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Effects of Poultry Co-Product Meal Replacing Fish Co-Product Meal on Integrated Zootechnical Performance (IZP) Indexes in Red Hybrid Tilapia (*Oreochromis* sp.): Application of Linear Programing Technique

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ABSTRACT

To minimize use of fish co-product meal (FCPM) in aquafeeds, we assessed the effect of full substitution of FCPM by poultry co-product meal (PCPM) in the juveniles (initial mean weight: 9.13 ± 3.88g) diet of red hybrid tilapia (RHT) (*Oreochromis* sp.) for 45 days. Two diets ($FCPM_{35}$-$PCPM_0$: diet without PCPM and $FCPM_0$-$PCPM_{35}$: diet without FCPM) were formulated using PCPM to replace FCPM protein at 100 % replacement level. After 45 days of exprement, growth performance (GP), nutrient utilization (NU) and integrated zootechnical performance (IZP) indexes of tilapia fed the diet with fishmeal ($FCPM_{35}$- $PCPM_0$) showed no significant differences ($P < 0.05$) compared to tilapia fed with 100% replacement of FCPM with PCPM ($FCPM_0$-$PCPM_{35}$). Additionally, $FCPM_0$- $PCPM_{35}$ diet induced the reproductive activity indexes (GSI: gonadosomatic index and HIS: hepatosomatic index) significantly better than $FCPM_{35}$- $PCPM_0$ diet (P<0.05) in fish. Moreover, the growth of RHT (*Oreochromis* sp.) is of negative allometric type (b=2.89 and R^2=0.94) for $FCPM_0$-$PCPM_{35}$ diet and positive allometric (b=3.10 and R^2=0.90) for $FCPM_{35}$-$PCPM_0$ diet. Furthermore, according to the GP, NU, GSI, HIS and IZP indexes, the PCPM is a good candidate to replace FCPM in diet for juveniles RHT (*Oreochromis* sp.). Finally, the combination of linear programing technique with GP, NU, GSI, HIS and IZP indexes is therefore a valuable tool that could be useful for sustainable aquaculture.

INTRODUCTION

Sustainable aquaculture (SA) is the practice that focuses on (1) environmental, (2) economic, and (3) social sustainability to improve capacity structure and exploit land effectively for the aquaculture sector **(Olaganathan & Kar Mun, 2017; Padhan, 2021)**. It could be the key feature of food security by feeding (nutritious) our growing population **(Osmundsen *et al*., 2020; Shepon *et al*., 2021; Bohnes *et al*., 2022)**. Besides, the cost of feed represents a significant part of the charge of production (over 50 %), which limits the economic value of aquaculture **(Guillaume *et al*., 1999; Djissou *et al*., 2017)**.

Fishmeal (FM) is the key ingredient that contributes to the charge of aquafeeds, which is used as the major source of protein in aquafeeds owed to its substantial protein content and high profile of amino acid, as well as its high digestibility and deficiency of ANFs **(Barlow, 2003; Bamba *et al*., 2008; Jackson & Shepherd, 2010)**. FM is also a great source of EFAs, digestible energy, micronutrients (minerals and vitamins) which meet the nutritional requirements of fish **(Guillaume *et al*., 1999; Barlow, 2003)**. Besides, fishmeal is the most costly ingredient in aquafeeds, which ultimately increases feed cost **(Fan *et al*., 2022)**. It will be necessary to minimize the quantity of dietary feedstuff (fish meal) added to aquafeed in order to optimize the diet.

Moreover, among suitable animal protein sources for farmed aquatic animal species (fish and crustaceans), PCPM derived from chicken hatchery seem to be good substitutes of expensive protein sources such as fish meal **(Irm *et al*., 2020; Marzouk *et al*., 2024)**. Additionally, PCPM is considered an essential ingredient feed for fish and other farm animals for the reason that of its low cost, high composition of nutrients and protein content (about 55-60 % of crude protein) **(Yones & Metwalli, 2015; Irm *et al*., 2020)**.It contains indispensable amino acids, healthy fats (MUFAs : C18:1 n-9), essential vitamins (A and B12) and minerals (calcium and phosphorus) for fish growth and production **(Pesti *et al*., 1986; Jafari *et al*., 2011; Yones & Metwalli, 2015; Irm *et al*., 2020; Dal Bosco *et al*., 2022)**. Furthermore, PCPM has been added into the diets of a number of freshwater species as a protein source including the NT (*Oreochromis niloticus*) **(Yones & Metwalli, 2016)** or marine fish species such as gilthead sea bream (GSB) (*Sparus aurata*) **(Hernández *et al*., 2014)** without any significant reduction in growth performance.

Tilapia is an important aquaculture species that is cultured in various world regions (Southeast Asia, Africa and Latin America) **(Dauda *et al*., 2018; Prabu, 2019; Sunarto *et al*., 2022; Syed *et al*., 2022; Chukwu *et al*., 2023)**. It is an omnivorous species with herbivorous tendency (relatively low dietary protein requirement ranges from 30-40 % for juveniles and 20-30 % for adult), well appreciated, with strong economic potential and good zootechnical performance **(Mensah *et al*., 2013; Djissou *et al*., 2017; Syed *et al*. 2022; Benfares *et al*., 2023)**.

