Latin American Journal of Aquatic Research, 52(3): 443-458, 2024
DOI: 10.3856/vol52-issue3-fulltext-3204

Research Article

Taurine improves juvenile *Seriola rivoliana* growth performance and biochemical profiles in blood serum and skeletal muscle

Marco A. Hernández-de Dios[1], Dariel Tovar-Ramírez[1], Deneb Maldonado-García[2] Mario A. Galaviz- Espinoza[3], Fernando Barreto-Curiel[3] Milton Spanopoulos-Zarco[4] & Minerva Maldonado-García[1]

[1]Centro de Investigaciones Biológicas del Noroeste (CIBNOR), La Paz, México
[2]CONACYT-Centro de Investigaciones Biológicas del Noroeste (CIBNOR), La Paz, México
[3]Facultad de Ciencias Marinas, Universidad Autónoma de Baja California (UABC), Ensenada, México
[4]Departamento de Ingeniería en Pesquerías, Universidad Autónoma de Baja California Sur (UABCS) La Paz, México
Corresponding author: Minerva Maldonado-García (minervam04@cibnor.mx)

ABSTRACT. Taurine supplementation has shown survival and feeding efficiency in larval fish development. Thus, the present study aims to evaluate the effects of adding taurine to the longfin yellowtail (*Seriola rivoliana*) diet for 60 days. Fish (n = 270) were distributed in three treatments: T0 without taurine, T1, and T2, supplemented with taurine at 1 and 2%, respectively. Growth performance, blood serum biochemistry, fatty acid, and amino acid profiles in skeletal muscle were evaluated. Notable improvements ($P < 0.05$) were observed in T1 and T2 in terms of specific growth rate (SGR) and weight gain (WG). Survival rates (SR) did not show significant differences ($P > 0.05$). In addition, a decrease was observed in intraperitoneal fat (IPF). Still, an increase was observed in blood parameters, including higher total protein (TP) and globulin (GLO) concentration, as well as a reduction in cholesterol (CHO) levels. Changes in fatty acid profiles were also detected in skeletal muscle with an increase in omega-3 fatty acids (EPA and DHA) and elevation in taurine concentration in T2. The results showed that adding 20 g kg^{-1} of taurine to the diet improved growth, skeletal muscle, and blood serum biochemistry. Therefore, the use of higher taurine concentrations is recommended in future studies to understand fully the extent of the benefits to longfin yellowtail juveniles.

Keywords: *Seriola rivoliana*; blood serum; amino acids; fatty acids; condition indexes; aquaculture

INTRODUCTION

In the aquaculture industry, one of the most widely used ingredients for food processing is fishmeal because it has been considered a valuable nutritional source in feeding carnivorous fish bred in captivity due to its high protein content and amino acids (AA) profile (Zhou et al. 2004, NRC 2011). However, processed foods do not always fully cover nutritional requirements. Therefore, supplementing fish with other food additives, such as taurine, is very important since its absence has been linked to diseases such as green liver in species such as red seabream *Pagrus major*, Japanese amberjack *Seriola quinqueradiata*, and totoaba *Totoaba macdonaldi* (Takagi et al. 2006, 2008, Satriyo et al. 2017). Feed supplemented with this AA provides different health benefits to fish, including enhancing fat absorption, boosting bile acid secretion, fostering retinal function, developing the brain, and improving liver function. Taurine is a β-sulfonic AA considered one of the conditionally essential amino acids (EAA) for fish development (Salze & Davis 2015). Although

Associate Editor: Carlos Álvarez

taurine is regarded as a semi-EAA, it is not part of the protein structure; instead, it stands out as the most abundant free amino acid (FAA) in vertebrate skeletal muscle (Schuller-Levis & Park 2003).

Several studies have focused on the importance of taurine use in diets for different fish development stages. For example, taurine supplementation has shown beneficial effects on survival and feeding efficiency in larval stage for cobia *Rachycentron canadum* (Salze et al. 2010), red seabream (Kim et al. 2016), Atlantic bluefin tuna *Thunnus thynnus* (Koven et al. 2018), greater amberjack *Seriola dumerili* (Matsunari et al. 2013), and yellowtail amberjack *Seriola lalandi* (Hawkyard et al. 2016). Similarly, supplying taurine to diets of carnivorous fish in the reproductive stage is essential due to their reduced ability to biosynthesize taurine within their body (El-Sayed 2014), which allows them to be healthier, have better reproductive performance (Hernandez-de Dios et al. 2022), and improve spawning quality in species, such as Japanese amberjack (Matsunari et al. 2006), yellowtail amberjack (Salze et al. 2019) and greater amberjack (Sarih et al. 2019).

Although taurine requirements in fish have not yet been precisely established, for some years, taurine deficiency has been suggested to be the cause of poor growth in various species fed diets with low animal protein levels (Yokoyama et al. 2001, Takagi et al. 2008, Magalhães et al. 2019, Sampath et al. 2020). Studies have also been conducted to examine how taurine affects fish growth and has a positive effect on their growth and body composition in species such as Japanese amberjack (Matsunari et al. 2005), yellowtail amberjack (Garcia-Organista et al. 2019, Candebat et al. 2020), Colorado snapper *Lutjanus colorado* (Hernández et al. 2018), red seabream (Matsunari et al. 2008), totoaba (Satriyo et al. 2017), rainbow trout *Oncorhynchus mykiss* (Biasato et al. 2022), striped catfish *Pangasianodon hypophthalmus* (Peter et al. 2022), and sterlet sturgeon *Acipenser ruthenus* (Bavi et al. 2022).

Longfin yellowtail (*Seriola rivoliana*) is a species of great commercial interest in aquaculture due to its growth potential, given that its success in culture lies in its good adaptation to captive production. In addition, this species is characterized by its resistance, fast growth rate, and high market value (Blanco et al. 2022). These qualities support current research and awaken future interest in the aquaculture development of this species. However, the AA requirements that the species requires for better growth as taurine are still unknown. Therefore, the present study aims to evaluate the effect of dietary taurine incorporation on the growth and biochemical composition of longfin yellowtail juveniles.

MATERIALS AND METHODS

Ethical procedures

Secretariat of Agriculture, Livestock, Rural Development, Fisheries, and Food (SAGARPA, by its Spanish acronym, Mexico) approved all the procedures used for fish handling through the Mexican Official Standard (NOM-062-ZOO 1999).

Experiment design and culture system

The experiment was conducted at Centro de Investigaciones Biológicas del Noroeste (CIBNOR, Baja California Sur, Mexico). The organisms were obtained by donation from the commercial company King Kampachi, Mexico. Before starting the experiment, the fish were acclimatized at 24.5°C for 20 days. Subsequently, 270 physically healthy fish were selected with an initial weight of 286.8 ± 35 g and a total length of 26.6 ± 1.2 cm, distributed homogeneously in 3000-L tanks with an open system, and evaluated in triplicate, using 30 fish per replicate. To maintain water quality, daily measurements of temperature (24.5 ± 0.5°C), dissolved oxygen (7.4 ± 1.2 mg L^{-1}), salinity (36 ± 0.7), and pH (7.8 ± 0.2) were taken using a multiparameter (YSI PRO20, YSI Inc/Xylem Inc, OH, USA). Nitrite (<0.25 ppm), nitrate (<5 ppm), and ammonium (<0.25 ppm) were also measured by colorimetry with the API® Saltwater Master Test Kit (USA). Treatments had a daily water replenishment rate of 100%, corresponding to a flow rate of 125 L h^{-1}. The organisms were maintained under a 12:12 h light:dark photoperiod.

Food design and feeding

Three diets were prepared based on a commercial AQUATEC® (QRO, Mexico) brand feed; the food was initially pulverized with a 1-HP meat grinder. The resulting particles were mixed with a 20-kg industrial mixer for 20 min. With a purity of 99.9% (Encapsuladoras Mexico®), taurine was previously dissolved in water and carefully added to ensure its effective incorporation and achieve the desired concentrations of 1 and 2%. The control diet (T0) was not supplemented with taurine. During the mixing process, 35% water was incorporated; subsequently, the feed was processed through an extruder, cutting it into pieces of approximately 5 mm. These pieces were collected and dried in a horizontal airflow oven (VWR 1680 Hafo

Series, USA) at 35°C for 15 h. Finally, the feed was stored at -20°C for later use.

The whole elaboration process was carried out at the CIBNOR Aquaculture Nutrition Laboratory. Table 1 shows the proximate composition analysis, including the methods for protein (960.52), lipids (920.97), and ash (942.05), carried out following the methods of the Association of Official Analytical Collaboration Methods of Analysis (AOAC 1995). In addition, the AAs (Barreto et al. 2019) and fatty acid composition were evaluated (Folch et al. 1957). The fish were fed for 60 days at 4% of total biomass four times daily (09:00, 12:00, 15:00, and 18:00 h). The amounts supplied were adjusted every 20 days according to biomass.

Table 1. Biochemical composition means values of longfin yellowtail diets. HIS: histidine, ARG: arginine, THR: threonine, VAL: valine, MET: methionine, LYS: lysine, ILE: isoleucine, LEU: leucine, PHE: phenylalanine, ASP: aspartic acid), SER: serine, GLU: glutamic acid, GLY: glycine, ALA: alanine, TYR: tyrosine, TAU: taurine.

