Interactions of full-fat canola seed, oat hulls as an insoluble fiber source and pellet temperature for nutrient utilization and growth performance of broiler chickens

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ABSTRACT The effectiveness of the addition of oat hulls (OH) as an insoluble fiber for improving nutrient digestibility and performance of birds fed diets containing full-fat canola seed (CS) was studied. A 2 × 2 × 2 factorial arrangement of treatments was used to assess the main effects of canola source (CS vs canola meal plus oil as control), OH (0 or 3%), pellet temperature (75 and 90°C) and their interactions. A total of 576 male day-old Ross 308 chickens were assigned to 8 experimental treatments, each replicated 6 times (12 birds per replicate). All birds were fed a same commercial starter diet for the first 10 d of age. Canola meal and canola oil in the control diets were replaced with CS at 11.6% and 13.5% in the grower (d 10 to 24) and finisher (d 24 to 35) diets, respectively. An interaction was observed between canola source and OH led to improved body weight gain ($P < 0.01$) and FCR ($P < 0.05$) in birds fed the combination of CS and OH in grower phase. Pelleting temperature at 75 vs 90°C did not affect performance of broilers. Birds fed diets containing OH had heavier gizzards at 24 and 35 d of age. Inclusion of CS in the diets depressed fat digestibility at d 24 ($P < 0.001$) and AME of the grower diets. At d 35, there was a significant interaction ($P < 0.05$) between CS and pellet temperature where birds fed CS diets pelleted at 75°C had higher fat digestibility than birds fed CS pelleted at 90°C. Regardless of canola source or pellet temperature, OH increased fat utilization at d 35 ($P < 0.001$) but had no effect on AME of the grower diets. In conclusion, CS can replace supplemental oil in broiler diets when an adequate source of insoluble fiber is included in the diet, which may help to maintain feed intake of broilers fed CS in steam-pelleted diets.

Key words: Canola seed, insoluble fiber, gut development, fat digestibility, amino acids

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INTRODUCTION

Whole canola seed (**CS**), due to its high oil content, is a high-energy ingredient that can potentially replace a substantial proportion of supplemental oil in poultry diets. However, high-level inclusion of CS in poultry diets is often avoided due to concerns over residual glucosinolates and adverse effect on feed consumption (Summers et al., 1982; Barekatain et al., 2015). The results of a recent experiment showed that despite a desirable outcome in bird performance of broiler diets containing CS, these diets were not fully utilized when steam pelleted, and therefore feed consumption and body weight was adversely affected (Barekatain et al., 2015). In addition, pre-grinding of the seed did not improve fat utilization or bird performance when diets were cold-pelleted, but there was marginal improvement in performance when the diets were steam-pelleted (Barekatain et al., 2015). The degree to which pelleting temperature can affect the nutritive values of CS is not fully understood. Furthermore, CS contains the enzyme myrosinase, which catalyzes the breakdown of glucosinolate to other metabolites, including isothiocyanates, which are bitter compounds; this concern can be minimized by applying heat to denature the myrosinase enzyme (Tripathi and Mishra, 2007).

The reduced fat digestibility in CS diets has been attributed to oil in seeds being contained in oil bodies that are surrounded by a peptide coating that may limit digestibility of the oil (Meng et al., 2006). Ways of breaking the peptide coating could include milling of the whole CS prior to diet mixing (Barekatain et al., 2015), use of exogenous enzymes (Slominski et al., 2006), or possibly addition of insoluble fiber to stimulate gizzard activity, which builds on known results for the beneficial effect of oat hulls (**OH**) in broiler diets. If fat digestibility is increased by addition of OH, then this is likely to lead to benefits when oil seeds are used commercially to replace supplemental oil in poultry diets.

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The beneficial impact of inclusion of insoluble fiber in the diet of broiler chickens has been well demonstrated in the literature. Studies conducted with broilers have shown that moderate amounts of dietary fiber result in significant improvement in utilization of most nutrients (Amerah et al., 2009; Mateos et al., 2012). In addition, Gonzalez-Alvarado et al. (2007) and Kalmendal et al. (2011) showed an increase in fat digestibility when fiber was included in broiler diets. However, the interaction between insoluble fiber sources (e.g., OH) with oil seeds such as CS has not been investigated. When it is assumed that fiber results in a more developed gizzard and intestine of the birds, it is hypothesized that there is increased scope for improved nutrient intake through nutrient release and lower carbohydrate solubilization in wheat-based diets that contain CS. If this hypothesis is proven successful, one can conclude that CS can be used in lieu of supplemental oil in broiler diets without compromising feed intake or body weight. Furthermore, there is no need for pre-grinding, which otherwise could be cumbersome and costly due to seed size and high oil content. Thus, it was proposed to investigate the effect of OH as a rich source of insoluble fiber, CS, and pelleting temperature on performance, intestinal development, and nutrient utilization.

Table 1. Chemical analysis (%) of canola meal and whole canola seed (as-is basis)[1].

Item	Canola meal	Whole canola seed
Moisture	10.10	5.73
Crude protein	38.23	27.35
Crude fiber	9.90	7.97
Crude fat	2.41	35.20
Ash	6.87	4.79
Indispensable amino acids		
Arg	2.24	1.67
Cys	0.92	0.71
His	1.00	0.74
Ile	1.40	1.01
Leu	2.69	1.88
Lys	2.20	1.69
Met	0.75	0.55
Phe	1.53	1.13
Thr	1.66	1.14
Trp	0.47	0.28
Val	1.83	1.31
Dispensable amino acids		
Ala	1.66	1.15
Asp	2.61	1.91
Glu	6.89	4.72
Gly	1.93	1.34
Pro	2.26	1.64
Ser	1.60	1.09
Tyr	0.96	0.68

[1] Values are the mean of duplicate samples.