Besides, a significant limitation of traditional zootechnical performance evaluation and nutrient utilization assessment in fish feed trials is their reliance on isolated or single parameters for example: the average daily growth (ADG), the viability and FCR (feed conversion ratio) index, among others. Additionally, nowadays, a few researchers assess the productivity for farmed specimens of animals using indexes, for example the EPEF (European production efficacy factor) for broilers **(Fuller, 2004)** and the production and management index for shrimps (PMI) **(Sonnenholzner *et al*., 2004)**. Moreover, to our best knowledge, no studies have been reported in literature which integrate the zootechnical performance (IZP) parameters (growth, viability, and feed conversion ratio) at one index.

The present study aimed to investigate the effect of full substitution of FCPM by PCPM on RHT (*Oreochromis* sp.) juveniles by using: (1) classical performance growth (final weight gain, daily gain and specific growth rate) and nutrient utilization (feed conversion ratio index and protein efficiency ratio), (2) reproductive activity indexes (GSI: gonadosomatic index and HIS: hepatosomatic index) and (3) integrated zootechnical performance (IZP) indexes.

MATERIALS AND METHODS

Formulation and manufacture of fish feed

Data sources for formulation

The feed formulation data collected for this work were sourced from scientific literature and excluded fish and poultry co-product meals. These co-product meals were prepared by the industry of sardine canning and poultry by-products, respectively **(Guillaume *et al*., 1999; Sauvant *et al*., 2004; CNRFS, 2011; Ghosh *et al*., 2011)**. The main sources for these data were based on: (1) ingredient (raw material) specification, (2) constrained imposed on the selected raw material and (3) the dietary nutrient requirements in juveniles of RHT (*Oreochromis* sp.). The proximate analysis of the meals was determined using the method described by **AOAC (2005)**.

Preparation of the fish and poultry by-product meals

Animals' by-products contained: (1) sardine offal, heads, and spine, moreover (2) chicken slaughter wastes including viscera, heads and legs, were supplied by the fish canning enterprise at Sétif-Algeria and locally poultry slaughterhouse.

Preparation of meals were carried out at the experimentation of feeds for farmed fish workshops at the National Centre for Research and Development of Fisheries and Aquaculture (NCRDFA), Bou-Ismaïl, Algeria. In brief, the transformation process of animal's by-products consists of (1) weighing, (2) cooking, (3) pressing, (4) drying and (5) grinding processes during which the oil and water are eliminated from the solid parts of the by-products. The obtained meals (FCPM and PBBM), with the yield of 23.09 and 23.83% for fish and poultry byproducts meals, respectively, were then packed in zip-lock plastic bags and temporarily stored in a fridge at -4°C before use. The biochemical compositions of the prepared meals (FCPM and PBBM) are presented in Table (1).

Table 1. Chemical composition of the meals prepared from sardine and poultry by-products.

Parameter	Fish meal	Poultry by-product meal
Crude protein	54.5 %	54.05 %
Fat	15.54 %	14.5 %
Calcium	9.74 %	1,80* %
Phosphorus	1.08 %	1.57* %
Carbohydrates	0.57 %	0.40* %
Moisture	10.00 %	11.20 %
Ash	26.98 %	10.65 %
Caloric value	338.17 Kcal/100g	607.00 Kcal/100g
Coast (DZA/Kg)	70.00	50.00

* (Data sources: **INRAE-CIRA-FEZ (2024)**).

Data analysis

In this paper, the linear programming (LP) technique was used for data analysis. The models were developed to reflect the percentages of inclusion, current market prices, chemical composition of nutrient, and different feedstuff combinations that were used in the conception (formulation). Microsoft Excel Solver (2013) was used to resolve LP problems by calculation of respective proportions of the ingredients chosen in the formulation.

***Developing an LP model for juvenile RHT* (*Oreochromis* sp.)**

According to **Guillaume *et al*. (1999),** the LP problem has the following form:

$$\text{Optimize: } C = \begin{bmatrix} c_i \\ c_2 \\ \vdots \\ c_n \end{bmatrix} \begin{bmatrix} x_j \\ x_2 \\ \vdots \\ x_n \end{bmatrix}; \begin{bmatrix} x_j \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \geq 0 \text{ ; Subject to } \begin{bmatrix} a_{ij}x_j & \cdots & a_{1n}x_n \\ a_{21}x_1 & \cdots & a_{2n}x_n \\ \vdots & \vdots & \vdots \\ a_{m1}x_1 & \cdots & a_{mn}x_n \end{bmatrix} \begin{matrix} \geq \\ \leq \\ \vdots \\ \geq \end{matrix} \begin{bmatrix} b_i \\ b_2 \\ \vdots \\ b_m \end{bmatrix}$$

$$\text{and } \sum_{j=1}^{n} X_j = 100.$$

Where, aij: coefficients of the component of nutrient, bi: nutritional requirement or maximum ranges (%) for nutrient intakes, and ci: ingredients cost (DZA/Kg)) are given constraints, and xj: ingredients quantities (%) are the decision variables. From the above format, we are seeking the values of the xj which will optimize (maximize or minimize) the objective function C (total cost of the ration (DZA/Kg)).

