JURNAL PERIKANAN DAN KELAUTAN
Volume 31 No. 2, June 2026: 279-286

e-issn : 2721-8902
p-issn : 0853-7607

Otolith Growth-Check Patterns and Morphometric Relationships of Nile Tilapia (*Oreochromis niloticus*) from the Deli River Estuary, North Sumatra, Indonesia

Pola Tanda Pertumbuhan Otolit dan Hubungan Morfometrik Ikan Nila (Oreochromis niloticus) dari Muara Sungai Deli, Sumatera Utara, Indonesia

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Received
1 June 2026

Accepted
30 June 2026

Abstract

Nile tilapia (*Oreochromis niloticus*) is tolerant of variable aquatic conditions, but fluctuations in growth can be recorded in the macrostructure of its otoliths. This study characterized sagittal otolith morphology, quantified fish–otolith morphometric relationships, described dark growth-check patterns, and evaluated concurrent water-quality conditions in the Deli River Estuary, Belawan Bahari, North Sumatra. Fifty fish (27 females and 23 males) obtained from four artisanal fishing occasions between October and December 2024 were measured for total length, body weight, otolith length, width, and weight. Length–weight relationships were estimated using $W = aL^b$, whereas total length–otolith relationships were assessed by linear regression. Fish measured 180–235 mm and weighed 152–300 g; sagittal otoliths were 4.30–6.77 mm long and 0.0063–0.0630 g in weight. The estimated length–weight exponent was 2.979 in females (95% CI: 2.545–3.414) and 2.463 in males (95% CI: 2.063–2.863), indicating near-isometric growth in females and negative allometry in males. Total length explained 78.4% of male otolith-length variation but only 13.9% in females. Dark growth checks ranged from zero to three; 45 fish (90%) had at least one check, and the first check occurred 0.225–0.300 mm from the nucleus. Temperature was 25–28 °C, pH was 6.0, and dissolved oxygen was 4.09 mg/L. The growth checks indicate episodes of reduced otolith accretion, but their causes and periodicity cannot be assigned without validation. Seasonal sampling, replicate readings, and otolith chemical or physiological analyses are recommended.

Keywords: Dark growth; Deli River Estuary; Otolith morphometry

Abstrak

Ikan nila (*Oreochromis niloticus*) toleran terhadap variasi kondisi perairan, tetapi perubahan pertumbuhannya dapat terekam pada makrostruktur otolit. Penelitian ini mengarakterisasi morfologi otolit sagita, mengukur hubungan morfometrik ikan–otolit, mendeskripsikan pola tanda pertumbuhan gelap, dan mengevaluasi kondisi kualitas air di Muara Sungai Deli, Belawan Bahari, Sumatera Utara. Sebanyak 50 ikan (27 betina dan 23 jantan) dari empat kali penangkapan nelayan pada Oktober–Desember 2024 diukur panjang total, bobot tubuh, panjang, lebar, dan bobot otolitnya. Hubungan panjang–bobot dianalisis menggunakan $W = aL^b$, sedangkan hubungan panjang total dengan ukuran otolit dianalisis melalui regresi linear. Panjang ikan berkisar 180–235 mm dan bobot 152–300 g; panjang otolit sagita 4,30–6,77 mm dan bobotnya 0,0063–0,0630 g. Nilai eksponen panjang–bobot sebesar 2,979 pada betina (IK 95%: 2,545–3,414) dan 2,463 pada jantan

(IK 95%: 2,063–2,863), yang menunjukkan pertumbuhan mendekati isometrik pada betina dan alometrik negatif pada jantan. Panjang total menjelaskan 78,4% variasi panjang otolit jantan, tetapi hanya 13,9% pada betina. Jumlah tanda pertumbuhan gelap berkisar 0–3; sebanyak 45 ikan (90%) memiliki sedikitnya satu tanda, dengan jarak tanda pertama dari inti 0,225–0,300 mm. Suhu perairan 25–28 °C, pH 6,0, dan oksigen terlarut 4,09 mg/L. Tanda pertumbuhan menunjukkan periode perlambatan akresi otolit, tetapi penyebab dan periodisitasnya belum dapat ditentukan tanpa validasi. Penelitian lanjutan perlu melibatkan pengambilan sampel antarmusim, pembacaan berulang, serta analisis kimia otolit atau indikator fisiologis.