MATERIALS AND METHODS

The Animal Ethics Committees of the University of Adelaide and Primary Industries and Regions South Australia approved all the experimental procedures.

Ingredient Analysis

Chemical analysis of CS and solvent extracted canola meal (**CM**) are shown in Table 1. An apparent metabolizable energy (**AME**) value of 4,837 kcal/kg was used for the CS, which was the average of the values reported in the literature (Barekatain et al., 2015). Wheat and sorghum were also analyzed prior to feed formulation. All samples were analyzed in duplicate using AOAC (2005) methods of 920.39 for crude fat, 978.10 for crude fiber, and 942.05 for ash.

Experimental Design and Diets

A 2 × 2 × 2 factorial arrangement of treatments was used to investigate 3 main factors of CS inclusion (CS vs CM), oat hulls inclusion (0 and 3%), and pellet temperature (75°C or 90°C). Canola seed was added as whole seeds when diets were mixed. Canola meal and oil in control diets were replaced with CS. Diets were calculated to be isoenergetic and isonitrogenous. In line to the level of CM and oil in control diets, inclusion rate of CS was 11.6% and 13.5% for grower (d 10 to 24) and finisher (d 24 to 35) diets, respectively (Table 2). All diets were formulated to meet the requirements of Ross 308 broiler chickens (Ross, 2014).

The diets were steam-conditioned at 2 different temperatures of 75 and 90°C at The University of Sydney, Camden, NSW, similar to the procedures previously described by Selle et al. (2013). The conditioning temperature was automatically regulated via a computer software package (Gordyn & Palmer, Hallam, Vic, Australia) equipped to the pellet press (Selle et al., 2013). The residence time in the conditioner was 30 s. A Palmer PP300 pellet press (Palmer Milling Engineering, Griffith, NSW, Australia) was used to steam-pellet the experimental diets. The die dimensions were 4-mm diameter and 45-mm length.

Housing and Bird Management

A total of 576 male day-old Ross 308 broiler chickens were obtained (Baiada hatchery, Willaston, South Australia). All birds were raised on a floor based pen receiving a same commercial diet from d 0 to d 10. On d 10, birds were assigned to 48 rearing pens on wood shavings in a temperature-controlled system. Each treatment was replicated 6 times with each replicate accommodating 12 birds. Temperature was set at 33 to 34°C on the d 1 of the experiment and then gradually decreased by 1°C every 2 d until a stable temperature of 24°C was reached by d 21. In the wk 1 of age, birds had 23 h light and 1 h dark. Subsequently, birds received 16 h light and 8 h dark. Feed and water were provided ad libitum throughout the experiment. At the end of each phase of feeding, birds were weighed and feed consumption and feed conversion ratio (**FCR**) were

Table 2. Ingredient, nutrient composition (calculated and/or measured) and pellet durability index of experimental grower and finisher diets.

	Grower				Finisher			
	Control	Control + Oat hulls	Canola seed	Canola seed + oat hulls	Control	Control + Oat hulls	Canola seed	Canola seed + oat hulls
Ingredient (%)								
Sorghum	22.000	22.000	19.180	22.000	22.000	22.000	22.000	22.000
Wheat	38.216	33.776	39.898	32.589	40.633	36.193	38.896	34.438
Oat hulls	0.000	3.000	0.000	3.000	0.000	3.000	0.000	3.000
Soybean meal	24.802	25.592	25.249	26.121	22.103	22.893	21.919	22.735
Canola seed	0.000	0.000	11.600	11.600	0.000	0.000	13.500	13.500
Canola meal	6.500	6.500	0.000	0.000	6.500	6.500	0.000	0.000
Canola Oil	4.320	5.150	0.000	0.784	4.986	5.816	0.000	0.834
Limestone	1.132	1.017	1.147	1.031	1.096	0.980	1.105	0.990
Dicalcium phosphate	1.144	1.083	1.147	1.093	1.002	0.940	1.002	0.941
Xylanase	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Phytase	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Sodium chloride	0.153	0.154	0.173	0.174	0.179	0.181	0.198	0.203
Sodium bicarbonate	0.306	0.299	0.292	0.290	0.268	0.262	0.261	0.250
TiO_2	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
Vitamin and mineral Premix[1]	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200
Choline Cl 70%	0.124	0.130	0.047	0.055	0.131	0.137	0.046	0.052
L-lysine HCl 78.4%	0.208	0.197	0.193	0.183	0.120	0.108	0.117	0.095
DL-methionine	0.262	0.269	0.251	0.260	0.200	0.207	0.186	0.192
L-threonine	0.118	0.118	0.107	0.107	0.068	0.068	0.056	0.055
Nutrient composition (% unless otherwise specified)								
ME kcal/kg	3038	3038	3038	3038	3100	3100	3100	3100
Crude Protein	21	21	21	21	19.9	19.9	19.9	19.9
Crude protein (measured)	21.16	20.89	21.70	21.67	20.62	20.80	20.53	20.36
Crude fat (measured)	6.15	7.19	7.41	7.26	6.47	6.86	6.52	7.68
Crude fiber (measured)	2.56	3.43	2.55	3.42	2.62	3.53	2.67	3.58
ADF (measured)	4.87	6.02	5.89	5.61	4.65	5.49	5.32	6.51
NDF (measured)	8.43	10.50	8.36	9.78	9.07	10.87	8.99	9.77
Digestible Arg	1.23	1.24	1.24	1.24	1.16	1.16	1.16	1.16
Digestible Lys	1.1	1.1	1.1	1.1	0.97	0.97	0.977	0.97
Digestible Met	0.55	0.55	0.53	0.54	0.47	0.48	0.46	0.47
Digestible Cys	0.29	0.28	0.29	0.28	0.28	0.27	0.28	0.28
Digestible M+C	0.84	0.84	0.84	0.84	0.76	0.76	0.76	0.76
Digestible Trp	0.24	0.24	0.24	0.24	0.22	0.22	0.22	0.22
Digestible Leu	1.39	1.39	1.37	1.39	1.32	1.33	1.32	1.32
Digestible Ile	0.84	0.84	0.84	0.84	0.80	0.80	0.80	0.80
Digestible Thr	0.73	0.73	0.73	0.73	0.65	0.65	0.65	0.65
Digestible Val	0.93	0.93	0.93	0.93	0.88	0.88	0.88	0.88
Calcium[2]	0.90 (0.92)	0.90 (0.94)	0.90 (0.89)	0.90 (0.87)	0.85 (0.86)	0.85 (0.83)	0.85 (0.81)	0.85 (0.92)
Phosphorus (available)	0.45	0.45	0.45	0.45	0.42	0.42	0.42	0.42
Phosphorus total (measured)	0.66	0.62	0.64	0.65	0.61	0.61	0.63	0.64
Sodium	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Chloride	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
PDI[3]	89	84	94.6	90.4	88.6	84.2	92.6	88.7