In this study, for the achievement of the objective's functions, the definite LP models were:

$$\text{Min C} = \begin{bmatrix} 51.50 \\ 620.00 \\ 70.00 \\ 58.90 \\ 50.00 \\ 0.350 \\ 73.00 \\ 50.00 \\ 200.0 \\ 2000 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \\ X_7 \\ X_8 \\ X_8 \\ X_{10} \end{bmatrix} \text{; were } \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \\ X_7 \\ X_8 \\ X_9 \\ X_{10} \end{bmatrix} = \begin{bmatrix} \text{Maize meal} \\ \text{Wheat gluten} \\ \text{Fish meal} \\ \text{Soyban cake meal} \\ \text{Polltry byproducts} \\ \text{Crude calcium} \\ \text{Dicalcium phosphate} \\ \text{Durum wheat} \\ \text{Sunflower oil} \\ \text{Vitamin Mineral Concentrate} \end{bmatrix}$$

$$\text{and } \sum_{j=1}^{n=9} X_j = 100.$$

Focused to the resulting constraints:

$$\begin{bmatrix} 9.00 & 19.10 & 54.50 & 42.50 & 0 & 0 & 0 & 15.60 & 0.00 \\ 3860 & 4530 & 6070 & 4150 & 0 & 0 & 0 & 3700 & 9000 \\ 1.90 & 4.60 & 14.50 & 1.80 & 0 & 0 & 0 & 6.50 & 100.00 \\ 0.77 & 1.80 & 0.32 & 0.85 & 0 & 0 & 0 & 0.00 & 0.00 \\ 2.20 & 6.80 & 1.30 & 7.40 & 0 & 0 & 0 & 10.00 & 0.00 \\ 1.60 & 0.30 & 10.65 & 6.00 & 0 & 0 & 0 & 4.40 & 0.00 \\ 0.37 & 6.80 & 2.32 & 1.27 & 0 & 0 & 0 & 0.62 & 0.00 \\ 0.25 & 6.00 & 2.64 & 2.70 & 0 & 0 & 0 & 0.65 & 0.00 \\ 0.01 & 1.30 & 2.09 & 0.30 & 0 & 38 & 24 & 0.15 & 0.00 \\ 0.27 & 8.20 & 1.04 & 0.62 & 0 & 0 & 18 & 0.93 & 0.00 \\ 0.00 & 3.20 & 0.40 & 10.0 & 0 & 0 & 0 & 0.40 & 0.00 \end{bmatrix}_{\text{FCPM35}-\text{PBPM0}} \begin{matrix} \geq \\ \geq \\ \leq \\ \geq \\ \leq \\ \leq \\ \geq \\ \geq \\ \geq \\ \geq \\ \leq \end{matrix} \begin{bmatrix} 30.00 \\ 3100 \\ 8.00 \\ 0.50 \\ 5.00 \\ 10.00 \\ 0.80 \\ 1.02 \\ 0.001 \\ 0.0006 \\ 42.00 \end{bmatrix}$$

$$\begin{bmatrix} 9.00 & 19.10 & 0 & 42.50 & 54.05 & 0 & 0 & 15.60 & 0.00 \\ 3860 & 4530 & 0 & 4150 & 6070 & 0 & 0 & 3700 & 9000 \\ 1.90 & 4.60 & 0 & 1.80 & 14.50 & 0 & 0 & 6.50 & 100.00 \\ 0.77 & 1.80 & 0 & 0.85 & 0.32 & 0 & 0 & 0.00 & 0.00 \\ 2.20 & 6.80 & 0 & 7.40 & 1.30 & 0 & 0 & 10.00 & 0.00 \\ 1.60 & 0.30 & 0 & 6.00 & 10.65 & 0 & 0 & 4.40 & 0.00 \\ 0.37 & 6.80 & 0 & 1.27 & 2.32 & 0 & 0 & 0.62 & 0.00 \\ 0.25 & 6.00 & 0 & 2.70 & 2.64 & 0 & 0 & 0.65 & 0.00 \\ 0.01 & 1.30 & 0 & 0.30 & 2.09 & 38 & 24 & 0.15 & 0.00 \\ 0.27 & 8.20 & 0 & 0.62 & 1.04 & 0 & 18 & 0.93 & 0.00 \\ 0.00 & 3.20 & 0 & 10.0 & 0.40 & 0 & 0 & 0.40 & 0.00 \end{bmatrix}_{\text{FCPM0}-\text{PBPM35}} \begin{matrix} \geq \\ \geq \\ \leq \\ \geq \\ \leq \\ \leq \\ \geq \\ \geq \\ \geq \\ \geq \\ \leq \end{matrix} \begin{bmatrix} 30.00 \\ 3100 \\ 8.00 \\ 0.50 \\ 5.00 \\ 10.00 \\ 0.80 \\ 1.02 \\ 0.001 \\ 0.0006 \\ 42.00 \end{bmatrix}$$

