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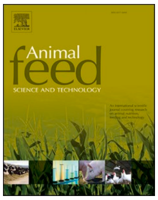

Using poultry by-product meal to replace soybean meal in grower -finisher pig diets

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ABSTRACT

This study investigated the effect of replacing soybean meal (SBM) with poultry by-product meal (PBM) in grower-finisher diets on pig feeding, growth performance, carcass yield and meat quality. The replacement levels were increased from no PBM (PBM0) to 37 g/kg PBM (PBM37), 85 g/kg PBM (PM85) and 111 g/kg PBM (PBM111). All diets met or exceeded nutrient requirements for pigs between 20 – 100 kg live weight (NRC, 2012). Sixty-four entire males (PIC 337 x PIC Camborough 42), at an average live weight (LW) of 27.60 ± 2.48 kg (mean ±SD) were blocked by LW and randomly assigned to 8 pens, with each diet replicated across 2 pens. Pigs had *ad libitum* access to diets via electronic feeders until they reached approximately 100 kg LW, at which time they were slaughtered. Results showed no significant effect of replacing SBM with PBM on pig feeding behavior parameters and the majority of pig growth performance, carcass yield, and meat quality traits, with the exception of higher feed conversion ratio (FCR) in pigs fed the PBM37 diet. Loin muscles from the group fed the PBM111 diet had significantly lower ultimate pH and a greater cooking loss than the other treatments ($P < 0.05$). Loin muscles from pigs fed high levels of PBM (PBM85 and PBM111) had greater ash content than those fed the PBM37 and control diets ($P = 0.001$). Overall, the present research indicated that PBM could be a viable primary protein source in diets for growing-finishing pigs, as it did not appear to have any adverse effects on pig feeding behavior, growth performance and meat quality. In addition, PBM is potentially a good source of calcium and phosphorus for growing–finishing pigs. However, due to the variation in quality and composition of available PBM, it is essential to measure nutritional composition before including PBM in diets for growing-finishing pigs.

1. Introduction

Soybean meal (SBM) is the primary protein source in concentrate diets for livestock due to its high protein content, excellent amino acid (AA) availability and palatability (Dei, 2011). The universally high demand for SBM as an ingredient in animal feed drives global soybean production (Goldsmith, 2008; Ritchie and Roser, 2021). Over two-thirds of global soybean production occurs in the USA and Brazil (Ritchie and Roser, 2021).

Abbreviations: AA, Amino acid; ADFI, average daily feed intake; ADG, average daily weight gain; BFD, back fat depth; FCR, Feed conversion ratio. GE, Gross energy; GMO, Genetically modified organism; PBM, Poultry by-product meal; SBM, soybean meal.

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Dependency on soybean production for farmed animals raises environmental and economic concerns. The expansion of soybean production plays a part in deforestation and biodiversity loss in Amazon countries (Ritchie and Roser, 2021). Furthermore, feed transportation accounts for substantial greenhouse gas emissions (Van der Werf et al., 2005). The high demand for SBM globally, especially in China, inflates SBM prices (OECD/FAO, 2022) and reduces profitability for the livestock industry, as feed is the major cost in livestock production (European Parliament, 2011). The COVID-19 pandemic highlighted the vulnerability of the supply chain to unexpected pressures, including the availability of imported SBM (Schmidhuber et al., 2020), which affected farm production and animal welfare (Hashem et al., 2020; Seleiman et al., 2020). To reduce reliance on imported feed for livestock, locally sourced ingredients and by-products are recommended as alternatives to prevent animal (and human) feed shortages (Zijlstra and Beltranena, 2013; Woyengo et al., 2014; Schader et al., 2015).

The European Parliament expressed concern over potential risks associated with reliance on soy-based feeds, including the possibility of protein-deficient human diets. As a result, they called for research to find alternative protein sources to soy-based feeds (European Union, 2019). In addition to the concern of SBM dependency, there is a growing trend in the European Union towards retailer certification schemes that assure animal products using diets free from genetically modified organisms (GMO). This trend could lead to a shift in feed demand towards other protein sources besides SBM. Lifting the ban on the use of processed animal protein (PAP) in feed for farmed non-ruminant animals (Regulation (EU) 2019/6) could partly address concerns relating to protein deficiencies and non-GMO products preference in Europe (Lusk et al., 2018; Dzwonkowski, 2021). The proposed legislation allows poultry processed protein to be used in pig feed.

