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Modeling of waste outputs in the aquatic environment from a commercial cage farm under neotropical climate conditions

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ABSTRACT: The present study used a bioenergetics modeling approach to estimate the solid and dissolved waste outputs of a Nile tilapia *Oreochromis niloticus* net-cage farm. Historical production data for 30 cages were obtained from a commercial farm in the Chavantes Reservoir, São Paulo State, Brazil. In addition, an experiment was carried out in 4 net-cages at the farm to validate this dataset and collect fish samples. A total of 32 400 tilapias with an initial weight averaging 35 ± 2.73 g were equally distributed in the experimental net cages. After 210 d, the fish showed a final individual weight of ~789 ± 5.12 g. Fish growth performance was monitored, and body composition was analyzed each month. Digestibility trials of commercial diets used for juvenile stages JVI and JVII and market weight were performed. Relationships of body weight with body content data of water, protein, fat, ash, gross energy, phosphorus, and nitrogen were evaluated by regression analysis. The total digestible energy requirement and estimated residues of the fish were assessed using the factorial bioenergetics model, adapted to the growing conditions of a neotropical reservoir. The model estimated ~320 kg of total solid waste released per tonne of tilapia, including ~10 kg of solid nitrogen and ~5 kg of solid phosphorus. Approximately 3 and 47 kg of dissolved phosphorus and nitrogen, respectively, were estimated per tonne of tilapia. The bioenergetics model is a valuable and equitable method for assessing and monitoring waste outputs. It can improve the nutritional and environmental efficiency of aquaculture activities, helping producers to reduce feed costs while strengthening the environmental sustainability of aquaculture.

KEY WORDS: Aquaculture · Bioenergetics · Carrying capacity · Circular economy · Fish farm waste · Tilapia

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1. INTRODUCTION

Aquaculture production has increased steadily in recent years due to favorable climate, abundant water resources, low labor costs, and rising domestic demand (Garcia et al. 2013). Furthermore, aquaculture is considered a source of high-quality protein, especially in developing countries, where increased food production is necessary to ensure food security (FAO 2022). In 2018, Nile tilapia *Oreochromis niloticus* had a global

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production of ~4.20 million t, increasing ~14% from the previous year. Brazil is now the 4th-largest tilapia producer globally with an annual output of ~324 000 t; tilapia represents 61% of total Brazilian fish production (Valenti et al. 2021).

The steady growth of tilapia aquaculture has raised concerns regarding the release of feed and waste into surrounding aquatic environments. Montanhini-Neto & Ostrensky (2015) reported that the production of 1 t of tilapia releases approximately 1000 kg of organic matter, 45 kg of N, and 14 kg of P directly into the surrounding waters. Alves & Baccarin (2005) reported that only 23% of P input through feeding in intensive aquaculture operations is retained in the animal biomass, while 66% is retained in the bottom sediment and 11% in the water column. In this scenario, fish farming often requires an environmental license and water use allocation. Yet, environmental agencies in many countries still need to define the methodology for quantifying effluent loads from fish farming (Yi 1998, Glencross 2008, Bueno et al. 2015). The lack of adequate methods to determine residue outputs has led to complications for the aquaculture sector for obtaining environmental licenses, insurance, bank credits, and legal authorization to carry out the activity (Valenti et al. 2021). New approaches are being developed for sustainable aquaculture (Sampaio et al. 2021).

Bioenergetics mathematical models have effectively determined feed requirements and solid and dissolved waste outputs of commercial aquaculture activities (Cho & Bureau 1998, Lupatsch & Kissil 1998, Yi 1998, Bureau & Hua 2010, Hua & Bureau 2010, Azevedo et al. 2011, Jobling 2011, Csargo et al. 2012). Previous studies focused on fish species such as salmon and trout farmed in cold climates under different conditions. The present study evaluated solid and dissolved residues (particularly N and P) using a nutritional bioenergetics modeling approach adapted for aquaculture activities in neotropical regions. The analyses were carried out using commercial net-cage production of Nile tilapia *O. niloticus* in a neotropical reservoir in São Paulo, Brazil.

2. MATERIALS AND METHODS

2.1. Experimental site and data collection

Historical data on tilapia production was obtained from a commercial fish farm (23° 22' 47.5" S, 49° 35' 14.9" W), located in the oligotrophic Chavantes Reservoir, São Paulo State, Brazil. The Köppen climate classification of the region is humid subtropical (Cwa) (Köppen 1948), characterized as having rainy summers, dry winters, and an average temperature of >22°C during the hottest month.

Modeling was based on a historical data set corresponding to 30 net-cages for the total grow-out production performed in 3 phases (GIFT-lineage tilapia). The experimental design used to validate this dataset consisted of 4 net-cages for each growth phase. Initially, stage I juveniles (JVI; 35.0 ± 2.73 g; mean ± SD) were stocked at 50 kg m^{-3} in 16.2 m^3 net-cages (~8100 fish $cage^{-1}$). After obtaining an average individual weight of >100 g (40 d), the fish were restocked at 40 kg m^{-3} in net-cages with a volume of 43 m^3 (~2150 fish $cage^{-1}$). All net-cages were 2.5 m tall. The fish were harvested with an average weight of ~800 g. Fish growth consisted of 3 phases: JVI (30–100 g), juvenile II (JVII; 100–500 g), and market weight (MW; >500 g). Fish growth performance and body composition were evaluated monthly, and the digestibility of the commercial diets was assessed for each growth phase. The relationships between body weight and body content of water, protein, fat, ash, gross energy (GE), P, and N were determined using regression analysis. These relationships determined the bioenergetics factorial model adapted for Nile tilapia (*Oreochromis niloticus*) production in neotropical conditions.

2.2. Diet and feeding

During the experiment, commercial extruded diets contained 35.6, 32.1, and 34.7% crude protein (CP); 17.5, 17.4, and 17.3 MJ kg^{-1} GE; and 1.2, 1.0, and 1.0% total P for the JVI, JVII, and MW phases, respectively. Fish were fed 4 times daily every 3 h until apparent satiation. Each net cage's daily feed values were quantified and recorded.

