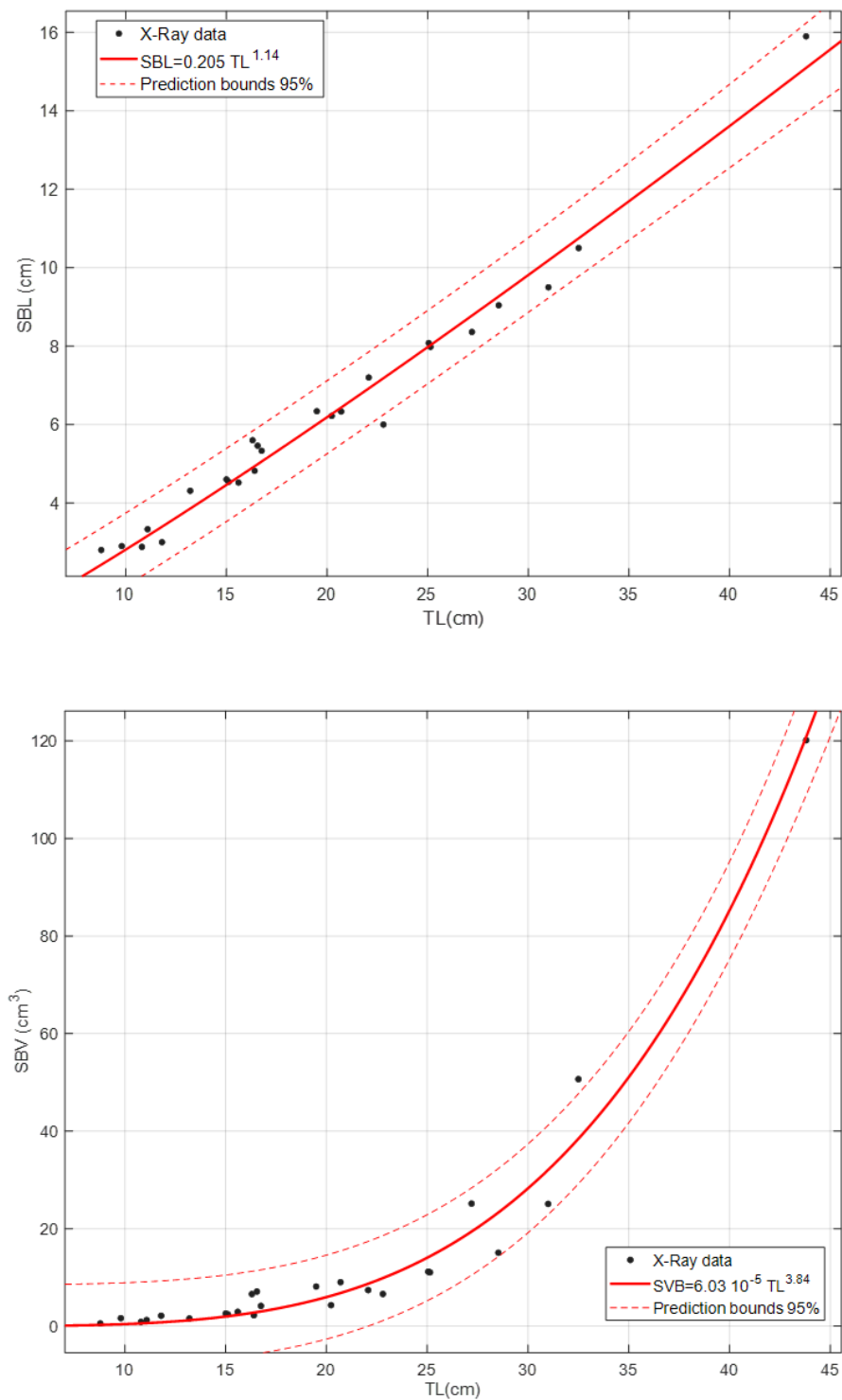


Figure 7. The figure shows the data obtained from X-ray images, the potential fit, and the 95% prediction intervals for the maximum lateral cross section of the swimbladder (SBCS) as a function of the total length of the fish (TL).