Kata kunci: Pertumbuhan gelap, Muara Sungai Deli; Morfometri otolit

1. Introduction

Estuaries are transitional environments in which riverine and marine processes interact, producing pronounced spatial and temporal variability in flow, turbidity, salinity, oxygen, nutrients, and contaminant exposure. Urbanization can intensify these gradients through wastewater inputs, shoreline modification, and altered hydrodynamics, thereby affecting habitat quality and fish performance (Freeman et al., 2019). Recent assessments in the Belawan–Deli system have likewise documented variable water quality and pollution pressures, emphasizing the need to interpret biological indicators together with site-specific environmental measurements (Muhtadi et al., 2025; Jamal et al., 2025).

Nile tilapia (*Oreochromis niloticus*) is native to Africa but is now widely cultured and introduced because of its rapid growth, omnivorous feeding, and broad environmental tolerance (Food and Agriculture Organization of the United Nations, 2009; Mengistu et al., 2020). Its performance nevertheless varies with temperature, dissolved oxygen, salinity, stocking conditions, and interactions among these factors (Likongwe et al., 1996; El-Sayed & Kawanna, 2008; Azaza et al., 2008; Qiang et al., 2013; Abd El-Hack et al., 2022). Salinity exposure can alter osmoregulation and ionic balance, while temperatures outside the preferred range can reduce feeding efficiency and growth (Mohamed et al., 2021; Islam et al., 2022).

Dissolved oxygen is particularly important because hypoxia can suppress feed intake, growth, and physiological condition, although responses depend on fish size, duration, and whether low oxygen is chronic or periodic (Tran-Duy et al., 2008; Abdel-Tawwab et al., 2014; Tran-Ngoc et al., 2016; Obirikorang et al., 2020). Field and controlled studies further show that temperature, oxygen, pH, and other physicochemical variables jointly influence tilapia production and health; therefore, a single water-quality measurement should not be interpreted as a complete record of the conditions experienced throughout a fish's life (Makori et al., 2017; Mengistu et al., 2020).

Otoliths are calcified structures that accrete throughout a fish's life and preserve macrostructural, microstructural, and chemical information associated with growth and habitat history (Campana & Thorrold, 2001; Green et al., 2009). Their size and shape may covary with somatic growth, diet, physiology, and environmental exposure, but these relationships can differ among species, populations, sexes, and life stages (Grønkjær, 2016; Mille et al., 2016; Chukwuka & Adeogun, 2024). Consequently, otolith morphology and banding are useful biological records, but they must be interpreted with appropriate validation and should not be treated as direct, stressor-specific diagnoses.

Experimental studies have demonstrated that somatic growth and otolith accretion can become partly uncoupled under changes in temperature or food availability (Mosegaard et al., 1988; Hüssy & Mosegaard, 2004; Høie et al., 2008). Otolith opacity and zone formation may also vary with temperature, feeding history, and changing environmental conditions (Neat et al., 2008; Hüssy et al., 2009; Hüssy, 2010). Reliable interpretation therefore requires standardized preparation, repeatable readings, and validation of increment periodicity whenever age or event timing is inferred (Campana & Moksness, 1991; Campana, 2001; Geffen, 1995; Rehberg-Haas et al., 2012).

Information on otolith macrostructure and fish–otolith morphometry of Nile tilapia from Indonesian urban estuaries remains limited. Accordingly, this study aimed to: (1) describe the size and morphology of sagittal otoliths; (2) quantify length–weight and fish–otolith relationships by sex; (3) determine the frequency and position of dark growth checks; and (4) evaluate whether the observed water-quality conditions provide a plausible environmental context for variation in otolith growth. The study was designed as a baseline survey rather than a validated age-determination analysis.

