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# The Use of Poultry Corn By-Product Meal on the Growth Performance of Channel Catfish, *Ictalurus punctatus*

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**Abstract:** In this study, three growth trials were conducted to check the efficacy of poultry corn by-product meal, which was a combination of wet poultry processing waste and corn that was co-dried. It was relatively a new product, and its first growth trial was conducted in a laboratory (aquarium study) to evaluate the substitution of whole corn meal with poultry plus corn by-product meal (PCBM) in practical diets for channel catfish. In this trial (84 days culture period), 7 levels of PCBM (0, 5, 10, 15, 20, 25 and 30%) were evaluated in a practical diet containing 32% protein and 6% lipid. The results indicated that fish fed PCBM20 had the highest FW, WG and WG% among all the treatments, and these values were significantly higher ($p < 0.05$) than at baseline or with PCBM5 treatment. The second trial (fingerlings to sub-market) was conducted in 12 raceways with 4 levels of PCBM (0, 10, 20 and 30%) and 600 fish (mean initial weight 42.3 ± 5.06 g) in each raceway. After 143 days of culture, the results demonstrated that there were no significant differences ($p > 0.05$) between the FW, WG and WG% and the survival of the fish. To validate our results again, the third trial (sub-market to market) was conducted in 6 raceways with 2 levels of PCBM (0 and 30%). A total of 600 fish (mean initial weight 136.8 ± 6.3 g) were stocked in each raceway. The results revealed that there were no significant differences ($p > 0.05$) between the FW, WG and WG% and fish survival after the culture period of 133 days. In all three trials, upon termination, the hepatosomatic index (HIS), the intraperitoneal fat (IPF), and the dress-out (headed and gutted) percentages were measured for trials 2 and 3. The results showed that there were no significant differences ($p > 0.05$) between all these parameters except for HIS in trial 1 and IPF in trial 2 ($p < 0.05$). In conclusion, PCBM can be used up to 30% in the diets of channel catfish.

**Keywords:** corn by-product meal; catfish; poultry waste; raceways; growth performance

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## 1. Introduction

The FAO predicts that world production of food will have to expand rapidly to meet the continued demands of an expanding population. As world food supply expands, there is a parallel demand for ingredients for animal feeds required to support animal protein production. This growing demand and limited resources push the industry to look towards recapture of nutrients whenever possible. In order to sustainably expand aquaculture and retain a constant seafood supply without damaging ecosystems, there is a need to improve resource-efficient approaches [1] and lessen aquaculture waste [2–5]. This also means we must continue to grow the feed industry, which relies on cost-effective and nutritious sources, which are limiting factors. Hence, to support circular economies within aquaculture [6–8] and the animal production industry [9], there is growing global awareness of and concerns regarding the valorization of accessible resources, especially the recycling of by-products and nutrients.

Rising production costs in aquaculture industries have prompted the investigation of low-cost food processing by-products in feeds. It has various important advantages, such as being to reduce dependence on expensive ingredients and the need for expensive waste management programs [10]. Numerous rendered animal by-products are used throughout the feed industry including in aquaculture. Taking the poultry industry as an example, the processing of poultry for human consumption produces a range of by-products including various grades and combinations of by-product meal and oil sources used in the feed industry. These are commonly used in aquaculture feeds and contribute to our recycling of nutrients.

There is a potential for rendered terrestrial animal products (e.g., poultry by-product meal, feather meal, bone and meat meal and blood meal) to be processed and used in high percentages for aquaculture production [5,11]. Hence, the application of both newly emerging and established recycling methods of animal processing have huge potential for making the industry more sustainable and significantly increasing production output. Retrieved solids and dissolved nutrients can all be repurposed to benefit the animal feed industry. For some by-products, this is relatively easy, but for liquid wastes, the recapture of nutrients is more problematic. Historically, only a small part of by-products was used for animal feed production. Most of them were handled as waste product: incinerated, dumped into the sea or deposited on land, contributing to severe environmental issues [12]. High moisture content in food by-products is a barrier to using them cost-effectively because drying in a conventional method is expensive [13]. Due to technological improvements, it is now viable to recycle these by-products instead of disposing of them in a less environmentally friendly manner [14].

Co-drying wet poultry by-products with other dry feed ingredients and subsequent fermentation may be an alternative tactic for the efficient utilization of poultry by-products in feed for aquaculture [15–17]. The latest improvements in manufacturing, checking of product quality, and blending have resulted in improved products and reduced variability in nutritional quality. Therefore, the objective of this study was to evaluate the efficacy of blended poultry by-product (combination of wet poultry processing waste and corn) and corn meal in the diet of catfish and to promote the concept of the circular economy as a mean of reducing waste by adding value to by-products and reintroducing them.