Analytical contents (dry matter %)	T0	T1	T2
Crude protein	49.4	49.4	49.3
Lipids	15	15.2	15
Ash	9.5	9.4	9.5
Amino acid (g 100 g^{-1})			
HIS	3.3	3.3	3.3
ARG	5.7	5.8	5.7
THR	2.2	2.2	2.2
VAL	1.5	1.5	1.5
MET	1.7	1.7	1.8
LYS	2.9	2.8	2.8
ILE	1.8	1.8	1.8
LEU	3.7	3.7	3.6
PHE	2.3	2.3	2.3
ASP	2.8	2.9	2.8
SER	2.7	2.7	2.7
GLU	5.8	5.9	5.8
GLY	6.2	6.2	6.4
ALA	3.1	3.1	3.1
TYR	1.8	1.8	1.8
Others			
TAU	1.4	1.4	1.4
Synthetic TAU	0	1	2
Fatty acids (%)			
Σn3	19.5	19.6	19.5
Σn6	13.7	13.6	13.7
Σn9	26.3	26.3	26.3
EPA+DHA	13.9	13.9	13.9

Serum biochemical parameters

Blood extractions were performed at the beginning and end of the experiment (n = 9 per treatment) using the methodology of Guzmán-Villanueva et al. (2014) with modifications. The organisms were previously anesthetized with eugenol (1 mL 10 L^{-1}) to facilitate extraction. Blood samples were obtained from the caudal vein using sterile syringes; subsequently, the samples were centrifuged at 3000 *g* for 5 min (GUSTO® High-speed, Heathrow Scientific, IL, USA) and stored at -80°C for biochemical analyses. The blood obtained was used to measure various parameters, including total protein (TP), albumin (ALB), glucose (GLU), and cholesterol (CHO), which were determined using kits from Pointe Scientific, Inc. (USA). Triglycerides (TRI), alanine aminotransferase (ALT), and aspartate aminotransferase (AST) were determined using Sigma-Aldrich® (USA) kits. Arithmetic calculations determined globulin (GLO), ALB:GLO, and AST:ALT ratios. Absorbance measurements were carried out using a Thermo Scientific Varioskan™ Flash multimode spectral scanning reader (Thermo Fisher Scientific, Inc., MA, USA).

Growth and somatic indexes

Length and weight measurements were performed on days 1, 20, 40, and 60 of the experiment to evaluate fish growth. In addition, nine fish per treatment were euthanized at the experiment's beginning and end. Each fish was measured and weighed to calculate specific growth rate (SGR), weight gain (WG), survival rate (SR), feed conversion ratio (FCR), protein efficiency ratio (PER), condition factor (K), and thermal growth coefficient (TGC). Liver and visceral fat samples were obtained to evaluate somatic indices at the beginning and end of the experiment. These samples were used to calculate the hepatosomatic index (HSI) and the intraperitoneal fat (IPF) amount.

$$SGR = \frac{\ln(\text{final weight}) - \ln(\text{initial weight})}{\text{number of days}} \times (100)$$

$$WG = \text{final weight} - \text{initial weight}$$

$$SR = \frac{\text{number of fish at the end}}{\text{number of fish at the start}} \times (100)$$

$$FCR = \frac{\text{total amount of feed consumed}}{\text{total weight gain}}$$

$$PER = \frac{\text{total wet weight gain}}{\text{protein intake (dry weight, g)}}$$

$$K = \frac{\text{total weight}}{\text{total length}^3} \times (100)$$

$$TGC = \frac{\text{final weight } ⅓ - \text{initial weight } ⅓}{T(°C) \times \text{days}} \times (1000)$$

$$HSI = \frac{\text{liver weight}}{\text{total body weight}} \times (100)$$

$$IPF = \frac{\text{intraperitoneal fat weight}}{\text{total body weight}} \times (100)$$

Amino acid and fatty acid profile

In the AA analysis, 100 mg of defatted and dried samples were taken and then hydrolyzed with a mixture of 6N HCl and 0.06% phenol. The mixture was then digested at ~113°C for 15 h in a closed vial under a nitrogen atmosphere to avoid oxidation and produce FAA. After the hydrolysis period, the samples were adjusted to a final volume of 100 mL, where they were filtered through 0.45 µm Acrodiscs (Cytiva, P.N. 4426T). A final volume of 1.5 mL was placed in a previously cleaned, calcined, and amber-colored vial. The samples were refrigerated at -30°C until processing in high-performance liquid chromatography (HPLC). Derivatization was carried out directly on the Agilent HPLC (Model 1200 Infinity Series, CA, USA). In general, 2.5 µL of phosphate buffer (Part Num. 5061-3339) was taken, followed by 0.5 µL of the sample at a 1:1:1 ratio of OPA:FMOC (orthophthaldehyde: fluorenylmethyloxycarbonyl). Subsequently, they were injected in a continuous sequence into the HPLC. A reverse-phase C18 Zorbax Eclipse AAA column (4.5 × 150 mm, 3.5µm, PN 963400-902) was used for the AAs separation, with an injection volume of 5 µL. For the run, a sodium phosphate buffer gradient at 40 mM (Sigma Aldrich, MO, USA, cat num. 71500-250 g) and a mixture of acetonitrile at 45%, methanol at 45%, and HPLC-grade water at 10% were used at a flow rate of 1 mL min^{-1}. The system is coupled with a fluorescence detector (1260 FLD series, Agilent Technologies, USA) and a DAD detector (1260 DAD-UV, Agilent Technologies, USA). These detectors were configured at two wavelengths, 340/450 nm for excitation/emission in fluorescence and 266/305 nm for excitation/emission, and for the DAD, at 380 nm (OPA) and 262 nm (FMOC).

The calibration curve was performed using a standard solution of AA (PN 061-3330) with concentrations from 50 to 350 pmol. Finally, the area under the curve was estimated using the "OpenLAB" program (Agilent Technologies 2000, CA, USA), thus obtaining the percentage of AAs concerning protein content in the samples.

The lipids used for fatty acid analysis were extracted according to the methodology described by Folch et al. (1957). Small modifications were incorporated, such as adding 0.01% of butyl-hydroxy-toluene or BHT ($C_{15}H_{24}O$) as an antioxidant solution, working at the lowest possible temperature, and making lipid extraction. The fatty acid methyl esters (FAMEs) of the lipid extracts from muscle tissues were prepared according to Christie (1993). The fatty acids were separated, identified, and quantified using gas chromatography. An AGILENT GC 7820A gas chromatograph (Agilent Technologies 2000, CA, USA) equipped with a Split/Splitless injector was used, including a flame ionization detector (FID) and an AGILENT 122-2361 DB-23 capillary column measuring 60 m × 0.25 mm with an internal diameter of 15 mm. Calculations were performed using the GC Chemstation Data Analysis software. The initial injection temperature was set at 50°C for 1 min, then raised to 190°C at a rate of 25°C min^{-1}, held for 0 min, and subsequently increased to 230°C at a rate of 6°C min^{-1}; nitrogen (N2) was used as the carrier gas at a flow rate of 0.9 mL min^{-1}. Fatty acids were identified by comparison with retention times of the following standards: 37 Component FAME Mix (Supelco®/ Sigma- Aldrich, USA); GLC 87, GLC 96 (Nu-ChekPrep®, MN, USA); RM-2, RM-6, and GLC90 (Supelco®/Sigma-Aldrich®); and PUFAs from marine oils (PUFA1 and 3, Supelco®/Sigma-Aldrich, USA) was also used as an identification standard; the OpenLab-CDS program (Agilent Technologies 2000, CA, USA) was used, and the composition of each fatty acid was calculated according to the corresponding area in the respective chromatogram. C19:0 fatty acid was used as an internal standard. The results are shown as the total percentage of methylated fatty acids.

Statistical analysis

Data related to growth, blood biochemistry, and amounts of fatty acids and AAs were tested for normality (Shapiro-Wilk) and homogeneity of variances (Levene). Where data followed a parametric distribution, a one-way analysis of variance (ANOVA) was used, followed by a Tukey's test to compare means. On the other hand, when the data were non-parametric, the Kruskal-Wallis test was applied, followed by Dunn's test for multiple comparisons. To evaluate growth (weight, length) and blood biochemistry, a factorial ANOVA was used to analyze the interactions between time and treatments.

A factor analysis was performed using the principal component analysis (PCA) method with Varimax rotation to explore the underlying structure of the body composition indices and blood parameters. This analysis aims to simplify data interpretation and improve the understanding of the interactions between these variables concerning the treatments.

RESULTS

Longfin yellowtail growth

The study showed differences in weight when an interaction between time (days) and groups supplemented with and without taurine (Fig. 1b). At the beginning of the experiment, the fish had a mean weight of 286.8 ± 35 g. After 20 days, no significant differences ($P > 0.05$) in weight were observed between the groups with and without taurine, with a mean weight of 392.9 ± 52 g. However, after 40 days, the fish of the T2 group (591 ± 22 g) started showing significant differences ($P < 0.05$) compared to T0 (505 ± 48 g). At the end of the experiment, T2 showed a greater WG, reaching 704 ± 95 g ($P < 0.05$) in contrast to T1 and T0, which recorded weights of 655 ± 88 and 611 ± 62 g, respectively.

Total length showed differences when an interaction of time (days) and groups supplemented with and without taurine (Fig. 1a). At the beginning of the experiment, no differences ($P > 0.05$) were observed between T0, T1, and T2 when fish started with a mean length of 26.6 ± 1.2 cm. After 20 days, no significant differences ($P > 0.05$) were found between the taurine and without taurine groups. However, at 40 days, T0 and T1 showed no difference between them ($P > 0.05$), but T2 (32.6 ± 1 cm) showed differences concerning T0 ($P < 0.05$). At the end of the experiment, T2 reached a total length of 37 ± 1.3 cm, showing significant differences with T1 and T0 ($P < 0.05$), which recorded lengths of 34 ± 1.9 cm and 33.4 ± 1.2 g, respectively.