Where $\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \\ X_7 \\ X_8 \\ X_9 \end{bmatrix} \leq \begin{bmatrix} 0.1 \\ 0.03 \\ 0.6 \\ 0.4 \\ 0.1 \\ 0.01 \\ 0.01 \\ 0.20 \\ 0.04 \end{bmatrix}; \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \\ X_7 \\ X_8 \\ X_9 \end{bmatrix} \geq 0; \sum_{i=1}^{n=8} x_i = 0.99$

Experimental diets

The experimental feeds were manufactured on the basis of the lowest price results. Two diets ($FCPM_{35}$-$PBPM_0$ and $FCPM_0$- $PBPM_{35}$) were formulated to incorporate 0% ($FCPM_{35}$-$PBPM_0$) and 100% ($FCPM_0$- $PBPM_{35}$) of poultry co-product meal (PCPM) levels, replacing the fish meal totally. Briefly, fish co-product meal (FCPM) and poultry co-product meal (PCPM) were used as sources of protein. Sunflower oil was used as the lipid source and wheat gluten meal as binder. Every ingredient was well-powdered (Hakka Electric Grain Grinder 3.0 kW) and mixed using electric mixer (Villa m100). The supplement vitamin mineral concentrate (VMC), sunflower oil and water were added according to feed formulation. For the extruder fish feeds production, the mixture was passed through a single screw fish feed extruder (DGP-60; China) with a 120°C extrusion temperature and 0.2cm die diameter **(Vijayagopal, 2004)**. The prepared trial diets were dried in the dryer (La Parmigiana) for 24h and then stored at - 20°C (Whirlpool). The **AOAC (2005)** method was utilized to do the diet's proximate analysis.

Experimental fish and feeding condition

Thirty juveniles RHT (*Oreochromis* sp.) were distributed randomly in aquariums (120L) under static system with daily changing (24h) of the medium water. Moreover, the feces were removed by siphoning every day. Basic parameters of the rearing water (temperature (29.21 ± 3.14°C), dissolved oxygen (5.09 ± 1.02mg. L^{-1}), salinity (1.49 ± 0.16mg. L^{-1}) , pH (7.85 ± 0.20), N-$NH_{3,4}$ (1.44 ± 1.00mg. L^{-1}), N-NO_3 (1.32 ± 0.40mg. L^{-1}), N-NO_2 (1.23 ± 0.40mg. L^{-1}) and P-PO_4 (0.25 ± 0.17mg. L^{-1})) were maintained at optimal values of growth for tilapia for the whole experimental period and were controlled using a Multiparameter portable (HI 98194). Ammonia, nitrate, nitrite and phosphorus were measured weekly by QuAAtro39 AutoAnalyzer (Seal analytical) on the same day of water sampling. Fish were fed 3 times a day with 5% of wet body weight during the 45 dyes of experiment. The amount of total feed was changed according to mortalities or zootechnical control. The body weights and sizes were recorded at fifteen days interval using a scale and an ichthyometer.

Growth performance, nutrient utilization and Weight-length relationship

The body weights and lengths were recorded at 15d interval during 45 days of feeding trial to assess the growth parameters (GP) : survival % (SR), WG (weight gain: g/j/ind), SGR (specific growth rate, %/day), nutrient utilization (NU): FCR index (feed conversion ratio), PER (protein efficiency ratio) and K (condition factor) and b (allometry coefficient) following the protocols described earlier **(Azaza *et al*., 2006; Moshood *et al*., 2014; Brah *et al*., 2019)**.

Proposal of integrated zootechnical performance (IZP) indexes for tilapia laboratory feed test

Based on the previous indexes (indices) proposed for other species **(Marcu *et al*., 2013; Muniesa *et al*., 2016)**, we have proposed the integrated zootechnical performance (IZP) indexes that could be used to integrate the results from the different zootechnical performances (WG, survival and FCR) and understand general/ global zootechnical growing performances of fishes in laboratory zootechnical test for fish feed and its applicability for all periods of growth. The IZP index is a method that provides a numeric value that integrates all these zootechnical paremetres such as: (1) the relative average daily growth, (2) the survival, and (3) FCR index.

IZP1 index or called "Laboratory production and Management Index for Tilapia (LPMI)" was calculated using the method of **Muniesa *et al*. (2016)**, as follows:

$$IZP_1 = LPMI_{Tilapia} = (1 + ADGr) \times (1 - EM) \times iFCR$$

Where:

Total weight gain (TWG, g) = Body weight (g) at the end-Body weight (g) at start.

Relative average daily growth (ADGr) = TWG / days of growth period/ Body weight (g) at start.

EM: estimated mortality at the end of experimental cycle.

Feed conversion ratio: FCR (kg feed/kg gain) = Cumulative feed intake (kg) /Total weight gain (kg);

FCR index: $iFCR = \sqrt{\frac{Log_{10}(2)}{Log_{10}\ (FRC+1)}}$; (ΔBiomass > 0; FCR > 0)

Thus, the worst IZP1 values are those that are closer to zero, while the highest IZP1 values are those that are higher.