[1] 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. Vitamin concentrate supplied per kilogram of diet: retinol, 12,000 IU; cholecalciferol, 5,000 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.

[2] values in parenthesis are the measured calcium.

[3] PDI: Pellet durability index was determined using a standardised method for durability (Method S269.4, ASAE, 1997) using Seedburo Pellet Durability Tester (developed by Kansas State University, Manhattan, KS).

measured. FCR was adjusted for mortality if occurred for any treatments.

Sample Collection, Viscosity Measurement, and Nutrient Digestibility Assay

On d 24 and 35, 3 birds per replicate were randomly chosen and euthanized in order to obtain ileal digesta and record visceral organ weights. The empty weight of duodenum, jejunum, ileum, proventriculus, and gizzard were expressed to body weight. The ileal contents of 3 birds were collected into ice-cold plastic containers, and subsequently pooled by each replicate pen. To measure the viscosity of ileal content (only on d 35), subsamples were immediately centrifuged (12,000 × g, 10 min, 4°C) to obtained supernatant. About 0.5 mL of thawed supernatant was used to measure viscosity with a Brookfield DVIII viscometer at 25°C with a CP 40 cone. The shear rate was from 5 to 500/s. The remaining samples were stored at -20°C and then freeze-dried before conducting further analyses.

The methods of AOAC (2005) were followed for determination of dry matter (**DM**) and fat content of diets and digesta. The N content analysis of the diets and digesta samples was performed using a LECO FP-2000 automatic analyzer (Leco Corporation, St. Joseph, MI). Amino acid determination was conducted by hydrolyzing the samples with 6 M HCl (containing phenol) for 24 h at 110 ± 2°C in glass tubes sealed under vacuum carried out by Macquarie University, NSW, Australia. Titanium contents of diets and ileal samples were measured using the method described by Short et al. (1996). Subsequent digestibility coefficients for amino acids, N, DM, and fat were calculated as follows:

$$\text{Apparent Ileal Digestibility Coefficient} = \frac{(\mathrm{NT/Ti})_{\mathrm{d}} - (\mathrm{NT/Ti})_{\mathrm{i}}}{(\mathrm{NT/Ti})_{\mathrm{d}}}$$

where, $(\mathrm{NT/Ti})_{\mathrm{d}}$ was the ratio of nutrient (NT) and titanium (Ti) in diet, $(\mathrm{NT/Ti})_{\mathrm{i}}$ was the ratio of nutrient (NT) and titanium (Ti) in ileal digesta

Apparent Metabolizable Energy

Apparent metabolizable energy bioassay was conducted for grower diets using total collection method. A total of 192 Ross 308 broiler chickens from same batch of birds used in the feeding study, were separately raised on a floor based pen with wood shavings as litter from d 1 to d 17 of age. All birds received a same commercial diet and had access to feed and water ad libitum. On d 18, birds were transferred to a total of 48 metabolism cages each accommodating 4 birds and were given 8 experimental treatments used in feeding trial after 2 d of adaptation period. Total excreta collection was conducted over 4 d consecutively. All collected excreta was oven dried at 85°C, weighed and then finely ground for gross energy (**GE**) analysis.

The GE content of experimental diets and excreta were determined using a Parr isoperibol bomb calorimeter (Parr Instrument Company, Moline, IL) with benzoic acid as the standard.

The AME of the experimental diets were determined using the following equation:

$$\text{AME (kcal/kg)} = (\text{GEI} - \text{GEE})/\text{FI}$$

where GEI is gross energy intake, GEE is gross energy output of excreta (kcal/kg of DM), and FI is the feed intake (kg).

Statistical Analysis

Data of the experiment were subjected to statistical analysis using 3-way analysis of variance (**ANOVA**) of GLM procedure of SAS (2003) according to a 2 × 2 × 2 factorial arrangement of treatments to assess the main effects of canola inclusion, oat hulls, pellet temperature and their 2- or 3-way interactions. Data were checked for normal distribution. One cage constituted an experimental unit and the values presented in the tables are means with pooled standard error of mean (SEM) (n = 48). If a significant effect was detected, differences between treatments or main effects were separated by Duncan multiple range test. All statements of significance are considered on a P-value < 0.05, and tendencies were specified for $0.05 < P < 0.10$.