Condition and food efficiency indexes

The different taurine levels significantly impacted the experimental fish's condition, feeding, and somatic indices (Table 2). WG was significantly higher ($P < 0.05$) in T2 (406.9 ± 63.8 g) compared to T1 (378.28 ± 83) and T0 (326.94 ± 53 g). In addition, SGR increased as the addition of taurine in the diet increased ($P < 0.05$) from 1.27 ± 0.06% in T0 to 1.48 ± 0.09% in T2, indicating faster growth with the addition of taurine (20 g kg^{-1}) in the diet. Regarding FCR, T0 (2.83 ± 0.5) showed the highest values ($P < 0.05$) concerning T1 (2.51 ± 0.6) and T2 (2.25 ± 0.3) ($P < 0.05$), which is a positive indicator since it suggests higher efficiency in feed conversion to body mass. On the other hand, PER showed a significant increase ($P < 0.05$) in T2 (1 ± 0.15) compared to T0 and T1 groups, which suggests a better utilization of dietary protein with a higher amount of taurine, contributing to the observed WG. Regarding K, T1 showed the highest values, 1.68 ± 0.1, with significant differences ($P < 0.05$) concerning T0 and T2. It is essential to highlight that a higher K value does not always indicate a better performance. Finally, HSI was higher in T0 (2.0 ± 0.24%) compared to T1 and T2 groups, but these differences were not significant ($P > 0.05$). In addition, IPF was significantly higher ($P < 0.05$) in T0 (2.03 ± 0.76%), with a difference of 1% compared to T2, suggesting an increase in fat accumulation in the abdominal cavity of longfin yellowtail juveniles due to the absence of synthetic taurine in the diet.

Blood biochemistry

Differences were found in blood parameters when the interaction between time (initial and final) and the groups supplemented with and without taurine were analyzed (Table 3). The T2 group at the final time showed differences concerning T0 and T1 ($P < 0.05$), increasing TP concentration (4.8 ± 1 g dL^{-1}), GLO (3 ± 0.1 g dL^{-1}), as well as a decrease in GLU (201 ± 10 mg dL^{-1}). However, taurine had no significant effect ($P > 0.05$) on ALB levels, maintaining a constant value of 1.6 ± 2 g dL^{-1} among the different treatments. Similarly, no differences ($P > 0.05$) were observed in TRI concentrations, with a mean of 114.6 ± 28 mg dL^{-1} between T0, T1, and T2. In addition, the T0 group showed higher CHO levels at the end (216 ± 20 mg dL^{-1}) than T2 ($P < 0.05$), suggesting a positive effect of taurine on total cholesterol levels. Variations in liver enzymes were also observed at the end of the experiment, where the T1 group presented differences ($P < 0.05$) in AST levels (74.2 ± 20 U L^{-1}) concerning T0 (45 ± 22). No significant differences ($P > 0.05$) were observed in ALT at the end between T0 (41.3 ± 28), T1 (64.1± 25), and T2 (63.6 ± 3) treatments. On the other hand, the AST:ALT ratio in T2 was lower (0.88 ± 0.2) compared to T0 and T1; however, no significant differences ($P > 0.05$) were observed, remaining similar to the initial values of the experiment.

Principal component analysis

The PCA applied to the blood parameters shows that PC1 is the most influential component, explaining 40.7% of the total variance and an eigenvalue of 4.07. The variables ALT, TP, and GLB have a strong relationship with this component, with loadings of 0.89, 0.91, and 0.90, respectively. The variables AST and ALB are also associated with PC1, although with lower loadings of 0.587 and 0.683. In addition, PC1 ordered GLU and ratio TGO: TGP, but with negative loadings of -0.167 and -0.77, respectively. As for PC2, which explained 19.12% of the total variance with an eigenvalue of 1.9, ordered TRI and CHO with loadings

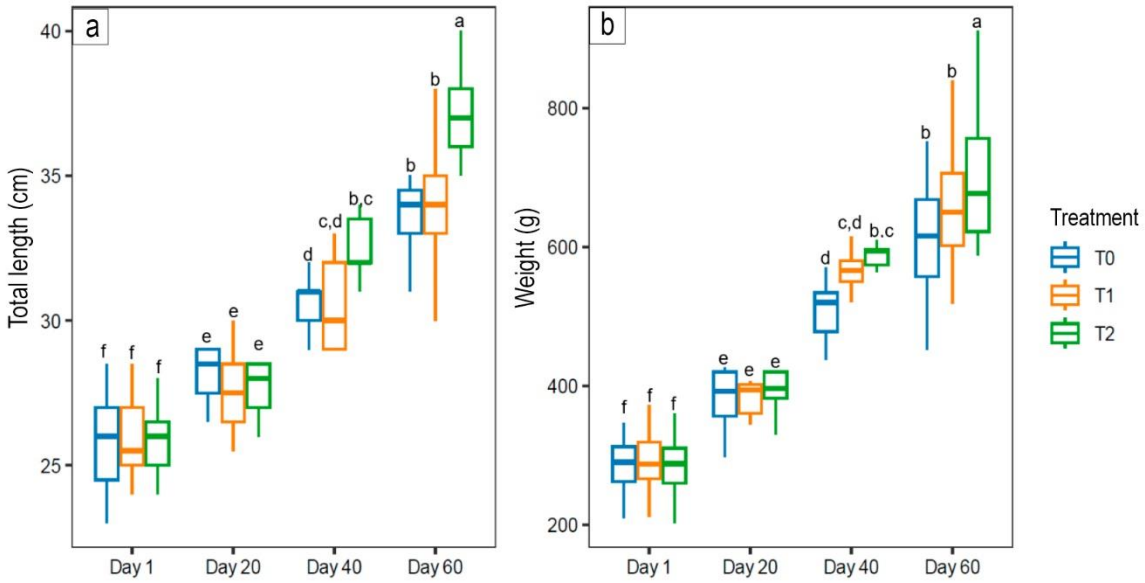

Figure 1. Growth evolution of longfin yellowtail during 60 days. a) Represents total length reached, and b) shows weight gain. Different letters indicate significant differences between time-treatment interactions ($P < 0.05$).

Table 2. Longfin yellowtail growth parameters, food efficiency, and somatic indexes (n = 3 per tank) fed taurine and control diet without taurine. Mean ± standard deviation. WG: weight gain, TGC: thermal growth coefficient, SGR: specific growth rate, FCR: food conversion ratio, PER: protein efficiency index, K: condition factor, HSI: hepatosomatic index, IPF: intraperitoneal fat index, and SR: survival rate. A different superscript letter in the same row indicates statistically significant differences ($P < 0.05$).

Parameters	T0	T1	T2	*P*-value
WG (g)	326.94 ± 53^{c}	378.28 ± 83.8^{b}	406.9 ± 63.8^{a}	<0.001
TGC	1.29 ± 0.11^{c}	1.47 ± 0.21^{b}	1.54 ± 0.12^{a}	<0.001
SGR (% d^{-1})	1.27 ± 0.06^{b}	1.44 ± 0.15^{a}	1.48 ± 0.09^{a}	<0.001
FCR	2.83 ± 0.52^{a}	2.51 ± 0.67^{b}	2.25 ± 0.3^{c}	<0.001
PER	0.8 ± 0.13^{c}	0.9 ± 0.2^{b}	1.0 ± 0.15^{a}	<0.001
K (%)	1.61 ± 0.07^{b}	1.68 ± 0.1^{a}	1.54 ± 0.04^{c}	<0.001
HSI (%)	2.00 ± 0.24^{a}	1.97 ± 0.33^{a}	1.77 ± 0.38^{a}	0.087
IPF (%)	2.03 ± 0.76^{a}	1.56 ± 0.32^{ab}	1.00 ± 0.23^{b}	<0.001
SR (%)	99 ± 1^{a}	98 ± 1^{a}	99 ± 1^{a}	0.421

of -0.679 and -0.51, respectively, and ALB:GLO ratio with a loading of 0.60. The biplot (Fig. 2a) highlights a correlation between the initial treatments and the parameters ALB, GLO, TP, and ALT; in contrast, the final group T0 is more associated with the AST:ALT ratio. The final groups, T1 and T2, show a higher correlation with GLU and CHO values.

In the PCA of growth-related parameters, PC1 is the principal component, explaining 63.2% of the total variance and an eigenvalue of 5.05. The variables TGC, WG, PER, and SGR have a strong relationship with this component, with loadings of 0.99, 0.94, 0.94, and 0.96, respectively. However, FCR shows a loading of -0.911. Regarding PC2, which explains approximately 21.1% of the total variance with an eigenvalue of 1.69, HSI and IPF present high loadings of 0.83 and 0.93, respectively, while K loads 0.469 on this component. The biplot (Fig. 2b) highlights a strong correlation between T0 and the somatic indexes HSI, IPF, as well as the condition factor K; in contrast, T2 is mainly linked to the parameters SGR, TGC, PER, and WG, while T1 shows a stronger relationship with WG and FCR.

Fatty acid and amino acid profiles in muscle

According to the data presented in Table 4, a decrease in the proportion of saturated fatty acids (SFA) is observed, of which T2 is the one that showed the lowest

Table 3. Serum biochemical parameters of longfin yellowtail at the initial time (day 1) and at the final time (day 60) (n = 3 per tank). Mean ± standard deviation. TP: total protein, ALB: albumin, GLO: globulin, ALB:GLO ratio, GLU: glucose, TRI: triglycerides, CHO: total cholesterol, AST: aspartate aminotransferase, ALT: alanine aminotransferase, and AST:ALT ratio. A different superscript letter in the same row indicates statistically significant differences between time-treatment interaction ($P < 0.05$).