Poultry by-product meal (PBM) is a potential protein source for pigs in terms of availability and quality. Up to 30% of the live weight of broilers is mainly inedible raw materials such as skin, bone, blood, organs, and feathers (Ockerman and Basu, 2014). Global poultry meat production in 2020 was 134 million tons, with an estimated 40 million tons of poultry by-products produced that year. Poultry meat production and its by-products are projected to increase in the next few decades (FAO, 2021). Meanwhile, PBM is a highly concentrated source of protein, minerals and energy for animals (Kerr et al., 2017). Valorizing poultry by-products for feed can also prevent waste contamination and reduce greenhouse gas emissions (Mozhiarasi and Natarajan, 2022). Numerous studies tried substituting fishmeal with poultry by-product meal for aquatic animals, with many being successful (Sabbagh et al., 2019; Galkanda-Arachchige et al., 2020; Fontinha et al., 2021). However, Europe’s ban on using PAP in non-ruminant diets lasted many years, so there is rare research investigating using poultry by-products in pig diets. Consequently, the lack of information on optimal PBM inclusion levels and the effect on pig performance has hindered farmers from incorporating this ingredient in pig diets.

The present study evaluated the nutritive value of PBM and investigated the effect of replacing SBM with PBM in growing-finishing pig diets on growth performance, carcass yield and meat quality. The aim was to provide more precise information on PBM inclusion in growing-finishing pig diets so that pig farmers have more comprehensive data when considering ingredient substitution.

2. Materials and methods

The experiment was carried out at the Massey University Pig Biology Unit, Palmerston North, New Zealand and was approved by the Massey University Animal Ethics Committee (MUAEC 22/09.).

2.1. Animals, experimental design and housing

2.1.1. Animals and experimental design

Sixty-four 10 week old entire male pigs (PIC 337 x PIC Camborough 42), at an average live weight (LW) of 27.60 ± 2.48 kg (mean ± SD), were purchased from a commercial indoor pig farm and transported to the Massey University Pig Biology Unit. They were randomly allocated into 8 pens, with 8 pigs per pen, and had one week of acclimatization before the experiment started. Partway through the experiment, one pig from PBM111 was removed due to illness and was not included in analyses.

2.1.2. Housing and facilities

The pigs were housed in pens measuring 20 m^2 with a solid concrete floor, enabling a space allowance of 2.5 m^2/pig. Each pen had an unlit sleeping area separated by a wall from where the feeder and drinker were located, and accessed via a doorway. The pigs had free access to all areas of the pen at all times. A thermostatically controlled heat lamp maintained air temperature inside the lying area. The temperature was maintained between 20 and 25 °C when the pigs were less than 50 kg LW, and 18–22 °C when the pigs were over 50 kg LW. Artificial lighting in the feeding area was provided daily from approximately 0700 to 1700.

Pigs had *ad libitum* access to water and feed throughout the experiment via a water nipple, and a feeder equipped in each pen. Automatic electronic feeders (Osborne FIRE System, Osborne Industries, Inc., Osborne, KS, USA) were used in the experiment. The feeders were calibrated at the start of the study and once each week thereafter, using a 500-g calibration weight. The feeder entrance featured an adjustable half-body race that enabled only one pig to eat at a time. A Radio Frequency Identification (RFID) ear tag identified each pig to the feeder, which in turn recorded the pig’s tag number automatically in addition to the amount of feed consumed per visit, the entry and exit time per visit, and visit duration. If a visit took place but no tag was identified, the visit was classified as a "Tag 0" event. Data were checked daily for errors and downloaded onto a hard drive until analysis. Error checks were based on the criteria detailed in Casey et al. (2005). Feeding areas were under video surveillance, and errors and “Tag 0” events were verified on the video recording to improve accuracy.

2.2. Experimental diets

PBM was sourced from Kakariki Protein (Marton, New Zealand) and diets were mixed and pelleted by Denver Stock Feeds (Palmerston North, New Zealand) before the start of the experiment. Only one batch of PBM was used to formulate all of the experimental diets with PBM included. The PBM comprised approximately 70% offal, 20% heads and feet and the remaining 10% as trimmings.

Four dietary treatments were produced by substituting PBM for SBM as the primary protein source: PBM0 (100% SBM), PBM37 (33% SBM was replaced with PBM), PBM85 (67% SBM was replaced with PBM), and PBM111 (100% PBM). All diets met or exceeded nutrient requirements for pigs between 20 – 100 kg LW (NRC, 2012) and were similar in crude protein, digestible energy, and AID Lysine (Table 2).

2.3. Data collection

2.3.1. Growth performance data

Feed intake was calculated daily, weekly and for the whole experimental period for each individual pig using the downloaded data generated by the automatic feeders. All pigs were weighed individually on the same day each week between 0700 and 0800. Feed conversion ratio (FCR) was calculated weekly for each pig by dividing the total amount of feed consumed in the week by the weekly weight gain.

2.3.2. Pig feeding behavior

Data generated from the feeders were used to analyze pig feeding behavior. Because the number of pigs per pen were not equal after week 9, feeding behavior was analyzed only until day 62. Values for each pig for the number of feeder visits per day, feed intake per visit, feeder occupation duration per visit, and feed consumption rate were calculated for the 62 day period.