## 2. Materials and Methods

### *2.1. Diet Preparation*

The test ingredient for all three growth trials, poultry corn by-product meal (PCBM), was sourced from Tyson Foods Springdale, AR, USA. For trial 1, all test diets were formulated on an isolipidic and isonitrogenous basis to contain 6% lipid and 32% protein. The proximate composition of the test ingredient is presented in Table 1. The formulation and proximate composition of the seven test diets are presented in Table 2. The basal and experimental diets were prepared to meet the nutritional requirements of the catfish (NRC, 2011). The basal diet was modified to produce 7 levels of inclusion (0.0, 5.0, 10.0, 15.0, 20.0, 25.0 and 30.0 g/100 g diet) using the poultry corn by-product meal to replace whole corn meal (30.0, 25.0, 20.0, 15.0, 10.0, 5.0, and 1.0 g/100 g diet) and cornstarch added as a filler as required.

The experimental diets were prepared at the Aquatic Animal Nutrition Laboratory at the School of Fisheries, Aquaculture, and Aquatic Sciences, Auburn University (Auburn, AL), by applying standard procedures for fish feeds. In brief, the pre-ground dry ingredients and oil were weighed and then stirred together in a food mixer (Hobart Corporation, Troy, OH, USA) for 15 min. Hot water was then added into the mixture to acquire a consistency suitable for pelleting. The diets were pressure pelleted using a meat grinder with a 3 mm die. The soggy pellets were then placed in a forced-air oven (<45 °C) for the night to result in a moisture content of less than 10%. Dry pellets were crushed, filled in sealed bags and kept in a freezer (−20 °C) until required. All the diets were analyzed at the University of

Missouri Agriculture Experiment Station Chemical Laboratories (Columbia, MO, USA) for proximate composition (Table 2).

**Table 1.** The proximate composition of the poultry corn by-product and whole corn used in growth trial 1.

| Ingredient | Poultry Corn by-Product Meal | Whole Corn Meal |
|---|---|---|
| Crude Protein | 11.8 | 7.83 |
| Moisture | 3.70 | 13.59 |
| Crude Fat | 13.20 | 6.80 |
| Crude Fiber | - | 1.80 |
| Ash | 1.40 | 1.06 |
| Alanine | 0.80 | 0.63 |
| Arginine | 0.60 | 0.40 |
| Aspartic Acid | 1.00 | 0.52 |
| Cysteine | 0.20 | 0.18 |
| Glutamic Acid | 1.80 | 1.54 |
| Glycine | 0.60 | 0.32 |
| Histidine | 0.40 | 0.24 |
| Isoleucine | 0.50 | 0.29 |
| Leucine | 1.10 | 1.03 |
| Lysine | 0.70 | 0.26 |
| Methionine | 0.40 | 0.18 |
| Ornithine | 0.10 | - |
| Phenylalanine | 0.50 | 0.42 |
| Proline | 0.80 | 0.74 |
| Serine | 0.60 | 0.40 |
| Taurine | 0.10 | - |
| Threonine | 0.50 | 0.30 |
| Tryptophan | 0.20 | 0.06 |
| Valine | – | 0.40 |
| Calcium (%) | 0.00 | 0.02 |
| Copper (ppm) | 3.50 | 2.10 |
| Iron (ppm) | 0.00 | 24.00 |
| Magnesium (%) | 0.10 | 0.10 |
| Manganese (ppm) | 0.00 | 7.60 |
| Phosphorus (%) | 0.30 | 0.28 |
| Potassium (%) | 0.30 | 0.38 |
| Sulfur (%) | 0.10 | 0.10 |
| Zinc (ppm) | 0.00 | 23.70 |

**Table 2.** The formulations and proximate compositions of the test diets used to evaluate the corn by-product (% as is) in the diets of channel catfish (Trial 1).

| Ingredients | Basal | PCBM5 | PCBM10 | PCBM15 | PCBM20 | PCBM25 | PCBM30 |
|---|---|---|---|---|---|---|---|
| Poultry meal [a] | 6.00 | 5.70 | 5.40 | 5.10 | 4.80 | 4.50 | 4.00 |
| Soybean meal [b] | 56.40 | 56.50 | 56.50 | 56.50 | 56.50 | 56.50 | 56.50 |
| Menhaden fish oil [c] | 2.63 | 2.35 | 2.07 | 1.79 | 1.50 | 1.22 | 0.90 |
| Corn Starch [d] | 1.42 | 2.00 | 2.58 | 3.16 | 3.75 | 4.33 | 4.15 |
| Poultry corn by-product [a] | 0.00 | 5.00 | 10.00 | 15.00 | 20.00 | 25.00 | 30.00 |
| Whole corn [e] | 30.00 | 25.00 | 20.00 | 15.00 | 10.00 | 5.00 | 1.00 |
| Mineral premix [f] | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Vitamin premix [g] | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 |
| Choline chloride [h] | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 |
| Rovimix Stay-C [i] | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| CaP-dibasic [j] | 1.85 | 1.85 | 1.85 | 1.85 | 1.85 | 1.85 | 1.85 |

