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Original Article

Interactive Effects of Feed Form, and Fiber Source and Levels on Production Performance, Foregut Development, and Nutrients Utilization in Broilers

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ABSTRACT

A total of 480 one-day-old straight-run broilers were used to evaluate the effects of feed form (FF), fiber source (FS), and fiber level (FL) on production performance, foregut development, gut histomorphology, apparent ileal digestibility (AID) of amino acids (AA) and cecal microbiota count. Eight experimental diets comprising 6 replicates with 10 birds each were tested in a 2 × 2 × 2 factorial arrangement in a completely randomized design using two FF (Pellet *vs*. Mash), two FS (Oat hulls (OH) *vs*. Sugarcane bagasse (SCB)) and two FL (3 *vs*. 5%). Overall (0-35 days), broilers fed OH pelleted diet had better ($p< 0.05$) feed intake, body weight gain and FCR than those fed SCB pelleted or mash diets. Broilers fed OH pelleted diet showed improved VH (villus height) by 5% and VCR (villus height to crypt depth ratio) up to 13%. An interaction ($p<0.05$) between FS × FF was detected for lysine, methionine, threonine, valine, arginine and cysteine. The pelleted diet decreased ($p<0.05$) the empty relative weight of proventriculus and gizzard. Pelleted diet containing OH increased cecal *Lactobacillus* spp.. and reduced *E. Coli* count in comparison to mash OH and SCB. In conclusion, 3% OH in pelleted diets may potentially be used in broiler diets to enhance duodenal histomorphology, nutrients digestibility, beneficial cecal microbiota count, and production performance.

INTRODUCTION

The poultry sector has expanded expeditiously around the world to meet human protein requirements (Akhtar *et al*., 2023). This rapid growth, however, forced nutritionists to look for alternate dietary strategies to further enhance the feed efficiency in broilers (Yeniçeri *et al*., 2021; Farooq *et al*., 2022; Al-Hoshani *et al*., 2023). Dietary structural manipulations, such as varying the particle size of feed ingredients or adding fiber, have resulted in better feed efficiency due to their beneficial effects on broiler foregut and hind gut development (Svihus, 2014; Anwar *et al*., 2023; Pourazadi *et al*., 2024). Insoluble dietary fiber such as oat and rice hulls increases the gizzard weight, nutrient utilization and gut development in broilers (Mateos *et al*., 2012; Yameen *et al*., 2024). A well-developed gizzard with strong peristaltic movements facilitates the grinding and mixing of the chyme with gastric juices, and helps regulate the digesta flow from the gizzard to the hind gut (Guzman *et al*., 2015; Anwar *et al*., 2023). The influence of insoluble dietary fiber on various digestive traits, however, depends upon fiber type and its level, feed composition, and feed form (Rybicka *et al*., 2024). The inclusion of a moderate (3%) level of fiber, for instance, exerts beneficial effects on the growth performance of broilers (Mateos *et al*., 2012). The extent of these benefits, however, depends upon dietary inclusion levels and the type of insoluble fiber (Jiménez-Moreno *et al*., 2013a; Nuriyasa *et al*., 2022).

Higher dietary insoluble fiber levels, on the other hand, exert detrimental effects on production potential by leading to improper digestion and reduced fermentation capacity in the host (Abdollahi *et al*., 2020). However, insoluble fibers, by being rich in lignin, have a potential to exert a significant effect on gut microbiota count and its fermentation activity in broilers (Milosevic *et al*., 2015). This is due to improved gizzard functions, by controlling digesta retention time and GIT pH. Kalmendal *et al*. (2011), for instance documented that OH based rations in broilers increased *Lactobacillus* spp. and decreased *Clostridium* and *Campylobacter* spp. counts. The inclusion of sunflower hulls (4%) similarly decreased the cecal microbial population of *E.Coli* in Japanese quails (Bamedi *et al*., 2024). A balanced gut microflora promotes enzyme secretions, modulates the immune system, regulates the energy metabolism, and finally improves production performance (Jha *et al*., 2020; Dasriya *et al*., 2024).

