








Potential of field peas and faba beans as protein-rich alternatives for partial or full replacement of soybean meal in broiler chicken diets

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ARTICLE INFO

Keywords:

Digestibility

Field peas

Faba beans

Protein

Soybean meal

ABSTRACT

This study aimed to evaluate the potential of field peas (FP), faba beans (FB), and their combination to replace soybean meal (SBM) in broiler diets. Experimental diets were formulated to progressively replace SBM with FP, FB, or both across four feeding phases: starter (0–10 d), grower (10–24 d), finisher (24–35 d), and withdrawal (35–42 d). Each of the six dietary treatments was replicated 10 times, with 6 straight-run Ross 308 broiler chicks per replicate. Growth performance was monitored, and nutrient utilization was assessed. Protein and starch digestibility were measured at the distal jejunum and distal ileum, and the starch to protein (S:P) disappearance rate and ratios were calculated for each intestinal segment. Progressive replacement of SBM up to 55 % in the starter, 66 % in the grower, and 100 % in the finisher and withdrawal phases resulted in final BW and FCR that were statistically similar to the control SBM-based diets. However, complete replacement of SBM from the grower phase onward significantly reduced BW, FCR, and breast meat yield, particularly in birds offered diets based on FP ($P < 0.05$). Dietary treatments had no significant effect on AME, AMEn, or the AME:gross energy ratio ($P > 0.05$). Diets containing FP, FB, or their combination significantly increased nitrogen retention and excreta dry matter, and reduced water intake ($P < 0.05$). No significant effects were observed on protein or starch digestibility or their disappearance rates at either the distal jejunum or distal ileum ($P > 0.05$). However, the inclusion of FP and FB significantly increased the S:P disappearance rate ratio in both intestinal segments ($P < 0.05$). These results indicate that both FP and FB can be used effectively only for partial replacement of SBM in broiler diets. While the increased S:P disappearance rate ratio suggests altered nutrient absorption dynamics and may explain the decline in performance of the birds fed high level of legumes, further investigation on underlying effects on intestinal functions is required.

Introduction

Feed cost represents a significant portion of broiler chicken meat production expenses, accounting for approximately 70 % of the total cost (Willems et al., 2013). Protein, which supplies essential amino acids (AA) and building blocks for muscle, are both functionally and financially important to poultry production. Soybean meal (SBM) has long been the primary protein source in broiler chicken diets globally due to its high protein content and AA digestibility (Selle et al., 2023). However, over 80 % of global soybean production is concentrated in just a few countries: Brazil (39 %), the USA (29 %), and Argentina (13 %)

(USDA, 2024). Regions outside these major producers, including Australia, the European Union, and various Asian countries, rely heavily on SBM imports. This dependency raises several concerns, including environmental impacts from long-distance transportation, supply chain instability and fluctuating cost; hence, exploring alternative protein rich ingredients, such as legumes, could provide a sustainable and economically viable solution to reduce reliance on imported SBM. This strategy is particularly important in Australia, where legumes are widely used as rotation crops to improve soil fertility, enhance nitrogen levels, and support sustainable farming.

Both faba beans (*Vicia faba*) and field peas (*Pisum sativum*) are

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<https://doi.org/10.1016/j.psj.2025.106191>

Received 20 October 2025; Accepted 2 December 2025

Available online 3 December 2025

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reported to serve as alternatives to SBM in poultry diets (Adekoya and Adeola, 2023) due to their high carbohydrate and protein content (Crépon et al., 2010; Ravindran et al., 2010). However, their inclusion in poultry diets requires careful consideration, especially in young birds, due to the presence of anti-nutritional factors, which can impact digestibility and overall performance. Both faba beans and field peas may contain compounds such as lectins, trypsin inhibitors, and tannins, which could potentially interfere with the digestive process (Brufau et al., 1998; Mariscal-Landin et al., 2002). Faba beans, in particular, contain glucosidic compounds such as convicine and vicine, which are known to pose health risks like favism in individuals with glucose-6-phosphate dehydrogenase deficiency (Arese et al., 2012; Gatei, 1994). Despite these challenges, the potential benefits of using faba beans and field peas as feed ingredients make them worthy of further exploration and optimization in broiler diets.

Several studies have highlighted the potential of faba beans and field peas as alternative protein sources in broiler chicken diets, though findings regarding optimal inclusion levels are not consistent. For instance, Perez-Maldonado et al. (1999) recommended a maximum inclusion of 20 % field peas in broiler diets to avoid adverse effects on performance. Conversely, Brenes et al. (1993) showed that broilers could be fed diets with up to 48 % field peas without compromising performance compared to a SBM-based diet. Similarly, the inclusion levels of faba beans in broiler diets that do not negatively impact growth performance have been reported to range widely from as low as 16 % (Koivunen et al., 2014) to as high as 45 % (Kopmels et al., 2020; Smit et al., 2021). These discrepancies in optimal inclusion levels for faba beans and field peas in broiler diets may stem from variations in their nutritional and anti-nutritional compositions, processing methods, and overall diet formulation. The chemical compositions of these legumes are inconsistent, particularly for protein, starch, and fibre content (Ramdath et al., 2020). Such variability can be attributed to factors including cultivar, growing condition, and analytical method (David et al., 2024). Therefore, it is necessary to re-evaluate the suitability of faba beans and field peas for modern broiler chickens, with updated nutrient requirements, faster growth rate, and improved feed efficiency, which may also affect their response to legume inclusions. Furthermore, many studies in the literature have not specifically aimed at reducing SBM but rather have incorporated legumes into the diet, often leading to higher overall dietary crude protein levels. This approach confounded the research outcomes by failing to distinguish the impact of dietary protein from the variation in raw materials.

Therefore, the current study was designed to assess the feasibility of using field peas and faba beans to partially or completely replace SBM across four phases of the entire production cycle. Beyond performance metrics, the study also investigates nutrient utilization and digestive dynamics of protein and starch in broiler chickens offered diets with various levels of faba beans and field peas.

Materials and methods

Animal ethics

All experimental protocols and procedures were reviewed and approved by the University of Sydney Animal Ethics Committee (Approval No: 2023/2267).

Experimental design and diets

The study included six treatments, including a control group that was offered diets based on SBM. The remaining treatments involved a step-wise reduction of SBM across four growth phases, using field peas or

Table 1

Layout of experimental design and dietary treatments (TRT).

TRT	Reduction of soybean meal in % (inclusion of legumes in %) ¹				legume
	Starter (0 -10 d)	Grower (10 -24 d)	Finisher (24 -35 d)	Withdrawal (35 -42 d)	
1	-	-	-	-	-
2	40 (12)	66 (17)	100 (25)	100 (25)	Field peas
3	40 (12)	66 (17)	100 (25)	100 (25)	Faba beans
4	55 (17)	100 (25)	100 (25)	100 (25)	Field peas
5	55 (17)	100 (25)	100 (25)	100 (25)	Faba beans
6	70 (12+12)	100 (12.5 + 12.5)	100 (12.5 + 12.5)	100 (12.5 + 12.5)	Field peas + Faba beans

¹ Reduction of soybean meal (%) is expressed relative to its inclusion level in the control diet (TRT 1) within each feeding phase. Values in parentheses indicate the inclusion level of legumes as a percentage of the complete diet (as-fed basis).

Table 2

Analysed chemical composition of soybean meal, field peas and faba beans.

Nutrient % ¹	Soybean meal	Field peas	Faba beans
Dry matter	90.9	91.3	90.4
Crude protein	47.3	22.9	25.3
Lysine	2.84	1.58	1.63
Methionine	0.59	0.19	0.17
Cysteine	0.62	0.29	0.28
Methionine + Cysteine	1.21	0.49	0.45
Threonine	1.80	0.80	0.87
Tryptophan	0.64	0.21	0.22
Arginine	3.25	2.07	2.37
Isoleucine	2.13	0.91	1.04
Leucine	3.50	1.52	1.79
Valine	2.23	1.02	1.16
Histidine	1.18	0.52	0.63
Phenylalanine	2.26	0.99	1.01
Glycine	1.92	0.94	1.04
Serine	2.30	1.00	1.17
Proline	2.39	0.88	1.04
Alanine	2.04	0.95	1.04
Aspartate	5.17	2.44	2.64
Glutamate	8.22	3.61	3.99
Starch	0.70	43.1	38.6
Fat	1.90	1.90	1.80
Crude fibre	3.2	6.30	7.90
Acid detergent fibre	5.1	8.8	11.9
Neutral detergent fibre	9.2	13.9	14.6
Trypsin inhibitor mg inh/g	2.3	1.16	1.30
Total phenolics (as tannic acid) g/kg	-	4.0	12.0
Condensed Tannins (as Leucocyanidin) g/kg	-	1.0	10.0
KOH soluble protein	72.7	82.4	78.5

¹ Unless specified otherwise, all values are expressed as percentages on an as-is basis.

faba beans as outlined in Table 1. The lowest replacement levels (T2 and T3) were 40 %, 66 %, 100 %, and 100 % reduction of SBM in the starter, grower, finisher, and withdrawal phases, respectively. In contrast, the most aggressive replacement levels (T6) were 70 %, 100 %, 100 %, and 100 % reduction of SBM across the four phases, respectively. The diets were offered for the starter (0-10 days), grower (10-24 days) finisher (24-35 days) and withdrawal periods (35-42 days). The diets were formulated based on Ross 308 nutrient specifications (Aviagen, 2022a) and were iso-caloric and balanced for estimated apparent metabolizable energy (AME), and digestible AA including lysine, methionine +

Table 3
Ingredients composition and calculated nutrient profile of the starter diets.