2.3.3. Slaughter

The pigs were slaughtered when they reached approximately 100 kg LW. The 25 heaviest pigs (6–7 per treatment group) were selected as the first cohort to be slaughtered. The following week, the 25 heaviest pigs (6–7 per treatment group) were selected for the second cohort, with the remainder (n = 13, 3–4 per treatment group) slaughtered the third week. The pigs were transported for less than 1 hour to a commercial abattoir (Land Meat Ltd, Wanganui), rested overnight, and slaughtered the following morning.

Hot carcass weight (without kidneys and leaf fat) and back fat depth (BFD) were recorded within 30 minutes of slaughter. The BFD was measured in the right side of the carcass at the P2 position, about 65 mm from the dorsal mid-line at the level of the last rib, using a Hennessy grading probe (Hennessy Technology, Auckland, New Zealand).

The following day, carcasses were cut and the deboned loins with fat and skin were transported to Massey University and stored frozen (-20°C) until meat quality analysis was carried out.

2.3.4. Meat quality

The loin (m. longissimus thoracis) was defrosted at 4°C over 24 hours. The subcutaneous fat and skin were removed from the loins, and each loin was subdivided into 4 portions. A 4 cm section of the cranial portion was used to measure pH. A 3 cm section in the mid portion was used to assess color and drip loss. The next two 2.5 cm sections in the mid loin were used for cooking loss followed by shear force measurements.

The samples were analysed in 6 batches. Within a batch, the samples from all the treatment were present.

2.3.4.1. Ultimate pH. The ultimate pH was measured as the average across three points from medial to distal across a transverse, internal cut of the loin with a pH spear (Hanna 99,163 pH meter with a FC232D combined temperature and pH insertion probe, Rhode Island, USA). The pH spear was calibrated to pH 4.01, 7.00 and 10.01 standard buffers.

2.3.4.2. Color. The lean meat color was measured on a freshly cut, transverse surface after a 30 minute bloom using a Minolta Color Meter calibrated to a standard white tile supplied by the manufacturer (CR-200, Konica Minolta Photo Imaging Inc., Mahwah, NJ, USA). The CIE L* (lightness), a* (redness) and b* (yellowness) values were measured. Chroma C* and Hue angle h° were calculated using the equations as follows:

$$C = \sqrt{(a^{*2} + b^{*2})}$$

$$H = \arctan\frac{a^*}{b^*}$$

2.3.4.3. Drip loss. A 3 × 3 × 3 cm cube of raw meat was weighed, then suspended in a net in a plastic bag at 4°C. After 24 hours and 48 hours the suspended cube was blotted with tissue paper and reweighed. The water loss was calculated as the original weight minus the weight after 24 hours (drip loss 24 hr) and 48 hours (drip loss 48 hr), with drip loss expressed as a percentage of the original weight.

2.3.4.4. Cooking loss. The two 2.5 cm sections were separately weighed, vacuum packed and cooked in a water bath at 70°C for 90 min. Fluid from inside the bag was decanted and the samples were left to cool at 1–2°C for 4 h. Meat was then removed from the bag, blotted dry, and re-weighed. Cooking loss was calculated as the difference in weight before and after cooking and expressed as a percentage of the weight before cooking.

2.3.4.5. Shear force. Cores (diameter = 1.27 cm) from the 2.5 cm portions prepared for cooking loss above were removed parallel to the longitudinal orientation of the muscle fibres. Shear force measurements were determined using a texture analyzer (Stable Micro System TA. HD Plus texture analyzer, Surrey, UK) fitted with a Warner-Bratzler shearing blade with a crosshead speed set at 200 mm/min. The samples were sheared perpendicular to muscle fiber orientation. Values for each pig were an average from 6 cores per sample.

2.4. Sample storage and chemical analyses

Samples of feed were pooled by diet and stored at 4°C, while meat samples were stored at -20°C. Chemical analyses of samples were performed at the Massey University Nutrition Laboratory, Palmerston North, New Zealand. Gross energy (GE) of the trial diets was determined by bomb calorimetry (AC-350, LECO Corporation, St. Joseph, MI, USA). Other analyses were according to the respective methods of AOAC (2005) or as follows: dry matter (AOAC 925.10 and 930.16); crude protein (AOAC 968.06, Dumas method); fat (AOAC 922.06, Mojonnier method,); crude fibre (AOAC 962.09/978.10 - modified); NDF (aNDFom, AOAC 2002.04); ADF (ADFom, AOAC 973.18); lignin (Lignin(sa)AOAC 973.18); starch (α-amylase Megazyme kit, AOAC 996.11); ash (Furnace 550°C, AOAC 942.05); minerals ICP-OES, sub-contracted); amino acid profile (acid stable: HCl hydrolysis followed by RP HPLC separation using AccQ Tag derivatization, AOAC 994.12); cysteine/methionine (performic acid oxidation, AOAC 985.28); tryptophan (AOAC 2017.03, sub-contracted, non-accredited);

Skatole levels in back fat samples were determined using the method of Hansen-Møller (1994).