The particle size of the feed for each phase was based on manufacturer guidelines, which were 4–6, 6–8, and 8–10 mm for the JVI, JVII, and MW phases, respectively. For the physio-chemical analysis of the diets for each culture phase, six 300 g samples of each diet were randomly collected from the batches and stored in labeled thermal bags at −10°C and subsequently compared with the values reported on the labels by the manufacturers.

2.3. Chemical analysis for estimating coefficients of equations for body composition

Fish performance was monitored throughout the culture by weighing individual fish each month, using

5% of the animals from each cage. All individuals were counted and weighed at the beginning of each culture phase, and 50 individuals from each cage (200 from each phase) were separated and euthanized to characterize the whole-body chemical composition. Fish were euthanized in 20 l containers with 50 mg l^{-1} of clove oil, according to Inoue et al. (2003). Animal handling procedures followed the World Society for the Protection of Animals (WSPA) recommendations. They were approved by the Ethics Committee on Animal Use (CEUA) of the Institute of Biological Sciences of the University of Brasilia (UnB; protocol no. 52708/2013).

Feed and whole fish samples were prepared, processed, and analyzed at the Advanced Analysis Laboratory and Biotechnology of the Federal University of Lavras (UFLA). Samples from the commercial diets were collected in triplicate and stored until further chemical analysis. Feed was oven-dried at 55°C, ground, and stored at −20°C. Whole-body fish samples of ~1.5 kg were obtained in triplicate, placed in thermal bags, and autoclaved at 121°C with a pressure of 1 kgf cm^{-3} for 90 min. Then, 0.6 ml of antioxidant (Etoxiquin®) was added to each bag to prevent nutrient degradation and deterioration. Whole-body samples were then homogenized in a food processor and frozen for 48 h at −90°C (AOAC 2000).

The proximate composition was carried out according to AOAC (2000) to determine dry matter content (DM). The Kjeldahl method determined N and CP contents with a Kjeltech 1030 auto analyzer (Tecator), where %CP = %N × 6.25. Lipid content was determined through acid hydrolysis, and ash content was obtained after incineration at 550°C (AOAC 2000). Total P content was analyzed using the colorimetric method (Mori & Nakamura 1959), while nitrogen-free extract (NFE) was calculated according to the formula NFE = DM – CP – lipids – ash. GE content was measured using bomb calorimetry (Parr Instruments). Samples with coefficients of variation >5% among the replicates were reanalyzed.

Relationships between live body weight (g $fish^{-1}$) and nutrient content (water, CP, total N, lipids, ash, P, and GE; g $fish^{-1}$) were assessed using regression analysis to obtain coefficients for predicting body weight (Dumas et al. 2010).

2.4. Water quality

Water quality parameters were measured weekly *in situ* at a depth of 1.5 m at 11:00 h using a multiparameter YSI probe. The water parameters included were temperature (T, °C), pH, dissolved oxygen (mg l^{-1}), and oxygen saturation (mg l^{-1}). Transparency (m) of the water was measured with a Secchi disk. Water samples were collected each month with a Van Dorn bottle for subsequent analyses of P and total N (APHA 2005).

2.5. Application of thermal growth coefficient model for growth curve prediction

For the accurate simulation of Nile tilapia growth in commercial facilities in cage farms, data from the experimental net-cages and the historical dataset of the farm were used in the thermal growth coefficient (TGC) model of fish growth as proposed by Iwama & Tautz (1981) and Cho & Bureau (1998). The commercial data included all net-cages of the experiment's 3 growth phases, representing a complete production cycle.

Growth data were analyzed using the following TGC model, which included a fixed exponent of body weight ($1 - b = 0.3333$) and a non-fixed exponent (Eq. 1). Body weight exponents were determined according to the recommendations of Dumas et al. (2010).

$$\text{TGC} = \{[\text{FBW}^{(1-b)} - \text{IBW}^{(1-b)}] / \Sigma(T \times d)\} \times 100 \quad (1)$$

IBW and FBW are initial and final body weight (g $fish^{-1}$), respectively, and d is days of culture. FBW was calculated by reorganizing Eq. (1) for the respective TCG model (Eq. 2).

$$\text{FBW} = [\text{IBW}^{(1-b)} + (\text{TGC}/100) \times \Sigma(T \times d)^{1/(1-b)}] \quad (2)$$

The residual sum of squares (RSS) was used to evaluate the relative adjustment of the predicted average body weight (ABW) of the TGC model to the corresponding ABW values estimated by the producer. RSS was calculated across all ABW observations made for each of the 30 net-cages and their different production stages, with parameters of the best performing exponential for the TGC model subsequently calibrated according to observed culture conditions (e.g. T and body growth), as well as to each of the 3 production stages. The performance of the TGC model was compared using the RSS values to identify the best exponential of the TGC model, thereby allowing for the appropriate adjustment for the conditions of T and tilapia metabolism in each production phase in a neotropical reservoir (see Table 3).

2.6. Digestibility of commercial feed

The digestibility of commercial feeds used during the experimental grow-out was determined *in vivo* at the Aquaculture Technology Center of the Department of Agriculture of the Federal District, Brazil (SEAGRO, DF). Nile tilapia specimens used for the digestibility test (GIFT lineage) were provided by the farm.

Before the beginning of the experiment, the animals were given 15 d to adapt to the facilities and management and another 7 d to adjust to the experimental diets. Feed digestibility was determined using protocols adapted from the Fish Nutrition Research Laboratory, University of Guelph (Cho et al. 1982). A total of 270 individuals (JVI: 30 ± 5 g; JVII: 350 ± 12 g; and MW: 550 ± 22 g) were randomly (as per the Guelph collection system) distributed in 6 conical tanks of 200 l (JVI: 30 fish tank^{-1}; JVII: 10 fish tank^{-1}; and MW: 5 fish tank^{-1}). Fish were reared for 10 d, with T and dissolved oxygen maintained at 27 ± 0.8°C and 5.0 ± 1.60 mg l^{-1}, respectively, which were similar to the conditions of the Chavantes reservoir.