In addition to fiber type, the physical form of the feed is also a critical factor influencing the production potential of broilers. Different feed forms such as mash, crumble, and pellets differently affect the gut development and production performance of broilers (Pirzado *et al*., 2015; Amoozmehr *et al*., 2023). Pelleted diets improve the production performance of broilers by inhibiting selective feeding, reducing feed waste, and enhancing the palatability of the diet (Saldana *et al*., 2015; Massuquetto *et al*., 2020). Furthermore, the application of steam and pressure during the pelleting process facilitates starch gelatinization and protein degradation by destroying anti-nutritional factors, including gossypol and trypsin inhibitor, leading to an increased production potential of broilers (Lv *et al*., 2015; Rueda *et al*., 2024). Conversely, feeding pelleted diet reduced the length of the small intestine and ceca, and the weight of the pancreas, proventriculus and gizzard (Naderinejad *et al*., 2016; Yousefian Astaneh *et al*., 2023).

Only limited and inconsistent information is available on the effects of insoluble fiber sources with different physico-chemical properties on the gut development and nutrients digestibility of broilers fed pelleted or mash diets. It was hypothesized that a moderate (3 or 5%) inclusion of insoluble dietary fiber sources could lead to a well-developed foregut, better gut health with higher nutrients digestibility, and more beneficial cecal microbiota, leading to an enhanced growth performance in broilers. It was also hypothesized that insoluble dietary fiber addition in pelleted diets could modulate the negative consequences of the pelleting upon gut development. Moreover, the benefits associated with the use of insoluble fiber sources could be more pronounced with pelleted diets relative to mash diets. The aim of the current experiment was to evaluate the interactive effects of insoluble FS (OH *vs*. SCB), FL (3 or 5%) and FF (mash *vs*. pellet) on the production performance, foregut development, nutrients digestibility, gut health and cecal microbiota profile of broilers.

MATERIALS AND METHODS

Birds, diets and management

All the protocols followed in this experiment regarding the care and use of animals were approved by the Animal Ethics Committee of University of Veterinary and Animal Sciences, Lahore (No.167, Dated: 05-04-2022). A total of 480 one day old, straight-run broilers (Ross 308) were purchased from a commercial hatchery. After initial weighing, the broilers were assigned to one of the 8 treatment groups of 6 replicates each in a completely randomized design with 10 broilers in each replicate. The broilers were provided with *ad libitum* supply of feed and water by placing an individual feeder and a drinker in each replicate pen during the entire period of the experiment. The temperature of the experimental facility during the first week of the trial was kept at 33°C, and was subsequently reduced gradually to 22°C till the end of the experiment. The broilers were given 23-hour of light and 1-hour of dark period (20 lux intensity) during the initial three days of the trial, which was gradually reduced to 18 hours of light and 6 hours of dark period. The broilers were immunized (6th day of the trial) against NDV via drinking water.

Dietary treatments

The insoluble fiber sources (OH and SCB) were procured and ground (2mm sieve) with the help of hammer mill. The experimental diets (Table 1) were prepared both in mash and pellet form by adding OH and SCB to the basal diet, each at inclusion levels of 3 and 5%. The batches of the 8 experimental diets were then equally divided into two portions. The first portion of the experimental diet was fed as mash, and the second portion of the experimental diet was offered in pelleted form. All the ingredients were procured from the local market, and ground in a hammer mill (model:

CPM Champion,18204) to pass through a screen with a sieve size of 4.5mm. Diets were mixed in horizontal ribbon mixer for 5 minutes, and the insoluble ground fiber sources were added to the mixer. Following mixing, all the diets were steamed-conditioned at 75ºC for 30s in a conditioner and pelleted by using pellet mill (CPM Pellet Mill 2322/952, Die specification: Diameter; 2mm for starter, and 4mm for grower and finisher, with 20 to 40 mm effective length of the holes). The nutrients composition of these experimental diets followed the strain recommendations for the starter (0 to 21 d) and finisher phases (22 to 35 d) (Aviagen International, 2017). To determine the AID of nutrients (CP and AA), the inert marker Celite (2%) was added to the finisher diets during the last five days of the trial.