2.5. Statistical analysis

All statistical analyses were performed using SAS® software (SAS, 2022). Individual pigs were the experimental unit in all analyses. A linear model (Proc GLM) with diet as a fixed effect was fitted to the feeding behavior, growth performance, carcass characteristics and skatole concentration.

For the meat quality parameters, the batch was added into the model as a random effect.

Statistical significance was at $P < 0.05$, and a trend was expressed when $P < 0.10$. LSD was used for the post hoc test. Results were presented as least square means.

3. Results

3.1. Crude protein and amino acid profile in PBM

Lab analyses results indicated that PBM is an excellent protein source for growing pigs, containing approximately 64% crude protein on an as-fed basis (Table 1). Furthermore, PBM is rich in essential AAs, including Lysine, Threonine, and Methionine, which account for 36.3, 22.5, and 12.4 g/kg of PBM, respectively Table 2.

Table 1
Analysed crude protein and amino acid profile of Poultry by-product meal and Soybean meal.

g/kg as fed basis	Poultry by-product meal	Soybean meal
Dry matter	953	885
Crude protein	638	416
Ash	242	60
Fat	73	9
Aspartic Acid	46.7	57.0
Threonine	22.5	19.7
Serine	24.3	24.6
Glutamic Acid	77.0	93.9
Proline	40.5	25.0
Glycine	64.2	20.5
Alanine	40.8	21.1
Valine	25.9	23.3
Isoleucine	22.1	22.5
Leucine	39.2	37.6
Tyrosine	16.2	16.5
Phenylalanine	21.6	24.5
Histidine	10.1	13.4
Lysine	36.3	31.0
Arginine	41.6	35.6
Cysteine	6.1	5.9
Methionine	12.4	6.7
Tryptophan	4.2	5.9

Table 2

Ingredient and proximal composition of experimental diets.

Feed ingredients	Dietary treatment[a]			
	PBM0	PBM37	PBM85	PBM111
	g/kg, as-fed			
Barley	744.25	778.42	822.1	846.3
Soybean Meal	200	134	46	0
Soybean oil	20	20	19	18
Poultry by-product meal	0	37	85	111
L-Lysine	1.05	1.78	2.8	3.3
Methionine	1	1	1.1	1.2
Threonine	1.5	1.5	1.5	1.7
Tryptophan	0	0.1	0.4	0.5
Vitamin + Mineral Premix[b]	2	2	2	2
Dicalcium Phosphate ($CaHPO_4$)	26	22	18	14
Sodium Phosphate dibasic (Na_2HPO_4)	4	2	2	2
Sodium Chloride (NaCl)	0.2	0.2	0.1	0
Calculated values[c]				
Crude protein	158	158	158	158
Digestible energy (MJ/kg)	13.84	13.84	13.78	13.76
Apparent ileal digestible Protein	121	122	124	125
Apparent ileal digestible Lysine	8.66	8.66	8.66	8.66
Apparent ileal digestible Methionine + Cystine	5.24	5.13	5.05	5.07
Apparent ileal digestible Threonine	6.95	6.59	6.09	5.85
Apparent ileal digestible Tryptophan	1.65	1.56	1.59	1.56
Lab chemical analysis				
Dry matter	878	878	877	877
Gross energy (MJ/kg)	16	16.1	16.2	16.2
Crude protein	165	160	147	153
Amino acid profile				
Aspartic Acid	18.2	14.1	13.1	11.1
Threonine	7.9	7.2	6.3	6
Serine	8.7	7.4	7	6.2
Glutamic Acid	31.4	34.2	27.2	24
Proline	11.8	12.3	12	11.2
Glycine	8.8	8.7	9	9.6
Alanine	7.6	7.1	7.3	7.3
Valine	8.7	8	7.7	7.3
Isoleucine	6.8	6.1	5.6	5.1
Leucine	12.4	11.3	10.6	9.7
Tyrosine	6.4	5.8	5.2	4.7
Phenylalanine	8.6	8.1	7.2	6.4
Histidine	4	3.5	3.2	2.8
Lysine	10.6	9.7	10.2	10.1
Arginine	11.3	9.9	9.1	8.3
Cysteine	2.8	2.6	2.7	2.6
Methionine	3	4.6	4.2	4
Tryptophan	2.2	2.1	2	2.2
Starch	342	339	385	371
Fat	29	33	35	33
Crude fibre	45	44	39	47
Neutral detergent fibre[d]	138	147	142	153
Acid detergent fibre[4]	47	50	44	52
Lignin[4]	10	10	11	11
Ash	56	52	52	49
Calcium	9.1	7.9	9.2	12
Potassium	8.1	6.4	5.2	4.4
Sodium	1.15	1.24	1.39	1.39
Phosphorus	8.4	7.5	8.2	9.1
Chloride	1.3	1.58	1.97	2.1

[a] PBM0 (0 PBM), PBM37 (37 g/kg PBM), PBM85 (85 g/kg PBM) and PBM111 (111 g/kg PBM).