Based on methods described in Cho et al. (1982), the commercial feed was ground for incorporating chromium oxide (Cr_2O_3) as an inert indicator at a proportion of 1.0%, and then the feed was pelleted again. The fish were fed ad libitum 6 times daily. Feces were collected over 7 d, and a pooled sample was formed for each experimental unit and subsequently frozen until chemical composition analysis. Apparent digestibility coefficients (ADCs) were calculated according to Eq. (3) (Cho et al. 1982):

$$\mathrm{ADC} = 1 - (F/D \times D_i/F_i) \tag{3}$$

where D is the % nutrient in the diet (or kJ g^{-1} for GE), F is the % nutrient in the feces (or kJ g^{-1}), D_i indicates the Cr_2O_3 content (%) in the diet, and F_i is the Cr_2O_3 concentration (%) in the feces.

2.7. Energy requirement for tilapia production

Feed requirement of fish considering different growth curves for tilapia stages of production was determined by digestible energy requirement ($\mathrm{DE_{req}}$), which was estimated based on the recovered energy (RE), basal metabolism (HeE), heat incrementation of feeding (HiE), and urinary and branchial excretion (UE + ZE), according to Cho & Bureau (1998).

$$\mathrm{DE_{req}} = \mathrm{RE} + \mathrm{HeE} + \mathrm{HiE} + (\mathrm{UE} + \mathrm{ZE}) \tag{4}$$

RE was calculated as the difference in GE content of the whole body on Day X and Day Y (i.e. IBW and FBW, respectively). HeE (kJ fish^{-1}) was calculated as a function of metabolic body weight ($\mathrm{BW}^{0.8}$) and water temperature (T, °C) (Eq. 5):

$$\mathrm{HeE} = (a + bT) \times \mathrm{BW}^{0.8} \tag{5}$$

where a and b are coefficients that describe the relationship between T, $\mathrm{BW}^{0.8}$, and HeE (Cho & Bureau 1998, Dumas et al. 2010). HiE (kJ fish^{-1}) was estimated using 61 data points observed across 15 published studies in tilapia, as described in Chowdhury et al. (2013). Energy expended through urine (UE) and gills (ZE) was calculated as 24.9 × (UN + ZN) kJ fish^{-1}, where UN and ZN are nitrogen lost through urinary and gill excretions, respectively, as described in Kaushik (1998). The values used for (UN + ZN) were obtained from Chowdhury et al. (2013), who obtained these values for tilapia.

2.8. Waste release from commercial tilapia production

Waste output loading from aquaculture operations was estimated using simple principles of nutrition and bioenergetics (Cho & Bureau 1998, Jobling 2011) that consider that ingested feedstuffs must be digested prior to utilization by the fish, and the digested protein, lipid, and carbohydrate are the potentially available energy and nutrients needed by the animal for maintenance, growth, and reproduction. The remainder of the feed (undigested) is excreted in the feces as solid waste (SW), and the byproducts of metabolism (ammonia, urea, phosphate, carbon dioxide, etc.) are excreted as dissolved waste (DW, g) mostly by the gills and kidneys.

Total aquaculture waste (TW, g) associated with feeding and production was made up of SW and DW, together with apparent feed waste (AFW, g):

$$\mathrm{TW} = \mathrm{SW} + \mathrm{DW} + \mathrm{AFW} \tag{6}$$

The SW output was estimated according to Eq. (7):

$$\mathrm{SW} = \mathrm{DM_{ingested}} \times (1 - \mathrm{ADC}) \tag{7}$$

where ADC is the value applicable for DM. SW of N and P were calculated similarly.

DW was estimated according to Eq. (8):

$$DW = (DM_{ingested} \times ADC) - \text{Nutrients retained} \quad (8)$$

Dissolved N and P wastes were calculated similarly, as the difference between the amount digested by the animal and that which is retained in the body.

The following equation quantified AFW:

$$AFW = \text{Actual feed input} - TFR \quad (9)$$

where TFR is the theoretical feed requirement. AFW was estimated based on the DE_{req} and expected weight gain (Section 2.5) for each phase of culture/weight of tilapia (JVI, JVII, MW) considering the production conditions in this cage culture system. Thus, TFR was calculated based on the nutritional energy balance as follows:

$$TFR = \text{Retained} + \text{Released} \quad (10)$$

The amount of feed input above the TFR should be assumed to be AFW, and all nutrient contents of the AFW must be included in the SW quantification. This allowed the calculating of the waste output from commercial tilapia production in net-cages simulated for different weight categories during a production cycle.

Total solid waste (TSW) generated from excess feeding (wastage rate), above apparent satiation, was estimated using additional simulations, assuming that 5 and 10% of feed inputs were wasted during feeding. The DM content of the feed at the assumed rates was added to TSW expressed in terms of kg t^{-1} of fish produced.

2.9. Statistical analyses

Water-quality parameters were tested for normality (Shapiro-Wilk) and homoscedasticity (Levene). As both conditions were met, data were subjected to a 1-way ANOVA (*F*-test). When significant differences were detected among treatments, means were compared using the post hoc Tukey test. All statistical analyses were carried out with SAS 9.3 (SAS Institute 1997), and the significance level considered was $\alpha = 0.05$.

3. RESULTS

3.1. Environmental conditions in the commercial tilapia fish farm

T fluctuated between 22 and 29°C and showed an average of 26°C, with significant differences ($p < 0.05$) shown in austral autumn (May and June, Table 1). Mean transparency and electrical conductivity values were 3.5 m and 36.5 µS cm^{-1}, respectively, after 210 d of culture. pH varied between 6.5 and 8.2, and dissolved oxygen ranged from 8.3 to 9.2 mg l^{-1}. Total N and P in the water near the net-cages decreased from 0.06 to 0.02 mg l^{-1} and from 0.06 to 0.03 mg l^{-1}, respectively ($p > 0.05$).

3.2. Feeding and growth performance

The diets for phases JVI, JVII, and MW showed ~32, 29, and 29% of digestible protein; ~15, 14, and 13 MJ kg^{-1} of digestible energy; and 0.85, 0.67, and 0.62% of digestible P, and 37.8, 39.9, and 40.3 of nitrogen-free extract (NFE), respectively (Fig. 1).