RESULTS

Growth Performance

The results of FI, body weight gain (BWG), and FCR of birds are given in Table 3. There were no 3-way interactions for any of performance parameters. Feed consumption tended ($P = 0.088$) to decrease in birds fed CS from d 10 to 24. At the same time, there was a tendency ($P = 0.078$) for higher FI when OH were included in the diets. For both grower and finisher phases, there was a significant interaction between OH and type of canola where birds fed both CS and OH had a higher FI than CS alone ($P < 0.05$). Pellet temperature did not influence performance of broiler at any stage of the experiment.

Canola seed and OH interacted significantly resulting in a higher BWG of birds from d 10 to 24 of age ($P < 0.01$). Inclusion of OH independently improved BWG from d 24 to 35 ($P < 0.01$) and when assessed for entire study ($P < 0.001$). By a significant interaction, FCR was improved in birds offered OH and CS in both grower ($P < 0.05$) and finisher ($P < 0.01$) phase of feeding.

Organ Weights

The relative weights of organs are presented in Table 4. Dietary treatments did not influence the relative weight of proventriculus at d 24 or 35. There was significant interaction between OH inclusion and pellet temperature for relative gizzard weight where higher pellet temperature increased gizzard weight only in absence of OH in the diet ($P < 0.05$). Addition of OH to the diets independently increased gizzard weight at both d 24 and d 35 ($P < 0.001$) and ileum weight ($P < 0.05$) at d 35. Canola seed inclusion and OH tended to interact for duodenal weight where birds fed diets containing CS and OH had heavier duodenum ($P = 0.07$). Increasing temperature to 90°C increased relative weight of duodenum at d 24 ($P < 0.05$) and d 35 ($P < 0.01$). On d 24, birds fed CS had heavier jejunum than birds receiving diets containing CM and oil ($P < 0.05$).

Ileal Nutrient Digestibility

The results of ileal DM, N, and fat digestibility measurements are given in Table 5. At d 24, there was an interaction between the type of canola inclusion and pellet temperature for DM digestibility ($P < 0.01$), in

Table 3. Feed intake, body weight gain, and feed conversion ratio of broiler chickens fed experimental grower and finisher diets[1].

Treatment	Oat hulls (%)	Temperature	Feed intake (g/bird)			Body weight gain (g/bird)			Feed conversion ratio		
			d 10–24	d 24–35	d 10–35	d 10–24	d 24–35	d 10–35	d 10–24	d 24–35	d 10–35
Canola meal	0	75°C	1462	2086	3548	1036	1270	2306	1.415	1.644^{a}	1.540
Canola meal	0	90°C	1450	2081	3530	1021	1293	2314	1.420	$1.610^{a,b}$	1.526
Canola meal	3	75°C	1474	2068	3542	1023	1344	2367	1.442	1.540^{c}	1.496
Canola meal	3	90°C	1451	2107	3558	1029	1324	2354	1.411	$1.592^{a\text{-}c}$	1.512
Canola seed	0	75°C	1410	1997	3407	1001	1283	2285	1.408	$1.561^{b,c}$	1.496
Canola seed	0	90°C	1416	2058	3474	1042	1305	2347	1.360	$1.578^{b,c}$	1.481
Canola seed	3	75°C	1445	2141	3587	1096	1355	2452	1.319	$1.580^{b,c}$	1.464
Canola seed	3	90°C	1454	2101	3556	1082	1329	2411	1.345	$1.581^{b,c}$	1.475
		SEM	6.02	9.90	12.81	5.97	8.00	11.13	0.0066	0.0066	0.0045
Main effects											
Canola		Meal	1458	2085	3544	1027	1308	2335	1.422	1.596	1.518^{a}
		Seed	1431	2074	3505	1055	1318	2372	1.359	1.575	1.478^{b}
Oat hulls (%)		0	1434	2055	3489	1022	1288^{b}	2311^{a}	1.402	1.597	1.511^{a}
		3	1456	2104	3560	1057	1338^{a}	2396^{b}	1.379	1.573	1.486^{b}
Pellet temperature		75°C	1448	2073	3521	1038	1313	2356	1.397	1.581	1.499
		90°C	1442	2087	3529	1043	1313	2351	1.384	1.590	1.498
Source of variation (P values)											
Canola			0.088	0.575	0.139	0.032	0.517	0.105	<.0001	0.116	<.0001
Oat hulls			0.078	0.018	0.009	0.007	0.003	0.001	0.088	0.069	0.010
Pellet temperature			0.692	0.503	0.739	0.639	0.997	0.803	0.313	0.501	0.944
Canola × oat hulls			0.217	0.030	0.025	0.004	0.900	0.134	0.020	0.009	0.609
Canola × temp			0.301	0.870	0.717	0.414	0.914	0.717	0.955	1.000	0.892
Oat hulls × temp			0.863	0.482	0.532	0.403	0.163	0.148	0.392	0.204	0.120
Canola × oat hulls × temp			0.792	0.075	0.206	0.101	0.928	0.340	0.089	0.057	0.924

[1] Each value represents the mean of 6 replicates for treatment effects and 24 replicates for main effects.

[a–c] Means within a column not sharing a superscript differ significantly at $P < 0.05$ for the treatment effects and at the P-value shown for the main effects.

which birds fed CS diets pelleted at 75°C had lower DM digestibility. There was no interaction between any of the 3 experimental factors for DM digestibility at d 35. At the same time, inclusion of either OH, CS or pelleting temperature at 90°C independently reduced DM utilization ($P < 0.05$).

There was no interaction between the experimental factors for ileal digestibility of N on either d 24 or 35. At d 24, feeding CS tended to decrease N digestibility ($P = 0.067$). For both grower and finisher diets, birds fed OH had higher N digestibility coefficient compared to birds fed OH-free diets ($P < 0.05$).