[b] Provided per kilograms of diet: 7000 IU of vitamin A, 1500 IU of vitamin D3, 35 IU vitamin E, 2 mg of vitamin K, 1.5 mg of vitamin B1, 3 mg of vitamin B2, 2 mg of vitamin B6, 15 μg of vitamin B12, 11 mg of pantothenic acid, 15 mg of niacin, 20 μg of biotin, 0.25 mg of folic acid, 90 mg of choline, 80 mg of iron (sulfate), 30 mg of manganese (sulfate), 1 mg of cobalt (chloride), 0.3 mg of selenium (sodium selenite), 115 mg of zinc (oxide), 20 mg of copper (carbonate), and 1 mg of iodine (potassium iodate).

[c] Morel et al. (1999)

[d] NDF assayed with a heat stable amylase and expressed exclusive of residual ash; ADF expressed exclusive of residual ash; Lignin determined by solubilization of cellulose with sulphuric acid.

3.2. Pig feeding behaviour characteristics

The effect of replacing SBM with PBM on pig feeding behavior is presented in Table 3. The results showed no difference in feeding behavior among pigs that were fed a PBM0 diet and those fed diets that had 37 g/kg, 85 g/kg, or 111 g/kg of of PBM. Specifically, the number of feeder visits per day, feed intake per visit, occupation duration per visit, and feeding rate were similar across the different dietary treatments ($P > 0.05$).

3.3. Pig growth performance and carcass yield

Table 4 displays the impact of substituting SBM with PBM on both pig growth performance and carcass yield. The results revealed that there were no differences between the PBM0 diets and the experimental diets with regards to pig growth performance and carcass yield ($P>0.05$). However, a difference was found for the feed conversion ratio (FCR) across the diets containing PBM, where pigs fed the PBM37 diet had a higher FCR compared to those fed the PBM85 and PBM111 diets (FCR = 2.28 vs. 2.13; $P < 0.05$). Furthermore, there was a tendency towards higher dressing percentages in pigs fed the PBM-containing diets compared to those fed the PBM0 diet ($P = 0.088$).

3.4. Physicochemical characteristic of meat

Overall, replacing SBM with PBM did not impact the majority of examined meat quality traits ($P > 0.05$, Table 5). No effects of dietary treatment were found regarding shear force, water holding capacity (expressed as drip loss), color of loin muscles (L*, a*, b*) and skatole concentration ($P > 0.05$). However, the variation of this trait was large. Dry matter, protein and fat content of loin were similar across the treatments.

Nevertheless, there were slight differences in some traits. For instance, the ultimate pH of pork in the PBM85 and PBM111 groups was lower than that of pork in the PBM0 diet and PBM37 group ($P < 0.05$). Additionally, the ash content of loin muscles from pigs fed diets with higher level of PBM (PBM and PBM111) was higher than those fed PBM37 and the PBM0 diet ($P = 0.001$). Finally, while the cooking loss of pork in the PBM111 diet was slightly higher than that of the other dietswith PBM, it was comparable to that of the PBM0 diet.

4. Discussion

Poultry by product meal (PBM) is a nutrient-rich feed ingredient derived from rendered poultry byproducts such as heads, feet, and internal organs. With its high levels of protein, ash, and other essential nutrients, PBM has shown promise as a replacement for fish meal in aquaculture and as a protein supplement in young pig diets (Galkanda-Arachchige et al., 2020; Zier et al., 2004). Yet, despite these encouraging findings, there remains a dearth of research into the effects of feeding PBM for growing–finishing pigs on growth performance and pork quality.

The ban on animal by-products in pig diets in Europe further complicates matters. Previous studies on PBM in growing-finishing pigs have yielded conflicting results compared with studies involving younger pigs. The recent lifting of the ban presents an opportunity to revisit this issue, there is still much to learn about the implications of using PBM for pigs, both in terms of growth performance and pork quality.

4.1. Feeding value of PBM

PBM is widely acknowledged as a valuable protein source for farmed animals owing to its high protein content, which is over 60%, and abundance of essential AAs. Nonetheless, the precise contents of PBM may differ between studies, owing to the varied characteristics of raw materials and processing conditions used in each study.

Table 3
Least square means for feeding characteristics of pigs fed diets substituting Soybean meal with Poultry by-product meal, during the first 62 days of the experiment.