Table 1. Mean (±SD) values of water variables from a commercial fish farm in a neotropical reservoir during the experiment. WT: water temperature (°C); AT: air temperature (°C); EC: electrical conductivity (µS cm^{-1}); SA: salinity (µS cm^{-1}); DO: dissolved oxygen (mg l^{-1}); TR: transparency (m); TN: total nitrogen (mg l^{-1}); TP: total phosphorus (mg l^{-1}). Different superscript letters in the same row indicate significant differences (Tukey's test, $p < 0.05$)

Variable	Dec	Jan	Feb	Mar	Apr	May	Jun
WT	26.0 ± 0.05^{a}	28.3 ± 0.08^{a}	29.0 ± 0.08^{a}	26.6 ± 0.00^{a}	25.6 ± 0.05^{a}	22.8 ± 0.02^{b}	21.6 ± 0.3^{b}
AT	27.7 ± 0.14^{a}	32.5 ± 0.01^{c}	36.6 ± 0.00^{c}	29.8 ± 0.00^{a}	28.5 ± 0.02^{a}	26.1 ± 0.01^{b}	25.4 ± 0.01^{b}
pH	7.4 ± 0.23^{a}	7.2 ± 0.12^{a}	7.8 ± 0.19^{a}	6.5 ± 0.08^{a}	6.9 ± 0.10^{a}	8.2 ± 0.21^{a}	7.6 ± 0.10^{a}
EC	46.1 ± 1.44^{a}	38.3 ± 2.53^{a}	50.0 ± 0.95^{a}	44.2 ± 1.50^{a}	51.0 ± 2.12^{a}	35.1 ± 1.12^{a}	35.0 ± 1.0^{a}
SA	0.02 ± 3.12^{a}	0.07 ± 2.75^{a}	0.02 ± 1.88^{a}	0.04 ± 1.15^{a}	0.02 ± 1.45^{a}	0.02 ± 1.45^{a}	0.02 ± 2.17^{a}
DO	9.0 ± 0.67^{a}	9.0 ± 0.88^{a}	8.5 ± 0.10^{a}	8.3 ± 0.51^{a}	8.4 ± 0.49^{a}	9.1 ± 0.83^{a}	9.2 ± 0.17^{a}
TR	3.8 ± 0.25^{a}	3.5 ± 0.02^{a}	4.0 ± 0.01^{a}	2.8 ± 0.00^{a}	3.1 ± 0.02^{a}	3.5 ± 0.01^{a}	4.0 ± 0.01^{a}
TN	0.06 ± 4.60^{b}	0.05 ± 6.74^{b}	0.03 ± 3.89^{a}	0.01 ± 4.80^{a}	0.01 ± 6.10^{a}	0.03 ± 5.75^{a}	0.02 ± 7.10^{a}
TP	0.06 ± 13.10^{b}	0.07 ± 14.12^{b}	0.05 ± 8.11^{a}	0.01 ± 7.41^{a}	0.02 ± 6.56^{a}	0.04 ± 9.01^{a}	0.03 ± 8.80^{a}

The performance parameters for JVI, JVII, and MW observed during the production cycle are shown in Table 2.

3.3. Body composition and growth curve prediction

The coefficients (±SD) obtained for predicting body composition were as follows: protein: 0.148 (±0.343) × BW, $r^2 = 0.93$; lipid: 0.086 (±0.253) × BW, $r^2 = 0.94$; ash: 0.043 (±0.153) × BW, $r^2 = 0.91$; GE: 6.128 (±8.593) × BW, $r^2 = 0.99$; and P: 0.005 (±0.015) × BW, $r^2 = 0.95$.

The exponential values of TGC and the calibration of the exponentials (revised TGC model, Eq. 1) for the JVI, JVII, and MW stages were efficient and showed a reduction in RSS from 88, 1554, and 1039 to 12, 25, and 45, respectively (Table 3). Using the revised TGC model, a TGC exponent of 0.6512 for JVI, 0.4811 for JVII, and 1.000 for MW provided the highest accuracy for the fish body growth curve of *Oreochromis niloticus* reared in neotropical conditions.

3.4. Bioenergetics model

The applied bioenergetics model (Table 4) allowed for the estimation of energy requirements of HeE (0.66 to 3.64 MJ kg^{-1}), HiE (3.05 to 4.40 MJ kg^{-1}), branchial and urinary losses (UE + ZE = 0.57 to 0.82 MJ kg^{-1}), total DE_{req} (10.41 to 14.98 MJ kg^{-1}), RE (6.13 MJ kg^{-1}), and average expectations for feed efficiency (FE) and feed conversion ratio (FCR) for body weights observed in the net-cage production of tilapia in neotropical conditions (Table 4).

3.5. Waste output estimation in the aquatic ecosystem

Feeding rates observed during the experimental grow-out in cages corresponded to rates predicted using the bioenergetics model, including those that assumed feed losses of 5 and 10% and rates described in a commercial feeding table that is commonly used by Brazilian tilapia farmers (Figs. 2 & 3). The model estimated ~283 kg of SW released t^{-1} of tilapia, including ~9.8 kg of solid N and ~5.1 kg of solid P. Approximately 2.9 and 44.8 kg of dissolved P and N t^{-1} of tilapia were also estimated (Fig. 2), and estimates of feed requirements of tilapia showed an average difference of 14% compared to corresponding feeding rates suggested in the commercial feeding table (Fig. 3).