	Initial time			Final time			
Parameters	T0	T1	T2	T0	T1	T2	*P*-value
TP (g dL^{-1})	5.5 ± 2^{a}	4.9 ± 0.01^{b}	5.6 ± 0.09^{a}	4.3 ± 2^{c}	4.4 ± 0.3^{c}	4.8 ± 1^{b}	<0.001
ALB (g dL^{-1})	2.0 ± 0.02^{a}	1.7 ± 0.04^{bc}	1.8 ± 0.1^{b}	1.6 ± 0.08^{c}	1.6 ± 0.08^{c}	1.6 ± 0.2^{c}	<0.001
GLO (g dL^{-1})	3.4 ± 0.2^{b}	3.1 ± 0.2^{c}	3.7 ± 0.02^{a}	2.8 ± 0.02^{d}	2.7 ± 0.04^{d}	3.0 ± 0.1^{c}	0.006
ALB:GLO	0.6 ± 0.03^{a}	0.55 ± 0.02^{a}	0.50 ± 0.03^{a}	0.58 ± 0.02^{a}	0.57 ± 0.03^{a}	0.55 ± 0.1^{a}	0.163
GLU (g dL^{-1})	224 ± 21^{abc}	245 ± 27^{a}	207 ± 29^{bc}	236 ± 26^{ab}	210 ± 13^{bc}	201 ± 10^{c}	0.009
TRI (g dL^{-1})	117 ± 0.6^{a}	104 ± 8^{a}	109 ± 4^{a}	124 ± 44^{a}	118 ± 23^{a}	102 ± 17^{a}	0.328
CHO (g dL^{-1})	215 ± 9^{ab}	218 ± 4^{ab}	223 ± 8^{a}	216 ± 20^{ab}	200 ± 18^{bc}	194 ± 8^{c}	0.007
AST (U L^{-1})	73.0 ± 12^{ab}	63.3 ± 10^{abc}	80.3 ± 18^{a}	45.0 ± 22^{c}	74.2 ± 20^{ab}	55.6 ± 13^{bc}	0.001
ALT (U L^{-1})	95.6 ± 5^{ab}	78.3 ± 15^{bc}	108.0 ± 23^{a}	41.3 ± 28^{d}	64.1 ± 25^{cd}	63.6 ± 3^{cd}	0.008
AST:ALT	0.76 ± 1^{a}	0.8 ± 0.06^{a}	0.73 ± 0.02^{a}	1.3 ± 0.5^{a}	1.3 ± 0.4^{a}	0.88 ± 0.2^{a}	0.094

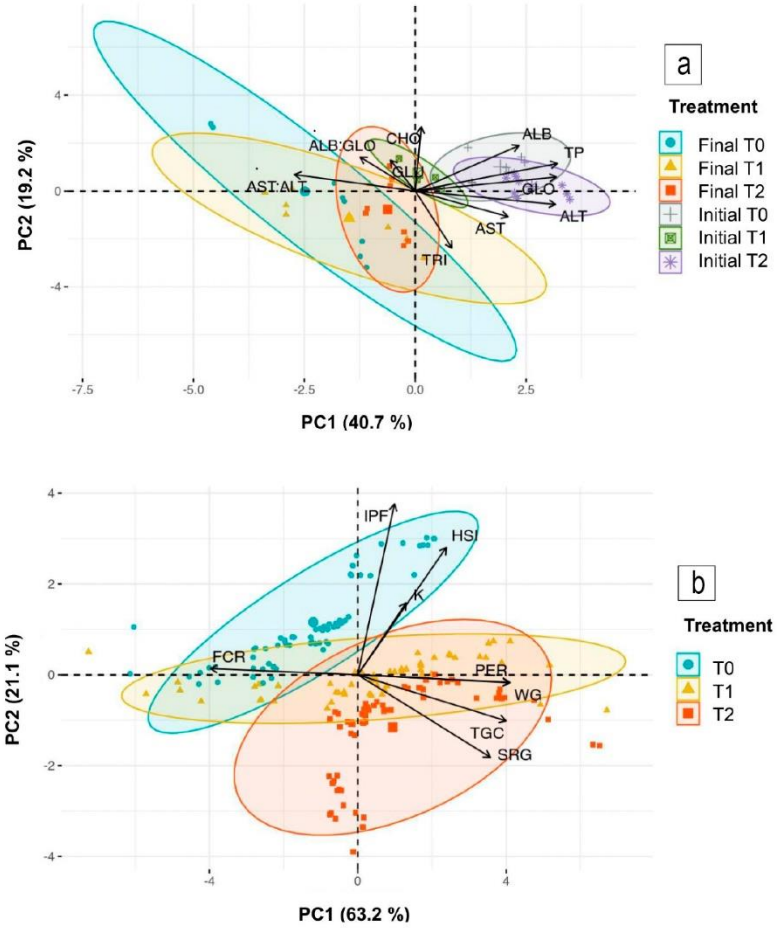

Figure 2. Principal component analysis (PCA) biplot. a) Indicates the relationship between blood biochemistry and diets, and b) shows the relationship of condition indexes concerning diets with and without taurine. TP: total protein, ALB: albumin, GLO: globulin, ALB:GLO ratio, GLU: glucose, TRI: triglycerides, CHO: total cholesterol, AST: aspartate aminotransferase, ALT: alanine aminotransferase, AST:ALT ratio, SGR: specific growth rate, WG: weight gain, FCR: food conversion ratio, PER: protein efficiency index, K: condition factor, TGC: thermal growth coefficient, HSI: hepatosomatic index, IPF: intraperitoneal fat index.

Table 4. Fatty acid profile of the different treatments and starting values (SV) in skeletal muscle of longfin yellowtail at 60 days. Mean ± standard deviation. NID: not identified, ND: not determined. A different superscript letter in the same row indicates statistically significant differences ($P < 0.05$).

Fatty acids (%)	SV	T0	T1	T2	*P*-value
C14:0	3.1 ± 0.1^{b}	3.0 ± 0.0^{b}	3.3 ± 0.1^{ab}	3.7 ± 0.0^{a}	<0.001
C15:0	0.3 ± 0.0^{a}	0.3 ± 0.0^{a}	0.3 ± 0.0^{a}	0.3 ± 0.0^{a}	1
C16:0	17.2 ± 0.1^{a}	16.0 ± 0.0^{b}	17.1 ± 0.1^{a}	17.2 ± 0.0^{a}	<0.001
C18:0	8.7 ± 4.6^{a}	6.3 ± 0.7^{b}	6.0 ± 0.6^{cb}	5.6 ± 0.3^{c}	<0.001
ΣSFA	29.3 ± 5.0^{a}	25.7 ± 0.8^{c}	26.7 ± 0.5^{b}	26.8 ± 0.0^{b}	<0.001
C16:1n7	4.7 ± 0.3^{a}	4.6 ± 0.0^{a}	4.6 ± 0.0^{a}	4.8 ± 0.0^{a}	0.112
C18:1n9	25.5 ± 4.6^{c}	27.9 ± 0.8^{a}	27.1 ± 0.1^{b}	26.9 ± 0.4^{b}	<0.001
C18:1n7	1.6 ± 0.3^{b}	1.7 ± 0.1^{b}	2.0 ± 0.2^{a}	2.0 ± 0.1^{a}	0.002
C20:1n9	1.5 ± 0.2^{a}	1.5 ± 0.0^{a}	1.4 ± 0.0^{a}	1.4 ± 0.0^{a}	0.441
C22:1	0.6 ± 0.2^{a}	0.5 ± 0.0^{b}	ND	ND	0.001
C24:1n9	0.4 ± 0.0^{b}	0.5 ± 0.0^{ab}	0.6 ± 0.0^{ab}	0.7 ± 0.0^{a}	0.030
ΣMUFAS	34.3 ± 5.1^{c}	36.7 ± 0.9^{a}	35.7 ± 0.1^{b}	35.7 ± 0.5^{b}	<0.001
C16:2n4	0.5 ± 0.2^{a}	0.5 ± 0.0^{a}	0.5 ± 0.0^{a}	0.5 ± 0.0^{a}	1
C16:3n4	0.4 ± 0.1^{a}	0.4 ± 0.1^{a}	0.5 ± 0.0^{a}	0.4 ± 0.1^{a}	0.552
C18:2n6	14.8 ± 0.1^{a}	15.1 ± 0.1^{a}	14.1 ± 0.1^{b}	13.9 ± 0.1^{b}	<0.001
C18:3n3	3.2 ± 0.1^{b}	3.4 ± 0.0^{a}	3.1 ± 0.0^{b}	3.1 ± 0.0^{b}	0.019
C18:4n3	0.8 ± 0.0^{b}	0.8 ± 0.0^{b}	0.9 ± 0.0^{ab}	1.0 ± 0.0^{a}	0.112
C20:2	0.7 ± 0.0^{a}	0.7 ± 0.0^{a}	0.7 ± 0.0^{a}	0.7 ± 0.0^{a}	1
C20:3n3	0.8 ± 0.0^{a}	0.7 ± 0.1^{a}	0.8 ± 0.0^{a}	0.8 ± 0.0^{a}	0.552
C20:4n6	0.5 ± 0.0^{a}	0.5 ± 0.0^{a}	0.5 ± 0.0^{a}	0.6 ± 0.1^{a}	0.552
C20:5n3	5.1 ± 0.1^{b}	5.5 ± 0.0^{ab}	5.5 ± 0.1^{ab}	5.6 ± 0.0^{a}	0.001
C22:5n3	1.9 ± 0.1^{a}	2.0 ± 0.0^{a}	1.9 ± 0.0^{a}	1.9 ± 0.0^{a}	0.552
C22:6n3	7.5 ± 0.2^{c}	8.0 ± 0.0^{b}	8.9 ± 0.2^{a}	8.5 ± 0.2^{a}	<0.001
ΣPUFAS	36.1 ± 0.3^{c}	37.7 ± 0.0^{a}	37.4 ± 0.4^{ab}	37.0 ± 0.0^{b}	<0.001
NID	0.4 ± 0.3^{a}	-	0.4 ± 0.0^{a}	0.7 ± 0.5^{a}	0.934
Σn3	19.2 ± 0.5^{c}	20.5 ± 0.0^{b}	21.1 ± 0.4^{a}	20.9 ± 0.2^{ab}	<0.001
Σn6	15.4 ± 0.1^{a}	15.6 ± 0.1^{a}	14.6 ± 0.1^{b}	14.5 ± 0.0^{b}	<0.001
Σn9	27.4 ± 4.5^{c}	30.0 ± 0.8^{a}	29.2 ± 0.2^{b}	28.9 ± 0.4^{b}	<0.001
EPA+DHA	12.5 ± 0.4^{c}	13.5 ± 0.0^{a}	14.3 ± 0.2^{b}	14.1 ± 0.2^{b}	<0.001

proportion compared to the other groups; this decrease was 0.7% compared to T0 ($P < 0.05$) and is attributed to C18:0 (stearic acid) decrease. On the other hand, at the end of the experiment, monounsaturated fatty acids (MUFAs) were lower than the baseline values (SV, 34.3%); however, T1 and T2 showed significant differences ($P < 0.05$) compared to T0, with a variation of 1%, since C22:1 (erucic acid) was not determined in the groups with taurine.