Ingredients %	T1	T2	T3	T4	T5	T6
Wheat 11 %	59.04	57.02	56.73	55.85	55.37	52.34
Soybean Meal 47 %	27.20	16.30	16.30	12.25	12.25	8.15
Field Peas 22.9 %	-	12.00	-	17.00	-	12.00
Faba Beans 25.3 %	-	-	12.00	-	17.00	12.00
Canola Meal 36.5 %	4.00	5.75	5.75	6.25	6.25	6.50
Canola Seed 21 %	4.00	2.23	2.32	1.64	1.81	1.56
Meat Meal 47 %	2.80	3.05	3.05	3.10	3.15	3.20
Limestone 38 %	0.725	0.695	0.715	0.685	0.715	0.700
Canola Oil	0.500	0.500	0.650	0.500	0.700	0.600
Lysine HCl	0.365	0.510	0.520	0.555	0.575	0.590
DL-Methionine	0.355	0.435	0.450	0.465	0.485	0.510
Na Bicarbonate	0.220	0.280	0.285	0.315	0.325	0.355
Vit/Min premix ¹	0.200	0.200	0.200	0.200	0.200	0.200
Salt	0.197	0.137	0.133	0.107	0.099	0.065
L-Threonine	0.180	0.275	0.280	0.305	0.315	0.340
L-Valine	0.064	0.185	0.184	0.228	0.226	0.265
Choline Chloride 60 %	0.060	0.115	0.115	0.135	0.135	0.160
L-Isoleucine	0.034	0.158	0.159	0.202	0.203	0.241
L-Arginine	0.032	0.142	0.126	0.176	0.153	0.168
Phytase (1500 FTU/kg)	0.015	0.015	0.015	0.015	0.015	0.015
Xylanase (200 FXU/kg)	0.010	0.010	0.010	0.010	0.010	0.010
L-Tryptophan	-	-	-	0.013	0.015	0.033
<i>Calculated nutrient composition</i>						
AME kcal/kg	2975	2975	2975	2975	2975	2975
NE Kcal/kg	2338	2340	2341	2341	2341	2343
Protein %	23.1	21.5	21.8	21.0	21.4	20.9
Starch to protein ratio	1.66	1.96	1.90	2.07	1.99	2.09
Dig Lys %	1.32	1.32	1.32	1.32	1.32	1.32
Dig Met %	0.66	0.70	0.71	0.71	0.72	0.74
Dig M + C %	1.00	1.00	1.00	1.00	1.00	1.00
Dig Thr %	0.88	0.88	0.88	0.88	0.88	0.88
Dig Ile %	0.88	0.88	0.88	0.88	0.88	0.88
Dig Leu %	1.50	1.30	1.31	1.22	1.24	1.17
Dig Trp %	0.26	0.22	0.21	0.21	0.21	0.21
Dig Arg %	1.40	1.40	1.40	1.40	1.40	1.40
Dig His %	0.51	0.45	0.45	0.43	0.43	0.41
Dig Val %	1.00	1.00	1.00	1.00	1.00	1.00
Gly equivalent %	1.92	1.76	1.78	1.71	1.73	1.68
Crude Fibre %	3.49	3.70	3.89	3.80	4.07	4.20
Starch %	38.3	42.1	41.4	43.4	42.5	43.7
Calcium %	0.95	0.95	0.95	0.95	0.95	0.95
Available Phosphorus %	0.50	0.50	0.50	0.50	0.50	0.50
Total Phosphorus %	0.56	0.54	0.55	0.54	0.54	0.53
Sodium %	0.20	0.20	0.20	0.20	0.20	0.20
Chloride %	0.26	0.26	0.26	0.25	0.25	0.24
Potassium %	0.83	0.75	0.75	0.72	0.72	0.70
DEB mEq/kg ²	226	205	204	200	200	200

¹ Vitamin concentrate supplied per kilogram of diet: retinol, 12000 IU; cholecalciferol, 5000 IU; tocopheryl acetate, 75 mg; menadione, 3 mg; thiamine, 3 mg; riboflavin, 8 mg; niacin, 55 mg; pantothenate, 13 mg; pyridoxine, 5 mg; folate, 2 mg; cyanocobalamin, 16 µg; biotin, 200 µg; cereal-based carrier, 149 mg; mineral oil, 2.5 mg. Trace mineral concentrate supplied per kilogram of diet: Cu (sulphate), 16 mg; Fe (sulphate), 40 mg; I (iodide), 1.25 mg; Se (selenate), 0.3 mg; Mn (sulphate and oxide), 120 mg; Zn (sulphate and oxide), 100 mg; cereal-based carrier, 128 mg; mineral oil, 3.75 mg.

² Dietary electrolyte balance.

cysteine, threonine, tryptophan, isoleucine, valine, arginine and glycine equivalents. However, the diets were not iso-nitrogenous and there was neither a minimum nor a maximum set for crude protein content (Tables 2 and 3). All diets contained phytase at 1500 FTU/kg and xylanase at 200 FXU/kg. Titanium dioxide was included at 5 g/kg in

withdrawal diets as an inert marker in order to determine nutrient digestibility coefficients in distal jejunum and distal ileum.

Prior to formulating the diets, representative subsamples of wheat, soybean meal, meat and bone meal, canola meal, canola seed, field peas, and faba beans were analyzed using near-infrared spectroscopy to predict proximate analysis, digestible AA concentrations, and metabolizable energy (ME). This was conducted with AMINONIR®PROX, AMINONIR®NIR, and AMINONIR®NRG (Evonik Nutrition & Care, Hanau, DE), respectively. The field peas and faba beans used were not dehulled; they were only ground and used as-is. The diets were then steam-pelleted at a conditioning temperature of 80 °C for 14 sec, using a pellet machine equipped with a die ring featuring 4.0 mm holes and 38 mm thickness. To further enhance feed intake, starter diets were crumbled. All diets were provided *ad libitum* to the broilers. Additionally, the pellet durability index (PDI) for all diets was assessed in triplicate using the NHP 200 New Holman Automatic Pellet Tester (TekPro Ltd, Norfolk, UK).

Birds' management

A total of 360 mixed-sex Ross 308 chicks were procured from a commercial hatchery. Upon arrivals the birds were individually wing-tagged and distributed to 60 metabolic cages, based on their initial body weights. Each treatment was replicated 10 times with 6 birds per replicate cage. The dimensions of the cages were 750 mm in both width and depth and 500 mm in height, providing a floor area of 0.56 m², which resulted in a maximum final stocking density of 35.5 kg BW/m² at day 42 (6 birds per cage with a maximum average BW of 3325 g/bird). The cages were housed in an environmentally controlled room, where birds had unlimited access to water and feed. The lighting regime was set to "23 h on, 1 h off" for the first three days, transitioning to an "18 h on, 6 h off" schedule for the remainder of the study. The room temperature was initially maintained at 32 °C during the first week, gradually decreasing to 22 °C by the end of the third week and remaining at this temperature for the duration of the feeding study. Body weight and feed consumption were monitored on a per-cage basis to calculate the feed conversion ratio (FCR). Daily records were kept of any dead or culled birds, with their body weights used to adjust FCR calculations. Additionally, all culled or deceased birds were dissected to determine gender based on the presence or absence of testis.

Data collection

Total excreta were collected from each cage between days 27 and 29 post-hatch to assess nutrient utilization parameters, including AME, metabolizable energy to gross energy ratios (AME:GE), nitrogen (N) retention, and N-corrected AME (AMEn). The excreta were dried in a forced-air oven at 80 °C for 24 h. Gross energy (GE) of both the excreta and diets was determined using an adiabatic bomb calorimeter. The AME values of the diets were calculated on a dry matter basis using the following equation:

$$AME_{\text{diet}} = \frac{(\text{Feed intake} \times GE_{\text{diet}}) - (\text{Excreta output} \times GE_{\text{excreta}})}{(\text{Feed intake})}$$

The AME:GE ratios were calculated by dividing the AME by the GE of the respective diets. N retention was calculated using the following equation:

$$\text{Retention (\%)} = \frac{(\text{Feed intake} \times \text{Nitrogen}_{\text{diet}}) - (\text{Excreta output} \times \text{Nitrogen}_{\text{excreta}})}{(\text{Feed intake} \times \text{Nitrogen}_{\text{diet}})} \times 100$$

Table 4
Ingredients composition and calculated nutrient profile of the grower diets.

Ingredients %	T1	T2	T3	T4	T5	T6
Wheat 11 %	66.05	60.73	60.88	58.68	58.65	58.66
Soybean Meal 47 %	19.50	6.65	6.65	-	-	-
Field Peas 22.9 %	-	17.00	-	25.00	-	12.50
Faba Beans 25.3 %	-	-	17.00	-	25.00	12.50
Canola Seed 21 %	5.00	3.35	3.90	2.37	3.22	2.79
Canola Meal 36.5 %	5.00	6.75	6.00	7.75	6.75	7.25
Meat Meal 47 %	1.05	1.45	1.35	1.55	1.65	1.60
Limestone 38 %	0.885	0.795	0.880	0.780	0.825	0.800
Canola Oil	0.500	0.500	0.500	0.500	0.500	0.500
Lysine HCl	0.425	0.555	0.580	0.635	0.665	0.650
Na Bicarbonate	0.330	0.405	0.425	0.480	0.480	0.480
DL-Methionine	0.325	0.425	0.445	0.475	0.505	0.490
Vit/Min premix ¹	0.200	0.200	0.200	0.200	0.200	0.200
L-Threonine	0.185	0.285	0.295	0.340	0.350	0.345
Salt	0.145	0.065	0.055	0.000	0.000	0.000
L-Arginine	0.137	0.224	0.208	0.282	0.253	0.268
L-valine	0.096	0.228	0.229	0.300	0.299	0.299
L-Isoleucine	0.076	0.211	0.214	0.284	0.288	0.286
Choline Chloride 60 %	0.075	0.140	0.140	0.175	0.175	0.175
Phytase (1500 FTU/kg)	0.015	0.015	0.015	0.015	0.015	0.015
Xylanase (200 FXU/kg)	0.010	0.010	0.010	0.010	0.010	0.010
K carbonate	-	-	-	0.045	0.060	0.052
L-Glycine	-	-	-	0.096	0.066	0.081
L-Tryptophan	-	0.015	0.018	0.043	0.048	0.045
<i>Calculated nutrient profile</i>						
AME kcal/kg	3050	3050	3050	3050	3050	3050
NE Kcal/kg	2413	2416	2416	2417	2417	2417
Protein %	20.2	18.6	18.9	17.8	18.4	18.1
Starch to protein ratio	2.12	2.51	2.43	2.74	2.58	2.66
Dig Lys %	1.180	1.180	1.180	1.180	1.180	1.180
Dig Met %	0.60	0.65	0.66	0.67	0.69	0.68
Dig M + C %	0.92	0.92	0.92	0.92	0.92	0.92
Dig Thr %	0.79	0.79	0.79	0.79	0.79	0.79
Dig Ile %	0.80	0.80	0.80	0.80	0.80	0.80
Dig Leu %	1.30	1.07	1.09	0.95	0.97	0.96
Dig Trp %	0.23	0.19	0.19	0.19	0.19	0.19
Dig Arg %	1.27	1.27	1.27	1.27	1.27	1.27
Dig His %	0.45	0.38	0.38	0.34	0.34	0.34
Dig Val %	0.91	0.91	0.91	0.91	0.91	0.91
Gly equivalent %	1.61	1.45	1.46	1.45	1.45	1.45
Crude Fibre %	3.56	3.95	4.25	4.11	4.54	4.33
Starch %	42.8	46.7	45.9	48.7	47.5	48.1
Calcium %	0.80	0.80	0.80	0.80	0.80	0.80
Available Phosphorus %	0.40	0.41	0.40	0.41	0.41	0.41
Total Phosphorus %	0.45	0.43	0.43	0.42	0.43	0.42
Sodium %	0.20	0.20	0.20	0.20	0.20	0.20
Chloride %	0.24	0.23	0.22	0.21	0.21	0.21
Potassium %	0.73	0.65	0.65	0.63	0.64	0.63
DEB mEq/kg ²	206	190	190	190	190	190

¹ Vitamin concentrate supplied per kilogram of diet: retinol, 12000 IU; cholecalciferol, 5000 IU; tocopheryl acetate, 75 mg; menadione, 3 mg; thiamine, 3 mg; riboflavin, 8 mg; niacin, 55 mg; pantothenate, 13 mg; pyridoxine, 5 mg; folate, 2 mg; cyanocobalamin, 16 µg; biotin, 200 µg; cereal-based carrier, 149 mg; mineral oil, 2.5 mg. Trace mineral concentrate supplied per kilogram of diet: Cu (sulphate), 16 mg; Fe (sulphate), 40 mg; I (iodide), 1.25 mg; Se (selenate), 0.3 mg; Mn (sulphate and oxide), 120 mg; Zn (sulphate and oxide), 100 mg; cereal-based carrier, 128 mg; mineral oil, 3.75 mg.