4. DISCUSSION

The bioenergetic model approach used in the present study regarding waste released into the aquatic environment from tilapia cage farms can be used to predict the potential environmental impact that similar enterprises may have on lakes and reservoirs. Adequate use of reliable information from the various

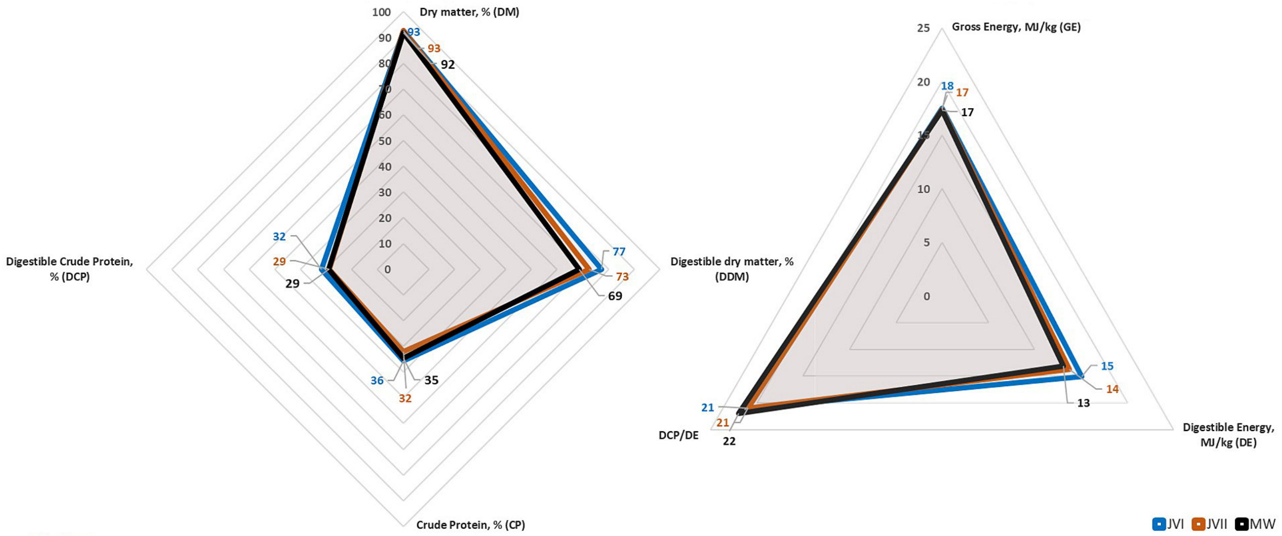

Fig. 1. Chemical composition (left) and nutrient digestibility (right) of commercial diets used during the 3 production stages of the growth trial (juvenile I [JVI]: 30–100 g, juvenile II [JVII]: 100–500 g, and market weight [MW]: >500 g) of a tilapia commercial fish farm in a neotropical reservoir. DCP/DE: relationship between protein and digestible energy

Table 2. Performance parameters (mean ± SD) of tilapia in net-cages at a commercial fish farm in a neotropical reservoir for juvenile I (JVI), juvenile II (JVII), and market weight (MW) during the production cycle. IBW: initial body weight; FBW: final body weight; DWG: daily weight gain; MO: mortality; FB: final biomass; FCR: feed conversion ratio; FE: feed efficiency; PER: protein efficiency ratio

Parameter	JVI	JVII	MW
IBW (g)	35 ± 2.73	135 ± 1.83	480 ± 2.11
FBW (g)	135 ± 4.05	1.6 ± 3.12	480 ± 2.66
DWG (g fish^{-1} d^{-1})	3.0 ± 5.78	789 ± 5.12	5.0 ± 2.12
MO (%)	4.0 ± 10.14	2.1 ± 6.54	1.0 ± 4.10
FB (kg m^{-3})	37 ± 9.77	79 ± 5.13	90 ± 3.12
FCR (feed:weight gain)	1.4 ± 0.89	1.8 ± 1.00	1.9 ± 1.20
FE (weight gain:feed)	0.8 ± 0.89	2.4 ± 1.11	0.6 ± 1.00
PER	2.2 ± 2.56	0.5 ± 1.20	1.9 ± 1.73

Table 3. Coefficients and residual sum of squares (RSS) model for thermal growth coefficient (TGC) adjusted to *Oreochromis niloticus* produced in net-cages in a neotropical reservoir for juvenile I (JVI), juvenile II (JVII), and market weight (MW)

Growth phase	Body weight category (g)	TGC coefficients	Revised TGC	Revised TGC exponent
JVI	35–135	0.12	0.90	0.6512
RSS	–	88	12	–
JVII	135–480	0.09	0.28	0.4811
RSS	–	1554	25	–
MW	480–789	0.10	22.82	1.0000
RSS	–	1039	45	–

forms of monitoring of environmental parameters can dictate the overall sustainability and expansion or constraint of the aquaculture sector, particularly in Asian and South American countries, which are mainly responsible for global tilapia production (FAO 2022). Across these continents, managers and producers are striving to adopt tools, technologies, and methods that can aid in monitoring and managing. This promotes responsible resource management and the need to reduce negative environmental impacts.

Environmental conditions in the Chavantes reservoir were considered suitable for farming neotropical fish (Garcia et al. 2013). T is an essential aspect of monitoring in fish farming. An increase in T can influence growth rates and feed intake of fish (Houlihan et al. 2001) and consequently affect waste release (Bueno et al. 2019). During the production cycle, T ranged from 21 to 29°C, approaching the appropriate limits for thermal comfort of tropical fish (26–30°C), according to Boyd & Tucker (1998).

The results for the chemical composition of the commercial diets were similar to values previously described for commercial tilapia feeds manufactured in Brazil (Mondriani-Neto & Ostrensky 2014). However, the digestibility differs from different commercial feeds despite the similar feed composition values. Low digestibility can interfere with water quality through the waste that accumulates in the environment of fish farms in reservoirs. The poor quality of aquafeeds is

Table 4. Energy, oxygen requirements, and expected feed conversion ratio (FCR, feed:gain) of Nile tilapia in net-cage in a neotropical reservoir. IF: ingested feed; DEF: digestible energy feed (from the feed in each respective fish growth phase); DE_{req}: digestible energy requirement (see Eq. 4); HeE: basal metabolism ($HeE = (30.33 - 2.37 \times T) \times BW^{0.8}$); HiE: heat increment of feeding ($HiE = 0.45 \times (RE + HeE)$); UE + ZE: urinary and branchial excretion ($UE + ZE = 0.0576 \times (RE + HeE + HiE)$); RE: recovered energy, calculated as the difference in GE content of the whole body on final body weight and initial body weight; EFE: expected feed efficiency; RO: required oxygen (RO = HeE + HiE/ oxycalorific coefficient (13.6 kJ g^{-1} O_2 consumed)); $BW^{0.8}$: metabolic body weight; T: temperature