The IZP_2 or called "the Laboratory Tilapia Production Efficiency Factor (LTPEF)" and the IZP_3 or called "Laboratory Fattening Tilapia index (LFTI)" were modified and used to assess the growing performance of laboratory fattening Tilapia as suggested by **Marcu *et al*. (2013)**, as follows:

$$IZP_2 = LTPEF_{Tilapia} = \frac{\text{Viability (\%) x BW (kg)}}{\text{Experiment duration (d)x FCR (Kg feed /Kg gain)}} * 100$$

$$IZP_3 = LFTI_{Tilapia} = \frac{\text{Viability (\%) x ADG (g/fish/day)}}{\text{FCR (Kg feed /Kg gain) x10}} * 100$$

Where:

Total weight gain (TWG, g) = Body weight (g) at the end-Body weight (g) at start;

Average daily growth (ADG: g/fish/d) = TWG (total weight gain) / days of growth period;

FCR (kg feed/kg gain) = Cumulative feed intake (kg) /Total weight gain (kg);

Viability (%) = 100 – Mortality (%).

Reproductive activity indexes (GSI and HIS indexes)

After growth performance measurements, specimens were sacrificed in the laboratory for gonads and liver collection. Gonadosomatic index (GSI) and Hepatosomatic index (HSI) of the tilapia fish were determined separately **(Parameswaran *et al*. 1979),** as follows:

$$GSI = \left(\frac{\text{Weight of gonad (g)}}{\text{body weight of fish (g)}}\right) * 100$$

$$\text{HSI} = \left(\frac{\text{Weight of Liver (g)}}{\text{body weight of fish (g)}}\right) * 100$$

Whole-body proximate composition

After reproductive activity indexes measurements, the soft tissues of specimens were weighed and frozen at -20°C. The samples were lyophilized (-55°C, 0,1 bar, 72h), weighed, and grounded into a fine powder before being stored in polyethylene pots until they were analyzed. The composition of whole-body proximate analysis in terms of crude protein (CP) and fat content was determined out using the method described by **AOAC (2005)**.

Statistical analysis

Data were analyzed by one way ANOVA test using IBM SPSS Statistics 25 software (2018, trial version) to analyze the differences of each treatment group. When a significant difference was observed, the least significant difference (LSD) test was used to compare means, whereas the Mann-Whitney's nonparametric test was used in the case of Kruskal-Wallis nonparametric test. Treatment effects and height were considered significant at confidence levels of $P < 0.05$ and $P < 0.01$ respectively.

RESULTS

1. Formulation

The results of analysis of optimal ingredient and nutrient composition generated by computerized LP and proximate compositions of the formulated feeds for juvenile of RHT (*Oreochromis* sp.) are presented in Table (2) .

Table 2. Composition of the diets (g/kg dry matter)

Ingredients (% in diet)	Diets			
	FM_{35}-$PBPM_{0}$		FM_{0}-$PBPM_{35}$	
Fish meal	35.00		0.00	
Soybean meal	30.00		25.00	
Poultry by products meal	0.00		35.00	
Durum wheat	19.80		19.80	
Maize	07.00		07.00	
Crude calcium	0.99		0.99	
Bi-calcite phosphate	0.99		0.99	
Sunflower oil	3.00		3.00	
Wheat gluten	2.22		2.22	
VMC	1.00		1.00	
Total (% in diet)	100		100	
Total coast (AD/Kg)	129.28		122.28	
Biochemical composition	Calculated	Analyzed	Calculated	Analyzed
Crude protein (% of DM)	35.96	35.26	35.96	41.38
Lipid (% of DM)	8.56	10.60	9.26	8.50
Ash (% of DM)	9.08	5.80	5.27	6.00
Moisture (% of DM)	-	11.40	-	12.00
Caloric value Kcal/100g	380.20	322.02	474.28	328.44

The results of analysis of optimal nutrients of least-cost diet generated by computerized LP for juvenile's hybrid red tilapia (*Oreochromis* sp.) satisfied the minimum constraint levels set. The level crude protein and energy of the optimized diet for juveniles of red tilapia (*Oreochromis* sp.) were 35.96 %, 35.96% and 380.20Kcal/ 100g, 474.28Kcal/ 100g for $FCPM_{35}$-$PCPM_0$ and $FCPM_0$-$PCPM_{35}$ diets, respectively. The lipid and ash content were: 8.56 %, 9.26 % and 9.08 %, 5.27 % for $FCPM_{35}$-$PCPM_0$ and $FCPM_0$-$PCPM_{35}$ diets, respectively. In addition, proximate compositions (Table 2) of the formulated feed comprised 35.26% and 41.30% protein, energy 322.02 and 328.44Kcal/ 100g, 10.60 and 8.50% lipid and 5,80 and 6% ash for $FCPM_{35}$-$PCPM_0$ and $FCPM_0$-$PCPM_{35}$ diets. respectively. These two diets compositions (optimized and real) are almost identical and are agreed well with the tilapia nutritional requirements set by **FAO (2017))**. In addition, the optimized diets ($FCPM_{35}$-$PCPM_0$ and $FCPM_0$-$PCPM_{35}$) had its costs at 129.28 AD. Kg^{-1} (0. 91 Dollar. Kg^{-1}) and 122.28 AD. Kg^{-1} (0.86 Dollar. Kg^{-1}), respectively, while the commercial diet in Algeria provided the highest feed cost of 160.00 AD. Kg^{-1} (1.13 Dollar. Kg^{-1}) (Table 2).