Increasing pellet temperature from 75 to 90°C caused a reduction in ileal N digestibility at d 35 ($P < 0.05$).

Inclusion of CS in the diets depressed fat digestibility at d 24 ($P < 0.001$). At d 35, there was a significant interaction ($P < 0.05$) between CS and pellet temperature where birds fed CS diets pelleted at 75°C had higher fat digestibility than birds fed CS pelleted at 90°C. Regardless of canola or pellet temperature, OH increased fat utilization at d 35 ($P < 0.001$).

Ileal Amino Acid Digestibility

Tables 6 and 7 show the results for apparent ileal digestibility coefficients of indispensable and dispensable amino acids (AA), respectively. There was no 3-way interaction for AA digestibility. Significant interaction was found between CS and OH showing a positive effect of OH on Arg ($P < 0.05$) and Met ($P < 0.001$) digestibility in CS fed birds. Pellet temperature and CS also interacted ($P < 0.05$) for Arg, His, Ile, Lys, Met, Thr, Asp, Ser, and Tyr in that CS inclusion resulted in lower digestibility only when diets were pelleted at 75°C.

Inclusion of CS in the diets independently reduced ($P < 0.05$) digestibility of Leu, Ala, Glu, and Pro. Addition of OH also increased digestibility of Ile ($P < 0.05$), Leu ($P < 0.05$), Phe ($P < 0.05$), Thr ($P < 0.05$), Val ($P < 0.05$), Ala ($P < 0.05$), Asp ($P < 0.01$), Gly ($P < 0.01$), and Tyr ($P < 0.05$).

Apparent Metabolizable Energy of Grower Diets and Ileal Viscosity

As shown in Table 5, with a 3-way interaction ($P < 0.05$), inclusion of CS in the diets decreased the AME of grower diets which was observed only when a high pellet temperature was applied. Ileal viscosity was not affected by experimental treatments when assessed at d 35 of age (Table 5).

DISCUSSION

The findings of this study and that of Barekatain et al. (2015) clearly highlights that a lower feed consumption is the main reason for the differences observed between the diets containing CS and CM. The

Table 4. Relative organ weights (g/100 g body weight) of broiler chickens on d 24 and 35[1].

Treatments	Oat hulls (%)	Temp[2]	Proventriculus		Gizzard		Liver		Duodenum		Jejunum		Ileum	
			d 24	d 35	d 24	d 35	d 24	d 35	d 24	d 35	d 24	d 35	d 24	d 35
Canola meal	0	75°C	0.46	0.35	1.87	1.24	3.10	2.33	1.08	0.66	1.79	1.33	1.20	0.89
Canola meal	0	90°C	0.50	0.31	2.17	1.34	3.00	2.29	1.14	0.70	1.99	1.23	1.25	0.83
Canola meal	3	75°C	0.49	0.35	2.19	1.54	3.06	2.27	1.00	0.67	1.97	1.30	1.19	0.96
Canola meal	3	90°C	0.49	0.34	2.29	1.51	3.00	2.36	0.99	0.73	1.82	1.24	1.33	0.84
Canola seed	0	75°C	0.46	0.32	1.93	1.35	2.93	2.40	1.02	0.68	1.92	1.32	1.23	0.83
Canola seed	0	90°C	0.49	0.33	2.12	1.41	3.11	2.38	1.18	0.71	2.07	1.16	1.31	0.85
Canola seed	3	75°C	0.47	0.33	2.28	1.45	2.97	2.31	1.06	0.66	1.94	1.31	1.19	0.88
Canola seed	3	90°C	0.48	0.34	2.22	1.55	3.00	2.38	1.13	0.75	2.12	1.43	1.21	0.93
		SEM	0.006	0.004	0.023	0.021	0.028	0.024	0.016	0.010	0.023	0.019	0.020	0.011
Main effects														
Canola		Meal	0.48	0.33	2.13	1.41	3.03	2.31	1.05	0.69	1.89^{b}	1.27	1.24	0.88
		Seed	0.47	0.33	2.14	1.44	3.00	2.37	1.09	0.70	2.01^{a}	1.30	1.23	0.87
Oat hulls (%)		0	0.47	0.32	2.02^{b}	1.33^{b}	3.03	2.35	1.10	0.68	1.94	1.26	1.25	0.85^{a}
		3	0.48	0.34	2.27^{a}	1.51^{a}	3.01	2.33	1.05	0.70	1.96	1.32	1.23	0.90^{b}
Pellet temperature		75°C	0.47	0.34	2.07^{b}	1.40	3.02	2.32	1.04^{b}	0.67^{b}	1.90	1.31	1.20	0.88
		90°C	0.49	0.33	2.20^{a}	1.45	3.02	2.35	1.11^{a}	0.72^{a}	1.99	1.26	1.27	0.86
Source of variation														
Canola			0.340	0.691	0.855	0.448	0.508	0.256	0.182	0.529	0.014	0.423	0.874	0.704
Oat hulls			0.749	0.096	<.001	0.001	0.657	0.641	0.055	0.450	0.683	0.107	0.619	0.025
Pellet temperature			0.253	0.487	0.006	0.193	0.832	0.606	0.024	0.006	0.056	0.188	0.067	0.227
Canola × oat hulls			0.655	0.842	0.971	0.186	0.890	0.629	0.077	0.737	0.790	0.060	0.170	0.621
Canola × temperature			1.000	0.079	0.154	0.601	0.116	0.953	0.151	0.801	0.123	0.449	0.561	0.006
Oat hulls × temperature			0.253	0.277	0.018	0.614	0.667	0.278	0.209	0.336	0.100	0.052	0.891	0.790
Canola × oat hulls × temperature			0.701	0.322	0.784	0.302	0.395	0.806	0.779	0.529	0.044	0.111	0.338	0.471

[1] Each value represents the mean of 6 replicates for treatment effects and 24 replicates for main effects.