² Dietary electrolyte balance.

AMEn values were calculated by adjusting the AME for N retention. This adjustment accounts for the energy associated with nitrogen retention in the body. The AMEn values were determined using the following equation:

$$\text{AMEn (kcal / kg DM)} = \text{AME (kcal / kg DM)} - (\text{N retained (g / kg DM)} \times 8.73 \text{ (kcal / g N retained)})$$

Where: N retained is the nitrogen retained in the body, expressed in

grams per kilogram of dry matter (g/kg DM). The energy equivalent of nitrogen retention was 8.73 kcal/g N retained. This correction provides a more accurate measure of the energy available for growth and maintenance, excluding the energy used for nitrogen retention.

On day 42, all the remaining birds in each cage were euthanized and

their gender was determined. Skinless breast meat (*pectoralis major* and *minor*), leg quarter (thigh + drumstick), and abdominal fat pad were

Table 5
Ingredients composition and calculated nutrient profile of the finisher diets.

Ingredients %	T1	T2 and T4	T3 and T5	T6
Wheat 11 %	69.77	58.35	58.10	58.35
Soybean Meal 47 %	14.35	-	-	-
Field Peas 22.9 %	-	25.00	-	12.50
Faba Beans 25.3 %	-	-	25.00	12.50
Canola Seed 21 %	6.00	4.98	5.82	5.40
Canola Meal 36.5 %	6.00	7.00	6.25	6.50
Limestone 38 %	0.810	0.815	0.855	0.835
Meat Meal 47 %	0.500	0.550	0.650	0.600
Canola Oil	0.500	0.500	0.500	0.500
Lysine HCl	0.440	0.510	0.535	0.525
Na Bicarbonate	0.370	0.375	0.390	0.380
DL-Methionine	0.300	0.410	0.440	0.425
Vit/Min premix ¹	0.200	0.200	0.200	0.200
L-Threonine	0.180	0.270	0.280	0.275
L-Arginine	0.160	0.184	0.155	0.169
Salt	0.125	0.085	0.075	0.080
L-Valine	0.102	0.233	0.232	0.233
L-Isoleucine	0.093	0.225	0.228	0.227
Choline chloride 60 %	0.075	0.150	0.150	0.150
Phytase (1500 FTU/kg)	0.015	0.015	0.015	0.015
Xylanase (200 FXU/kg)	0.010	0.010	0.010	0.010
L-Tryptophane	-	0.025	0.030	0.028
L-Glycine	-	0.112	0.081	0.096
<i>Calculated nutrient profile</i>				
AME kcal/kg	3100	3100	3100	3100
NE Kcal/kg	2464	2467	2467	2467
Protein %	18.5	17.1	17.6	17.4
Starch to protein ratio	2.44	2.84	2.69	2.75
Dig Lys %	1.08	1.08	1.08	1.08
Dig Met %	0.56	0.61	0.63	0.62
Dig M + C %	0.86	0.86	0.86	0.86
Dig Thr %	0.72	0.72	0.72	0.72
Dig Ile %	0.75	0.75	0.75	0.75
Dig Leu %	1.18	0.95	0.97	0.96
Dig Trp %	0.21	0.17	0.17	0.17
Dig Arg %	1.17	1.17	1.17	1.17
Dig His %	0.41	0.34	0.34	0.34
Dig Val %	0.84	0.84	0.84	0.84
Dig Val %	1.46	1.40	1.40	1.40
Crude Fibre %	3.69	4.41	4.84	4.62
Starch %	45.2	48.5	47.3	47.9
Calcium %	0.70	0.70	0.70	0.70
Available Phosphorus %	0.37	0.36	0.36	0.36
Total Phosphorus %	0.41	0.37	0.38	0.38
Sodium %	0.20	0.20	0.20	0.20
Chloride %	0.23	0.23	0.23	0.23
Potassium %	0.67	0.62	0.62	0.62
DEB mEq/kg ²	194	180	180	180

¹ Vitamin concentrate supplied per kilogram of diet: retinol, 12000 IU; cholecalciferol, 5000 IU; tocopheryl acetate, 75 mg, menadione, 3 mg; thiamine, 3 mg; riboflavin, 8 mg; niacin, 55 mg; pantothenate, 13 mg; pyridoxine, 5 mg; folate, 2 mg; cyanocobalamin, 16 µg; biotin, 200 µg; cereal-based carrier, 149 mg; mineral oil, 2.5 mg. Trace mineral concentrate supplied per kilogram of diet: Cu (sulphate), 16 mg; Fe (sulphate), 40 mg; I (iodide), 1.25 mg; Se (selenate), 0.3 mg; Mn (sulphate and oxide), 120 mg; Zn (sulphate and oxide), 100 mg; cereal-based carrier, 128 mg; mineral oil, 3.75 mg.

² Dietary electrolyte balance.

removed, weighed, and calculated as g per 100 g live bodyweight of sacrificed birds.

Distal jejunum and distal ileum digesta samples were collected from all sacrificed birds and pooled per cage. Digesta samples were freeze-dried and ground through 0.5 mm screen. Digesta samples were analyzed for the content of the indigestible marker, protein, and starch. Apparent digestibility coefficient of nutrient was calculated based on the

Table 6
Ingredients composition and calculated nutrient profile of the withdrawal diets.

Ingredients %	T1	T2 and T4	T3 and T5	T6
Wheat 11 %	69.04	55.81	55.35	55.58
Soybean Meal 47 %	12.10	-	-	-
Field Peas 22.9 %	-	25.00	-	12.50
Faba Beans 25.3 %	-	-	25.00	12.50
Canola Seed 21 %	7.00	7.00	7.00	7.00
Canola Meal 36.5 %	7.00	7.00	7.00	7.00
Canola Oil	1.30	1.20	1.60	1.40
Limestone 38 %	0.675	0.685	0.750	0.715
TiO ₂	0.500	0.500	0.500	0.500
Meat meal 47 %	0.500	0.500	0.500	0.500
Lysine HCl	0.410	0.415	0.440	0.430
Na Bicarbonate	0.310	0.280	0.290	0.285
DL-Methionine	0.260	0.360	0.385	0.370
Vit/Min premix ¹	0.200	0.200	0.200	0.200
L-Arginine	0.162	0.129	0.097	0.113
L-Threonine	0.155	0.225	0.230	0.230
Salt	0.140	0.120	0.115	0.120
L-Valine	0.081	0.179	0.176	0.177
L-Isoleucine	0.081	0.178	0.180	0.179
Choline chloride 60 %	0.065	0.125	0.125	0.125
Phytase (1500 FTU/kg)	0.015	0.015	0.015	0.015
Xylanase (200 FXU/kg)	0.010	0.010	0.010	0.010
L-Tryptophan	-	0.013	0.018	0.015
L-Glycine	-	0.054	0.021	0.037
<i>Calculated nutrient profile</i>				
AME kcal/kg	3150	3150	3150	3150
NE Kcal/kg	2515	2520	2520	2520
Protein %	17.8	16.8	17.4	17.1
Starch to protein ratio	2.51	2.79	2.61	2.70
Dig Lys %	1.02	1.02	1.02	1.02
Dig Met %	0.51	0.56	0.58	0.57
Dig M + C %	0.82	0.82	0.82	0.82
Dig Thr %	0.68	0.68	0.68	0.68
Dig Ile %	0.70	0.70	0.70	0.70
Dig Leu %	1.13	0.96	0.98	0.97
Dig Trp %	0.20	0.16	0.16	0.16
Dig Arg %	1.12	1.12	1.12	1.12
Dig His %	0.39	0.35	0.35	0.35
Dig Val %	0.80	0.80	0.80	0.80
Gly equivalent %	1.42	1.35	1.35	1.35
Crude Fibre %	3.85	4.65	5.04	4.84
Starch %	44.7	46.9	45.5	46.2
Calcium %	0.65	0.65	0.65	0.65
Available Phosphorus %	0.36	0.36	0.36	0.36
Total Phosphorus %	0.40	0.37	0.38	0.38
Sodium %	0.19	0.19	0.19	0.19
Chloride %	0.23	0.23	0.23	0.23
Potassium %	0.65	0.63	0.63	0.63
DEB mEq/kg ²	184	178	177	178

¹ Vitamin concentrate supplied per kilogram of diet: retinol, 12000 IU; cholecalciferol, 5000 IU; tocopheryl acetate, 75 mg, menadione, 3 mg; thiamine, 3 mg; riboflavin, 8 mg; niacin, 55 mg; pantothenate, 13 mg; pyridoxine, 5 mg; folate, 2 mg; cyanocobalamin, 16 µg; biotin, 200 µg; cereal-based carrier, 149 mg; mineral oil, 2.5 mg. Trace mineral concentrate supplied per kilogram of diet: Cu (sulphate), 16 mg; Fe (sulphate), 40 mg; I (iodide), 1.25 mg; Se (selenate), 0.3 mg; Mn (sulphate and oxide), 120 mg; Zn (sulphate and oxide), 100 mg; cereal-based carrier, 128 mg; mineral oil, 3.75 mg.

² Dietary electrolyte balance.

following equation:

$$\text{Digestibility Coefficient} = \frac{(\text{Nutrient}/\text{TiO}_2)_{\text{diet}} - (\text{Nutrient}/\text{TiO}_2)_{\text{digesta}}}{(\text{Nutrient}/\text{TiO}_2)_{\text{diet}}}$$

Once the digestibility coefficients were calculated the following equation was used to calculate starch and protein (S:P) disappearance

Table 7
Pellet durability index of experimental diets.

Treatments	Pellet durability index (%)		
	Grower	Finisher	Withdrawal
T1 – SBM	93.2 ^b	90.8 ^b	91.5
T2 – Field peas	95.2 ^a	93.5 ^a	90.0
T3 – Faba beans	94.5 ^a	93.2 ^a	90.1
T4 – Field peas	95.6 ^a	93.5 ^a	90.0
T5 – Faba beans	95.4 ^a	93.2 ^a	90.1
T6 – FP + FB	95.3 ^a	93.4 ^a	90.3
SEM	0.25	0.39	0.37
P-value	<.001	0.001	0.062

^{ab}Means within a column not sharing the same superscript are significantly different at *P* < 0.05.