**Table 2.** *Cont.*

| Ingredients | Basal | PCBM5 | PCBM10 | PCBM15 | PCBM20 | PCBM25 | PCBM30 |
|---|---|---|---|---|---|---|---|
| Proximate composition [1] (g/100 g as is) | | | | | | | |
| Moisture | 7.35 | 7.25 | 7.55 | 6.89 | 8.48 | 6.62 | 6.46 |
| Dry matter | 92.65 | 92.75 | 92.45 | 93.11 | 91.52 | 93.38 | 93.54 |
| Protein | 34.60 | 34.70 | 34.30 | 37.90 | 34.20 | 33.20 | 33.20 |
| Fat | 6.01 | 5.11 | 5.16 | 4.17 | 4.71 | 5.27 | 5.37 |
| Fiber (acid detergent) | 8.07 | 8.88 | 6.99 | 9.82 | 7.48 | 9.67 | 9.15 |
| Ash | 6.46 | 6.33 | 6.15 | 6.38 | 6.12 | 5.94 | 5.86 |
| Starch (gelatinized) | 10.00 | 10.00 | 11.00 | 10.00 | 13.00 | 16.00 | 17.00 |
| Starch (total) | 23.00 | 23.00 | 23.00 | 19.00 | 21.00 | 24.00 | 24.00 |
| Percent gelatinized | 45.00 | 45.00 | 49.00 | 56.00 | 63.00 | 68.00 | 68.00 |

[a] Tyson Foods, Inc., Springdale, AR, USA. [b] De-hulled Solvent Extracted Soybean Meal, Bunge Limited, Decatur, AL, USA. [c] Omega Protein Inc., Houston, TX, USA. [d] MP Biomedicals Inc., Solon, OH, USA. [e] Faithway Feed Co., Gunterville, AL, USA. [f] Trace mineral premix (g/100 g premix): Cobalt chloride, 0.004; Cupric sulfate pentahydrate, 0.250; Ferrous sulfate, 4.000; Magnesium sulfate anhydrous, 13.862; Manganese sulfate monohydrate, 0.650; Potassium iodide, 0.067; Sodium selenite, 0.010; Zinc sulfate heptahydrate, 13.193; Alpha-cellulose, 67.964. [g] Vitamin premix (g/kg premix): Thiamin HCl, 0.438; Riboflavin, 0.632; Pyridoxine HCl, 0.908; Ca-Pantothenate, 1.724; Nicotinic acid, 4.583; Biotin, 0.211; folic acid, 0.549; Cyanocobalamin, 0.001; Inositol, 21.053; Vitamin A acetate, 0.677; Vitamin D3, 0.116; Menadione, 0.889; dL-alpha-tocoperol acetate, 12.632; Alpha-cellulose, 955.589. [h] VWR Amresco, Suwanee, GA, USA. [i] Stay-C® (L-ascorbyl-2-polyphosphate 35% Active C), Roche Vitamins Inc., Parsippany, NJ, USA. [j] VWR Amresco, Suwanee, GA, USA. [l] Analysis conducted by University of Missouri Agricultural Experimental Station Chemical Laboratories (Columbia, MO, USA). (Results are expressed on g/100 g of feed as is unless otherwise indicated.). Abbreviations used: Poultry corn by-product meal (PCBM).

For trial 2, four levels of poultry corn by-product were used, replacing 0, 10, 20% or 30% of the corn and a portion of the soybean meal and/or poultry meal. The diet formulations and proximate compositions are presented in Table 3. Trial 3 was conducted with the same diets but only with two percentages of poultry corn by-products (0 and 30%).

**Table 3.** The formulations and proximate compositions of the test diets used to evaluate the poultry corn by-product (% as is) in the diets of channel catfish (for trials 2 and 3).

| Diet Name | Basal | PCBM10 | PCBM20 | PCBM30 |
|---|---|---|---|---|
| Soybean Meal | 56.10 | 56.45 | 56.61 | 55.34 |
| Poultry meal | 5.97 | 5.02 | 4.01 | 2.94 |
| Corn | 31.36 | 22.08 | 12.53 | 3.43 |
| Poultry corn by-product | 0.00 | 10.04 | 20.04 | 29.41 |
| Midds | 0.75 | 1.76 | 2.96 | 4.41 |
| Calcium | 1.49 | 1.51 | 1.50 | 1.47 |
| Bio Phos | 0.40 | 0.40 | 0.45 | 0.69 |
| Cat-Vit PX | 0.10 | 0.10 | 0.10 | 0.10 |
| Vitamin C | 0.10 | 0.10 | 0.10 | 0.10 |
| Fish oil | 3.63 | 2.46 | 1.60 | 2.01 |
| Choline | 0.10 | 0.10 | 0.10 | 0.10 |
| Proximate composition | | | | |
| Moisture % | 10.2 | 12.05 | 12.07 | 11.57 |
| Protein % | 30.2 | 33.2 | 34.4 | 35.4 |
| Fat (acid hydrolysis) % | 8.26 | 7.61 | 6.91 | 6.07 |
| Fiber (acid detergent) % | 6.7 | 8.9 | 6.1 | 9 |
| Ash % | 6.32 | 6.49 | 6.75 | 6.93 |
| Phosphorus % | 0.81 | 0.7 | 0.68 | 0.76 |
| Potassium % | 1.34 | 1.48 | 1.48 | 1.56 |
| Magnesium % | 0.26 | 0.23 | 0.23 | 0.26 |