[2] Temperature.

[a,b] Means within a column not sharing a superscript differ significantly at $P < 0.05$ for the treatment effects and at the P-value shown for the main effects.

mechanism behind lower FI of birds fed CS is not fully clear. However, possible residual isothiocyanate levels resulting from breakdown of glucosinolates may have contributed to the palatability of the diets containing CS (Tripathi and Mishra, 2007). It is known that the enzyme myrosinase is responsible for breaking glucosinolates into the extremely bitter compounds of isothiocyanates and goitrin (Tripathi and Mishra, 2007), which may adversely affect feed consumption. Another observation worth mentioning was the pellet durability index of the experimental diets (Table 2), which was observed to be higher in the diets containing CS without OH. Therefore, hardness of the pellets may have also contributed to the differences observed for FI. Nevertheless, the BW of birds in the current study was comparable to control birds, which shows that CS can replace a substantial proportion of supplemental oil without adverse effect on feed efficiency.

In the present study, neither independent nor combined effect of pellet temperature was significant for the bird performance. In the literature, there is evidence that increasing temperature above 60°C can reduce the performance of birds fed wheat-based diets (Bedford et al., 2003; Abdollahi et al., 2013a). Abdollahi et al. (2010) found that birds fed diets pelleted at 90°C gained more weight compared with 75°C when fed a maize-based diet, but there was no effect when assessed for wheat-based diets. The experimental diets in the present study comprised combinations of sorghum, wheat, and soybean meal as major ingredients, which may have contributed to the differences in observations between the studies. This study, to our knowledge, is the first that has investigated the effect of pellet temperature specifically for CS in which we found no clear effect of pellet temperature for bird performance. Shen et al. (1983) postulated that heating *per se* may be an influencing factor in steam-pelleting of CS, but there was no direct comparison of temperature in that experiment. As heat treatment is able to reduce the activity of myrosinase (Fenwick et al., 1986), it was thought that a higher pellet temperature may possibly affect FI of birds through deactivation of myrosinase. Unfortunately, under the conditions of this experiment, it was not feasible to measure the activity of myrosinase as this enzyme acts rapidly after the seed breaks during the process of feed manufacturing. Therefore, the measurement of myrosinase on manufactured feed had little relevance. A separate *in vitro* investigation may possibly provide an answer to this question.

Independent and positive effect of OH on FCR of birds when assessed for the entire experiment is in line with experiments conducted by other researchers (Jiménez-Moreno et al., 2013; Jiménez-Moreno et al., 2016). Jimenez-Moreno et al. (2016) showed that regardless of the feed form, inclusion of moderate amount of fiber can still enhance growth performance of broiler chickens. On the other hand, some recent research showed that in pelleted diets, addition insoluble fiber

Table 5. Apparent ileal nutrient digestibility coefficients of grower (d 24) and finisher diets (d 35), AME and viscosity of ileal content[1].

	Oat hulls (%)	Temperature	DM	DM	N	N	Fat	Fat	AME (kcal/kg)	Viscosity
			d 24	d 35	d 24	d 35	d 24	d 35		d 35
Canola meal	0	75°C	0.718	0.746	0.821	0.836	0.833	0.850	3121^a	1.68
Canola meal	0	90°C	0.705	0.730	0.819	0.831	0.833	0.840	3120^a	1.74
Canola meal	3	75°C	0.718	0.732	0.830	0.844	0.816	0.873	3119^a	1.59
Canola meal	3	90°C	0.707	0.719	0.822	0.835	0.834	0.864	3109^a	1.62
Canola seed	0	75°C	0.673	0.739	0.805	0.838	0.768	0.822	3114^a	1.75
Canola seed	0	90°C	0.704	0.713	0.809	0.814	0.754	0.753	3021^b	1.65
Canola seed	3	75°C	0.689	0.716	0.812	0.841	0.789	0.822	3040^b	1.72
Canola seed	3	90°C	0.703	0.719	0.831	0.837	0.764	0.796	3049^b	1.71
		SEM	0.0030	0.0025	0.0022	0.0021	0.0073	0.0036	0.020	0.033
Main effects										
Canola		Meal	0.712	0.732^a	0.823	0.836	0.829^a	0.857	3116	1.66
		Seed	0.692	0.721^b	0.814	0.832	0.769^b	0.798	3054	1.71
Oat hulls (%)		0	0.700	0.731^a	0.814^a	0.829^a	0.797	0.816^a	3090	1.70
		3	0.704	0.721^b	0.824^b	0.839^b	0.801	0.839^b	3083	1.66
Pellet temperature		75°C	0.700	0.733^a	0.817	0.840^a	0.801	0.842	3097	1.67
		90°C	0.705	0.720^b	0.820	0.829^b	0.796	0.813	3074	1.68
Source of variation (P values)										
Canola			0.002	0.049	0.067	0.328	<0.001	<0.001	<0.001	0.453
Oat hulls			0.473	0.039	0.024	0.028	0.812	0.003	0.406	0.548
Pellet temperature			0.401	0.013	0.466	0.015	0.730	0.001	0.022	0.910
Canola × oat hulls			0.589	0.679	0.361	0.422	0.434	0.899	0.148	0.375
Canola × temperature			0.007	0.692	0.078	0.433	0.323	0.013	0.069	0.453
Oat hulls × temperature			0.533	0.120	0.600	0.358	0.910	0.137	0.096	0.802
Canola × oat hulls × temperature			0.440	0.184	0.273	0.192	0.623	0.158	0.023	0.661

[1] Each value represents the mean of 6 replicates for treatment effects and 24 replicates for main effects.