Growth phase (g fish^{-1})	36	80	140	238	353	475	581	738	900
Growth (g^{-1} fish^{-1} d^{-1})	1.32	1.47	2.00	3.27	3.83	4.07	3.53	5.23	5.40
IF (% weight)	5.70	4.00	3.70	3.20	2.50	1.60	1.80	1.60	1.40
DEF (MJ kg^{-1})	15.12	15.00	14.12	14.00	14.10	13.70	13.50	13.30	13.10
DE_{req} (MJ kg^{-1} for fish)	10.41	12.25	11.98	13.48	14.72	14.65	13.52	14.26	14.98
HeE (MJ kg^{-1})	0.66	1.86	1.69	2.66	3.47	3.43	2.69	3.17	3.64
HiE (MJ kg^{-1})	3.05	3.60	3.52	3.95	4.32	4.30	3.97	4.19	4.40
UE + ZE (MJ kg^{-1})	0.57	0.67	0.65	0.73	0.80	0.80	0.74	0.78	0.82
RE (kJ fish^{-1})	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13
EFE	1.46	1.24	1.26	1.02	0.93	0.94	1.01	0.92	0.87
Expected FCR	0.69	0.81	0.79	0.98	1.07	1.07	0.99	1.09	1.14
RO (g kg^{-1} weight gain)	273	401	482	486	563	578	589	641	791

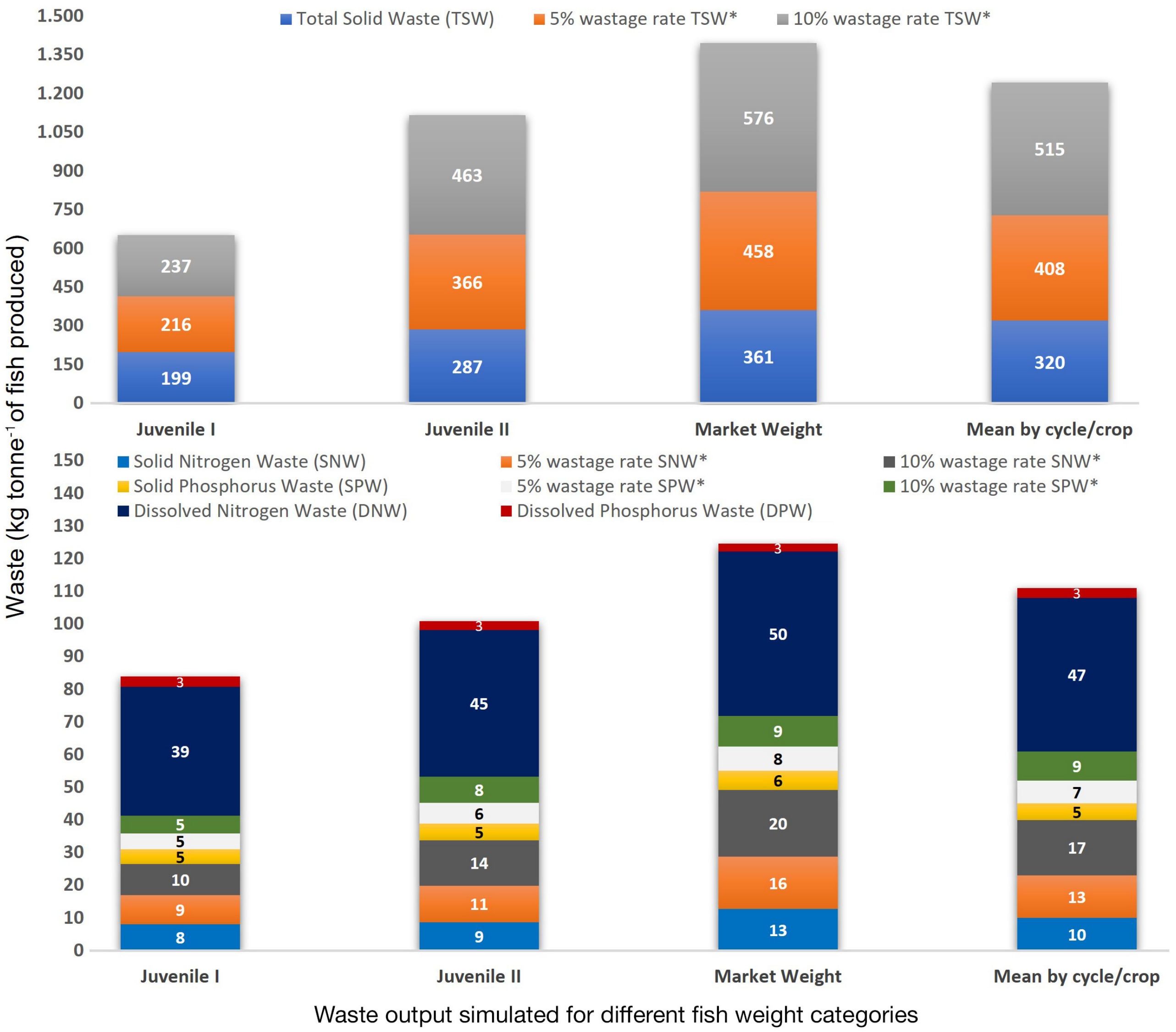

Fig. 2. Estimation of waste outputs (top: total waste; bottom: nitrogen and phosphorus waste) in the aquatic environment from *Oreochromis niloticus* commercial production in net-cages simulated for different weight categories during a production cycle under neotropical conditions. *Total wastes generated from excess feeding (wastage rate), above apparent satiation, were estimated using additional simulations, assuming that 5 and 10% of feed inputs were lost or wasted during feeding. Cycle/crop: obtained based on a 210 d cycle, with an individual average weight of 1 kg at harvest

one of the main factors that generates phosphorus and nitrogen wastes (Fialho et al. 2021). According to the NRC (2011), fish diets with high levels of protein (28–50%) and energy lead to increased concentrations of nitrogen catabolites in water. The variation of feed composition and digestibility percentages reinforces the need for public policies for feed industries to present the ingredients' digestibility levels on the product labels. This would help when choosing aquafeeds with less polluting potential.