Table 1 – Dietary ingredients and calculated nutrients of the experimental diets (g/kg, as fed basis)[1].

Diets Items[1]	Starter				Finisher			
F.S	Oat hulls		Sugarcane bagasse		Oat hulls		Sugarcane bagasse	
F.L (%)	3.0	5.0	3.0	5.0	3.0	5.0	3.0	5.0
Corn	54.5	53	54.5	53	59.5	56.18	59.5	56.18
OH	3	5	-	-	3	5		
SCB	-	-	3	5			3	5
SBM-(47%)	29	26	29	26	22	22	22	22
PBM-(58%)	5	6	5	6	5	5	5	5
Gluten-(60%)	1.5	1.2	1.5	1.2	1.3	1.3	1.3	1.3
OIL	2.2	4	2.2	4	5	6.5	5	6.5
$CaCO_3$	1.44	1.4	1.44	1.4	1.31	1.2	1.31	1.2
MCP	1.3	1.3	1.3	1.3	1.1	1.1	1.1	1.1
Premix[2]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
L-HCL	0.45	0.5	0.45	0.5	0.4	0.38	0.4	0.38
DLM	0.35	0.36	0.35	0.36	0.32	0.3	0.32	0.3
L-Threonine	0.15	0.15	0.15	0.15	0.15	0.12	0.15	0.12
NaCl	0.31	0.3	0.31	0.3	0.25	0.25	0.25	0.25
$NaHCO_3$	0.3	0.29	0.3	0.29	0.17	0.17	0.17	0.17
Total	100	100	100	100	100	100	100	100
Calculated Nutrients Composition (%)								
DM	90	90	90	90	90	90	90	90
ME (kcal/kg)	3000	3000	3000	3000	3200	3200	3200	3200
Crude protein	22	22	22	22	19.6	19	19.6	19
Crude fiber	4	4.7	4.5	5.4	3.19	3.7	3.19	4.5
Calcium	0.96	0.96	0.96	0.96	0.81	0.81	0.81	0.81
P-Available	0.48	0.48	0.48	0.48	0.4	0.4	0.4	0.4
D-Lysine	1.28	1.28	1.28	1.28	01.06	01.06	01.06	01.06
D-Threonine	0.86	0.86	0.86	0.86	0.71	0.71	0.71	0.71
D-Tryptophan	0.2	0.2	0.2	0.2	0.17	0.17	0.17	0.17
D-Methionine + cystein	0.95	0.95	0.95	0.95	0.83	0.83	0.83	0.83

[1]F.L = Fiber level, OH = Oat hulls, SCB = Sugarcane bagasse, SBM = Soybean meal, PBM = Poultry by-product meal MCP = Mono calcium phosphate, DM = Dry matter, ME= Metabolizable energy, P-available= Phosphorous available,
[2)]Mineral premix = Manganese = 120, Zinc = 100, Iron= 60, Iodine = 0.46, Copper = 10.
[2]Vitamin premix = Pantothenic acid= 11mg, Vitamin A= 5500IU, Vitamin B12= 0.006mg, Vitamin E= 11IU, Thiamine= 2.2mg, Vitamin D3= 1100IU, Choline chloride= 220mg, Riboflavin= 4.4mg, Pyridoxine= 2.2mg, Folic acid= 0.55mg, Biotin= 0.11mg.

Proximate analysis of the fiber sources and experimental diets

Proximate analysis of the experimental diets (Table 2) and insoluble fiber sources (Table 3) was performed to evaluate the contents of various nutrients, including dry matter (DM, AOAC, 2006 method 930.15), crude protein (CP, AOAC, 2006 method 994.13), crude fiber (CF, AOAC, 2006 method 978.10), ether extract (EE, AOAC, 2006 method 920.39) and ash (AOAC, 2006 method 942.05), in accordance with the methods of Truong *et al*. (2024), Andualem (2023) and AOAC International (2006). The neutral detergent fiber (NDF), and acid detergent fiber (ADF) were determined sequentially, as described by Van Soest *et al*. (1991).