[a,b] Means within a column not sharing a superscript differ significantly at $P < 0.05$ for the treatment effects and at the P-value shown for the main effects.

had limited effect (van der Hoeven-Hangoor et al., 2014). Insoluble fiber is shown to consistently increase gizzard weight by large inclusion of hulls in broiler diets (Svihus et al., 2010; Sacranie et al., 2012), an observation that was also confirmed in the current trial, although to a lesser extent, possibly due to lower inclusion of OH. The coarse material in the diets must be ground to a certain critical size so that gizzard adapts itself to develop in response to the gizzard content (Sacranie et al., 2012).

In the present study, for the first time, we observed the effect of an insoluble source of fiber for utilization of CS. There was a clear interaction between OH and the type of canola included in the diets for the grower phase of feeding. When diets contained CS without OH, a lower FI was observed compared with other group of birds, which concurs with a previous study (Barekatain et al., 2015). However, OH offered no synergistic effect on FI but rather was effective in maintaining the FI of birds fed CS compared to control birds. The exact mechanism behind this interaction cannot be immediately explained by the measured nutrient utilization. However, the differences between fiber content of the diets and a possible effect of pellet hardness may be among the contributing factors. The presence of this interaction cast doubt on an independent effect of OH on the FI of birds.

Inclusion of CS in the diets resulted in a distinct retardation of fat utilization both in grower and finisher phase of feeding. This reduction was exacerbated by higher temperature only in finisher diets, most likely due to higher inclusion of CS compared with grower diets. It is well documented that some of the oil in CS remains encapsulated in the peptide shell oil bodies that in turn impede maximum fat utilization (Slominski et al., 2006; Barekatain et al., 2015). The fat utilization of CS appears to be, at least to some extent, dependent on pelleting condition such as steam pelleting (Barekatain et al., 2015), and in this experiment, pellet temperature; that was, however, not reflected in any performance difference for the birds. The experiments conducted for the effect of pellet temperatures on fat utilization are very limited. While Jimenez-Moreno et al. (2009) showed that steam cooking may increase fat utilization in maize-based diet, Abdollahi et al. (2013b) found that ileal fat digestibility varied depending on cereal composition of the diets. It is unknown why a higher temperature has impaired the fat utilization only in the diets fed CS; this requires further research. Nevertheless, we previously found that applying steam to the diets reduced fat digestibility in birds fed CS compared with cold-pellet diets (Barekatain et al., 2015).

The adverse effect of OH and CS on DM was expected due to the difference between fiber content of the diets. Inclusion of OH improved fat digestibility in finisher diets, although there was no interaction with CS inclusion. This result concurs with other studies in

Table 6. Apparent ileal digestibility coefficient of indispensable amino acids for broiler chickens fed grower diets (d 24)[1].

	Oat hulls (%)	Temperature	Arg	His	Ile	Leu	Lys	Met	Phe	Thr	Val
Canola meal	0	75°C	0.884	0.849	0.828	0.830	0.866	0.946	0.846	0.800	0.817
Canola meal	0	90°C	0.876	0.840	0.818	0.820	0.860	0.942	0.836	0.792	0.804
Canola meal	3	75°C	0.883	0.843	0.816	0.812	0.863	0.945	0.835	0.793	0.803
Canola meal	3	90°C	0.877	0.841	0.819	0.820	0.861	0.945	0.838	0.790	0.805
Canola seed	0	75°C	0.858	0.817	0.798	0.799	0.842	0.933	0.819	0.761	0.785
Canola seed	0	90°C	0.867	0.834	0.811	0.806	0.853	0.936	0.825	0.779	0.797
Canola seed	3	75°C	0.874	0.839	0.812	0.810	0.854	0.940	0.827	0.782	0.799
Canola seed	3	90°C	0.883	0.846	0.828	0.825	0.869	0.947	0.842	0.797	0.814
		SEM	0.0016	0.0020	0.0023	0.0024	0.0020	0.0009	0.0021	0.0027	0.0024
Main effects											
Canola		Meal	0.880	0.843	0.820	0.820^{a}	0.862	0.944^{a}	0.839^{a}	0.794^{a}	0.807
		Seed	0.870	0.834	0.812	0.809^{b}	0.854	0.939^{b}	0.828^{b}	0.780^{b}	0.799
Oat hulls (%)		0	0.871	0.833^{b}	0.811	0.809	0.854	0.940	0.829	0.780^{b}	0.797^{b}
		3	0.879	0.843^{a}	0.821	0.821	0.862	0.944	0.838	0.793^{a}	0.808^{a}
Pellet temperature		75°C	0.874	0.837	0.813	0.812	0.856	0.941	0.832	0.784	0.801
		90°C	0.876	0.840	0.819	0.817	0.861	0.943	0.835	0.789	0.805
Source of variation (P values)											
Canola			0.008	0.025	0.084	0.035	0.057	0.006	0.017	0.012	0.093
Oat hulls			0.017	0.017	0.029	0.018	0.083	0.032	0.049	0.027	0.029
Pellet temperature			0.744	0.445	0.231	0.319	0.283	0.339	0.431	0.352	0.390
Canola × oat hulls			0.019	0.071	0.290	0.489	0.132	0.009	0.346	0.181	0.345
Canola × temperature			0.020	0.036	0.058	0.218	0.042	0.047	0.103	0.049	0.059
Oat hulls × temperature			0.900	0.285	0.607	0.601	0.992	0.911	0.813	0.728	0.543
Canola × oat hulls × temperature			0.880	0.852	0.396	0.167	0.552	0.296	0.225	0.932	0.354

[1] Each value represents the mean of 6 replicates for treatment effects and 24 replicates for main effects.