2. Growth performance, nutrient utilization and Length -weight relationship

SR (%), WG (g/day), SGR (%/day), PER, FCR index of RHT (*Oreochromis* sp.) fed $FCPM_{35}$-$PBPM_0$ diet showed no significant differences ($P > 0.05$) among RHT (*Oreochromis* sp.) fed the other experimental diet: $FCPM_0$-$PCPM_{35}$ (Table 3).

The LWR parameters: (1) values of determination coefficients (R^2) and (2) corresponding regression coefficients are demonstrated in Table (3). There was a strong correlation between length and weight. The value of the determination coefficients obtained from the LWR was 0.90 and 0.94 for RHT (*Oreochromis* sp.) feed on different levels of PCPM: 0.0 and 100%, respectively.

The K for the RHT (*Oreochromis* sp.) is revealed in Table (3). The K computed for RHT (*Oreochromis* sp.) were 1.46 and 2.27, respectively for tilapia fish feed on different PCPM levels (0 and 100%, respectively). In addition, in $FCPM_0$-$PBPM_{35}$ diet, the slopes in the height-weight dependence were lower than the theoretical value of 3 (b = 2.89), reflecting negative allometric growth, i.e., increase in length was not balanced by the weight gain or the weight gain was slower than length gain **(Asmamaw *et al*., 2018; Loukou *et al*., 2023)**. Contrary, in $FCPM_{35}$-$PCPM_0$ diet, the regression slope was 3.10 ($P < 0.01$) indicating that the fish had positive allometric growth **(Asmamaw *et al*., 2018; Diallo *et al*., 2022; Loukou *et al*., 2023)**.

Table 3. Growth performances of juvenile red tilapia (*Oreochromis* sp.) fed with experimental diet for 45 days (*$P > 0.05$; **$P < 0.05$; ***$P < 0.01$)

Zootechnical parameter	Diets	
	FM_{35}-$PBPM_0$	FM_0-$PBPM_{35}$
Survival (%)	99.00 ± 0.00*	100.00 ± 0.00*
Weight gain (g/day)	0.26 ± 0.13*	0.32 ± 0.11*
Specific growth rate (%/day)	2.88 ± 0.3*	3.07 ± 1.75*
Protein efficiency ratio	1.55 ± 0.15*	1.72 ± 0.52*
Feed conversion ratio	1.42 ± 0.13*	1.36 ± 0.37*
Weight-length relationship	K=1.46* b = 3.10 R^2= 0.90	K=2.27*** b = 2.89 R^2= 0.94

Survival (SR; %) = (total fish − dead fish) × 100/total fish.
Weight gain (WG; g/day)) = (Final wt.-initial wt.) /60 days.
Specific growth rate (SGR; %/day) = [(Ln Final wt.-Ln initial wt.)/60 days] ×100.
Protein efficiency ratio (PER) =Wt. gain/protein intake.
Feed efficiency ratio = [feed given (g) /Wt. gain (g)].

3. Zootechnical performance (IZP) indexes for tilapia laboratory feed test

The results in terms of integrated zootechnical performance (IZP) indexes (IZP_1, IZP_2 and IZP_3), which includes daily weight gain, survival percentage and feed conversion ratio are summarized in Table (4). No significant ($P > 0.05$) differences were detected among all fish groups in IZP_1, IZP_2 and IZP_3 indexes. Higher values of these indexes indicate (IZP) that the animals are healthy **(Bhamare *et al.*, 2016)**. Based on the innovative integrated zootechnical performance (IZP) indexes, the IZP indexes can be classified as follows: IZP_1 ($FCPM_{35}$-$PCPM_0$) > IZP_1 ($FCPM_0$-$PCPM_{35}$) with $P > 0.05$; IZP_2 ($FCPM_{35}$-$PCPM_0$) > IZP_2 ($FCPM_0$-$PCPM_{35}$) with $P > 0.05$, and IZP_3 ($FCPM_{35}$-$PCPM_0$) > IZP_3 ($FCPM_0$-$PCPM_{35}$) with $P > 0.05$.

Table 4. Integrated zootechnical performance (IZP) indexes for red tilapia (*Oreochromis* sp.) fed with experimental diet for 45 days (*$P > 0.05$; **$P < 0.05$; ***$P < 0.01$)

IZP indexes parameter	Diets	
	FM_{35}-$PBPM_0$	FM_0-$PBPM_{35}$
IZP_1 (LPMI)	0.97 ± 0.09*	0.93 ± 0.003*
IZP_2 (LTPEF)	71.63 ± 7.51*	53.31 ± 16.71*
IZP_3 (LFTI)	238.77 ± 25.03*	177.71 ± 55.70*

IZP_1: integrated zootechnical performance 1 or LPMI: Laboratory Management Index.
IZP_2: integrated zootechnical performance 2 or LTPEF: Laboratory Tilapia Production Efficiency Factor Index.
IZP_3: integrated zootechnical performance 3 or LFTI: Laboratory Fattening Tilapia index.