Feeding behaviour characteristics	Treatment[a]				SE[b]	P value
	PBM0	PBM37	PBM85	PBM111		
Number of feeder visits per day (N)	13.37	14.30	15.61	14.19	0.963	0.433
Feed intake per visit (g/visit)	186	179	157	171	13.9	0.487
Occupation duration per visit (min/visit)	5.81	5.61	4.77	5.38	0.434	0.364
Feeding rate (g/min)	31.84	32.75	32.64	31.88	1.204	0.922

The pen per day was the experimental unit.

[a] PBM0 (0 PBM), PBM37 (37 g/kg PBM), PBM85 (85 g/kg PBM) and PBM111 (111 g/kg PBM).

[b] SE: standard error

Table 4

Least square means for growth performance and carcass traits for pigs fed diets substituting Soybean meal with Poultry by-product meal.

Growth performance and carcass traits[c]	Treatment[a]				SE[b]	P value
	PBM0	PBM37	PBM85	PBM111		
Experimental period (days)	69	69	69	68	1.3	0.953
Live weight start (kg)	27.72	27.19	27.81	27.67	0.636	0.899
Live weight finish (kg)	103.72	101.91	101.98	103.66	1.286	0.609
ADG (kg/d)	1.11	1.09	1.09	1.12	0.029	0.832
ADFI (kg/d)	2.44	2.47	2.31	2.39	0.063	0.331
FCR (kg/kg)	2.21^{ab}	2.28^{a}	2.13^{b}	2.13^{b}	0.039	0.014
Carcass weight (kg)	77.20	77.32	76.51	78.07	1.002	0.754
Dressing out (kg/100 kg)	74.45	75.85	75.02	75.33	0.390	0.088
Backfat thickness (mm)	10.56	11.06	10.06	10.47	0.499	0.563

[a, b] Values in the same row with different superscripts are different ($P < 0.05$).

The individual pig is the experimental unit. There was 15 pigs in PBM111 and 16 pigs in the other treatment group.

[a] PBM0 (0 PBM), PBM37 (37 g/kg PBM), PBM85 (85 g/kg PBM), and PBM111 (111 g/kg PBM).

[b] SE: standard error.

[c] Abbreviations: ADG: average daily weight gain; ADFI: average daily feed intake; FCR: Feed conversion ratio.

Table 5

Least square means for pork quality parameters of pigs fed diets substituting Soybean meal with Poultry by-product meal.

Pork quality parameters	Treatment[a]				SE[b]	P value
	PBM0	PBM37	PBM85	PBM111		
Ultimate pH	5.44^{ab}	5.46^{a}	5.37^{b}	5.35^{b}	0.028	0.011
Drip loss 24 hr (%)	7.04	5.69	8.38	7.19	0.976	0.27
Drip loss 48 hr (%)	8.40	7.35	10.39	9.00	1.005	0.179
Cooking loss (%)	30.0^{ab}	29.4^{b}	29.5^{b}	30.5^{a}	0.33	0.041
Shear force (kgF)	6.31	6.68	6.06	6.56	0.318	0.508
Lightness (L*)	45.50	44.57	44.43	45.93	0.736	0.513
Redness (a*)	5.95	5.88	5.29	6.26	0.354	0.513
Yellowness (b*)	4.24	3.99	3.42	4.55	0.278	0.104
Chroma	7.33	7.16	6.31	7.77	0.419	1.662
Hue	34.79	33.25	33.2	34.98	1.336	0.618
Skatole (ng/ml of fat)	7.52	4.68	3.95	10.78	2.786	0.311
Chemical composition, g/100 g fresh meat						
Dry matter	25.88	25.71	25.69	25.82	0.189	0.883
Crude protein	23.53	23.65	23.70	23.59	0.161	0.888
Fat	1.36	1.14	1.10	1.21	0.121	0.458
Ash	1.19^{a}	1.19^{a}	1.22^{b}	1.23^{b}	0.008	0.001

[a, b] Values in the same row with different superscripts are different ($P < 0.05$).

The individual pig is the experimental unit. There were 15 pigs in PBM111 and 16 pigs in the other treatment group.

[a] PBM0 (0 PBM), PBM37 (37 g/kg PBM), PBM85 (85 g/kg PBM), and PBM111 (111 g/kg PBM).

[b] SE: standard error

The laboratory analysis conducted in this study revealed that the levels of crude protein and AAs in PBM were similar to values reported by NRC (2012) and other recent publications (Kerr et al., 2019; Lewis et al., 2019; Yoo et al., 2019). However, the crude protein and AA profile of PBM revealed in the present study were lower than those in the other studies such as Keegan et al. (2004) and Sung et al. (2022). In contrast, several studies have reported much lower values of crude protein and AA profiles than those observed in our experiment (Ye et al., 2011; Mahmood et al., 2018). From 16 PBM samples representing different geographical locations and animal rendering facilities, Kerr et al. (2019) observed a range from 55% to 71% for CP, 3.1–4.6% for Leucine, 2.7–4.0 for Lysine, 1.8–2.6% for Methionine. Similarly, a meta-analysis conducted by Galkanda-Arachchige et al. (2020) reported protein content ranging from 51% to 72% for PBM across 47 studies. The composition of PBM, which is made from inedible materials from poultry slaughter including bones, offal, and undeveloped eggs, can vary across facilities resulting in a highly variable chemical composition. Meanwhile, nutritional values of SBM are relatively constant due to uniform processing conditions and homogeneous soybean varieties used in the process (Ferket et al., 2002).