[a,b] Means within a column not sharing a superscript differ significantly at the *P*-value shown for the main effects.

Table 7. Apparent ileal digestibility coefficient of dispensable amino acids for broiler chickens fed grower diets (d 24)[1].

	Oat hulls (%)	Temperature	Ala	Asp	Glu	Gly	Pro	Ser	Tyr
Canola meal	0	75°C	0.807	0.808	0.887	0.799	0.843	0.810	0.814
Canola meal	0	90°C	0.796	0.796	0.878	0.793	0.834	0.800	0.810
Canola meal	3	75°C	0.783	0.794	0.878	0.792	0.835	0.800	0.818
Canola meal	3	90°C	0.797	0.790	0.882	0.789	0.837	0.799	0.804
Canola seed	0	75°C	0.763	0.762	0.869	0.763	0.821	0.776	0.780
Canola seed	0	90°C	0.775	0.785	0.875	0.782	0.829	0.794	0.784
Canola seed	3	75^C	0.781	0.789	0.869	0.793	0.826	0.793	0.796
Canola seed	3	90°C	0.799	0.804	0.880	0.804	0.836	0.806	0.817
		SEM	0.0031	0.0025	0.0017	0.0025	0.0020	0.0025	0.0025
Main effects									
Canola		Meal	0.796^{a}	0.797	0.881^{a}	0.793	0.837^{a}	0.802	0.811
		Seed	0.780^{b}	0.784	0.873^{b}	0.785	0.828^{b}	0.791	0.794
Oat hulls (%)		0	0.779	0.782	0.875	0.781^{b}	0.830	0.792	0.796
		3	0.796	0.799	0.878	0.797^{a}	0.834	0.801	0.809
Pellet temperature		75°C	0.783	0.788	0.876	0.789	0.831	0.794	0.802
		90°C	0.792	0.793	0.878	0.792	0.834	0.799	0.804
Source of variation (P values)									
Canola			0.013	0.020	0.028	0.122	0.025	0.051	0.001
Oat hulls			0.012	0.003	0.441	0.004	0.284	0.063	0.014
Pellet temperature			0.189	0.278	0.385	0.320	0.480	0.301	0.675
Canola × oat hulls			0.455	0.197	0.901	0.050	0.704	0.382	0.022
Canola × temperature			0.262	0.011	0.101	0.064	0.131	0.047	0.030
Oat hulls × temperature			0.479	0.407	0.567	0.575	0.559	0.506	0.190
Canola × oat hulls × temperature			0.246	0.961	0.191	0.852	0.467	0.871	0.700

[1] Each value represents the mean of 6 replicates for treatment effects and 24 replicates for main effects.

[a,b] Means within a column not sharing a superscript differ significantly at the *P*-value shown for the main effects.

the literature and has been attributed to the possible beneficial effect of dietary fiber on gizzard development and subsequent increase in bile acids and digestive enzyme secretion (Mateos et al., 2012). Indeed, the gizzard development was evident in the current study as a result of OH inclusion. A well-functioning gizzard offers a wide range of benefits, including increased antiperistaltic movement (Sacranie et al., 2012), better mixing of digestive juices with digesta as well as reduction in pH of the hindgut, which consequently may benefit enzyme activation (Mateos et al., 2012). All of these possibilities may provide an explanation for observed improvement in nutrient digestibility that resulted from including OH in the diet.

In the present study, it was hypothesized that inclusion of OH may improve fat digestion of the diets containing CS. The results showed that the effect of OH for improved fat digestibility in finisher diets was independent of CS inclusion. Similar benefits for fat utilization resulted from inclusion of an insoluble fiber source in broiler diets have been reported (Gonzalez-Alvarado et al., 2007; Kalmendal et al., 2011).

Inclusion of CS in the diets reduced the AME of grower diets, which is in line with reduced fat digestibility of CS-fed birds. It is possible that the AME value of the tested seed may have been slightly overestimated when formulating the diets. There was no effect of OH inclusion on AME of grower diets, which could be related to the fact that all the diets were formulated to be isoenergetic. In an experiment conducted by Sacranie et al. (2012), diets that were simply diluted with OH resulted in a substantial reduction of AME, which could then be improved by a higher nutrient utilization in the birds. Given the lack of effect of OH in birds fed the control diets, it appears that balancing the diets for energy and nutrient when formulating diets is of particular importance in response to OH inclusion. Leeson et al. (1996) showed that dilution of diets with 7.5% OH caused an increase in FI as a sign of the birds' ability to regulate their FI in response to dietary energy. Therefore, in agreement with several other studies (González-Alvarado et al., 2010; Mateos et al., 2012; Jiménez-Moreno et al., 2016), the response to dietary fiber in terms of growth performance may vary depending on several factors, including but not limited to the composition of basal diets, age, health status, and genetic potential (Jiménez-Moreno et al., 2016).

There were lower AA digestibility coefficients for 11 AAs in the diet containing CS compared with CM in control diets. This observation is in disagreement with a previous study in which the CS used contained a higher amount of oil and the diets were pelleted on average at a lower temperature (Barekatain et al., 2015).

It can be concluded that CS can be used in broiler diets in whole form in steam-pelleted diets containing a moderate amount of insoluble fiber such as 3% OH. Inclusion of OH appears to interact with CS to maintain feed consumption, which otherwise would be adversely affected by inclusion of CS in the diets. The mechanism of this interaction needs further investigation. A positive effect of OH was observed for fat and AA digestibility. Under the condition of this experiment, birds were not responsive to pellet temperature for performance parameters. However, some negative effect of high pelleting temperature on nutrient utilization, fat in particular, was apparent, which may suggest a need to maintain the pellet temperature at around 75°C when CS is included in broiler diets.

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