Polyunsaturated fatty acids (PUFAs) remained relatively stable with a slight difference of 0.7% between T0 and T2, where docosahexaenoic acid (C22:6n3, DHA) and eicosapentaenoic acid (C20:5n3, EPA) showed an increase after taurine treatments. DHA increased its concentration in T2 and T1 by 0.5 and 0.9%, respectively, compared to T0 ($P < 0.05$), while EPA increased from 5.1 to 5.6% SV compared to T2. Furthermore, the total proportion of omega-3 (Σn3) remained constant between T0 and T2 ($P > 0.05$), which was slightly higher in T1 compared to T0 ($P < 0.05$). On the other hand, the total omega-6 (Σn6) ratio decreased significantly between T0 and taurine groups ($P < 0.05$).

Regarding the AA profile, the results in Table 5 demonstrate that the number of AA in longfin yellowtail muscle was significantly influenced by taurine treatments, except for alanine ($P > 0.05$). The EAA, HIS, ARG, THR, VAL, MET, LYS, ILE, LEU, and PHE showed the highest value in T1 compared to T0 ($P < 0.05$). However, no significant differences were observed in ARG, MET, and LYS content between T2 and T0 ($P > 0.05$). The maximum values of EAA were

Table 5. Amino acid profile in skeletal muscle of the different treatments and starting values (SV) for longfin yellowtail at 60 days. Mean ± standard deviation. HIS: histidine, ARG: arginine, THR: threonine, VAL: valine, MET: methionine, LYS: lysine, ILE: isoleucine, LEU: leucine, PHE: phenylalanine, ASP: aspartic acid, SER: serine, GLU: glutamic acid, GLY: glycine, ALA: alanine, TYR: tyrosine, TAU: taurine. A different superscript letter in the same row indicates statistically significant differences ($P < 0.05$).

Amino acid (g 100 g^{-1})	SV	T0	T1	T2	*P*-value
Essential amino acids					
HIS	5.8 + 0.1^{ab}	4.7 + 0.01^{c}	6.0 + 0.4^{a}	5.3 + 0.2^{b}	0.005
ARG	8.8 + 0.01^{a}	7.7 + 0.1^{b}	9.2 + 0.6^{a}	8.5 + 0.3^{ab}	0.003
THR	3.0 + 0.01^{b}	2.6 + 0.01^{d}	3.1 + 0.01^{a}	2.9 + 0.01^{c}	<0.001
VAL	2.0 + 0.01^{b}	1.7 + 0.01^{d}	2.1 + 0.01^{a}	1.9 + 0.01^{c}	<0.001
MET	1.9 + 0.1^{b}	2.8 + 0.01^{a}	2.0 + 0.4^{b}	2.3 + 0.2^{ab}	0.005
LYS	4.5 + 0.1^{a}	3.9 + 0.1^{b}	4.6 + 0.3^{a}	4.3 + 0.1^{ab}	0.005
ILE	2.5 + 0.01^{ab}	2.2 + 0.01^{c}	2.6 + 0.1^{a}	2.4 + 0.1^{b}	0.007
LEU	5.2 + 0.01^{a}	4.4 + 0.1^{c}	5.4 + 0.1^{a}	4.9 + 0.1^{b}	<0.001
PHE	2.8 + 0.01^{b}	2.4 + 0.01^{d}	3.0 + 0.1^{a}	2.6 + 0.0^{c}	<0.001
Non-essential amino acids					
ASP	3.8 + 0.01^{a}	3.3 + 0.1^{b}	4.0 + 0.1^{a}	3.7 + 0.3^{ab}	0.005
SER	3.7 + 0.01^{a}	3.1 + 0.01^{c}	3.8 + 0.1^{a}	3.5 + 0.0^{b}	<0.001
GLU	8.4 + 0.01^{ab}	7.2 + 0.2^{c}	8.6 + 0.0^{a}	8.1 + 0.3^{b}	<0.001
GLY	9.3 + 0.1^{a}	7.2 + 0.2^{b}	9.7 + 1.1^{a}	8.2 + 0.3^{ab}	0.003
ALA	4.4 + 0.01^{a}	3.7 + 0.01^{a}	2.3 + 3.1^{a}	4.2 + 0.1^{a}	0.397
TYR	2.7 + 0.01^{ab}	2.4 + 0.01^{c}	2.8 + 0.1^{a}	2.6 + 0.0^{b}	<0.001
Others					
TAU	1.5 + 0.01^{bc}	1.2 + 0.01^{c}	1.7 + 0.01^{b}	5.1 + 0.3^{a}	<0.001
Total	70.3	60.4	70.8	70.4	

observed in longfin yellowtail fed with taurine in T1 and T2 diets. As for non-essential amino acids (NEAA), SER, GLU, GLY, and TYR showed significant differences ($P < 0.05$) between T1 and T2 in comparison to T0. Finally, the taurine analysis showed that its concentration varied significantly between treatments ($P < 0.05$), having a higher concentration in T2 (5.1 + 0.3) compared to T0 and T1, indicating that taurine supplementation in the diet has an important effect on muscle accumulation.

DISCUSSION

Growth and condition indexes

Several authors have documented the benefits of incorporating taurine into the diet of different fishes (Salze & Davis 2015, Sampath et al. 2020). However, taurine requirements in marine fish are still not well studied because the optimal amounts in various species are unknown; for example, a meta-analysis by Li et al. (2022) revealed that marine fish require more taurine in the diet than freshwater fish, suggesting an average of 0.79% taurine. However, as shown, different carnivorous fish species require different taurine concentrations in the diet due to little or no ability to synthesize it (Yokoyama et al. 2001), as is the case of Japanese amberjack that requires 1-2 g kg^{-1} (Matsunari et al. 2005), Colorado snapper 16.3 g kg^{-1} (Hernández et al. 2018), European seabass *Dicentrarchus labrax* 10.0 g kg^{-1} (Saleh et al. 2020), common dentex *Dentex dentex* 2 g kg^{-1} (Chatzifotis et al. 2008) and cobia 0.5 g kg^{-1} (Lunger et al. 2007).

The present study showed a significant improvement when the diet contained 20 g kg^{-1} taurine (T2), with differences occurring after 40 days. Different parameters, such as growth, food utilization, and somatic indexes, improved in fish-fed taurine compared to the treatment without taurine. The inclusion of taurine showed an improvement in SGR and WG, which is consistent with previous findings in studies on yellowtail amberjack (Garcia-Organista et al. 2019), Japanese amberjack (Matsunari et al. 2005, Takagi et al. 2008), bastard halibut *Paralichthys olivaceus* (Park et al. 2001a, Kim et al. 2005), where taurine has been associated with improved growth. The growth improvement effect of taurine supplementation could be related to the ability to stimulate food consumption, as demonstrated with other FAA which have appetite-

stimulating effects (Kasumyan & Doving 2003); enhancing digestive enzyme activity (Park et al. 2001b, Abdel-Tawwab & Monier 2018); nutrient absorption, due to the increased intestinal brush border membrane surface (Tian et al. 2016) and the improvement of intestinal barriers (Wen et al. 2020). On the other hand, PER showed the highest value in T2 (1 ± 0.10), showing similar values to those reported by Hernández et al. (2018) in Colorado snapper with 1.2 ± 0.10 in fish fed 0.6, 1.2, and 1.8 g 100 g^{-1}, evidencing that taurine can help to improve dietary protein utilization. In this regard, Salze et al. (2012) also demonstrated an increase of trypsin in cobia larvae fed taurine-supplemented live foods, which enhance protein digestion.

In all the treatments, the K factor was found to be significantly greater than 1, although a slight difference was noted in the value of T0 compared to the taurine-supplemented groups. This result can be attributed to the fact that the fish in T1 and T2 increased their muscle mass without experiencing a significant change in length. This phenomenon is similar to that observed in sterlet sturgeon, where a decrease in the K factor was reported as the taurine concentration in the increased diet (Bavi et al. 2022). In addition, taurine does not affect HSI in longfin yellowtail; on the contrary, as reported in cobia, HSI was lower with the addition of taurine (3.11%) and higher in the diet without taurine (5.07%) (Lunger et al. 2007). However, taurine influenced a lower accumulation of IPF, showing a difference of 1% between T0 and T2, which suggests a possible increase in the concentration of bile acids, as reported for Senegalese sole *Solea senegalensis* (Aragão et al. 2023).

The effects of taurine supplementation in the commercial diet on growth and somatic indexes demonstrated a strong relationship, clarified through PCA. This analysis evidenced a greater separation between T0 and T2, corroborating that the absence of taurine strongly correlates with increased IPF. At the same time, its addition is more related to SGR due to the improvement of muscle hyperplasia, as reported by (Wijerath-Wiriduge et al. 2020), indicating that taurine influences this variable to a greater extent.

Blood biochemistry

Blood biochemistry is valuable for evaluating fish health (Chen et al. 2004). It allows for identifying conditions, such as physiological stress (Lermen et al. 2004, Huang et al. 2021) and detecting pathological diseases or pathophysiological disorders (Stockham & Scott 2013).