Furthermore, digestible AA of PBM were not comparable with that of SBM (Rojas and Stein, 2013). Some animal proteins could contain a high proportion of collagen (around 80%), which is derived from connective tissue, skin, tendon and cartilage (Chiba, 2000). Collagen is a source of low biological value AAs that can reduce the overall digestibility of AAs in the protein (Eastoe and Long, 1960). In addition, excess heat during processing PBM to remove high moisture content and inactivate potentially harmful microorganisms might cause Maillard reaction and racemization, reducing AA digestibility and decreasing energy utilization (Oliveira et al., 2020; Sung et al., 2022). For example, Sung et al. (2022) reported that autoclaving time during PBM processing linearly reduced apparent total tract digestibility (ATTD) of gross energy (GE) and nitrogen and metabolizability of GE (Sung et al., 2022). The quality of AAs in

PBM affects the estimation of standardized ileal digestibility of AAs, which differs by 20–30% across peer reports (Kerr et al., 2019). In our study, the diets we formulated on apparent ileal digestibility.

Inaccurate nutritive value information of PBM leads to inadequate or imbalanced nutrient supply for growth. The wide range of nutritive quality and digestibility of PBM make it challenging to formulate diets for pigs, however, it is better to balance diets based on the nutrient digestibility rather than chemical composition of PBM diets. In the present study, we did not evaluate the digestibility of PBM for growing-finishing pigs. Instead, we have used the gross chemical analysis of the PBM and the apparent ileal digestibility AA coefficients from NRC (2012) to formulate the diets that exceeded nutrient requirements for growing pigs. The purpose of this study was to investigate if SBM can be substituted by PBM in grower-finisher pig diets. As there is some variation in the nutritive value of PBM, it is important to have information on the gross chemical composition before formulating diets. Our study showed that under those conditions it is possible to use PBM instead of SBM in grower-finisher pig diets without compromising performance or meat quality.

4.2. Effect of replacing SBM with PBM on growing-finishing pig production

Based on the nutritive value of PBM, it is expected to be an excellent protein source for pigs. However, previous research on using PBM for weaner and growing pigs yielded conflicting results. This underscores the need for further investigation and careful consideration of the specific growth stage when making dietary recommendations.

Studies on young pigs showed no effects on growth performance with diets that substituted other more expensive protein sources with PBM. A study by Zier et al. (2004) found that 20% PBM could replace blood meal and fish meal, as well as a portion of SBM in weaner pig diets, without affecting the overall performance of young pigs. Additionally, Keegan et al. (2004) demonstrated that PBM could be used in weaner diets in place of spray-dried animal plasma. That study also showed a linear increase in gain:feed of weaners when PBM was included in the corn-soybean diet with 10% spray-dried whey. In contrast, the two studies that fed diets with PBM to growing-finishing pigs reported a negative impact on pig growth performance. As reported by Tibbetts et al. (1987), pigs fed a diet containing 30% poultry offal silage (60% ground poultry offal, 30% ground shelled corn, 5% dried molasses, and 5% *L. acidophilus* culture) had a slower growth rate, poorer feed conversion, and smaller longissimus muscle size compared to those fed a commercial diet. Similarly, Shelton et al. (2001) reported that finishing pigs fed diets using PBM as the sole protein source had a lower average daily gain and average daily feed intake and increased average backfat relative to pigs fed a SBM-based diet.

The failure to effectively use PBM in pig diets may be due to inaccurate diet formulation that failed to meet requirements for growing pigs. As mentioned above, PBM poses a challenge to feed formulation due to variation in its nutritive value. For example, Tibbetts et al. (1987) explained that the lower level lysine in poultry offal silage diet resulted in the negative impact of the diet on pig growth performance. In the present study, all the diets were formulated to meet or exceed the nutrient requirements and were equal in digestible energy and lysine There was no difference in ADG between treatments. The FCR of pigs fed the PBM85 was the poorest, which could be explained by the fact those pigs had a numerically higher ADFI and backfat thickness.