It should be noted that the exponent of this potential relationship, $SBCS = 0.01 TL^{2.62}$, is related to the slope of the TS-log(L) relationship (McClatchie et al., 2003). Because the gas-filled swimbladder accounts for about 90–95% of the backscattering cross-section in swim bladdered fishes, if the TS is effectively governed by the swim bladder’s effective acoustic cross-section, it would be expected that this slope, both from the numerical estimations and experimental measurements, to be close to, but not higher than, 10 b, being $b = 2.62$ (2.39, 2.86) (Table 4).

Table 4. Parameters (a, b) of the potential fits $f(L) = aTL^b$ of the morphometric variables of the swim bladder (SBL, SBV, SBCS) as a function of the total length of the fish. Values in parentheses indicate the 95% confidence bounds for b .

Fit $f = a\log(TL) + b$	a	b (95% CI)	R^2
$f = \text{SBL}$	0.205	1.14 (1.07, 1.21)	0.98
$f = \text{SBV}$	6.03×10^{-5}	3.84 (3.50, 4.18)	0.97
$f = \text{SBCS}$	0.0105	2.62 (2.39, 2.86)	0.96

The numerical model considered six sizes distributed along the experimental size range. Based on the best elliptical fits of the swim bladder masks in the two orthogonal planes, the corresponding three-dimensional geometry was constructed. To account for the variation in the swimming direction of the fish, the directivity of the backscattered acoustic wave was evaluated. Figure 8 shows the TS values for different relative orientations between the fish’s axis and the direction of propagation of the acoustic beam for a swim bladder corresponding to an individual of TL=27 cm.

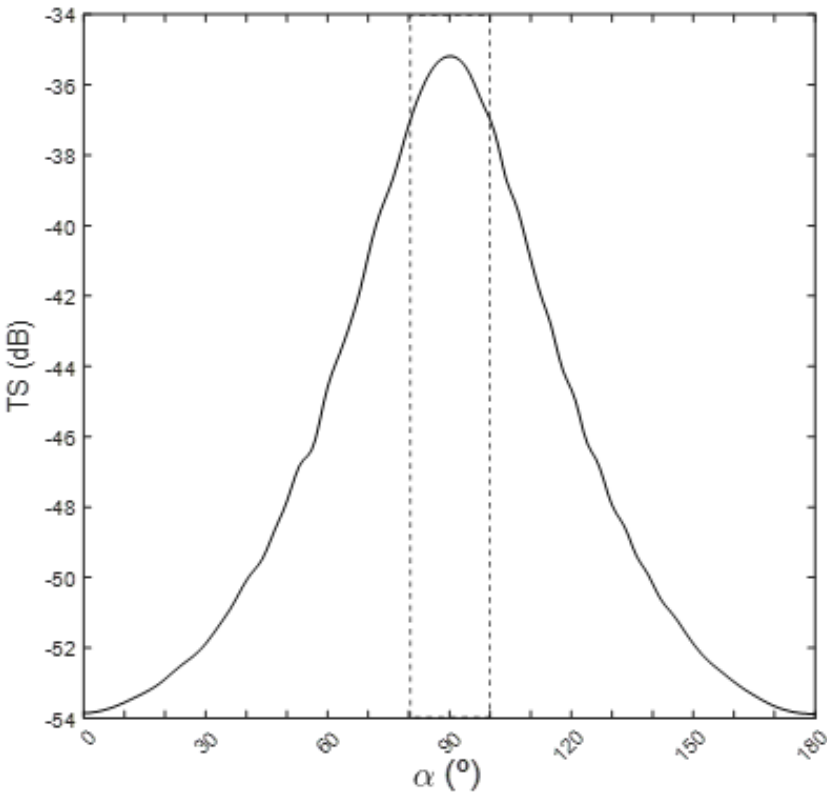


Figure 8. Directivity of the TS from swim bladder prolate sphere model corresponding to a TL=27 cm Nile tilapia. Angle α denotes the relative angle between the fish axis and the beam propagation direction. Dashed lines signal the limits of the swimming direction considered.