4. Reproductive activity indexes (GSI and HSI)

The summary of the reproductive activity indexes (GSI and HSI) of fish fed two different feeds is shown in Table (5). Mean reproductive activity indexes of RHT (*Oreochromis* sp.) juveniles cultured with the experimental diets showed that in fish, highest IGS (1.37 ± 1.28) and HSI (1.05 ± 0.56) were obtained in juveniles fed diet $FCPM_{35}$-$PCPM_0$ compared with fish fed diet $FCPM_0$-$PCPM_{35}$ which had a mean IGS of 0.71 ± 0.58 with a mean HSI of 0.79 ± 0.54 (Table 5).

Table 5. Means of GSI and HSI values for red tilapia (*Oreochromis sp*.) fed with experimental diet for 45 days (**P*> 0.05; ***P* < 0.05; ****P* < 0.01).

IZP indexes parameter	Diets	
	FM_{35}-$PBPM_0$	FM_0-$PBPM_{35}$
IGS	1.37 ± 1.28**	0.71 ± 0.58**
IHS	1.05 ± 0.56**	0.79 ± 0.54**

5. Whole-body proximate composition

Results of whole fish body composition in terms of crude protein (g/100g wet basis) and fat (lipid, g/100g wet basis) content, were not affected by the full replacement of FCPM by PCPM between experimental diets ($FCPM_{35}$-$PCPM_0$ and $FCPM_0$-$PCPM_{35}$) (Table 6).

Table 6. Whole-body proximate composition of Nile tilapia (g/100g wet basis)

Items	Diets	
	FM_{35}-$PBPM_0$	FM_0-$PBPM_{35}$
Crude protein	18.54	18.56
Crude lipid	3.60	3.78

DISCUSSION

In this decade, an important aim for each aquaculture industry and feed-manufacture company is to replace dietary FM in aquafeeds with readily available and less costly alternatives protein sources, such as poultry co-product meal **(Yones & Metwalli, 2015)**. The result of this study demonstrated that the incorporation of fish and poultry by-product meals at 35.00% in tilapia juveniles' diet is economical and may minimize the cost of feeding by as much as 19.20 and 23.57%, respectively. This will invariably maximize productivity in farmed fish. The costs of the diets can be classified as follows: Commercial feed > $FCPM_{35}$-$PCPM_0$ > $FCPM_0$-$PCPM_{35}$.

The results of the present work showed that PCPM is a suitable replacement of FCPM in experimental diet for RHT (*Oreochromis* sp.). In addition, when the replacement level of FCPM up to 100%, this fish species had better tolerance for dietary PBPM supplementation without significant (*P*< 0.05) reduction in studied parameters: (1) classical performance growth (SR (%), WG (g/j/ind), SGR (%/day)) and nutrient utilization (FCR index and PER), (2) reproductive activity indexes (GSI and HIS), as well as (3) IZP indexes.

The findings of the present work agree with numerous other studies for different freshwater and marine fish species such as tilapia, European sea bass and sea bream (**Yones & Metwalli, 2015, Hernandez *et al*., 2010; Irm *et al*., 2020; Marzouk *et al*., 2024)**. In scientific literature, some studies demonstrated that FM can be replaced by 75 or 100% PCPM without adverse effects on growth performance, but other studies have revealed that, FM could only be substituted with PCPM at a level which did not exceed 50% for some marine fish species **(Nengas *et al*., 1999; Yang *et al*., 2006; Hu *et al*. 2008)**. **Yang *et al*. (2006)** and **Hu *et al*. (2008)** stated that the optimal substitution level of 66.5 and 66.7% was recommended for the optimum growth performance for gibel carp (*Carassius auratus gibelio*). Additionally, the level of replacement (Full, partial and optimum levels) of FCPM by PCPM in fish diets depend on many factors such as: fish species, origin and quality of the tested meals (FCPM and PCPM), processing preparation methods of meals, EAAs levels in meals and the ratio of PCPM to FCPM in the diet **(Shapawi *et al*., 2007; Yones & Metwalli, 2015; Zhou *et al*., 2018; Irm *et al*., 2020)**. The results of the present study are in agreement with the results observed by **Hernandez *et al*. (2010)** in fingerlings NT (*Oreochromis niloticus*), by **Yones and Metwalli (2015)** in Juvenile NT (*Oreochromis niloticus*), and by **Nik Sin *et al*. (2020)** in giant freshwater prawn, *Macrobrachium rosenbergii*, who reported that the complete replacement of FM by poultry by-product meals in practical diets for aquatic specimens does not distress the growth performance. **Nik Sin *et al*. (2020)** reported that the substitution of FM protein with poultry co-product meal protein did not cause a significant reduction or deficiency in any of the amino acids profile (AAs) and this is probably because the AAs profile of PCPM compares favorably with that of FCPM.

In addition, unbalanced AAs intake can impact negatively: (1) growth, (2) survival, and (3) physiological status of fish **(Rawles *et al*., 2006; Wang *et al*., 2022)**. **Rawles *et al*. (2006)** declared that PCPM had lower growth than sunshine bass fed FCPM (control diet). They attributed that: (1) imbalance of some limiting AAs content and (2) reduced palatability for PCPM. According to **Wang *et al*. (2022)**, an imbalanced AAs supplement can lead to an unnatural buildup of AAs content in muscle, which results in needless nutrient intake. However, in the present work the balance in limiting amino acid, all diets were consumed similarly and satisfy all nutrient requirements for growth of RHT (*Oreochromis* sp.). **Hernandez *et al*. (2010)** reported that poultry by-product has been shown to enhance growth performance of the Nile tilapia.