Each value for each treatment represents the mean of 4 replicates.

rate, and S:P disappearance rate ratios in both intestinal segments.

$$\text{Disappearance rate (g / bird / day)} = \text{apparent digestibility coefficient} \times \text{dietary nutrient concentration (g / kg)} \times \text{withdrawal daily feed intake (g / bird / day)}.$$

In addition, the S:P disappearance rate ratio was derived by dividing starch disappearance rate by protein disappearance rate for each segment.

Table 8
The effects of dietary treatments on growth performance of broilers over the starter (0-10 d), grower (10-24 d) phases and from day 0 to 24¹.

Treatments	Body weight (g/b)			Body weight gain (g/b)			Feed intake (g/b)			FCR (g/g)		
	D 0	D 10	D 24	0 – 10 d	10-24 d	0 – 24 d	0 – 10 d	10-24 d	0 – 24 d	0 – 10 d	10-24 d	0 – 24 d
T1 – SBM	46.2	295.6 ^b	1478 ^{ab}	249.4 ^b	1183 ^a	1434 ^a	268.3	1566 ^a	1836 ^a	1.076 ^{ab}	1.324 ^d	1.281 ^c
T2 – Field peas	46.1	307.1 ^{ab}	1482 ^a	261.0 ^{ab}	1174 ^a	1434 ^a	273.6	1571 ^a	1844 ^a	1.048 ^{ab}	1.338 ^{cd}	1.285 ^{bc}
T3 – Faba beans	46.1	302.0 ^{ab}	1465 ^{ab}	255.9 ^{ab}	1163 ^a	1419 ^{ab}	278.6	1590 ^a	1869 ^a	1.088 ^a	1.369 ^{bc}	1.318 ^a
T4 – Field peas	46.1	306.0 ^{ab}	1332 ^c	260.0 ^{ab}	1027 ^b	1290 ^c	270.5	1450 ^b	1724 ^b	1.041 ^{ab}	1.413 ^a	1.337 ^a
T5 – Faba beans	46.3	313.8 ^a	1405 ^{bc}	267.5 ^a	1091 ^b	1357 ^{bc}	273.7	1504 ^{ab}	1777 ^{ab}	1.024 ^b	1.379 ^{ab}	1.309 ^{abc}
T6 – FP + FB	46.4	300.5 ^{ab}	1369 ^c	254.0 ^{ab}	1068 ^b	1319 ^c	263.4	1469 ^b	1729 ^b	1.038 ^{ab}	1.376 ^b	1.311 ^{ab}
SEM	0.18	3.55	18.1	3.54	16.6	17.5	4.57	21.7	22.7	0.014	0.008	0.006
P-value												
Treatment	0.629	0.014	<.001	0.013	<.001	<.001	0.267	<.001	<.001	0.016	<.001	<.001
Male ratio	0.231	0.528	0.108	0.568	0.066	0.016	0.491	0.175	0.047	0.753	0.175	0.301

^{a-c} Means within a column not sharing a superscript differ significantly at the *P* < 0.05.

Each value for each treatment represents the mean of 10 replicates of 6 birds each.

Table 9
Growth performance of broilers over the finisher (24-35 d) and from day 0 to 35.

Treatments	BW (g/b)	Body weight gain (g/b)		Feed intake (g/b)		FCR (g/g)	
		24 - 35 d	0 - 35 d	24-35 d	0-35 d	24-35 d	0-35 d
T1 – SBM	2581 ^a	1102 ^a	2540 ^a	1703 ^a	3545 ^a	1.547 ^b	1.397 ^b
T2 – Field peas	2489 ^{ab}	1010 ^{ab}	2442 ^{ab}	1579 ^{ab}	3420 ^{ab}	1.562 ^{ab}	1.400 ^b
T3 – Faba beans	2504 ^{ab}	1039 ^{ab}	2459 ^{ab}	1619 ^{ab}	3490 ^a	1.557 ^{ab}	1.419 ^b
T4 – Field peas	2287 ^c	951 ^b	2247 ^c	1606 ^{ab}	3339 ^{ab}	1.688 ^a	1.487 ^a
T5 – Faba beans	2376 ^{bc}	973 ^b	2327 ^{bc}	1450 ^b	3223 ^b	1.488 ^b	1.384 ^b
T6 – FP + FB	2409 ^{bc}	1040 ^{ab}	2353 ^{bc}	1585 ^{ab}	3304 ^{ab}	1.522 ^b	1.404 ^b
SEM	33.6	25.4	32.8	57.1	62.5	0.033	0.015
P-value							
Treatment	<.001	0.001	<.001	0.086	0.005	0.004	0.004
Male ratio	0.231	0.002	<.001	0.030	0.002	0.858	0.976

^{a-c} Means within a column not sharing a superscript differ significantly at the *P* < 0.05.

Each value for each treatment represents the mean of 10 replicates of 6 birds each.

Chemical analysis

Titanium dioxide concentrations in feed and digesta samples were determined in duplicate using the colorimetric method described by Short et al. (1996), which involves acid digestion followed by spectrophotometric measurement at 410 nm. The nitrogen content of raw ingredients, diets, digesta and excreta samples were determined on a 0.25-g sample in a combustion analyzer (FP-2000, LECO Corp., St Joseph, MI) using ethylenediaminetetraacetic acid (EDTA) as a calibration standard, with crude protein being calculated by multiplying percentage nitrogen by a correction factor (6.25) as described by Siriwan et al. (1993).

Starch concentration of the ingredients, diets and digesta samples were determined by a procedure based on dimethyl sulfoxide, α-amylase and amyloglucosidase, as described in Mahasukhonthachat et al. (2010) using commercial kits (Megazyme, Bray Business Park, Bray, Co. Wicklow, Ireland). The gross energy of diets and digesta were deter-

mined by bomb calorimetry using an adiabatic calorimeter (Parr 1281 bomb calorimeter, Parr Instruments Co., Moline, IL). Dry matter content of diets, digesta and excreta were determined.

Table 10
Growth performance of broilers over the withdrawal (35-42 d) and the entire production period (0 to 42).

Treatments	BW (g/b)	Body weight gain (g/b)		Feed intake (g/b)		FCR (g/g)		BWc FCR ¹	Age to 2.5 BW
	D 42	35-42 d	0-42 d	35-42 d	0-42 d	35-42 d	0-42 d	0-42 d	Day
T1 – SBM	3325 ^a	745	3283 ^a	1338	4876	1.798 ^{ab}	1.486 ^b	1.477 ^c	32.1 ^b
T2 – Field peas	3223 ^{ab}	736	3181 ^{ab}	1355	4780	1.846 ^{ab}	1.503 ^{ab}	1.521 ^{bc}	33.1 ^{ab}
T3 – Faba beans	3277 ^{ab}	768	3225 ^{ab}	1424	4912	1.836 ^{ab}	1.521 ^{ab}	1.527 ^{abc}	32.7 ^{ab}
T4 – Field peas	3078 ^b	785	3026 ^b	1380	4705	1.771 ^b	1.558 ^a	1.595 ^a	34.8 ^a
T5 – Faba beans	3144 ^{ab}	772	3102 ^{ab}	1373	4601	1.787 ^b	1.483 ^b	1.519 ^{bc}	33.9 ^{ab}
T6 – FP + FB	3178 ^{ab}	775	3132 ^{ab}	1468	4783	1.888 ^a	1.525 ^{ab}	1.558 ^{ab}	33.7 ^{ab}
SEM	57.4	44.6	59.6	91.5	116.6	0.035	0.016	0.017	0.60
<i>P</i> -value									
Treatment	0.041	0.967	0.048	0.923	0.450	0.213	0.019	0.004	0.037
Male ratio	0.002	0.047	0.001	0.469	0.085	0.004	0.088	<.001	0.009

^{a-c} Means within a column not sharing a superscript differ significantly at the $P < 0.05$.

Each value for each treatment represents the mean of 10 replicates of 6 birds each.

¹ Bodyweight corrected FCR.

Table 11
The impact of dietary treatments on carcass parameters determined at day 42.

Main effects	Absolute weight (g/b)					Relative weight (g/100 g BW)				
	<i>P</i> . Major	<i>P</i> . Minor	<i>P</i> . Total	Leg Q	Fat pad	<i>P</i> . Major	<i>P</i> . Minor	<i>P</i> . Total	Leg Q	Fat pad
T1 – SBM	710 ^a	133 ^a	843 ^a	670	34.6	21.1 ^a	3.94 ^a	25.1 ^a	20.5	1.04
T2 – Field peas	642 ^{bc}	132 ^a	773 ^{bc}	703	35.4	19.7 ^{bc}	4.03 ^a	23.7 ^b	21.6	1.09
T3 – Faba beans	677 ^{ab}	130 ^{ab}	808 ^{ab}	694	35.4	20.3 ^{ab}	3.90 ^{ab}	24.2 ^{ab}	20.9	1.08
T4 – Field peas	580 ^d	119 ^{bc}	699 ^d	677	36.8	18.4 ^c	3.75 ^{abc}	22.1 ^c	21.5	1.18
T5 – Faba beans	612 ^{cd}	121 ^{bc}	733 ^{cd}	674	32.6	18.8 ^{cd}	3.67 ^{bc}	22.4 ^c	20.8	1.01
T6 – FP + FB	593 ^{cd}	118 ^c	712 ^d	689	35.4	18.4 ^c	3.64 ^c	22.1 ^c	21.5	1.11
SEM	13.1	2.6	14.9	15.7	1.84	0.29	0.067	0.32	0.39	0.055
<i>Sex</i>										
Female	548 ^b	101 ^b	650 ^b	605 ^b	35.0	18.5 ^b	3.41 ^b	22.0 ^b	20.5 ^b	1.18 ^a
Male	722 ^a	150 ^a	872 ^a	763 ^a	35.1	20.3 ^a	4.22 ^a	24.5 ^a	21.5 ^a	0.99 ^b
SEM	6.44	1.73	7.34	7.72	0.90	0.14	0.033	0.15	0.19	0.02
<i>P</i> -value										
Treatment	<.001	<.001	<.001	0.609	0.756	<.001	<.001	<.001	0.144	0.437
<i>Sex</i>	<.001	<.001	<.001	<.001	0.967	<.001	<.001	<.001	0.002	<.001
<i>Sex</i> × Treatment	0.193	0.738	0.246	0.320	0.749	0.577	0.911	0.704	0.331	0.630

Each value for each treatment represents the mean of 10 replicates of 6 birds each.

^{a-d} Means within a column not sharing a superscript differ significantly at the $P < 0.05$.

P: Pectoralis muscle; Leg Q: Leg quarter (thigh + drumstick).