**Table 3.** *Cont.*

| Diet Name | Basal | PCBM10 | PCBM20 | PCBM30 |
|---|---|---|---|---|
| Calcium % | 1.41 | 1.42 | 1.24 | 1.44 |
| Sodium % | 0.05 | 0.04 | 0.04 | 0.04 |
| Iron ppm | 192 | 172 | 175 | 202 |
| Manganese ppm | 48.3 | 65.4 | 37.7 | 44.7 |
| Copper ppm | 16.5 | 18 | 18 | 15.8 |
| Zinc ppm | 87.2 | 93.4 | 88.4 | 63.3 |

### *2.2. Experimental Systems*

The first growth trial was conducted in an indoor recirculation system. The growth trial comprised 28 75-L glass aquaria coupled to a common reservoir tank (800-L). Water quality was maintained by recirculation through a vertical fluidized bed biological filter (600-L volume with 200-L of Kaldnes media) using a 0.25 hp centrifugal pump and Aquadyne bead filter (0.2 $m^2$ media, 0.6 m $\times$ 1.1 m). Mean water flow for an aquarium was 4 L/min with an average turnover of ~21 min/tank. Dissolved oxygen was maintained near saturation using air stones in each culture tank and the sump tank using a common airline connected to a regenerative blower. Throughout the trial, dissolved oxygen (DO), temperature and salinity were checked twice daily using a YSI 55 multi-parameter instrument (YSI, Yellow Springs, OH, USA), and total ammonia N (TAN) and nitrite-N were measured twice per week using a YSI 9300 photometer (YSI, Yellow Springs, OH, USA). During the whole experimental period, the pH of the water was measured twice weekly using the pHTestr30 (Oakton Instrument, Vernon Hills, IL, USA), while the alkalinity, hardness and nitrate level of water were measured twice per month using the WaterLink-Spin TouchFF photometer (LaMotte Company, Chestertown, MD, USA). During growth trial 1, DO, temperature, salinity, pH, total ammonia nitrogen (TAN), nitrite, alkalinity and nitrate were maintained within the acceptable ranges for channel catfish at 6.07 $\pm$ 1.09 mg/L, 27.1 $\pm$ 2.17 °C, 4.15 $\pm$ 0.22 g/L, 7.9 $\pm$ 0.66, 0.25 $\pm$ 0.26 mg/L, 0.05 $\pm$ 0.06 mg/L, and 50.0 $\pm$ 1.7 g/L, 36.3 $\pm$ 4.7 g/L, respectively.

Growth trials 2 and 3 were conducted at the E.W. Shell Fisheries Research Station in Auburn, Alabama. The experiment with channel catfish was carried out in a 4046 $m^2$ research pond equipped with research-scale in-pond raceway systems. The raceways have continual water flow supplied via individual airlift pumps. The enclosure dimensions are 4.5 m $\times$ 1.2 m with a 1.3 m water depth (1.5 m deep with freeboard) providing a rough volume of 5.67 $m^3$.

### *2.3. Growth Trial*

**Aquarium trial in RAS**: In the 1st growth trial, 15 juvenile fish (mean initial weight of 8.2 $\pm$ 0.21 g) obtained from USDA, Auburn, AL, USA were stocked into each aquarium in the experimental system. Each diet was randomly assigned to the aquaria and given to fish in four replicates. Diets were given to fish at 3.0–6.5% BW daily over two feedings, Fish were weighed every other week and based on growth and observation of the feeding response, the ration was adjusted each week. Upon termination, after 12 weeks, fish were counted and group weighed to determine the final biomass mean, final weight, survival, weight gain and feed conversion ratio (FCR). Four fish per aquarium were randomly sampled and euthanized and then dissected to take out the liver and intraperitoneal fat. The liver weight and intraperitoneal fat were used to calculate the hepatosomatic index (HSI) as follows: HSI (%) = (liver weight/body weight) $\times$ 100 and IPF (%) = (fat weight/body weight) $\times$ 100. Another 5 fish were taken randomly from each aquarium, packed in sealed bags, and stored in a freezer ($-20$ °C) for further analysis.

**Fingerlings to Sub-market**: In the 2nd growth trial, 12 raceways were used. The 4 feeds were randomly assigned to 600 fish (mean initial weight 42.3 $\pm$ 5.06 g) in each raceway, in total almost 7200 stocked sfish per $m^2$. After stocking, the catfish were initially fasted (two weeks) to allow acclimation to the raceway system. Low levels of feed were offered to test feeding responses and then fish were fed two feedings per day to apparent satiation. Prior to harvest, the raceways were sampled to determine size distribution and dress-out. The following week, the raceways were harvested after a total of 143 days of the culture period. At the end of the trial, survival, growth, weight gain, food conversion ratio and total production were determined. Just prior to termination, 30 fish per raceway were sampled to determine the length and weight of the fish followed by 15 fish used to determine interperitoneal fat content, hepatosomatic index and condition index ($K = 100{,}000 \times \text{weight}/\text{length}^3$) and dress out (headed and gutted weight). Four fish were ground for the determination of the proximate composition of the whole body of fish.