Besides, in nutrition experiments, feed and gain are typically employed to assess conversion at the farm level **(Gidenne & Maertens 2016)**. The efficiency of transforming feed into live weight growth is expressed using the FCR. The FCR is typically the most important bio-indicator for (1) farming efficiency, (2) economic and (3) environmental performance, as it is composed of feed cost which defines the feed charge per kilo **(FAO,**

2018; Iversen *et al*., 2020). In Table (3), the FCR for testes red tilapia were 1.42 ± 0.13 and 1.36 ± 0.37 for $FCPM_{35}$-$PCPM_0$ and $FCPM_{35}$-$PCPM_0$ diets, respectively. Similar and comparable results of FCR were recorded with tilapia **(Hernandez *et al*., 2010; Yones & Metwalli, 2015)**. Based on the zootechnical performance, the feed conversion ratio (FCR) can be classified as follows: FCR ($FCPM_{35}$-$PCPM_0$) < FCR ($FCPM_{35}$-$PCPM_{35}$) with $P>$ 0.05.

The performance of tilapia fishes was also evaluated in terms of Laboratory Management Index (LPMI or IZP_1), Laboratory Tilapia Production Efficiency Factor Index (LTPEF or IZP_2) and Laboratory Fattening Tilapia index (LFTI or IZP_3), which includes WG (g/j/ind), SR (%) and FCR index. **Bhamare *et al*. (2016)** reported that higher values of these indicators indicate that the health. **Muniesa *et al*. (2016)** reported that the results of index closer to zero will be the worst, and the highest values of index will be the best ones for this index. As can be seen from Table (3), the FCR, was not significantly differed ($P<0.05$) between groups and the best value was recorded by $FCPM_{35}$-$PCPM_0$. These results agree with the obtained results of growth performances (Feed conversion ratio) of juvenile red tilapia (*Oreochromis* sp.). In addition, the absence of indexes for tilapia laboratory feed test makes it difficult to compare the innovative IZP indexes with others scientific works. Also, the application of the IZP indexes for tilapia laboratory feed test exposed that these indexes are consistent and useful for detecting potential handling, environmental, or sanitary problems **(Bhamare *et al*., 2016)**.

Besides, measures of reproductive activity indexes (GSI and HIS) parameters are significantly different ($P<0.05$) between experimental diets ($FCPM_0$-$PCPM_{35}$ and $FCPM_0$-$PCPM_0$). These results are comparable with the study in tilapia recorded by **Felix *et al*. (2020)** and other species such as mud catfish (*H. longifilis)* **(Keremah, 2014)**, African catfish (*C. gariepinus*) **(Raymond *et al*., 2018)**, sunshine bass (*M. chrysops and M. saxatlis)* **(Pine *et al*., 2008)** and rabbitfish (*S. sutor*) **(Shirinabadi *et al*., 2013)**.

Moreover, the results of the present work indicated that the LW relationship and K of RHT (*Oreochromis* sp.) were affected by the incorporation of 100% poultry by-product meal. In addition, the growth of RHT (*Oreochromis* sp.) is of negative allometric type (b=2.89 and R^2=0.94) for $FCPM_0$-BPM_{35} diet and positive allometric (b=3.10 and R^2=0.90) for $FCPM_{35}$-$PBPM_0$ diet. These results are in agreement with the results observed in tilapia and other freshwater and marine species **(Anani *et al*., 2016; Mazumder *et al*., 2016; Karapanagiotidis *et al*., 2018; Kop *et al*., 2019; Kefas *et al*., 2020; Zhang *et al*. 2023; Kamble *et al*., 2024;;)**.

In the present work, the whole tilapia body composition via CP (g/100g wet basis) and fat (g/100g wet basis) content, of RHT (*Oreochromis* sp.) presented that the CP and fat (lipid) were not influenced by incorporation of 100% PBPM. Similar results have been reported for tilapia by **Hernandez *et al*. (2010)**, **Yones and Metwalli (2015) and Olopade *et al*. (2016)** for NT (*Oreochromis niloticus*).

Finally, we have sought to combine of valorized bioresources (animal biowaste: Fish and poultry by-products) with linear programming technique permitted to reduce animal wastes pollution and avoid the import of raw materials (FCPM and PBPM), while producing a least cost formulate fish feed, rich by essential macro/micronutrients.

CONCLUSION

The results of the present work recommend that potential full replacing of fish co-product (FCPM) meal with poultry co-product meal (PCPM) in the feed of RHT *Oreochromis niloticcus*, without (1) compromising classical performance growth and nutrient utilization, (2) reproductive activity indexes (GSI and HIS) and (3) IZP indexes. Also, the application of the IZP indexes for laboratory zootechnical test for fish feed showed that these indexes are consistent and useful for detecting potential handling, environmental, or sanitation problems.

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