The present study indicates that increased dietary taurine levels increase TP and GLO values. This observation has been corroborated in situations where taurine is increased to 30 g kg^{-1} in the diet, leading to an increase in TP levels in species such as sterlet sturgeon (Bavi et al. 2022) and North African catfish *Clarias gariepinus* (Adeshina & Abdel-Tawwab 2020). Improving these parameters by incorporating taurine could indicate a possible recovery from liver damage and a positive impact on protein anabolism (Valente et al. 2011). Likewise, the increase in these proteins may be associated with an increase in defensive proteins, which could result in a better physical state of the organism (Saleh et al. 2020) and the improvement of the immune system in fish (Adeshina & Abdel-Tawwab 2020). The ALB content was not affected by taurine (Table 3), indicating that protein metabolism and transport of hormones, unconjugated bilirubin, and some fatty acids were not affected (Andreeva 2010). Now, the ALB:GLO ratio values vary according to each species, where an imbalance in these variables indicates inflammation and liver dysfunction (Mazzaferro et al. 2002, Giannini et al. 2005). Nonetheless, in the present study, values were found to range from 0.55 to 0.58, in agreement with those reported for Chinese sturgeon *Acipenser sinensis* (Zheng et al. 2023), which did not show significant changes in the ALB:GLO ratio between its control diet and that supplemented with taurine. The blood values for longfin yellowtail juveniles indicate that they are in healthy ranges, according to Lepkovsky (1930), who established a range between 0.26 to 1.7 in the ALB:GLO ratio.

Including taurine in T1 and T2 diets reduced blood serum glucose concentration. This effect may be related to the ability of taurine to enhance glucose metabolism by boosting the activity and gene expression of several enzymes, including glucokinase, pyruvate kinase, glucose-6-phosphate dehydrogenase, glycogen synthase, and glucose transporter 2 (Sampath et al. 2020). Although Martins et al. (2018) did not observe changes in glucose levels in European seabass, other studies have corroborated that taurine can decrease blood glucose levels in totoaba (Bañuelos-Vargas et al. 2014) and Persian sturgeon *Acipenser persicus* (Hoseini et al. 2018). These findings suggest that taurine may play an important role in regulating glucose metabolism in longfin yellowtail, which contributes to improving their metabolic health.

Taurine has been demonstrated to reduce cholesterol synthesis (Chen et al. 2012), meaning its concentration decreases as the amount of taurine in the diet increases. An example is the research of Tong et al. (2020), who

observed a decrease in CHO when dietary taurine was increased (20 g kg^{-1}) in blackhead seabream *Acanthopagrus schlegelii*. This result agrees with that reported in the present study, where a significant decrease was observed in CHO as the amount of dietary taurine increased. In contrast, a decrease was also observed in TRI as taurine increased, but the variations detected were not statistically significant. Our results agree with other studies where the increase of taurine decreased the amount of TRI by increasing taurine supplementation at 0.5 and 1.5% (Aragão et al. 2023) and 15, 30, and 50 g kg^{-1} (Bavi et al. 2022) in the diet.

Liver ALT and AST enzymes indicate liver or muscle cell damage when released into the bloodstream in high concentrations (Center 2007). The results showed that AST levels had significant differences, higher at T1 (74.2 U L^{-1}), but no differences were observed between T0 and T2. Liver ALT did not show significant differences between treatments; the values of the three treatments for ALT and AST were lower than the reference values at the beginning of the experiment. These results are like those reported by Tong et al. (2020), who found higher AST and ALT activities due to taurine supplementation in the diet of blackhead seabream. On the other hand, the AST:ALT ratio can serve as an indicator of liver failure; a ratio higher than 1 indicates a significantly damaged liver, but this ratio can increase or decrease depending on the conditions in which the fish may be found (Bonifacio et al. 2016). In the present study, the AST:ALT ratio was significantly lower in T2 (0.88), and T0 and T1 showed a ratio of 1.3. Nevertheless, it is difficult to indicate some liver damage due to the lack of information since it can be highly variable between species and the developmental stage of the fish. Further investigations should be performed by using other studies, such as histology.

Effects of taurine on muscle composition

Research has shown that adding taurine as a supplement can increase taurine levels in muscles (Yatabe et al. 2009), influencing the regulation of fatty acid oxidation and transport (Ito et al. 2010, De Luca et al. 2015, Thirupathi et al. 2020). Regarding fatty acid composition, the results indicate that taurine concentration influenced the concentrations of specific fatty acids; for example, a significant increase in the levels of C14:0, C16:0, C16:1n7, C18:1n7, C24:1n9, C18:4n3, and C20:4n6 was observed in T2 compared to T0. However, total omega-3 and DHA concentrations were higher in T1, while EPA concentration was higher in T2. These differences suggest that taurine may have a modulatory effect on the concentration of fatty acids in muscle. However, the effect may vary depending on the specific type of fatty acid. Further studies are needed to fully understand the underlying mechanisms of how taurine affects the fatty acid profile and the effect they may have on longfin yellowtail juveniles, e.g. an imbalance in the ratio of these fatty acids may lead to inflammation and other chronic diseases (Harris 2010, Djuricic & Calder 2021).

On the other hand, an increase was observed in taurine accumulation in muscle when taurine was increased in the diet, coinciding with investigations in other species such as European seabass (Kotzamanis et al. 2019, 2020) and bastard halibut (Kim et al. 2005). However, the overall AA profile was higher for T1, with a decrease in EAA and NEAA in T2. Nonetheless, both were higher than T0 except for MET, which was higher than the taurine groups. These results contrast those that Ishikura et al. (2011) reported: taurine consumption implied a decrease in alanine, threonine, and serine. Nevertheless, a direct relationship between taurine and other AA has not been established; taurine may influence the activity of other AA since both are involved in metabolic and energetic processes in the body. Therefore, more research is needed to understand this possible relationship fully.

CONCLUSIONS

The results of the present study demonstrated that adding taurine in commercial feed in amounts of 20 g kg^{-1} positively affects growth rates, blood biochemistry, and muscle composition of juvenile longfin yellowtail. Although the current results are promising and suggest that taurine has a positive impact on juvenile fish, continuing with further research is essential to deepen our understanding of the biochemical mechanisms mediating the action of taurine and clarify its physiological role in longfin yellowtail by multidisciplinary approaches.

Credit author statement

M.A. Hernández-de Dios: Conceptualization, validation, methodology, formal analysis, writing-original draft; M.C. Maldonado-García: Funding acquisition, project administration, supervision, review, and editing; D. Tovar-Ramírez: Methodology, validation, supervision, review, editing; D. Maldonado-García: Methodology, supervision, validation, review and editing; M.A. Galaviz-Espinoza: Methodology, data curation, formal analysis, review, and editing; Barreto-Curiel: Methodology, formal analysis, review and

editing; M. Spanopoulos-Zarco: Formal analysis, review & editing. All authors have read and accepted the published version of the manuscript.

Funding

The Consejo Nacional de Humanidades, Ciencias y Tecnología (CONAHCYT) in Mexico has provided partial funding for this research under the grant number CONACYT-PRONACES 321279 FOP07 and Kampachi Farms México project N°20464.

ACKNOWLEDGMENTS

The authors thank CONAHCYT (Consejo Nacional de Humanidades, Ciencias y Tecnología, Mexico) for research financial support and doctoral grant (registration number 868038); also thankful to technical staff Francisco Encarnación Ramírez, Roxana Bertha Inohuye Rivera, Pedro Uriarte Ureta, Juan Carlos Pérez Urbiola, Pablo Monsalvo Spencer, Carlos Ernesto Ceseña, Laura Teresa Guzmán Villanueva, Andressa Teles, Daniela Alejandra Corona Rojas, and Rodrigo Alejandro Hernández Victoria for their invaluable help in various phases of the experiment and the care of the fish; to Diana Fischer for English language edition.

REFERENCES

Abdel-Tawwab, M. & Monier, M.N. 2018. Stimulatory effect of dietary taurine on growth performance, digestive enzyme activity, antioxidant capacity, and tolerance of common carp, *Cyprinus carpio* L., fry to salinity stress. Fish Physiology and Biochemistry, 44: 639-649. doi: 10.1007/s10695-017-0459-8

Adeshina, I. & Abdel-Tawwab, M. 2020. Dietary taurine incorporation to high plant protein-based diets improved growth, biochemical, immunity, and antioxidants biomarkers of African catfish, *Clarias gariepinus* (B.). Fish Physiology and Biochemistry, 46: 1323-1335. doi: 10.1007/s10695-020-00791-y

Andreeva, A.M. 2010. Structure of fish serum albumins. Zhurnal Evoliutsionnoi Biokhimii I Fiziologii, 46: 111-118.

Aragão, C., Teodósio, R., Colen, R., Richard, N., Rønnestad, I., Dias, J., et al. 2023. Taurine supplementation to plant-based diets improves lipid metabolism in Senegalese sole. Animals, 13: 1501. doi: 10.3390/ani13091501

Association of Official Analytical Chemists (AOAC). 1995. Analysis of Official Analytical Chemists. AOAC, Arlington

Bañuelos-Vargas, I., López, L.M., Pérez-Jiménez, A. & Peres, H. 2014. Effect of fishmeal replacement by soy protein concentrate with taurine supplementation on hepatic intermediary metabolism and antioxidant status of totoaba juveniles (*Totoaba macdonaldi*). Comparative Biochemistry and Physiology - Part B: Biochemistry and Molecular Biology, 170: 18-25.