**Sub-Market to Market**: This was the third trial, conducted in six raceways with two diets (0 and 30%) of poultry corn by-products. A total of 600 catfish (mean initial weight $136.8 \pm 6.3$ g) were stocked in each raceway. Diets were randomly assigned to each raceway, and the feeding experiment lasted for 133 days. Fish were fed to apparent satiation once daily. At the end of the feeding trial, fish were harvested, batch-weighed and counted to determine growth performance indices including weight gain, food conversion ratio and survival. A total of 20 fish per raceway were randomly sampled to determine length, weight, intraperitoneal fat content, hepatosomatic index, condition and dress-out percentages.

### *2.4. Analytical Method*

In all 3 growth trials, the moisture contents of both fish and feed samples were determined as moisture content (%) = (wet weight of sample − weight of the dry sample)/wet weight of sample × 100, by recording their original weight (wet), putting them in ceramic crucibles, drying them in an isothermal oven at 105 °C for 24 h, placing them in desiccators until they were at room temperature and recording their final weight (dry). In growth trial 1, net protein retention (NPR%) was calculated as (final weight × final protein content × final dry matter) − (initial weight × initial protein content × initial dry matter)/(protein in feed × amount of feed consumed). Energy contents of all diets of trial 1 were determined using a bomb calorimeter (1425 Semimicro Calorimeter, Moline, IL, USA) and calculated as net energy retention = (energy in final fish × final weight × dry matter of final fish) − (energy in initial fish × initial weight × dry matter of initial fish)/(energy in feed × amount of feed consumed).

### *2.5. Statistical Analysis*

All the data were analyzed using SAS (V9.4, SAS Institute, Cary, NC, USA). In all three trials, one-way ANOVA was followed by Tukey's multiple-comparison test to evaluate significant differences ($p < 0.05$) between treatment means.

## 3. Results

The trial 1 growth performance data (FW, WG, WG%, FCR, survival, NPR, and NER) on the juvenile catfish fed with diets containing various levels of poultry corn by-product are presented in Table 4. The fish fed PCBM20 had the highest FW, WG and WG% among all the treatments, and the values were significantly higher ($p < 0.05$) than the basal values and those with CBM5 treatment. No significant differences were found in survival among all treatments, as the survival was 100% in all treatments. The feed conversion ratios ranged from 1.33 to 1.47. The lowest FCR was found with the PCBM20 diet and the highest with the basal diet. There were no significant differences ($p > 0.05$) in intraperitoneal fat content (IPF) between all treatments, but for the hepatosomatic index (HIS), the fish fed the basal diet had significantly higher ($p < 0.05$) HIS (1.0%) than that with treatments PCBM10 (0.7%) and PCBM20 (0.8%). Regarding NPR and NER, PCBM25 had the highest NPR (35%) among all the treatments, and these were significantly higher ($p < 0.05$) than PCBM10 (31%) and PCBM15 (28.3%). There were no differences ($p > 0.05$) in NER between all treatments, but on linear regression analysis, NER was highest with PCBM20 ($r^2 = 15.9$, $p$-value = 0.03) (Table 4). Net protein retention and net energy retention ranged from 28.30 to 36.60% and 24.50 to 29.80%, respectively. There was no significant difference found in proximate whole body composition of catfish like moisture, protein and Ash. But as far as fat is concerned there was significant difference found between treatments (Table 5).

**Table 4.** The biological indices for catfish (mean initial weight 8.2 ± 0.21 g) fed experimental diets over a period of 12 weeks in growth trial 1.