2. Material and Method

2.1. Time and Place

Sampling was conducted from October to December 2024 in the main Deli River Estuary, Belawan Bahari, Medan, North Sumatra, Indonesia. Fish were obtained from local fishers on four sampling occasions. The respective samples comprised 15, 15, 10, and 10 fish, yielding a total of 50 individuals. Fish were captured with gillnets of approximately 2-cm mesh size and were transported on ice to the Aquatic Biology Laboratory, Faculty of Fisheries and Marine Science, Universitas Riau. Because fishing effort was not standardized, the number of fish collected on each occasion is interpreted as sample composition rather than catch per unit effort or population abundance.

2.2. Methods

Each fish was identified as *Oreochromis niloticus* and classified by sex during laboratory examination. Total length (TL, mm) and body weight (BW, g) were recorded. Sagittal otoliths were removed from the cranial cavity, cleaned, dried, and measured for otolith length (OL, mm), width (OWd, mm), and weight (OW, g). The sagittae were selected because they are generally the largest otolith pair and are commonly used for fish growth and life-history analyses (Campana & Thorrold, 2001; Green et al., 2009).

2.3. Procedures

2.3.1. Otolith preparation and growth-check reading

Otoliths were progressively ground and polished until the nucleus and banding pattern were visible. Prepared otoliths were examined using an Olympus CX21 microscope equipped with an ocular micrometer. Dark growth checks were counted, and the distance from the outer edge of the nucleus to the first dark check was measured. A dark check was operationally defined as a continuous, visually distinct opaque band at least 0.05 mm thick under the stated observation conditions. This threshold was used for descriptive consistency rather than as a validated annual mark. Readability and band classification followed the general principles of standardized otolith interpretation, which emphasize repeated readings and caution when periodicity has not been validated (Campana & Moksness, 1991; Campana, 2001; Rehberg-Haas et al., 2012).

2.3.2. Water-quality measurements

Water temperature, transparency, depth, current velocity, pH, dissolved oxygen (DO), and free carbon dioxide (CO_2) were measured during the field survey using standard field procedures. The observed pH and DO values were compared with the Class II surface-water criteria in Indonesian Government Regulation No. 22 of 2021. Aquaculture-based optimal ranges were used only as supporting biological context, not as legal standards

2.4. Data Analysis

The length–weight relationship was estimated separately for females and males using the power model $W = aL^b$, where W is body weight (g), L is total length (mm), a is the intercept, and b is the allometric coefficient. Parameters were estimated after log transformation, following the recommendations of Froese (2006). A two-sided t-test was used to evaluate whether b differed from 3. Linear regression was used for fish–otolith morphometric relationships. Pearson's r and R^2 were reported, and statistical significance was evaluated at $\alpha = 0.05$. Dark-check frequencies and core-to-first-check distances were summarized descriptively because the study did not validate band periodicity.

3. Result and Discussion

3.1. Sample Composition and Fish Size

The sample consisted of 27 females and 23 males. The female-to-male ratio was 1.17:1 and did not differ significantly from an expected 1:1 ratio ($\chi^2 = 0.32$, $p = 0.572$). Total length ranged from 180 to 235 mm and body weight from 152 to 300 g. The largest number of fish occurred in the 188–195 mm class (n = 14), followed by the 180–187 mm class (n = 10). Descriptive measurements by sex are presented in Table 1, and the size-class distribution is shown in Table 2.