Differences were shown between nutritional compositions of commercial feeds reported by manufacturers and those determined through laboratory analyses. The manufacturer-provided values of the commercial feed used in the present study were 32% CP, 92% DM, 6% fat, 13% ash, 17.50 MJ kg^{-1} GE, and 1.5% P, while the same feed analyzed using proximate analysis obtained different results (Fig. 1, market weight commercial diet). Thus, more attention should be given to nutrient composition analyses of commercial feeds used in experimental conditions, as well as improving the access for producers, industry stakeholders, researchers, and legislative bodies to updated and reliable information regarding the nutritional composition of feeds (Gule & Geremew 2022).

Cho & Bureau (2001) suggested that fish with dif-

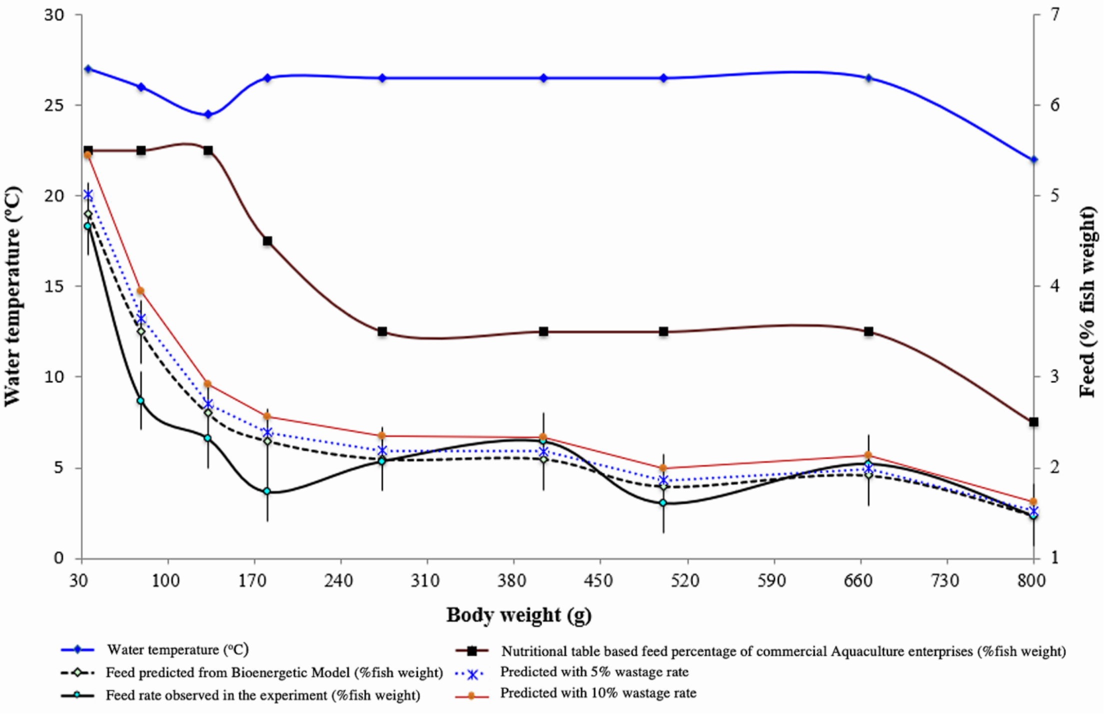

Fig. 3. Feeding rate predicted by the bioenergetics model and calculated by commercial feeding tables, considering feed losses of 5 and 10% (wastage rate) to the aquatic environment

ferent growth rates will vary in their absorption of nutrients, resulting in distinct requirements of total energy and feed. As such, energy requirements must be calculated according to expected growth rates, performance, feed composition, and life stage, among other factors (Bueno et al. 2017). Consequently, using each species' DE_{req} allows more dynamic and precise quantification of the release of SW for different scenarios (Cho & Bureau 1998, Azevedo et al. 2011). DE_{req} is not considered in waste estimation and environmental impact assessment of aquaculture in Asia and South American environmental agencies and several other countries, where there is no defined methodology to quantify the effluent loads from fish farming (Yi 1998, Glencross 2008, Bueno et al. 2015). Montanhini-Neto & Ostrensky (2015) and Fialho et al. (2021) assessed the waste output and environmental impact of tilapia farming in similar conditions to those in the present study. However, the methodologies used by these authors to evaluate waste from aquaculture operations have limitations. They do not consider several factors directly related to the waste release into the aquatic environment. For example, the effect of water temperature that alters feed intake and fish excretion. Therefore, models for intensive farming conditions have been developed using a limited array of empirical data, and some components of these models may have very low predictability (Chowdhury et al. 2013). This indicates that the aquaculture industry and institutions can use the bioenergetics model as an efficient and applicable solution for environmental inspection and monitoring activity in continental water resources.

The DE_{req} obtained was ~10.5, 12.0, and 15.0 MJ kg^{-1} for phases JVI, JVII, and MW, respectively, and the energy required for HiE by tilapia is similar to the retained energy, about 50% (JVI and JVII) and 70% for MW, consuming about a third of the total digestible energy intake. Chowdhury et al. (2013) also verified similar values for this species. Although tilapia exhibits a consistent pattern of DE_{req} in relation to energy demand influencing fish biomass, Trung et al. (2011) point out that for other fish species, particularly carnivores, there is a difference in HiE depending on the growth potential. Xie et al. (1997) also reported this fact when studying the protein and energy requirements for tilapia using a bioenergetics factorial modeling approach. The present study verified that the energy needs of tilapia for the growth curve in neotropical conditions directly influence the FCR, which was 20% higher than in the JVI phase, and decreased feed efficiency (0.8 to 0.5 weight gain:feed), which consequently generated a more significant release of waste for the aquatic environment. These indicators must be evaluated with a view to more sustainable production practices.