| Diets | Final Weight (g) | Weight Gain [a] (g) | Weight Gain (%) | Dry Feed (g) | FCR [b] | Survival (%) | Protein Retention (%) | Energy Retention (%) | HIS [d] (%) | IPF [e] (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Basal | 57.8 $^{c}$ | 49.7 $^{c}$ | 612.0 $^{b}$ | 73.1 | 1.47 $^{a}$ | 100.0 | 32.0 $^{abc}$ | 24.5 | 1.0 $^{a}$ | 2.1 |
| PCBM5 | 59.2 $^{bc}$ | 50.9 $^{bc}$ | 620.3 $^{b}$ | 72.2 | 1.42 $^{ab}$ | 100.0 | 31.8 $^{abc}$ | 26.5 | 0.90 $^{ab}$ | 2.1 |
| PCBM10 | 61.0 $^{abc}$ | 52.8 $^{abc}$ | 641.7 $^{ab}$ | 75.4 | 1.40 $^{ab}$ | 100.0 | 31.0 $^{bc}$ | 27.8 | 0.70 $^{b}$ | 1.7 |
| PCBM15 | 61.02 $^{abc}$ | 52.9 $^{abc}$ | 634.8 $^{ab}$ | 75.5 | 1.43 $^{ab}$ | 100.0 | 28.3 $^{c}$ | 26.8 | 0.8 $^{ab}$ | 1.8 |
| PCBM20 | 65.6 $^{a}$ | 57.5 $^{a}$ | 710.1 $^{a}$ | 76.5 | 1.33 $^{c}$ | 100.0 | 35.0 $^{ab}$ | 29.8 | 0.8 $^{b}$ | 1.8 |
| PCBM25 | 65.0 $^{ab}$ | 56.7 $^{ab}$ | 683.1 $^{ab}$ | 77.5 | 1.37 $^{bc}$ | 100.0 | 36.6 $^{a}$ | 28.9 | 0.9 $^{ab}$ | 1.97 |
| PCBM30 | 60.8 $^{abc}$ | 52.8 $^{abc}$ | 653.1 $^{ab}$ | 75.3 | 1.43 $^{ab}$ | 100.0 | 32.7 $^{abc}$ | 27.2 | 0.8 $^{ab}$ | 1.65 |
| PSE [c] | 2.55 | 2.51 | 32.87 | 2.89 | 0.03 | 0.00 | 2.22 | 2.49 | 0.10 | 0.43 |
| $p$-value | 0.002 | 0.002 | 0.004 | 0.186 | 0.001 | 0.00 | 0.0009 | 0.1329 | 0.009 | 0.587 |
| Linear Regression | | | | | | | | | | |
| r-square | 27.5 | 28.2 | 27.6 | 18.7 | 19.3 | 0.0 | 12.7 | 15.9 | 7.07 | 9.58 |
| $p$-value | 0.004 | 0.004 | 0.005 | 0.02 | 0.01 | 0.0 | 0.06 | 0.03 | 0.17 | 0.1 |

Note: One-way ANOVA followed by the Tukey's multiple comparison test to evaluate significant differences ($p < 0.05$) between treatment means. Values with different superscripts within the same column are significantly different based on Tukey Pairwise Comparisons. [a] Weight gain = (final weight − initial weight)/initial weight × 100%. [b] FCR = Feed conversion ratio = feed offered/(final weight − initial weight). [c] PSE = Pooled standard Error. [d] HIS = Hepatosomatic index. [e] IPF = Intraperitoneal fat. Dry feed = It's the total amount of feed used in the trail I.

**Table 5.** Whole-body compositions (on wet weight basis) of channel catfish fed different levels of poultry corn by-product meal for 12 weeks (trial 1).

| Diets | Moisture % | Protein % | Fat % | Ash % |
|---|---|---|---|---|
| Basal | 72.10 | 16.40 | 8.33 $^{ab}$ | 2.85 |
| PCBM5 | 72.48 | 15.75 | 8.72 $^{ab}$ | 3.51 |
| PCBM10 | 72.65 | 15.40 | 9.25 $^{a}$ | 3.07 |
| PCBM15 | 73.40 | 15.50 | 7.44 $^{b}$ | 3.59 |
| PCBM20 | 72.63 | 16.05 | 8.78 $^{ab}$ | 2.90 |
| PCBM25 | 71.85 | 16.68 | 9.03 $^{ab}$ | 3.42 |
| PCBM30 | 71.13 | 15.70 | 8.25 $^{ab}$ | 3.34 |
| PSE [b] | 1.17 | 0.72 | 0.72 | 0.72 |
| $p$-value [a] | 0.22 | 0.16 | 0.03 | 0.66 |

Fish whole body analysis was conducted at Midwest Laboratories, Inc., Omaha, NE, USA. [a] Analysis of variance was used to determine significant differences ($p < 0.05$) among the treatment means ($n = 4$). [b] Pooled standard error of treatment means. Values with different superscripts within the same column are significantly different based on Tukey Pairwise Comparisons.

The trial 2 growth performance data (FW, WG and FCR) of catfish are presented in Table 6. Although there were no significant differences ($p > 0.05$) in these parameters, the fish fed the basal diet had the highest FW and WG among all the treatments. There were no significant differences ($p > 0.05$) in survival among all treatments, but the highest survival was observed in fish fed diet PCBM20, while fish fed diet PCBM10 had the lowest survival. Feed conversion ratios ranged from 2.2 to 2.9 (Table 6). There were no significant differences ($p > 0.05$) observed in total length, weight, condition factor (K), HSI or dress-out among all the treatments. However, PCBM30 had a significantly higher IPF (3.16%) than the other treatments (Table 7). The proximate and mineral compositions of whole-body catfish in trial 2 showed no significant difference at all except for the dry matter (Table 8).