Statistical analysis

Data were checked for normality and then subjected to statistical analysis using one-way ANCOVA of GLM procedure in JMP®13 (SAS Institute Inc., JMP Software, Cary, NC) with the male ratio (number of male birds to total birds in each cage) included as a covariate. Carcass components were analysed as a 2-way ANOVA to assess the main effects of diets, and gender, and their interaction. Each cage was considered as an experimental unit and the values presented in the tables are means with pooled standard error of mean (SEM). If a significant effect of treatment was detected, differences between treatments or main effects were separated by least square differences test. Significance was considered at $P < 0.05$ and $P < 0.1$ was indicated and discussed as a trend.

Pearson's correlation coefficients (r) and associated P -values were generated in JMP® 13 to assess relationships between the starch:protein disappearance rate ratio in the distal jejunum and distal ileum and growth performance (BWG, FI, and FCR; 0-42 d) and carcass yield component (breast meat, leg quarter and fat pad; day 42).

Results

Chemical composition of the test ingredients

Table 2 presents the analysed chemical composition of SBM, field peas (FP), and faba beans (FB). As expected, SBM had the highest crude

Table 12

The effect of dietary treatments on nutrient utilisation, excreta dry matter and water intake.

Treatment	AME (Kcal/ kg)	AMEn (Kcal/ kg)	N retention (%)	AME/ GE	Excreta DM (%)	Water intake (mL/b/ d)
T1 – SBM	3048	2754	67.0 ^c	0.77	30.8 ^b	236 ^a
T2 – Field peas	3048	2765	69.3 ^b	0.76	36.4 ^a	206 ^b
T3 – Faba beans	3025	2754	68.9 ^b	0.76	35.5 ^a	206 ^b
T4 – Field peas	3020	2741	70.7 ^{ab}	0.76	36.6 ^a	208 ^b
T5 – Faba beans	3072	2808	71.5 ^a	0.77	35.1 ^a	200 ^b
T6 – FP + FB	3062	2788	71.2 ^a	0.77	35.7 ^a	204 ^b
SEM	16.3	22.3	0.65	0.004	1.15	5.7
<i>P</i> -value						
Treatment	0.207	0.316	<.001	0.222	0.007	0.005
Male ratio	0.968	0.717	0.016	0.968	0.513	0.017

Each value for each treatment represents the mean of 10 replicates of 6 birds each.

^{a-b} Means within a column not sharing a superscript differ significantly at the $P < 0.05$.

protein content (47.3 %) compared to FP (22.9 %) and FB (25.3 %) and contained substantially higher levels of all essential AAs. In contrast, FP and FB were rich in starch (43.1 % and 38.6 %, respectively) relative to SBM (0.70 %). Both legumes had higher crude fibre, acid detergent fibre, and neutral detergent fibre levels than SBM, with FB having the highest fibre content overall. Trypsin inhibitor activity was lower in FP and FB than in SBM, while total phenolics and condensed tannins were notably higher in FB (12.0 g/kg and 10.0 g/kg, respectively) than in FP (4.0 g/kg and 1.0 g/kg). Despite lower protein content, both legumes had higher KOH-soluble protein (Tables 4–6).

Pellet durability and growth performance

In the grower and finisher phases, diets containing FP, FB, or their combination improved pellet durability compared to the control diet ($P < 0.01$, Table 7). However, inclusions of legumes in the withdrawal diets had no effect on pellet durability index ($P = 0.062$). In addition, there was a negative quadratic relationship between feed intake during the grower phase and PDIs of the grower diets ($R^2 = 0.31$; $P < .001$). During the starter period (0–10 d), birds fed the T5 diet containing 17 % FB achieved the highest BW at d10 and the lowest FCR ($P < 0.05$). In contrast, birds offered the high FP (T4) and FP + FB (T6) diets generally showed the lowest BW, with the SBM control (T1), FP (T2) and lower FB (T3) treatments being intermediate. Starter feed intake was not significantly affected by diet ($P > 0.05$), although it was numerically highest in birds fed T3 and lowest in those fed T6 (Table 8). However, in the grower phase (10–24 d), birds fed the SBM control (T1) and the partial SBM replacement diets (T2 and T3) achieved the highest BWG and FI, whereas complete replacement of SBM (T4–T6) led to significantly lower BWG and FI ($P < 0.01$). Within this phase, birds receiving the T4 diet with 100 % SBM replacement and 25 % inclusion of FP recorded the highest FCR, T5 and T6 showed intermediate FCR values, and those on the control diet had the lowest FCR ($P < 0.01$). Over the cumulative period from day 0 to 24, a broadly similar pattern was observed where T1 and T2 supported the highest BWG and FI and the lowest overall FCR, T3 and T5 generally showed intermediate performance, and the full SBM replacement diets T4 and T6 yielded the lowest BWG and FI and the poorest FCR.

According to the data presented in Table 9, during the finisher phase (24–35 d), significant differences were observed among treatments in

Table 13

Effect of dietary treatments on apparent protein (N) and starch digestibility coefficients and disappearance rates (g/bird/day) and starch:protein disappearance rate ratios in distal jejunum at 42 days post-hatch.

Treatment	Digestibility coefficient			Disappearance rate		S:P disappearance ratio
	Protein	Starch	DM	Protein	Starch	
T1 – SBM	0.578	0.888	0.550	19.0	69.4	3.66 ^c
T2 – Field peas	0.546	0.871	0.512	16.4	75.5	4.63 ^{ab}
T3 – Faba beans	0.573	0.866	0.570	19.6	78.7	4.01 ^{bc}
T4 – Field peas	0.536	0.880	0.536	17.1	81.7	4.84 ^a
T5 – Faba beans	0.577	0.873	0.546	17.9	71.5	4.00 ^{bc}
T6 – FP + FB	0.548	0.861	0.535	19.2	79.5	4.20 ^{abc}
SEM	0.021	0.016	0.018	1.28	5.18	0.162
<i>P</i> -value						
Treatment	0.520	0.880	0.365	0.432	0.508	<.001
Male ratio	0.959	0.384	0.981	0.652	0.603	0.926

Each value for each treatment represents the mean of 10 replicates of 6 birds each.

^{a-b} Means within a column not sharing a superscript differ significantly at the $P < 0.05$.

Table 14

Effect of dietary treatments on apparent protein (N) and starch digestibility coefficients and disappearance rates (g/bird/day) and starch:protein disappearance rate ratios in distal ileum at 42 days post-hatch.

Treatment	Digestibility coefficient			Disappearance rate		S:P disappearance ratio
	Protein	Starch	DM	Protein	Starch	
T1 – SBM	0.774	0.945	0.683	25.8	73.7	2.86 ^c
T2 – Field peas	0.770	0.946	0.695	23.1	81.9	3.53 ^a
T3 – Faba beans	0.773	0.953	0.708	26.5	86.6	3.26 ^b
T4 – Field peas	0.756	0.942	0.684	24.3	87.4	3.59 ^a
T5 – Faba beans	0.782	0.956	0.694	24.3	78.2	3.23 ^b
T6 – FP + FB	0.771	0.945	0.700	26.9	87.3	3.26 ^b
SEM	0.011	0.005	0.010	1.64	5.31	0.047
<i>P</i> -value						
Treatment	0.742	0.561	0.556	0.547	0.348	<.001
Male ratio	0.102	0.295	0.036	0.792	0.510	0.167

Each value for each treatment represents the mean of 10 replicates of 6 birds each.

^{a-b} Means within a column not sharing a superscript differ significantly at the $P < 0.05$.

BWG, FI, and FCR. Birds in the control group had the highest BW (2581 g) and BWG (1102 g), which were significantly higher than those in T4 (100 % SBM reduction using FP) and T5 (100 % SBM reduction using FB), while T2, T3 and T6 showed intermediate BW and BWG values ($P < 0.01$). T5 recorded the lowest FI (1450 g) and numerically the lowest FCR, whereas T4 had the poorest FCR and the lowest BW, with T2, T3 and T6 again exhibiting intermediate FI and FCR values ($P < 0.01$). Over the entire 0–35 d period, birds fed the control diet maintained the highest BWG and FI, T4 showed the lowest values, and the remaining treatments (T2, T3, T5 and T6) were intermediate ($P < 0.01$). Cumulative FCR was significantly higher in T4 compared to all other treatments ($P < 0.01$). The male ratio was significant for BWG and FI, but not for FCR.

During the withdrawal phase (Table 10), no significant differences in BWG or FI were observed among treatments ($P > 0.05$). However, FCR was affected by dietary treatments, with T4 and T5 (100 % of SBM reduction using FP and FB, respectively) birds recording the lowest FCR, while T6 birds had the highest (100 % of SBM reduction using a combination of FP and FB). Over the entire production period (0–42 d), treatment effects on final BW and FCR were more pronounced (Table 10). Birds in the control group had the highest final BW and BWG, which were significantly greater than those in T4 ($P < 0.05$), while T2, T3, T5 and T6 showed intermediate BW and BWG values that did not differ from either T1 or T4. Cumulative FI was not affected by treatment ($P > 0.05$). T4 also recorded the highest cumulative FCR, whereas control and T5 (100 % SBM reduction using FB) had the lowest FCR values, with T2, T3 and T6 again intermediate ($P < 0.05$). When FCR values were corrected to the BW of control birds, T1 (SBM-based diet) had the most efficient BWc FCR, significantly lower than T4 and T6, while T2, T3 and T5 exhibited intermediate corrected FCR values ($P < 0.01$). Birds in the control group also reached 2.5 kg BW faster than all other groups, whereas T4 birds recorded the slowest growth rate, with T2, T3, T5 and T6 reaching 2.5 kg at intermediate ages ($P < 0.05$). The male ratio significantly influenced final BW, BWG, corrected FCR and age to 2.5 kg, but had limited interaction with diet for other parameters. Overall mortality (0–42 d) was below 4 % and was not affected by dietary treatments.

Carcass characteristics

Significant treatment effects were observed for both absolute and relative breast muscle weights (Table 11). Birds fed the control diets had the highest absolute *pectoralis major* and total breast weight, as well as the highest relative *pectoralis major* weight, significantly higher than all other treatments except for birds in T3 (partial SBM reduction using FB) ($P < 0.01$). In contrast, birds fed T4 (100 % of SBM reduction using FP) had the lowest breast muscle weights and yields, with significantly reduced relative values as well ($P < 0.01$). Treatments had no significant effect on leg quarter weight and fat pad weight ($P > 0.05$). Sex differences were significant across most carcass traits. Males had significantly greater absolute and relative weights for all breast components and leg quarters compared to females ($P < 0.01$) and also had lower fat pad weight ($P < 0.01$). However, no significant sex \times treatment interactions were detected for any carcass parameters ($P > 0.05$).