The leading indicators of aquaculture enterprise environmental sustainability are feed inclusion and digestibility of P and N and the excretion of these elements into the aquatic environment (Hua & Bureau (2010), David et al. 2017, Bohnes & Laurent 2020). When evaluating these indicators in the present study, it was found that the levels of digestible P in the feeds were 0.85, 0.72, and 0.63% for the JVI, JVII, and MW phases, respectively, which met the suggested requirements of 0.80–1.1% for tilapia farming (Miranda et al. 2000, Furuya et al. 2008, Furuya 2010). Digestible protein levels were ~32, 29, and 29% for the JVI, JVII, and MW phases, respectively. In tropical and neotropical regions, these nutrients increase their potential for polluting action (Sampaio et al. 2021). The difference in phosphate waste excretion using P levels above 0.8% total P in aquafeeds and hot temperatures above 28°C can increase fish SW excretion by ~40% (Bueno et al. 2019, te Velde et al. 2022). Thus, the regulatory bodies and managers responsible for this economic activity must determine maximum levels of P and N inclusion in commercial feeds without compromising the species' nutritional requirements and maintaining acceptable marketing costs. However, this is a challenge for the aquaculture industry when aiming to incorporate responsible practices of cleaner production.

The release of phosphate and nitrogen can directly affect the environmental carrying capacity of aquatic environments for fish production and compromise the aquaculture business' economic viability and sustainability (Ferreira et al. 2013, Ross et al. 2013, Weitzman & Filgueira 2020). These residues commonly come from animal metabolic wastes and leftover aquafeeds not consumed during aquaculture operations (Azevedo et al. 2011, Montanhini-Neto & Ostrensky 2015). Penczak et al. (1982) demonstrated that only 32% of P is used for fish metabolism while the remaining 68% is excreted into surrounding waters. This was also evident in the current study when each production phase (JVI, JVII, and MK) was separately evaluated in 210 d of cultivation, considering the amount of waste produced per tonne of fish. A difference was observed in TSW from 199 to ~361 kg t^{-1} fish produced, where the mean by-cycle production was 320 kg of TSW, 10 kg of solid N, 5 kg of solid P, with 47 and 3 kg of dissolved N and P, respectively for kg t^{-1} fish produced (Fig. 2). Montanhini-Neto & Ostrensky (2015) estimated potential waste loads of commercial tilapia farming to be 1040.63 kg of organic matter, 44.95 kg of N, and 14.26 kg of P t^{-1} of fish produced. These waste loads represent 78, 65, and 72% of the quantities provided in the feed. Values in this study were closed to those reported in Chowdhury et al. (2013) for tilapia using the varying dietary protein levels (40, 38, and 35%). They demonstrated an increase in the excretion of P from 4.2 to 5.0 kg t^{-1} with decreasing protein levels and a decrease in N excretion levels from 46.2 to 40.9 kg t^{-1} of tilapia. This indicates the importance of adjusting the fish's nutritional needs with the feed provided, as feed supply and consumption will affect the waste release and, consequently, the potential environmental impact on the aquatic environment.

Currently, several environmental licenses and authorizations for fish production in lakes and reservoirs are based on the values of P or N released into the environment without considering specific characteristics related to the size of the enterprise and other factors related to aquaculture operations. This could be over- or under-estimating the true impact of fish farms. Hatchery production has a different environmental impact than fish farms (Csargo et al. 2012). The environmental impact will differ if one considers the differences between species, genetics, nutritional quality, and management, among other factors not considered in several studies that estimate the animal waste release and determine the aquatic environment's environmental carrying capacity. Therefore, this highlights the need for waste management support programs to efficiently analyze the application of more sustainable production practices and assess environmental carrying capacity studies for installing and monitoring aquaculture enterprises (Weitzman & Filgueira 2020, Sampaio et al. 2021, te Velde et al. 2022).

The use of the bioenergetics model to estimate feed requirements of tilapia showed an average difference of 14% compared to corresponding feeding rates suggested by commercial feeding tables (Fig. 3). The scenario simulated through the bioenergetics model, in which 10% feed loss was assumed during feeding, was close to predicting the total feed consumption observed at the farm. The waste (i.e. uneaten feed) rates in this scenario were similar to those observed by Yi (1998), Azevedo et al. (2011), and Montanhini-Neto & Ostrensky (2014) for commercial farming activities. In mathematical models of waste prediction, accurate prediction of the chemical composition of a fish commercially grown for a specified body weight improves feed efficiency, reduces feed wastes globally (Bureau & Hua 2010), and consequently increases the activity's profitability. Therefore, this work emphasizes the urgency of applying more precise techniques to determine feeding rates based on the different requirements of each life stage, and climatic influences, among other variations.

Brazil has the potential to become the 2nd-largest producer of aquatic protein in the world if 10% of the available area in artificial dams, water reservoirs, and coastline were to be used by aquaculture (Valenti et al. 2021). It can become one of the leading world protagonists in ending hunger and a place of great opportunities for investors and entrepreneurs in this sector. Thus, this case study presents an approach for other tilapia-producing countries that aim for sustainable production, based on the general guidelines that meet the concepts of a circular economy, aligned with the objectives of sustainable development. The challenge for the tilapia industry is to develop sustainable and innovative systems that optimize production efficiency through innovations that produce non-negative changes in natural resource stocks and environmental quality.

5. CONCLUSIONS

The bioenergetics modeling approach estimated an average of 320 kg of TSW, 10 kg of solid N, 5 kg of solid P, 47 kg of dissolved N, and 3 kg of dissolved P per tonne of tilapia produced. The nutritional bioenergetics model is a practical and efficient tool to estimate and monitor waste outputs in aquaculture activities in neotropical regions. The tropical aquaculture industry and regulatory bodies can adopt the proposed method to improve the nutritional and environmental efficiency of aquaculture. The method allows for a reduction of feed waste and an improvement in the environmental sustainability of aquaculture.

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