Barreto-Curiel, F., Focken, U., D'Abramo, L.R., Mata-Sotres, J.A. & Viana, M.T. 2019. Assessment of amino acid requirements for *Totoaba macdonaldi* at different protein levels using stable isotopes and a non-digestible protein source as a filler. Aquaculture, 503: 550-561. doi: 10.1016/j.aquaculture.2019.01.038

Bavi, Z., Zakeri, M., Mousavi, S.M. & Yavari, V. 2022. Effects of dietary taurine on growth, body composition, blood parameters, and enzyme activities of juvenile sterlet (*Acipenser ruthenus*). Aquaculture Nutrition, 2022: 1713687. doi: 10.1155/2022/1713687

Biasato, I., Chemello, G., Caimi, C., Bellezza-Oddon, S., Capucchio, M.T., Colombino, E., et al. 2022. Taurine supplementation in plant-based diets for juvenile rainbow trout (*Oncorhynchus mykiss*): Effects on growth performance, whole body composition, and histomorphological features. Animal Feed Science and Technology, 289: 115314. doi: 10.1016/j.anifeedsci.2022.115314

Blanco, V., Ohs, C., Rhody, N. & Hans, R. 2022. Candidate species for Florida aquaculture: Almaco jack, *Seriola rivoliana*. FA249, 12/2022. EDIS, 2022: 6. doi: 10.32473/edis-fa249-2022

Bonifacio, A.F., Cazenave, J., Bacchetta, C., Ballesteros, M.L., de los Ángeles-Bistoni, M., Amé, M.V., et al. 2016. Alterations in the general condition, biochemical parameters, and locomotor activity in *Cnesterodon decemmaculatus* exposed to commercial formulations of chlorpyrifos, glyphosate and their mixtures. Ecological Indicators, 67: 88-97. doi: 10.1016/j.ecolind.2016.02.011

Candebat, C.L., Booth, M., Codabaccus, M.B. & Pirozzi, I. 2020. Dietary methionine spares the requirement for taurine in juvenile yellowtail kingfish (*Seriola lalandi*). Aquaculture, 522: 735090. doi: 10.1016/j.aquaculture.2020.735090

Center, S.A. 2007. Interpretation of liver enzymes. Veterinary Clinics of North America: Small Animal Practice, 37: 297-333. doi: 10.1016/j.cvsm.2006.11.009

Chatzifotis, S., Polemitou, I., Divanach, P. & Antonopoulou, E. 2008. Effect of dietary taurine supplementation on growth performance and bile salt activated lipase activity of common dentex, *Dentex dentex*, fed a fish

meal/soy protein concentrate-based diet. Aquaculture, 275: 201-208. doi: 10.1016/j.aquaculture.2007.12.013

Chen, W., Guo, J.-X. & Chang, P. 2012. The effect of taurine on cholesterol metabolism. Molecular Nutrition & Food Research, 56: 681-690. doi: 10.1002/mnfr.201100799

Chen, C.-Y., Wooster, G.A. & Bowser, P.R. 2004. Comparative blood chemistry and histopathology of tilapia infected with *Vibrio vulnificus* or *Streptococcus iniae* or exposed to carbon tetrachloride, gentamicin, or copper sulfate. Aquaculture, 239: 421-443. doi: 10.1016/j.aquaculture.2004.05.033

Christie, W.W. 1993. Preparation of ester derivatives of fatty acids for chromatographic analysis. Advances in Lipid Methodology, 2: e111.

De Luca, A., Pierno, S. & Camerino, D.C. 2015. Taurine: the appeal of a safe amino acid for skeletal muscle disorders. Journal of Translational Medicine, 13: 243. doi: 10.1186/s12967-015-0610-1

Djuricic, I. & Calder, P.C. 2021. Beneficial outcomes of omega-6 and omega-3 polyunsaturated fatty acids on human health: An update for 2021. Nutrients, 13: 2421. doi: 10.3390/nu13072421

El-Sayed, A.-F.M. 2014. Is dietary taurine supplementation beneficial for farmed fish and shrimp? A comprehensive review. Reviews in Aquaculture, 6: 241-255. doi: 10.1111/raq.12042

Folch, J., Lees, M. & Sloane-Stanley, G.H. 1957. A simple method for the isolation and purification of total lipids from animal tissues. Journal of Biological Chemistry, 226: 497-509.

Garcia-Organista, A.A., Mata-Sotres, J.A., Viana, M.T. & Rombenso, A.N. 2019. The effects of high dietary methionine and taurine are not equal in terms of growth and lipid metabolism of juvenile California yellowtail (*Seriola dorsalis*). Aquaculture, 512: 734304. doi: 10.1016/j.aquaculture. 2019.734304

Giannini, E.G., Testa, R. & Savarino, V. 2005. Liver enzyme alteration: A guide for clinicians. Canadian Medical Association Journal, 172: 367-379. doi: 10.1503/cmaj.1040752

Guzmán-Villanueva, L.T., Ascencio-Valle, F., Macías-Rodríguez, M.E. & Tovar-Ramírez, D. 2014. Effects of dietary β-1, 3/1, 6-glucan on the antioxidant and digestive enzyme activities of Pacific red snapper (*Lutjanus peru*) after exposure to lipopolysaccharides. Fish Physiology and Biochemistry, 40: 827-837. doi: 10.1007/s10695-013-9889-0

Harris, W. 2010. Omega-6 and omega-3 fatty acids: partners in prevention. Current Opinion in Clinical Nutrition & Metabolic Care, 13: 125. doi: 10.1097/MCO.0b013e3283357242

Hawkyard, M., Stuart, K., Langdon, C. & Drawbridge, M. 2016. The enrichment of rotifers (*Brachionus plicatilis*) and *Artemia franciscana* with taurine liposomes and their subsequent effects on the larval development of California yellowtail (*Seriola lalandi*). Aquaculture Nutrition, 22: 911-922. doi: 10.1111/anu.12317

Hernández, C., Sánchez-Gutiérrez, E.Y., Ibarra-Castro, L., Peña, E., Gaxiola, G. & De la Barca, A.M.C. 2018. Effect of dietary taurine supplementation on growth performance and body composition of snapper, *Lutjanus colorado* juvenile. Turkish Journal of Fisheries and Aquatic Sciences, 18: 1227-1233. doi: 10.4194/1303-2712-v18_10_09

Hernandez de-Dios, M.A., Tovar-Ramírez, D., Maldonado-García, D., Galaviz-Espinoza, M.A., Spanopoulos-Zarco, M. & Maldonado-García, M.C. 2022. Functional additives as a boost to reproductive performance in marine fish: A review. Fishes, 7: 5. doi: 10.3390/fishes7050262

Hoseini, S.M., Hosseini, S.A., Eskandari, S. & Amirahmadi, M. 2018. Effect of dietary taurine and methionine supplementation on growth performance, body composition, taurine retention and lipid status of Persian sturgeon, *Acipenser persicus* (Borodin, 1897), fed with plant-based diet. Aquaculture Nutrition, 24: 324-331.

Huang, J., Guo, Z., Zhang, J., Wang, W., Wang, Z., Amenyogbe, E., et al. 2021. Effects of hypoxia-reoxygenation conditions on serum chemistry indicators and gill and liver tissues of cobia (*Rachycentron canadum*). Aquaculture Reports, 20: 100692. doi: 10.1016/j.aqrep.2021.100692

Ishikura, K., Miyazaki, T., Ra, S.-G., Endo, S., Nakamura, Y., Matsuzaka, T., et al. 2011. Effect of taurine supplementation on the alterations in amino acid content in skeletal muscle with exercise in rat. Journal of Sports Science & Medicine, 10: 306-314.

Ito, T., Oishi, S., Takai, M., Kimura, Y., Uozumi, Y., Fujio, Y., et al. 2010. Cardiac and skeletal muscle abnormality in taurine transporter-knockout mice. Journal of Biomedical Science, 17: S20. doi: 10.1186/1423-0127-17-S1-S20

Kasumyan, A.O. & Doving, K.B. 2003. Taste preferences in fishes. Fish and Fisheries, 4: 289-347.

Kim, Y.-S., Sasaki, T., Awa, M., Inomata, M., Honryo, T., Agawa, Y., et al. 2016. Effect of dietary taurine enhancement on growth and development in red sea

bream *Pagrus major* larvae. Aquaculture Research, 47: 1168-1179. doi: 10.1111/are.12573

Kim, S.-K., Takeuchi, T., Akimoto, A., Furuita, H., Yamamoto, T., Yokoyama, M., et al. 2005. Effect of taurine-supplemented practical diet on growth performance and taurine contents in whole body and tissues of juvenile Japanese flounder *Paralichthys olivaceus*. Fisheries Science, 71: 627-632. doi: 10.1111/j.1444-2906.2005.01008.x

Kotzamanis, Y., Kumar, V., Tsironi, T., Grigorakis, K., Ilia, V., Vatsos, I., et al. 2019. Effects of taurine supplementation in soy-based diets on growth performance and fillet quality in European sea bass (*Dicentrarchus labrax*). Aquaculture, 520: 734655. doi: 10.1016/j.aquaculture.2019.734655

Kotzamanis, Y., Tsironi, T., Brezas, A., Grigorakis, K., Ilia, V., Vatsos, I., et al. 2020. High taurine supplementation in plant protein-based diets improves growth and organoleptic characteristics of European seabass (*Dicentrarchus labrax*). Scientific Reports, 10: 12294. doi: 10.1038/s41598-020-69014-x

Koven, W., Nixon, O., Allon, G., Gaon, A., El Sadin, S., Falcon, J., et al. 2018. The effect of dietary DHA and taurine on rotifer capture success, growth, survival and vision in the larvae of Atlantic bluefin tuna (*Thunnus thynnus*). Aquaculture, 482: 137-145. doi: 10.1016/j.aquaculture.2017.09.039

Lepkovsky, S. 1930. The distribution of serum and plasma proteins in fish. Journal of Biological Chemistry, 85: 667-673. doi: 10.1016/S0021-9258(18)76970-6

Lermen, C.L., Lappe, R., Crestani, M., Vieira, V.P., Gioda, C.R., Schetinger, M.R.C., et al. 2004. Effect of different temperature regimes on metabolic and blood parameters of silver catfish *Rhamdia quelen*. Aquaculture, 239: 497-507. doi: 10.1016/j.aquaculture.2004.06.021

Li, L., Liu, H.-Y., Xie, S.-Q., Zhang, P.-Y. & Yang, Z.-C. 2022. Effects of taurine supplementation on growth performance and feed utilization in aquatic animals: A meta-analysis. Aquaculture, 551: 737896. doi: 10.1016/j.aquaculture.2022.737896

Lunger, A.N., McLean, E., Gaylord, T.G., Kuhn, D. & Craig, S.R. 2007. Taurine supplementation to alternative dietary proteins used in fish meal replacement enhances growth of juvenile cobia (*Rachycentron canadum*). Aquaculture, 271: 401-410. doi: 10.1016/j.aquaculture.2007.07.006