Nutrient retention and digestibility

As summarised in Table 12, no significant differences were observed in AME, AMEn or AME:GE ratio among treatments ($P > 0.05$), indicating that overall energy utilisation was comparable across diets. However, nitrogen retention differed significantly among treatments ($P < 0.01$). Birds fed T5 (100 % of SBM reduction using FB) and T6 (100 % of SBM reduction using FP + FB) diets showed the highest nitrogen retention values (71.5 % and 71.2 %, respectively), significantly greater than the control group (67.0 %). T2, T3, and T4 showed intermediate values but still significantly higher than the control birds. Excreta dry matter (DM) content was significantly influenced by diet, with control birds showing lower excreta DM (30.8 %) compared to all other treatments ($P < 0.01$). Water intake was also significantly affected by treatment ($P < 0.01$). Birds fed the control diet consumed more water (236 mL/bird/day) than all other treatments, which ranged between 200 and 208 mL/bird/day. Male ratio had a significant effect on nitrogen retention ($P = 0.016$) and water intake ($P = 0.017$), but not on AME or excreta DM content.

No significant differences were observed among treatments in protein, starch or DM digestibility, and starch or protein disappearance rate in the distal jejunum ($P > 0.05$). However, S:P disappearance rate ratio was significantly lower in control group ($P < 0.01$), with birds in T2 and T4 (diets based on FP) recording the highest ratios (Table 13). Similar trends in nutrient digestibility, S:P disappearance rate and S:P disappearance rate ratios were observed in distal ileum, where dietary treatments had no significant effect on nutrient digestibility ($P > 0.05$). However, birds in the control group recorded the lowest distal ileal S:P disappearance rate ratio, whereas T2 and T4 (FP-based diets) had the highest ratios, with T3, T5 and T6 showing intermediate values which were statistically higher than T1 but lower than T2 and T4 (Table 14; $P < 0.01$).

The overall FCR (0–42 d) was positively correlated with the S:P disappearance rate ratio in the distal jejunum ($r = 0.33$, $P = 0.010$) and distal ileum ($r = 0.31$, $P = 0.016$). In contrast, no statistically significant associations were detected between the S:P disappearance rate ratio and BWG in either jejunum ($r = -0.19$, $P = 0.145$) or ileum ($r = -0.22$, $P = 0.099$). Breast meat yield was negatively correlated with S:P disappearance rate ratio in jejunum ($r = -0.35$, $P = 0.006$) and ileum ($r = -0.38$, $P = 0.003$). No significant correlations were observed for fat pad weight. However, leg quarter yield was positively correlated with the S:P ratio in both intestinal segments (jejunum: $r = 0.33$, $P = 0.009$; ileum: $r = 0.42$, $P = 0.001$).

Discussion

Growth performance and nutrient utilisation

Overall, all the birds in this study exceeded the 2022 Aviagen performance objectives for as-hatched Ross 308 broilers (Aviagen, 2022b),

achieving a higher average body weight (3150 g/bird vs. 2998 g/bird) and a slightly improved feed conversion ratio (1.512 vs. 1.531). However, the focus of the current study was to introduce FP and FB as protein rich raw material to replace SBM in broiler diets. During the starter phase the growth performance results showed that either legume or their combination can successfully replace up to 70 % of SBM without depressing BWG or feed efficiency. Similarly, in grower phase, 66 % replacement of SBM with either FP or FB did not compromise growth parameters, but complete replacement of SBM with these legumes or their combination led to lower BWG and higher FCR, with birds fed the diets with highest inclusion of FP recording the lowest BWG and highest FCR. The presence of some antinutritional factors in these legumes such as tannins and trypsin inhibitors have been reported to negatively affect growth performance in poultry by compromising nutrient digestibility, particularly protein and starch (Lacassagne et al., 1988; Vilarinho et al., 2009). Interestingly, in our study the analysed total tannins (4.0 vs 12 g/kg), and condensed tannins (1.0 vs 10.0 g/kg) was lower in FP than FB, yet diets with FP alone resulted in lower performance than FB. In addition, we did not observe any negative effect of either FP or FB on energy utilization, protein, starch and DM digestibility neither in distal jejunum nor in distal ileum. According to the literature, the negative effect of tannins on nutrient and energy digestibility is highly dependent on their concentration in the diets. For example, Vilarinho et al. (2009) reported a negative linear relationship between dietary tannin content coming from FB with energy and protein digestibility in broiler chickens. Similarly, Iji et al. (2004) found that the effects of tannins on broiler performance were variable for example negative, neutral, or even positive, depending on their dietary concentration. Therefore, given that no negative effects of FP or FB inclusion were observed on nutrient utilization or the measured AME and AMEn of the experimental diets, it is unlikely that tannins or trypsin inhibitors were responsible for any variation or compromised growth performance associated with the inclusion of these legumes. Furthermore, the trypsin inhibitor activity in FP (1.16 mg/g) and FB (1.3 mg/g) was lower than that of SBM (2.3 mg/g), suggesting that these levels were unlikely to have negatively impacted protein digestibility or utilization in the present study. In addition, the steam-pelleting process used in preparing the experimental diets may have contributed to the deactivation of trypsin inhibitors, as the conditioning temperatures in steam-pelleting process have been reported to breakdown antinutritional factors, including protease inhibitors (Svihus and Zimonja, 2011). Cho et al. (2019) evaluated four FB cultivars differing in tannin concentration (low and high) at inclusion levels of 12 %, 24 %, and 36 % in starter, grower, and finisher diets, respectively. Their findings indicated that vicine and convicine content had a greater influence on broiler performance than tannin concentration. Notably, dehulling the beans to reduce tannin levels had no significant effect on growth performance, suggesting that in modern FB cultivars, the presence of vicine and convicine is a more critical consideration than tannin content when formulating poultry diets. Similarly, Zduńczyk et al. (2022) fed finisher turkeys graded inclusions of coloured-flowered pea and white-flowered pea seeds that differed markedly in tannin content (4.66 g/kg vs 0.67 g/kg). Their results showed that tannin concentration did not affect the comparative suitability of pea seeds for finisher-turkey broilers.

A portion of the starch in FP and FB exists as resistant starch (RS), which is either poorly digested or entirely resistant to enzymatic hydrolysis, depending on its subtype (Perz et al., 2023). The RS content of FP has been reported to range from 2.07 % to 6.31 % (Dostálová et al., 2009), while FB may contain higher levels, approximately 13 % to 15 % (Nilsson et al., 2022; Perz et al., 2023). These values, however, can vary considerably depending on the total starch content and compositional differences among cultivars. In the current study, at the maximum inclusion level of 25 % in the finisher and withdrawal diets, FP and FB would have contributed approximately 0.5 % to 1.5 % RS to the overall diet. Therefore, the RS content of the diets was likely too low to have a meaningful impact on starch digestibility in either the jejunum or ileum.

Furthermore, all experimental diets were steam-pelleted, and the high pellet durability index indicates effective conditioning and thermal processing. The use of steam at temperatures around 60 to 90 °C during pelleting has been shown to enhance starch gelatinisation and improve digestibility (Abdollahi et al., 2011). This likely further minimised any potential effect of the RS present in FP and FB on overall starch utilization in the current study. Further supporting the positive impact of pelleting on nutrient utilization of legume seeds in broiler chickens, Ivarsson and Wall (2017) demonstrated that broiler growth performance was maintained when 20 % FB were included in a pelleted diet. In contrast, the same inclusion level in a mash diet led to reductions in both FI and BW, regardless of whether the FB had been pre-toasted. Similar results were reported by Gous (2011) who observed that when diets were offered in mash form, growth rate and feed conversion efficiency declined linearly, while FI increased with increasing FB inclusion. However, when the same diets were pelleted, broiler performance remained consistent across all levels of FB inclusion, suggesting that the heat generated during the pelleting process may have inactivated some heat-labile anti-nutritional factors present in FB. Similar to our findings, Koivunen et al. (2014) evaluated FB inclusion at 0 %, 8 %, 16 %, and 24 % in broiler diets and concluded that up to 16 % could be safely incorporated without negatively affecting performance. However, inclusion at 24 % led to reductions in both BWG and FI. Notably, the design of their study closely mirrored the current trial, as FB were used to partially replace SBM, resulting in a concurrent reduction in dietary crude protein. Likewise, Laudadio et al. (2011) replaced SBM with 31 % FB and, consistent with our observations, reported a reduction in BW of approximately 100 g per bird and a 9-point increase in FCR. In contrast, when FP or FB are introduced without the specific aim of displacing SBM, substantially higher inclusion rates can be used without compromising performance. For example, Tomaszewska et al. (2018) reported no adverse effects on broiler growth, tibial bone properties, or intestinal morphology when unprocessed high-tannin FB were included at 15 % in starter and 22 % in grower diets. However, even at 22 % FB inclusion, the grower diets still contained 26 % SBM and had comparable crude protein levels. Similarly, Janocha et al. (2022) recommended inclusion rates of 15 % for FP in starter diets and 25 % in grower diets without detrimental effects on key performance parameters. Again, even at 25 % FP inclusion, their diets retained 30 % SBM and maintained similar crude protein content to the diets without FP. Therefore, interpreting the growth performance outcomes observed in the current study solely in relation to the inclusion of FP and FB, without considering the confounding effects of diet structure and reduced crude protein levels, may not provide a complete or accurate understanding of the results.

In our study, the inclusion of FP or FB led to a marked reduction in total dietary crude protein and a corresponding increase in non-bound amino acid (NBAA) content. For example, in the grower diets, replacing 66 % of SBM with either FP or FB increased the total NBAA content by approximately 56 % (from 12.5 to 19.5 g/kg). When SBM was completely replaced (100 %), NBAA levels nearly doubled (from 12.5 to 24.6 g/kg). These compositional changes were accompanied by a reduction of approximately 15 g/kg in crude protein. Similar patterns were observed in the finisher and withdrawal diets. Although all the diets were formulated to similar levels of digestible essential amino acids, including tryptophan and glycine equivalent, the reduction in crude protein and the increase in NBAA content may partly explain the observed reduction in BW and increase in FCR when SBM was fully replaced with FP, FB or their combination. In fact, the observed improvement in nitrogen retention, increased excreta DM content, and reduced water intake in response to SBM reduction and its replacement with FP or FB aligns with previous findings from our lab, where similar outcomes were reported following reductions in dietary crude protein levels particularly in wheat-based diets (Chrystal et al., 2021; Greenhalgh et al., 2022; Macelline et al., 2022, 2023a). Birds fed diets low in crude protein generally drink less because there is less surplus amino acid to deaminate and excrete as uric acid. As noted by Francesch and

Brufau (2004) excess dietary protein must be catabolised and excreted as uric acid via the kidneys, which increases water consumption. Consistent with this mechanism, a recent meta-analysis showed that reducing dietary CP from 19 % to 17 % in broiler diets decreased N excretion, plasma uric acid, daily water consumption and litter moisture (Alfonso-Avila et al., 2022). As suggested by Wu (2009), NBAA are absorbed more rapidly in the intestine than their protein-bound counterparts, indicating a lack of bioequivalence between the two forms. This discrepancy likely contributes to post-enteral amino acid imbalances, where the rapid influx of NBAA may result in post-prandial oxidation of surplus amino acids (Selle et al., 2023). The imbalanced amino acid uptake may result in asynchronous availability at the site of protein synthesis, which can impair muscle accretion, reduce growth rate, and increase FCR (Macelline et al., 2023b). Elevated starch and NBAA content of reduced crude protein diets based on wheat have been identified as key factors contributing to compromised growth performance in broiler chickens (Selle et al., 2023). Therefore, the higher N retention observed in birds fed FP- and FB-based diets reflects more efficient utilisation of a smaller N intake, whereas reduced crude protein and NBAA-driven post-enteral amino acid imbalances can still constrain muscle accretion and body weight gain. However, it is worth noting that there is no treatment impact on jejunal protein digestibility in the present study which is often an indicator of protein digestion rate.