In order to compare with the experimental data, a Gaussian swimming distribution centered at $\alpha = 90^\circ$ (fish axis perpendicular to the direction of propagation) with a standard deviation of $\pm 10^\circ$ is considered. The numerical estimation is carried out for six TL values distributed along the measurement range based on the x-ray images. A linear relationship is obtained for both TS_{max} and TS_{mean} with respect to $\log(TL)$. The results of these fits are (10),(11):

$$TS_{max} = 23.2\log(TL) - 68.7; R^2 = 0.99 \tag{10}$$

$$TS_{mean} = 22.71 \log(TL) - 69.2; R^2 = 0.99. \quad (11)$$

Figure 5 shows the comparison between the experimental data and the numerical predictions of the simplified models that consider swim bladder within a prolate spheroid shape.

4. Discussion

The results of this study establish a direct relationship between Target Strength (TS) and the total length (TL) of Nile tilapia (*Oreochromis niloticus*). The empirical equations derived for both TS_{mean} and TS_{mean} exhibit high correlation coefficients ($R^2 > 0.9$), validating the use of acoustic systems to monitor growth in aquaculture. Furthermore, the robust correlation found between TS and weight (W)-with R^2 values reaching 0.96- suggests that biomass can be estimated through acoustic methods, facilitating real-time non-invasive production management. This acoustic approach presents some advantages over video-based systems that are typically used for fish sizing in aquaculture. Video systems are limited by water depth and turbidity, which often hinder visibility in ponds. In contrast, underwater acoustics can estimate biomass and size in turbid waters and across larger working distances, providing a complementary tool for various farm layouts. The morphology of the swim bladder was confirmed as the dominant factor in these acoustic measurements. Numerical simulations using the Method of Fundamental Solutions (MFS) indicated that the gas-filled swim bladder accounts for 90–95% of the backscattering cross-section [20]. Allometric analysis of X-ray images revealed that the maximum lateral cross-section of the swim bladder (SBCS) follows a power relationship: $SBCS = 0.0105TL^{2.62}$. As noted by McClatchie et al. [17], the slope of the TS vs. $\log(TL)$ relationship is closely tied to this exponent (b); if TS is governed by the SBCS, the slope would be expected to approach 10b (approximately 26.2 in this case). There is a very good agreement between the experimental results and the numerical predictions generated by the Method of Fundamental Solutions (MFS). This correspondence confirms that the numerical model incorporates a Gaussian swimming distribution centered at a lateral aspect ($\alpha = 90^\circ$) to capture the influence of the behavior of the fish. While the numerical model predicted values that were consistently slightly higher than the experimental ones, this discrepancy is justified by the fact that the numerical model uses an idealized pressure-release surface for the swim bladder and assumes a perfectly controlled environment [17,21,22]. In the experimental pond, factors such as the acoustic damping from fish flesh, natural variations in swimming tilt, and the biological complexity of free-swimming fish inevitably lead to slightly lower TS values compared to the theoretical maximums of a prolate spheroid model. In a real-world fish farm, these results could be applied by installing fixed or mobile single-beam transducers to monitor growth rates without the need for manual sampling. Being the fish measured while swimming freely - unlike previous studies where fish were anchored - the resulting equations could be applicable to commercial tanks and ponds [10].

5. Conclusions

This study shows that acoustic methodologies are a very reliable and non-invasive approach to monitor the growth of Nile tilapia (*Oreochromis niloticus*) in aquaculture ponds. The establishment of solid empirical equations ($R^2 > 0.9$) indicates that Target Strength (TS) can be used to estimate both total length (TL) and weight (W). This study uses a calibrated 200 kHz single-beam echosounder, which is significantly more cost-effective than scientific split-beam systems, offering a practical and accessible tool for real-time biomass estimation while avoiding the physiological stress associated with traditional manual sampling. The procedure has been designed to be used in commercial production settings. It is also shown that the allometric relationship for the swim bladder's cross-section ($SBCS \propto TL^{2.62}$) explains the slopes of the TS that were observed. The good agreement between the experimental results and the numerical predictions shows that the prolate spheroid model is adequate to describe the lateral insonification of the Nile tilapia swimbladder. This method directly helps the FAO's Blue Transformation goals for aquaculture growth, providing a non-intrusive and effective way to track the fish growth parameters. Sustainable and economically viable by providing for keeping track of growth

parameters. Non-intrusive monitoring reduces fish stress and economical costs, in the way forward to a more sustainable and technologically advanced aquaculture.

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