**Table 6.** Harvest data (trial 2) for channel catfish (mean initial weight 42.3 ± 5.06 g) reared in outdoor raceway systems and offered four commercially produced test diets.

| Treatment | Biomass (Kg) | Mean Weight (g) | Weight Gain (g) | Total Feed (Kg) | FCR | Survival (%) |
|---|---|---|---|---|---|---|
| Basal | 132.6 | 225.3 | 200.05 | 225.6 | 2.2 | 98.0 |
| PCBM10 | 107.8 | 188.6 | 164.60 | 228.9 | 2.9 | 93.9 |
| PCBM20 | 123.8 | 190.5 | 164.24 | 243.3 | 2.5 | 108.0 |
| PCBM30 | 113.1 | 184.4 | 158.43 | 232.0 | 2.7 | 102.7 |
| PSE | 13.22 | 8.10 | 9.34 | 10.56 | 0.25 | 7.71 |
| *p*-value | 0.57 | 0.16 | 0.18 | 0.67 | 0.31 | 0.62 |

Total feed (Kg) = The total amount of feed used in trial 2.

**Table 7.** Sampling data (trial 2) for catfish to determine condition index (K), hepatosomatic index (HIS), intraperitoneal fat (IPF) and dress out (headed and gutted).

| Treatment | Total Length (mm) [1] | Weight (g) [1] | K [1] | HIS [2] % | IPF [2] % | Dress Out [2] % |
|---|---|---|---|---|---|---|
| Basal | 292.29 | 208.09 | 0.85 | 0.99 | 3.65 [a] | 69.05 |
| PCBM10 | 293.46 | 230.42 | 0.87 | 0.99 | 3.94 [a] | 67.36 |
| PCBM20 | 285.93 | 202.87 | 0.81 | 0.99 | 4.17 [a] | 69.19 |
| PCBM30 | 287.56 | 208.16 | 0.84 | 1.01 | 3.16 [b] | 69.03 |
| PSE | 4.83 | 10.72 | 0.02 | 0.02 | 0.13 | 0.86 |
| *p*-value | 0.65 | 0.33 | 0.48 | 0.83 | 0.00 | 0.43 |

[1] $n = 30$, [2] $n = 15$. Values with different superscripts within the same column are significantly different based on Tukey Pairwise Comparisons.

**Table 8.** The proximate and mineral compositions of whole-body catfish consisting of four fish pooled per raceway (trial 2).

| g/100 g Dry Weight | Basal | PCBM10 | PCBM20 | PCBM30 | *p*-Value | PSE |
|---|---|---|---|---|---|---|
| Dry matter (as is) | 34.76 | 36.70 | 36.10 | 33.16 | 0.04 | 0.77 |
| Protein | 50.87 | 55.93 | 50.33 | 49.67 | 0.25 | 2.21 |
| Fat | 39.67 | 35.87 | 40.30 | 41.83 | 0.22 | 1.88 |
| Ash | 8.44 | 9.67 | 7.08 | 8.48 | 0.30 | 0.89 |
| Calcium | 2.12 | 2.59 | 2.02 | 2.26 | 0.78 | 0.41 |
| Phosphorus | 1.52 | 1.80 | 1.53 | 1.62 | 0.70 | 0.18 |
| Potassium | 0.81 | 0.96 | 0.89 | 0.88 | 0.19 | 0.04 |
| Sodium | 0.28 | 0.30 | 0.30 | 0.29 | 0.80 | 0.01 |
| Sulfur | 0.53 | 0.58 | 0.56 | 0.53 | 0.44 | 0.02 |
| Magnesium | 0.07 | 0.09 | 0.08 | 0.08 | 0.24 | 0.00 |
| Iron | 82.47 | 69.27 | 102.90 | 85.53 | 0.87 | 28.63 |
| Manganese | 5.70 | 5.03 | 4.83 | 4.07 | 0.47 | 0.69 |
| Copper | 1.70 | 1.57 | 5.70 | 1.37 | 0.47 | 2.17 |
| Zinc | 45.70 | 46.87 | 53.40 | 49.20 | 0.70 | 4.88 |

Fish whole body analysis and mineral composition were conducted at Midwest Laboratories, Inc., Omaha, NE, USA.

The growth performance of the catfish in trial 3 is summarized in Table 9. There were no significant differences ($p > 0.05$) between FW, WG, FCR, and survival of fish. There were also no significant differences ($p > 0.05$) observed in total length, weight, condition factor (K), his or dress-out among all the treatments (Table 10).

**Table 9.** Harvest data (trial 3) for channel catfish (mean initial weight 136.8 ± 6.3 g) reared in outdoor raceway systems and offered two commercially produced test diets.

| Treatment | Biomass (Kg) | Mean Weight (g) | Weight Gain (g) | Total Feed (Kg) | FCR | Survival (%) |
|---|---|---|---|---|---|---|
| Basal | 228.7 | 448.3 | 311.9 | 321.0 | 2.2 | 90.3 |
| PCBM30 | 228.8 | 425.3 | 289.6 | 321.5 | 2.1 | 98.4 |
| PSE | 32.8 | 44.9 | 48.6 | 31.2 | 0.28 | 17.8 |
| *p*-value | 0.99 | 0.56 | 0.60 | 0.98 | 0.87 | 0.60 |

**Table 10.** Sampling data (trial 3) for catfish to determine condition index (K), hepatosomatic index (HIS), intraperitoneal fat (IPF) and dress-out (headed and gutted).