Soybean meal contains negligible amounts of starch, with concentrations close to zero. In contrast, both FP and FB contain substantial levels of starch, as shown in Table 2. As a result, replacing SBM with these legumes introduced a structural shift in the diets, increasing the starch-to-protein (S:P) ratio across all four feeding phases. Despite digestibility coefficients of protein and starch, and their disappearance rate were not statistically affected by dietary treatments neither in distal jejunum nor in distal ileum, but the S:P disappearance rate ratio was constantly lower in control diet compared to the diets with FP or FB, with diets 2 and 4 with FP recording the highest ratios at both jejunum and ileum. A high dietary S:P disappearance rate ratio may compromise growth performance in broiler chickens via asynchronous nutrient release. When the S:P disappearance rate ratio is elevated, starch is digested and glucose is absorbed more rapidly than amino acids, especially those derived from protein-bound sources. This mismatch may lead to an insufficient supply of amino acids at the sites of protein synthesis, limiting the efficiency of muscle protein accretion. As a result, birds may exhibit reduced BWG and poorer feed conversion. This was demonstrated in maize-based diets by Chrystal et al. (2020), who observed that increases in the distal jejunum S:P disappearance rate ratio were strongly associated with inferior FCR and greater fat deposition. Similarly, Greenhalgh et al. (2022) showed that capping the dietary S:P ratio in reduced crude protein diets improved BWG and feed efficiency by an average of 3.5 %. Similarly in the current study, FCR was positively correlated with the S:P disappearance rate ratio in both distal jejunum and distal ileum.

The asynchronous glucose and amino acid supply may lead to deamination of excess amino acids that increases maintenance energy costs. This has been thoroughly reviewed by Selle et al. (2023), who highlighted that diets high in S:P ratio and NBAA, particularly under reduced-crude protein conditions, promote such inefficient amino acid utilization. In addition to post-absorptive inefficiencies, competition at the level of intestinal transport and nutrient signalling may also impair performance. Blood glucose and its downstream effector insulin are known regulators of AA transport and whole-body protein turnover (Javed and Fairweather, 2019). For instance, Moss et al. (2018) reported that intestinal glucose absorption can hinder AA uptake, as both processes rely on shared Na⁺-coupled transport mechanisms. Similarly, Yamamoto et al. (2017) found that high glucose concentrations suppress AMP-activated protein kinase (AMPK) activity, leading to a reduction in the mRNA expression of L-type amino acid transporter 1 (LAT1) in mammalian cell models. LAT1 is responsible for the uptake of large neutral amino acids including essential amino acids such as leucine,

isoleucine, valine, phenylalanine, tyrosine, tryptophan, and methionine, which are critical for muscle accretion. Therefore, when replacing SBM with legume seeds, it is essential to consider not only the concentrations of antinutritional factors but also the dietary starch and protein contents, and the resulting S:P ratio, to avoid negative impacts on growth performance.

Given the potential impact of FP and FB on intestinal integrity and function (Aranda-Olmedo and Rubio, 2020; Röhe et al., 2017) further investigation into intestinal mechanisms may provide deeper insights into the responses of broiler chickens and help explain the differences in growth performance observed in the present study.

Carcass characteristics

In the current study, partial replacement of SBM with FB did not affect breast meat yield. However, partial replacement with FP, as well as full replacement with either FP or FB, resulted in a significant reduction in breast meat yield without affecting abdominal fat pad weights. As with the observed differences in growth performance, it is plausible that the reduction in breast meat yield associated with the inclusion of FP and FB reflects an artefact of diet structure particularly the elevated dietary S:P ratio and a higher S:P disappearance rate ratio in these diets rather than the direct effect of these legumes themselves. The negative correlation between breast meat yield and the S:P disappearance rate ratio in both the jejunum and ileum further shows the confounding effect of diet structure on breast meat yield. Liu and Selle (2015) reviewed the concept of digestive dynamics of starch and protein in broiler diets, emphasizing that optimal muscle growth in broilers is influenced not only by the total digestibility of nutrients but also by the timing of their absorption. They proposed that balanced nutrient delivery kinetics, specifically the synchronized availability of glucose and amino acids at the sites of protein synthesis, are essential for efficient lean tissue accretion.

Earlier studies reported no adverse effects of FB (Laudadio et al., 2011) or FP (Nalle et al., 2010) inclusion on carcass characteristics in broiler chickens. However, more recent findings suggest that modern broiler genotypes may be more sensitive to the quality and quantity of dietary protein supply, particularly in relation to breast meat yield. Kopmels et al. (2020) reported that inclusion of FB at 20 % to 40 % resulted in progressive reductions in carcass yield. Similarly, Cho et al. (2019) found that both zero- and high-tannin FB cultivars significantly reduced chilled carcass weight and dressing percentage compared to a wheat-SBM control. Supporting this, Ivarsson and Wall (2017) showed that when 20 % FB were included in broiler diets formulated with two levels of crude protein (19.9 % and 18.1 %), the lower-protein diet significantly reduced both total carcass and breast meat yields. Overall, carcass outcomes are likely driven by both legume inclusion *per se* and also protein quantity, and the kinetics of nutrient delivery. To maintain optimal carcass, particularly breast meat yield, when incorporating FP and FB, diets must ensure adequate protein density, precise amino-acid balance, and a controlled S:P ratio that synchronizes glucose and amino acid absorption.

Conclusion and implementation

Both FP and FB are viable alternatives for partial replacement of SBM in broiler diets. However, complete SBM replacement results in reduced BWG, feed efficiency and breast meat yield. Our findings indicate that these legumes, and possibly their antinutritional components, such as tannins and trypsin inhibitors, do not negatively impact nutrient (protein, starch and energy) digestibility or utilization directly. Rather, when formulating iso-energetic diets, their inclusion leads to increased levels of dietary NBAA and starch, which increases both the dietary S:P ratio and their disappearance rate ratios. This change in nutrient dynamics may lead to asynchronous absorption of glucose and amino acids, impairing protein utilization for muscle growth and thereby reducing

BWG and feed efficiency. Therefore, when formulating broiler diets with FP or FB as alternatives to SBM, it is essential to understand diet structure alteration to maintain optimal growth performance.

CRedit authorship contribution statement

Vahideh Shay Sadr: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Shemil P. Macelline:** Methodology, Formal analysis, Writing – review & editing. **Eunjoo Kim:** Writing – review & editing, Supervision, Investigation, Data curation. **Mehdi Toghyani:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Obright Hamungalu:** Writing – review & editing, Methodology. **Timothy J. Wester:** Writing – review & editing, Methodology, Conceptualization. **Reza Berekatain:** Writing – review & editing, Visualization, Validation, Supervision. **Sonia Yun Liu:** Conceptualization, Methodology, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Disclosures

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgements

The study was part of the AgriFutures Chicken Meat Consortium – Nutrition, Gut Health and Environment project (PRO-016111) which is funded and supported by the AgriFutures Chicken Meat Program with its associated levy payers, five research providers, seven industry partners and nine international universities. We would like to appreciate the technical support provided by Mr. Jordan Fletcher, Mr. Duwei Chen, Ms. Kylie Warr, Ms. Joy Gill and PhD students; Ms. Mengzhu Wang (Jojo) and Miss Carria Xie from the Poultry Research Foundation for their assistance on animal husbandry and sample collection. Finally, we acknowledge the scholarships offered to Shay Sadr, this includes The Gary Sansom Scholarship, a prestigious PhD scholarship designed specifically to support the AgriFutures Chicken Meat Program industry priorities.

References

- Abdollahi, M., Ravindran, V., Wester, T., Ravindran, G., Thomas, G., 2011. Influence of feed form and conditioning temperature on performance, apparent metabolisable energy and ileal digestibility of starch and nitrogen in broiler starters fed wheat-based diet. *Anim. Feed Sci. Technol.* 168, 88–99.
- Adekoya, A.A., Adeola, O., 2023. Energy and phosphorus utilization of pulses fed to broiler chickens. *Poult. Sci.* 102, 102615.
- Alfonso-Avila, A., Cirot, O., Lambert, W., Létourneau-Montminy, M., 2022. Effect of low-protein corn and soybean meal-based diets on nitrogen utilization, litter quality, and water consumption in broiler chicken production: insight from meta-analysis. *Animal* 16, 100458.
- Aranda-Olmedo, I., Rubio, L.A., 2020. Dietary legumes, intestinal microbiota, inflammation and colorectal cancer. *J. Funct. Foods* 64, 103707.
- Arese, P., Gallo, V., Pantaleo, A., Turrini, F., 2012. Life and death of glucose-6-phosphate dehydrogenase (G6PD) deficient erythrocytes—role of redox stress and band 3 modifications. *Transfus. Med. Hemother.* 39, 328–334.
- Aviagen, 2022a. Ross 308/Ross 308 FF Broiler: Nutrition Specifications. Aviagen, Inc, Huntsville, AL, USA.
- Aviagen, 2022b. Ross 308/Ross 308 FF Broiler: Performance Objectives. Aviagen, Inc, Huntsville, AL, USA.
- Brenes, A., Rotter, B., Marquardt, R., Guenter, W., 1993. The nutritional value of raw, autoclaved and dehulled peas (*Pisum sativum* L.) in chicken diets as affected by enzyme supplementation. *Can. J. Anim. Sci.* 73, 605–614.
- Brufau, J., Boros, D., Marquardt, R., 1998. Influence of growing season, tannin content and autoclave treatment on the nutritive value of near-isogenic lines of faba beans (*Vicia faba* L.) when fed to leghorn chicks. *Br. Poult. Sci.* 39, 97–105.
- Cho, M., Smit, M., He, L., Kopmels, F., Beltranena, E., 2019. Effect of feeding zero-or high-tannin faba bean cultivars and dehulling on growth performance, carcass traits and yield of saleable cuts of broiler chickens. *J. Appl. Poult. Res.* 28, 1305–1323.
- Chrystal, P.V., Greenhalgh, S., McInerney, B.V., McQuade, L.R., Akter, Y., de Paula Dorigam, J.C., Selle, P.H., Liu, S.Y., 2021. Maize-based diets are more conducive to