Table 1. Descriptive characteristics of sampled Nile tilapia and sagittal otoliths

Sex	n	Total length (mm)	Body weight (g)	Otolith length (mm)	Otolith weight (g)	Dark checks
Female	27	180–220	152–290	4.30–6.39	0.0212–0.0630	0–3
Male	23	180–235	152–300	4.30–6.77	0.0063–0.0441	0–3
Overall	50	180–235	152–300	4.30–6.77	0.0063–0.0630	0–3

Table 2. Distribution of sampled fish among total-length classes

Length class (mm)	Female	Male	Total
180–187	5	5	10
188–195	7	7	14
196–203	6	2	8
204–211	7	2	9
212–219	1	1	2
220–227	1	5	6
228–235	0	1	1

3.2. Length–Weight Relationship

The female length–weight equation was $W = 2.998 \times 10^{-5}L^{2.979}$ ($R^2 = 0.889$). The 95% confidence interval for b was 2.545–3.414, and b did not differ from 3 ($p = 0.922$); female growth was therefore statistically consistent with isometry. The male equation was $W = 0.001282L^{2.286}$ ($R^2 = 0.410$). The 95% confidence interval for b was 1.050–3.521, and b also did not differ significantly from 3 ($p = 0.247$). Although the male point estimate was below 3, its broad confidence interval reflects the small sample and restricted length range. Length–weight parameters are sensitive to sample structure, season, sex, maturity, food availability, and environmental conditions; consequently, comparisons should prioritize confidence intervals and comparable sampling designs rather than the point estimate alone (Froese, 2006; Abd El-Hack et al., 2022).

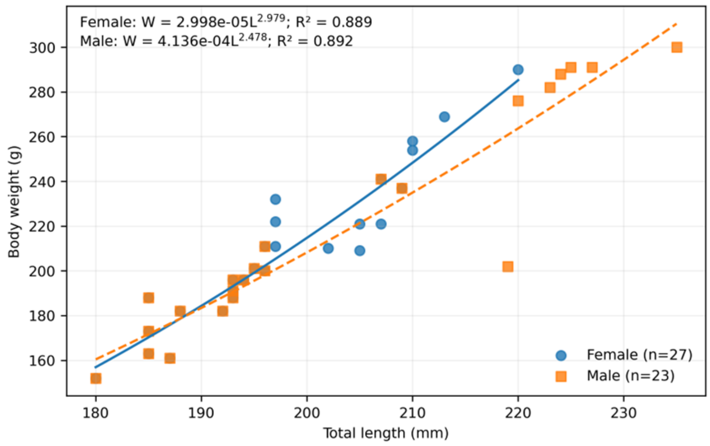

Figure 1. Length–weight relationships of female and male Nile tilapia. Curves were fitted using $W = aL^b$.

3.3. Otolith morphology and fish–otolith relationships

The sagittal otoliths were white to translucent, broadly oval, convex, and characterized by an irregular or serrated margin. The nucleus was generally positioned near the central region. Otolith length ranged from 4.30 to 6.77 mm, width from 1.32 to 3.97 mm, and dry weight from 0.0063 to 0.0630 g. Otolith form can be influenced by genetic background, growth trajectory, feeding ecology, and environmental history; thus, the observed morphology should be regarded as a population-level description rather than a species-wide diagnostic form (Mille et al., 2016; Grønkjær, 2016). Recent work on *Oreochromis niloticus* in urbanized tropical waters also indicates that environmental disturbance may be associated with altered otolith growth or asymmetry. However, such effects require replicated spatial designs and independent exposure data (Chukwuka & Adeogun, 2024).

Figure 2. Intact sagittal otolith (left) and a polished otolith under the microscope (right). The annotated image identifies the nucleus and representative light and dark bands.

The relationship between total length and otolith length differed markedly by sex. In females, OL = 0.8243 + 0.02248TL, with a weak relationship ($R^2 = 0.139$, $r = 0.372$, $p = 0.056$). In males, OL = −4.260 + 0.04757TL, with a stronger relationship ($R^2 = 0.784$, $r = 0.885$, $p < 0.001$). Otolith weight increased significantly with total length in both sexes: OW = −0.06105 + 0.000445TL for females ($R^2 = 0.405$, $r = 0.637$, $p < 0.001$) and OW = −0.06802 + 0.000465TL for males ($R^2 = 0.590$, $r = 0.768$, $p < 0.001$). These relationships indicate that otolith growth broadly accompanies body growth, but the weak female length–otolith-length regression confirms that somatic and otolith growth are not necessarily tightly coupled in every group (Mosegaard et al., 1988; Hüssy & Mosegaard, 2004). Sex-specific differences should be interpreted cautiously because the sampled size distributions were unequal.