Magalhães, R., Martins, N., Martins, S., Lopes, T., Díaz-Rosales, P., Pousão-Ferreira, P., et al. 2019. Is dietary taurine required for white seabream (*Diplodus sargus*) juveniles? Aquaculture, 502: 296-302. doi: 10.1016/j.aquaculture.2018.12.019

Martins, N., Estevão-Rodrigues, T., Diógenes, A.F., Diaz-Rosales, P., Oliva-Teles, A. & Peres, H. 2018. Taurine requirement for growth and nitrogen accretion of European sea bass (*Dicentrarchus labrax*, L.) juveniles. Aquaculture, 494: 19-25. doi: 10.1016/j.aquaculture.2018.05.007

Matsunari, H., Hamada, K., Mushiake, K. & Takeuchi, T. 2006. Effects of taurine levels in broodstock diet on reproductive performance of yellowtail *Seriola quinqueradiata*. Fisheries Science, 72: 955-960. doi: 10.1111/j.1444-2906.2006.01243.x

Matsunari, H., Takeichi, T., Takahashi, M. & Mushiake, K. 2005. Effect of dietary taurine supplementation on growth performance of yellowtail *Seriola quinqueradiata*. Fisheries Science, 71: 1131-1135. doi: 10.1111/j.1444-2906.2005.01072.x

Matsunari, H., Furuita, H., Yamamoto, T., Kim, S.-K., Sakakura, Y. & Takeuchi, T. 2008. Effect of dietary taurine and cystine on growth performance of juvenile red sea bream *Pagrus major*. Aquaculture, 274: 142-147. doi: 10.1016/j.aquaculture.2007.11.002

Matsunari, H., Hashimoto, H., Iwasaki, T., Oda, K., Masuda, Y., Imaizumi, H., et al. 2013. Effect of feeding rotifers enriched with taurine on the growth and survival of larval amberjack *Seriola dumerili*. Fisheries Science, 79: 815-821. doi: 10.1007/s12562-013-0657-y

Mazzaferro, E.M., Rudloff, E. & Kirby, R. 2002. The role of albumin replacement in the critically ill veterinary patient. Journal of Veterinary Emergency and Critical Care, 12: 113-124. doi: 10.1046/j.1435-6935.2002.00025.x

Norwegian Refugee Council (NRC). 2011. Nutrient requirements of fish and shrimp. NRC, Oslo.

Park, G.S., Takeuchi, T., Seikai, T. & Yokoyama, M. 2001a. The effects of dietary taurine on growth and taurine levels in whole body of juvenile Japanese flounder *Paralichthys olivaceus*. Nippon Suisan Gakkaishi, 67: 238-243. doi: 10.2331/suisan.67.238

Park, S., Kim, H. & Kim, S.J. 2001b. Stimulation of ERK2 by taurine with enhanced alkaline phosphatase activity and collagen synthesis in osteoblast-like UMR-106 cells. Biochemical Pharmacology, 62: 1107-1111. doi: 10.1016/s0006-2952(01)00741-9

Peter, N., Pradhan, C., Dileep, N., Musharraf, M. & Thazhakot-Vasunambisan, S. 2022. Dietary taurine improved growth performance, nutrient utilization, and antioxidant enzyme activities in pangasius *Pangasianodon hypophthalmus*. Journal of the World

Aquaculture Society, 53: 106-121. doi: 10.1111/jwas.12778

Saleh, N.E., Wassef, E.A. & Ashry, A.M. 2020. Is a taurine supplement necessary in fishmeal-based feeds for juvenile European sea bass (*Dicentrarchus labrax*)? Aquaculture International, 28: 321-333. doi: 10.1007/s10499-019-00464-5

Salze, G.P. & Davis, D.A. 2015. Taurine: a critical nutrient for future fish feeds. Aquaculture, 437: 215-229. doi: 10.1016/j.aquaculture.2014.12.006

Salze, G.P., Davis, D.A., Stuart, K. & Drawbridge, M. 2019. Effect of dietary taurine in the performance of broodstock and larvae of California yellowtail *Seriola dorsalis*. Aquaculture, 511: 734262. doi: 10.1016/j.aquaculture.2019.734262

Salze, G., McLean, E. & Craig, S.R. 2012. Dietary taurine enhances growth and digestive enzyme activities in larval cobia. Aquaculture, 362: 44-49. doi: 10.1016/j.aquaculture.2012.07.021

Salze, G., McLean, E., Battle, P.R., Schwarz, M.H. & Craig, S.R. 2010. Use of soy protein concentrate and novel ingredients in the total elimination of fish meal and fish oil in diets for juvenile cobia, *Rachycentron canadum*. Aquaculture, 298: 294-299. doi: 10.1016/j.aquaculture.2009.11.003

Sampath, W.W.H.A., Rathnayake, R.M.D.S., Yang, M., Zhang, W. & Mai, K. 2020. Roles of dietary taurine in fish nutrition. Marine Life Science & Technology, 2: 360-375. doi:10.1007/s42995-020-00051-1

Sarih, S., Djellata, A., Roo, J., Hernández-Cruz, C.M., Fontanillas, R., Rosenlund, G., et al. 2019. Effects of increased protein, histidine and taurine dietary levels on egg quality of greater amberjack (*Seriola dumerili*, Risso, 1810). Aquaculture, 499: 72-79. doi: 10.1016/j.aquaculture.2018.09.011

Satriyo, T.B., Galaviz, M.A., Salze, G. & López, L.M. 2017. Assessment of dietary taurine essentiality on the physiological state of juvenile *Totoaba macdonaldi*. Aquaculture Research, 48: 5677-5689. doi: 10.1111/are.13391

Schuller-Levis, G.B. & Park, E. 2003. Taurine: new implications for an old amino acid. FEMS Microbiology Letters, 226: 195-202. doi: 10.1016/S0378-1097(03)00611-6

Stockham, S.L. & Scott, M.A. 2013. Fundamentals of veterinary clinical pathology. John Wiley & Sons, New Jersey.

Takagi, S., Murata, H., Goto, T., Endo, M., Yamashita, H. & Ukawa, M. 2008. Taurine is an essential nutrient for yellowtail *Seriola quinqueradiata* fed non-fish meal diets based on soy protein concentrate. Aquaculture, 280: 198-205. doi: 10.1016/j.aquaculture.2008.05.012

Takagi, S., Murata, H., Goto, T., Ichiki, T., Endo, M., Hatate, H., et al. 2006. Efficacy of taurine supplementation for preventing green liver syndrome and improving growth performance in yearling red sea bream *Pagrus major* fed low-fishmeal diet. Fisheries Science, 72: 1191-1199. doi: 10.1111/j.1444-2906.2006.01276.x

Thirupathi, A., Pinho, R.A., Baker, J.S., István, B. & Gu, Y. 2020. Taurine reverses oxidative damages and restores the muscle function in overuse of exercised muscle. Frontiers in Physiology, 11: 582449.

Tian, Q., Hu, Y., Mao, P., Xie, J., Fang, B. & Peng, H. 2016. Effect of dietary taurine supplementation on growth, intestine structure, and resistance to acute crowding stress in juvenile black carp (*Mylopharyngodon piceus*) fed low fish meal diets. Journal of Fisheries of China, 40: 1330-1339.

Tong, S., Wang, L., Kalhoro, H., Volatiana, J.A. & Shao, Q. 2020. Effects of supplementing taurine in all-plant protein diets on growth performance, serum parameters, and cholesterol 7α-hydroxylase gene expression in black sea bream, *Acanthopagrus schlegelii*. Journal of the World Aquaculture Society, 51: 990-1001. doi: 10.1111/jwas.12611

Valente, L.M.P., Linares, F., Villanueva, J.L.R., Silva, J.M.G., Espe, M., Escórcio, C., et al. 2011. Dietary protein source or energy levels have no major impact on growth performance, nutrient utilization, or flesh fatty acids composition of market-sized *Senegalese sole*. Aquaculture, 318: 128-137. doi: 10.1016/j.aquaculture.2011.05.026

Wen, C., Guo, Q., Wang, W., Duan, Y., Zhang, L., Li, J., et al. 2020. Taurine alleviates intestinal injury by mediating tight junction barriers in diquat-challenged piglet models. Frontiers in Physiology, 11: 449. doi: 10.3389/fphys.2020.00449

Wijerath-Wiriduge, H.A.S., Zhang, Y., Liu, J., Yang, M., Zhang, W. & Mai, K. 2020. Dietary taurine improves muscle growth and texture characteristics in juvenile turbot (*Scophthalmus maximus*). Aquaculture Reports, 17: 100305. doi: 10.1016/j.aqrep.2020.100305

Yatabe, Y., Miyakawa, S., Ohmori, H., Mishima, H. & Adachi, T. 2009. Effects of taurine administration on exercise. Advances in Experimental Medicine and Biology, 643: 245-252. doi: 10.1007/978-0-387-75681-3_25

Yokoyama, M., Takeuchi, T., Park, G.S. & Nakazoe, J. 2001. Hepatic cysteinesulphinate decarboxylase acti-

vity in fish. Aquaculture Research, 32: 216-220. doi: 10.1046/j.1355-557x.2001.00017.x

Zheng, Y., Liu, J., Xu, J., Fan, H., Wang, Y., Zhuang, P., et al. 2023. Comparison of artificial feed and natural food by the growth and blood biochemistry in Chinese sturgeon *Acipenser sinensis*. Fishes, 8: 1. doi: 10.3390/fishes8010045

Zhou, Q.-C., Tan, B.-P., Mai, K.-S. & Liu, Y.-J. 2004. Apparent digestibility of selected feed ingredients for juvenile cobia *Rachycentron canadum*. Aquaculture, 241: 441-451. doi: 10.1016/j. aquaculture.2004.08.044

Received: January 10, 2024; Accepted: March 7, 2024