Overall, the present research demonstrated that PBM could effectively substitute SBM without detrimental effects on pig growth performance during the grower-finisher stage. Furthermore, we found that pig feeding behavior was not adversely affected when PBM was included in their diets. Voluntary feed intake is affected by dietary factors such as palatability,bulkiness or an imbalance in nutrients (Nyachoti et al., 2004). Given no effect of the diet on feed intake, our research suggests that the PBM used in this study (70% offal, 20% heads and feet and 10% trimmings) is similar to SBM in terms of palatability.

4.3. Effect of replacing SBM with PBM on meat quality

Our research showed no effect of partly or completely replacing SBM with PBM on any of the evaluated meat quality traits, or skatole concentration. As far as we know, this is the first study to examine effect of incorporating PBM in diets of pigs during their growth and finishing stage on meat quality. However, further study needs to evaluate the effect of feeding PBM on fat characteristics.

The results of the present study align with other findings where SBM was substituted for alternative dietary protein sources. Altmann et al. (2019) reported that meat from pigs fed Spirulina or *Hermetia illucens* larval meal was comparable in quality to meat from soy-fed animals, according to sensory and physico-chemical meat quality analyses, although this study found an effect on fat characteristics of backfat. Alternative plant-based protein sources, such as local oilseed meals or legume plants, can possibly replace SBM in pig diets without compromising meat quality. Qin et al. (2015) noted a decrease in muscle-specific AAs when substituting 100% SBM with cottonseed meal but found no impact on meat quality traits. Similarly, Zmudzińska et al. (2020) found neither pork meat quality parameters determining the technological suitability of the meat, nor proximal composition of loin muscles, were affected by feeding pigs with a diet based on legume seeds and rapeseed meal instead of a conventional the diet based on SBM. These finding suggests that while the type of protein source used in pig diets may affect fat characteristics or AA profile of loin muscles, it may not have a significant impact on overall meat quality. Consequently, when considering the integration of alternative protein sources, such as plant-based meals, in pig diets, it is vital to evaluate their impact on pig performance and fat characteristics while not requiring a thorough examination of their impact on meat quality.

In addition, compared with plant protein sources, PBM can be a better source of phosphorus for growing-finishing pigs due to its higher biological availability of phosphorus (P) from bones included in PBM (Woyengo and Nyachoti, 2013; Woyengo et al., 2022). In our calculation to balance mineral contents across diets, less dicalcium phosphate (CaHPO4) and sodium phosphate dibasic (Na2HPO4) were used in diets containing high inclusion of PBM. We assumed that the calcium (Ca) and P content of our PBM were 446.6 g/kg and 24.1 g/kg, respectively. However, a more accurate diet formulation will be achieved if the PBM used is also analyzed for its mineral content. Furthermore, there is a lack of information on the digestibility of P and Ca in protein sources derived from slaughter by-products fed to pigs. Such information will help pig producers to formulate optimal diets based available P and Ca contents. Further research needs to evaluate biological availability of these minerals in PBM for growing-finishing pigs.

The success of using PBM in diets formulated for growing-finishing pigs expands the opportunities to select alternative protein sources. Global PBM production is estimated at around 40 million tons per year, which can be tapped to reduce reliance on SBM as a protein source, particularly in countries that do not produce much or any SBM. Using PBM has two key benefits. Firstly, it can address supply chain disruptions because PBM is widely available and can be produced locally in countries with high poultry production. Secondly, using PBM instead of SBM can help achieve environmental sustainability goals by reducing waste and lowering the carbon footprint of pig diets that rely on soybean production and transportation. Given that PBM can be used instead of SBM, the price of these ingredients will be determined by their dietary inclusion levels when least cost diet formulation is used. Given that pigs are already efficient at converting feed into animal protein, incorporating more PBM in pig feed can make pork more sustainable, leading to a more efficient, profitable, and sustainable livestock industry. The research findings offer valuable insights into how the quest for alternative feedstuffs can avoid compromising pig growth performance and meat quality.

5. Conclusion

Our study suggests that poultry by-product meals can serve as a viable primary protein source in growing-finishing pig diets without compromising pig production. The inclusion of poultry by-product meals in pig feed can contribute to a more efficient and sustainable livestock industry. However, given the significant variation in its quality and composition, it is crucial to ensure that this by-product is added in a manner that meets the nutrient requirements for optimal pig growth. Our findings can serve as a useful reference for nutritionists and producers who are unable to conduct lab analyses for feed ingredients, particularly given the observed variability in poultry by-product meal quality in previous research.

CRediT authorship contribution statement

K.L. Chidgey: Investigation, Writing – review & editing, Supervision. **Thanh T. Nguyen:** Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **N.M. Schreurs:** Conceptualization, Investigation, Methodology. **T.J. Wester:** Investigation, Supervision, Writing – review & editing. **Patrick Morel:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author agreement statement

I, the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

I confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. I further confirm that the order of authors listed in the manuscript has been approved by all of us.

I understand that the Corresponding Author is the sole contact for the Editorial process. He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs

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