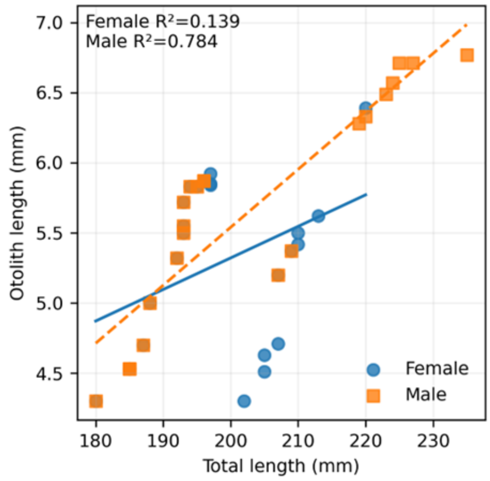

Figure 3. Relationships of total length with otolith length (left) and otolith weight (right). Solid and dashed lines indicate female and male regressions, respectively.

3.4. Dark Growth-Check Patterns

The number of dark growth checks ranged from zero to three. Five fish had no dark check, 14 had one, 15 had two, and 16 had three. Thus, 45 of 50 fish (90%) displayed at least one dark check. Female frequencies for zero, one, two, and three checks were 1, 11, 7, and 8 fish, respectively; the corresponding male frequencies were 4, 3, 8, and 8 fish. Check number did not increase monotonically with total length, indicating that the bands were not a simple function of fish size. Among the 45 fish with one or more checks, the distance from the nucleus to the first check ranged from 0.225 to 0.300 mm, with a median of 0.250 mm (Figure 4).

Dark or opaque bands indicate changes in optical density or accretion relative to adjacent otolith material, but their formation can reflect interacting effects of growth rate, temperature, feeding history, physiology, and season (Høie et al., 2008; Neat et al., 2008; Hüssy et al., 2009). The variable number of checks and the overlapping core-to-first-check distances in the present sample suggest that band formation was not synchronized across all individuals. However, the study design cannot determine the specific event responsible for each band, nor can it establish that the bands were annual. Similar difficulties in assigning age or environmental meaning to opaque zones have been reported when increment periodicity is not independently validated (Hüssy, 2010; Campana, 2001). Accordingly, the dark checks are best interpreted as descriptive evidence of variable individual growth histories, not as direct proof of pollution, food limitation, disease, migration, or reproductive stress (Grønkjær, 2016; Chukwuka & Adeogun, 2024).

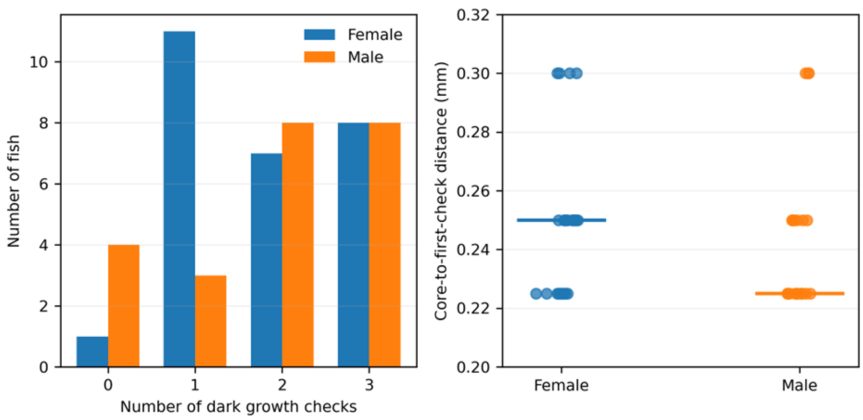

Figure 4. Frequency of dark growth checks by sex (left) and core-to-first-check distance among fish with at least one check (right). Horizontal bars indicate medians