| Treatment | Total Length (mm) | Weight (g) | K | HSI % | IPF % | Dress Out % |
|---|---|---|---|---|---|---|
| Basal | 373.78 | 571.77 | 1.00 | 1.47 | 2.28 | 66.98 |
| PCBM30 | 361.38 | 497.19 | 0.96 | 1.60 | 1.82 | 64.71 |
| PSE | 11.3 | 69.0 | 0.05 | 0.22 | 0.54 | 2.31 |
| *p*-value | 0.25 | 0.25 | 0.32 | 0.50 | 0.35 | 0.29 |

## 4. Discussion

The sustainable intensification of aquaculture is not straightforward. Nevertheless, better nutrient recycling procedures through technological enhancements in harvesting and handling wastewaters and by-products along with the optimization of feeding compositions [18,19] and formulations can improve sustainable productive output to consumers and industry.

Given that the poultry industry is the largest animal production sector in the world, using by-products from this industry is an excellent way to recycle nutrients. Clearly, poultry by-product meal (PBM), the rendered product of poultry processing waste, made from inedible portions of poultry, has been used extensively in aquaculture [20–25]. Yet there are other waste streams that could be captured including liquid wastes. In this study, a novel ingredient was used in the diet of catfish that was the combination of liquid poultry waste and corn to produce a by-product meal. The results from the first trial of this study demonstrated that poultry corn by-product meal (PCBM) can be used up to 30% in the diet of catfish when replacing whole corn meal and a small quantity of poultry meal without causing any negative effects on the growth of the fish. The highest weight gain (57.50 g) was found in treatment PCBM20 compared with weight gain (52.80 g) in PCBM30, but there were no significant pairwise differences among the treatments ranged from PCBM10 to PCBM30 (Table 4). PCBM may be viewed as having a better ingredient profile compared with whole corn meal as it contains more protein (11.8% in PCBM compared with 7.83% in whole corn meal). Consequently, essential amino acids like lysine and methionine are higher (Table 1).

In this first trial, there was no significant differences in energy retention across all treatments, but there were significant differences in the protein retention in the fish. The highest protein retention (36.60%) was found in PCBM25 and lowest (28.30%) in PCBM15 (Table 4) with no clear trend in the data. The intraperitoneal fat ratio and hepatosomatic index are both indicators of the status of energy reserves in fish. Regarding HSI and IPF in this first trial, there was no significant difference in IPF, indicating similar levels of energy reserves. The HSI of fish maintained on the basal diet was significantly higher (1.00%) than fish offered the CBM10 (0.70%) and PCBM20 (0.80%) diets. The higher HSI was associated with higher fat content, and this could be the reason the basal diet had higher fat (6.01%) than the other diets (Table 2). With regard to the proximate compositions of the fish from trial I, there were no significant differences in moisture, protein or ash in the whole bodies of the fish in all treatments, but there were significant differences in fat content as treatment CBM10 had significantly higher fat content (9.25%) than PCBM15 (7.44%) (Table 5).

In the second growth trial, conducted in 12 raceways with four commercial diets based on poultry and corn by product meal, the results showed that there were no significant differences between all the growth indices: biomass, mean weight, weight gain, total feed, FCR and the survival of the catfish in all treatments (Table 6). Survival slightly exceeded 100% in treatments PCBM20 (108%) and PCBM30 (102%), which was due to a stocking error; it is possible that not all fish were cleared from the raceway prior to stocking or fish were miscounted.

To determine the condition index (K), 30 fish were sampled in each raceway, and total length and weight were recorded. The results demonstrated that there were no significant differences in total length, weight or condition index of catfish reared on the various diets (Table 7). For HSI, IPF and dress out percentage 15 fish were sampled in every raceway and the results showed that there was no significant difference in HIS and dress out % of catfish (Table 7) but there was a significant difference in IPF of fish as PCBM20 had significantly high IPF (4.17%) than rest of the other treatments (Table 7). As far as the proximate composition of fish was concerned, the results revealed that there was no significant difference in protein, fat and ash of whole body of fish in all treatments (Table 8).

The third growth trial was conducted in six raceways with two diets; the commercial diets were the same as in trial 2, but two levels were chosen (basal diet and PCBM30). The results showed that there were no significant differences between any of the growth indices: biomass, mean weight, weight gain, total feed, FCR and survival of catfish in all treatments (Table 9). To check the condition index (K), HIS, IPF and dress-out percentage, 15 fish were sampled in every raceway, and the results showed no significant differences in any of these parameters (Table 10).

## 5. Conclusions

The findings from the current study indicated that poultry corn by-product meal (PCBM) can be used up to 30% in the diets of channel catfish. As the rendering industry goes on to refine its processes and modify the compositions of co-products that are sold on the market, it is proposed that the new products be re-evaluated for their efficiency. This work showed that by-product recycling plays a major role in increasing production output. The circular economy can allow aquaculture to grow and contribute to sustainable nutrition.

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