- crude protein reductions than wheat-based diets for broiler chickens. *Anim. Feed Sci. Technol.* 275, 114867.
- Chrystal, P.V., Moss, A.F., Khoddami, A., Naranjo, V.D., Selle, P.H., Liu, S.Y., 2020. Effects of reduced crude protein levels, dietary electrolyte balance, and energy density on the performance of broiler chickens offered maize-based diets with evaluations of starch, protein, and amino acid metabolism. *Poult. Sci.* 99, 1421–1431.
- Crépon, K., Marget, P., Peyronnet, C., Carrouée, B., Arese, P., Duc, G., 2010. Nutritional value of faba bean (*Vicia faba* L.) seeds for feed and food. *Field Crops Res.* 115, 329–339.
- David, L.S., Nalle, C.L., Abdollahi, M.R., Ravindran, V., 2024. Feeding value of lupins, field peas, faba beans and chickpeas for poultry: an overview. *Animals* 14, 619.
- Dostálová, R., Horáček, J., Hasalová, I., Trojan, R., 2009. Study of resistant starch (RS) content in peas during maturation. *Czech J. Food Sci.* 27, S120–S124.
- Francesch, M., Brufau, J., 2004. Nutritional factors affecting excreta/litter moisture and quality. *World's Poult. Sci. J.* 60, 64–75.
- Gatel, F., 1994. Protein quality of legume seeds for non-ruminant animals: a literature review. *Anim. Feed Sci. Technol.* 45, 317–348.
- Gous, R., 2011. Evaluation of faba bean (*Vicia faba* cv. Fiord) as a protein source for broilers. *S. Afr. J. Anim. Sci.* 41, 71–78.
- Greenhalgh, S., Chrystal, P.V., Lemme, A., de Paula Dorigam, J.C., Macelline, S.P., Liu, S.Y., Selle, P.H., 2022. Capping dietary starch: protein ratios enhances performance of broiler chickens offered reduced-crude protein, maize-based diets. *Anim. Feed Sci. Technol.* 290, 115374.
- Iji, P.A., Khumalo, K., Slippers, S., Gous, R.M., 2004. Intestinal function and body growth of broiler chickens on maize-based diets supplemented with mimosa tannins and a microbial enzyme. *J. Sci. Food Agric.* 84, 1451–1458.
- Ivarsson, E., Wall, H., 2017. Effects of toasting, inclusion levels and different enzyme supplementations of faba beans on growth performance of broiler chickens. *J. Appl. Poult. Res.* 26, 467–475.
- Janocha, A., Milczarek, A., Gluchowska, J., 2022. Efficiency of peas in broiler chicken feeding. *Anim. Sci. Genet.* 18.
- Javed, K., Fairweather, S.J., 2019. Amino acid transporters in the regulation of insulin secretion and signalling. *Biochem. Soc. Trans.* 47, 571–590.
- Koivunen, E., Tuunainen, P., Rossow, L., Valaja, J., 2014. Digestibility and utilization of faba bean (*Vicia faba* L.) diets in broilers. *Acta Agric. Scand. A Anim. Sci.* 64, 217–225.
- Kopmels, F.C., Smit, M.N., Cho, M., He, L., Beltranena, E., 2020. Effect of feeding 3 zero-tannin faba bean cultivars at 3 increasing inclusion levels on growth performance, carcass traits, and yield of saleable cuts of broiler chickens. *Poult. Sci.* 99, 4958–4968.
- Lacassagne, L., Francesch, M., Carré, B., Melcion, J., 1988. Utilization of tannin-containing and tannin-free faba beans (*Vicia faba*) by young chicks: effects of pelleting feeds on energy, protein and starch digestibility. *Anim. Feed Sci. Technol.* 20, 59–68.
- Laudadio, V., Ceci, E., Tufarelli, V., 2011. Productive traits and meat fatty acid profile of broiler chickens fed diets containing micronized fava beans (*Vicia faba* L. var. minor) as the main protein source. *J. Appl. Poult. Res.* 20, 12–20.
- Liu, S., Selle, P., 2015. A consideration of starch and protein digestive dynamics in chicken-meat production. *World's Poult. Sci. J.* 71, 297–310.
- Macelline, S.P., Chrystal, P.V., Selle, P.H., Liu, S.Y., 2022. Protein sources and starch-protein digestive dynamics manipulate growth performance in broiler chickens defined by an equilateral-triangle response surface design. *Anim. Nutr.* 9, 204–213.
- Macelline, S.P., Chrystal, P.V., Toghyani, M., Selle, P.H., Liu, S.Y., 2023a. Dietary crude protein reductions in wheat-based diets with two energy densities compromised performance of broiler chickens from 15 to 36 days post-hatch. *Poult. Sci.* 102, 102932.
- Macelline, S.P., Kidd, M.T., Chrystal, P.V., Toghyani, M., Selle, P.H., Liu, S.Y., 2023b. The influence of non-bound amino acid inclusions and starch-protein digestive dynamics on growth performance of broiler chickens offered wheat-based diets with two crude protein concentrations. *Anim. Nutr.* 15, 399–408.
- Mahasukhonthachat, K., Sopade, P., Gidley, M., 2010. Kinetics of starch digestion in sorghum as affected by particle size. *J. Food Eng.* 96, 18–28.
- Mariscal-Landín, G., Lebreton, Y., Sèv, B., 2002. Apparent and standardised true ileal digestibility of protein and amino acids from faba bean, lupin and pea, provided as whole seeds, dehulled or extruded in pig diets. *Anim. Feed Sci. Technol.* 97, 183–198.
- Moss, A.F., Sydenham, C.J., Khoddami, A., Naranjo, V.D., Liu, S.Y., Selle, P.H., 2018. Dietary starch influences growth performance, nutrient utilisation and digestive dynamics of protein and amino acids in broiler chickens offered low-protein diets. *Anim. Feed Sci. Technol.* 237, 55–67.
- Nalle, C., Ravindran, V., Ravindran, G., 2010. Evaluation of Faba beans, white lupins and peas as protein sources in broiler diets. *Int. J. Poult. Sci.* 9, 567–573.
- Nilsson, K., Sandström, C., Özeren, H.D., Vilaplana, F., Hedenqvist, M., Langton, M., 2022. Physicochemical and thermal characterisation of faba bean starch. *J. Food Meas. Charact.* 16, 4470–4485.
- Perez-Maldonado, R., Mannion, P., Farrell, D., 1999. Optimum inclusion of field peas, faba beans, chick peas and sweet lupins in poultry diets. I. Chemical composition and layer experiments. *Br. Poult. Sci.* 40, 667–673.
- Perz, K., Kaczmarek, S., Nowaczewski, S., Cowieson, A., Ciszewski, A., Hejdysz, M., 2023. The effect of reduction of resistant starch content of faba bean and pea by amylase supplementation on performance, nutrient digestibility, and sialic acid excretion of broiler chickens. *Anim. Feed Sci. Technol.* 298, 115621.
- Ramdath, D.D., Lu, Z.-H., Maharaj, P.L., Winberg, J., Brummer, Y., Hawke, A., 2020. Proximate analysis and nutritional evaluation of twenty Canadian lentils by principal component and cluster analyses. *Foods* 9, 175.
- Ravindran, G., Nalle, C.L., Molan, A., Ravindran, V., 2010. Nutritional and biochemical assessment of field peas (*Pisum sativum* L.) as a protein source in poultry diets. *J. Poult. Sci.* 47, 48–52.
- Röhe, I., Borojoni, F.G., Zentek, J., 2017. Effect of feeding soybean meal and differently processed peas on intestinal morphology and functional glucose transport in the small intestine of broilers. *Poult. Sci.* 96, 4075–4084.
- Selle, P.H., Macelline, S.P., Chrystal, P.V., Liu, S.Y., 2023. The challenge to reduce crude protein contents of wheat-based broiler diets. *Anim. Prod. Sci.* 63, 1899–1910.
- Short, F., Gorton, P., Wiseman, J., Boorman, K., 1996. Determination of titanium dioxide added as an inert marker in chicken digestibility studies. *Anim. Feed Sci. Technol.* 59, 215–221.
- Siriwan, P., Bryden, W., Mollah, Y., Anison, E., 1993. Measurement of endogenous amino acid losses in poultry. *Br. Poult. Sci.* 34, 939–949.
- Smit, M.N., He, L., Beltranena, E., 2021. Feeding different cultivars and quality levels of faba bean to broiler chickens. *Transl. Anim. Sci.* 5, txab094.
- Svihus, B., Zimonja, O., 2011. Chemical alterations with nutritional consequences due to pelleting animal feeds: a review. *Anim. Prod. Sci.* 51, 590–596.
- Tomaszewska, E., Muszyński, S., Dobrowolski, P., Kwiecień, M., Klebaniuk, R., Szymańczyk, S., Tomczyk, A., Kowalik, S., Milczarek, A., Świetlicka, I., 2018. The influence of dietary replacement of soybean meal with high-tannin faba beans on gut-bone axis and metabolic response in broiler chickens. *Ann. Anim. Sci.* 18, 801.
- USDA, S. U., 2024. Stocks: on-farm, off-farm, and total by quarter, US soybean acreage planted, harvested, yield, soybean and soybean meal production, value, price and supply and disappearance prices, 1999/00-2023/24. <https://www.ers.usda.gov/data-products/oil-crops>.
- Vilarino, M., Métayer, J., Crépon, K., Duc, G., 2009. Effects of varying vicine, convicine and tannin contents of faba bean seeds (*Vicia faba* L.) on nutritional values for broiler chicken. *Anim. Feed Sci. Technol.* 150, 114–121.
- Willems, O.W., Miller, S.P., Wood, B.J., 2013. Assessment of residual body weight gain and residual intake and body weight gain as feed efficiency traits in the turkey (*Meleagris gallopavo*). *Genet. Sel. Evol.* 45, 26.
- Wu, G., 2009. Amino acids: metabolism, functions, and nutrition. *Amino Acids* 37, 1–17.
- Yamamoto, Y., Sawa, R., Wake, I., Morimoto, A., Okimura, Y., 2017. Glucose-mediated inactivation of AMP-activated protein kinase reduces the levels of L-type amino acid transporter 1 mRNA in C2C12 cells. *Nutr. Res.* 47, 13–20.
- Zduńczyk, Z., Mikulski, D., Jankowski, J., Slominski, B.A., Juśkiewicz, J., 2022. The effect of the dietary inclusion of pea seeds of colored-flowered and white-flowered varieties on gastrointestinal function in turkeys. *Anim. Nutr.* 10, 167–177.