3.5. Water Quality and Environmental Interpretation

Water-quality observations are summarized in Table 3. Temperature ranged from 25 to 28 °C, overlapping the range in which Nile tilapia generally maintain effective growth, although optimum performance varies with strain, size, feeding, and other environmental factors (El-Sayed & Kawanna, 2008; Azaza et al., 2008; Mengistu et al., 2020). Dissolved oxygen was 4.09 mg/L, slightly above the Indonesian Class II minimum of 4 mg/L. Controlled studies show that reductions in oxygen availability can decrease maximum feed intake, growth, and physiological performance, particularly under sustained hypoxia (Tran-Duy et al., 2008; Abdel-Tawwab et al., 2014; Tran-Ngoc et al., 2016). Nile tilapia can partly compensate behaviorally or metabolically, but chronic and periodic hypoxia do not necessarily produce equivalent responses (Obirikorang et al., 2020; Islam et al., 2022).

Transparency was 38 cm, depth was approximately 3.28–3.30 m, current velocity was 2.03 m/s, and free CO_2 ranged from 14.98 to 17.47 mg/L. No direct Class II criteria were applied to transparency, depth, current velocity, or free CO_2 because comparable limits were not specified in the cited regulation. The measured pH of 6 was at the lower boundary of the Class II range (6–9). Tilapia responses to water quality are multivariate: temperature and oxygen affect feeding and growth, while salinity alters osmotic and ionic regulation (Likongwe et al., 1996; Qiang et al., 2013; Mohamed et al., 2021). Field studies also show that physicochemical variables can act jointly and fluctuate substantially through time (Makori et al., 2017). Because salinity, nutrients, contaminants, diel oxygen variation, and seasonal hydrology were not monitored continuously, the present measurements describe conditions during sampling only and cannot be used to identify the cause of individual otolith checks. This caution is especially important in a dynamic urban estuary such as the Deli–Belawan system (Freeman et al., 2019; Muhtadi et al., 2025; Jamal et al., 2025).

Table 3. Water-quality measurements and interpretive benchmarks

Parameter	Unit	Observed value	Benchmark/context	Interpretation
Temperature	°C	25–28	Optimal production commonly reported at 27–32 °C	Tolerable; lower values below reported optimum
Transparency	cm	38	No Class II criterion applied	Descriptive value
Depth	m	3.28–3.30	No Class II criterion applied	Descriptive value
Current velocity	m/s	2.03	No Class II criterion applied	High field measurement; requires tidal replication
pH	—	6.0	Class II: 6–9	At lower regulatory boundary
Dissolved oxygen	mg/L	4.09	Class II minimum: 4; >5 often recommended for optimal tilapia growth	Compliant but marginal for optimal growth
Free CO_2	mg/L	14.98–17.47	No Class II criterion applied	Reported without formal classification

Sources: Republic of Indonesia (2021); El-Sayed & Kawanna (2008); Mengistu et al. (2020); Makori et al. (2017).

4. Conclusions

The 50 Nile tilapia sampled from the Deli River Estuary measured 180–235 mm in total length and 152–300 g in body weight. Females exhibited a length–weight exponent close to isometry (b = 2.979), whereas males showed significant negative allometry (b = 2.463). Male body length was strongly related to otolith length and weight, but the corresponding female relationships were weak and not statistically significant. Dark growth checks ranged from zero to three, and 90% of the fish had at least one check. Their occurrence and position varied among individuals and were not a simple function of fish size. The observed pH and dissolved oxygen met the Class II regulatory criteria, but dissolved oxygen was only marginally above the minimum and below commonly recommended conditions for optimal tilapia growth. The otolith bands therefore provide evidence of variable growth history, but they cannot by themselves identify the timing or cause of growth disturbance.

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