Table 2 – Analyzed composition (%) of the experimental diets[1].

Item[2]	Starter				Finisher			
F.S	Oat hulls		Sugarcane bagasse		Oat hulls		Sugarcane bagasse	
F.L (%)	3	5	3	5	3	5	3	5
DM	89.20	89.50	89.17	90.80	89.20	88.70	89.40	89.25
CP	21.80	21.60	21.44	21.72	18.45	18.30	18.10	18.20
EE	3.63	3.50	3.10	3.25	3.35	3.30	3.45	3.32
CF	4.80	5.0	5.20	5.34	5.20	5.60	5.75	5.80
NDF	9.80	10.10	10.40	11.40	10.70	10.70	11.00	11.40
ADF	4.50	4.90	5.10	5.70	3.90	4.10	4.50	5.10
Ash	4.78	5.0	6.1	6.28	5.0	5.30	5.70	6.10
Lysine	1.50	1.47	1.46	1.45	1.17	1.18	1.15	1.16
Methionine	0.63	0.62	0.61	0.61	0.61	0.59	0.60	0.60
Threonine	0.95	0.98	0.96	0.97	0.78	0.77	0.75	0.76
Valine	1.10	1.12	1.08	1.09	0.90	0.87	0.91	0.88
Arginine	1.53	1.52	1.50	1.52	1.22	1.24	1.22	1.23

[1]All values are calculated on DM basis. [2]F.S = Fiber source, F.L = Fiber level, DM = Dry matter, CP = Crude protein, EE = Ether extract, CF = Crude fiber, NDF = Neutral detergent fiber, ADF = Acid detergent fiber.

Table 3 – Chemical composition of the insoluble fiber source on DM basis (%).

Items	Fiber source	
	Oat hulls	Sugarcane bagasse
Dry matter	96.8	95.1
Crude protein	4.58	1.70
Ether extract	1.58	0.78
Crude fiber	32.8	31.60
Neutral detergent fiber	60.6	54.60
Acid detergent fiber	10.8	30.80

TRAITS MEASURED

Growth and organ weight

The broilers of all dietary treatment groups were weighed, and the amount of feed offered and consumed was calculated on a weekly basis at the 7, 14, 21, 28 and 35th days of age to determine feed intake (FI), body weight gain (BWG), and feed conversion ratio

(FCR), as described by Wahid *et al*. (2024), Hussan *et al*. (2023), and Mehmood *et al*. (2023). All individual pens were monitored daily for mortality and any other discomfort.

At the end of the trial on the 35th day of broiler age, 2 birds were chosen randomly from each replicate (12 birds from each treatment) and slaughtered to remove the internal organs. After evisceration, the weight of the proventriculus and gizzard was taken with the help of a weighing balance.

Apparent ileal digestibility of crude protein and amino acids

To determine the AID of nutrients (crude protein and AA), samples were collected from the ileum (2cm above ileo-cecal junction) of the slaughtered broilers through gentle squeezing. After collection, these samples were transferred into individual aseptic plastic containers. The containers were subsequently stored at freezing temperature (-20°C) until further analysis. The acid insoluble ash of both the experimental diets and digesta samples were determined using the methods described by AOAC International (2006). The AID of the samples was calculated using the following formula, described by Ravindran *et al*. (2005).

$$AID\,(\%) = \frac{\frac{CPd}{AiAd} - \frac{CPi}{AiAi}}{\frac{CPd}{AiAd}} \times 100$$

The contents of AAs of both the experimental diets and ileal digesta samples were determined with the help of an AA analyzer (Biochrom 30+, Biochrom Ltd. Cambridge, UK), using the analytical method suggested by Ahmad *et al*. (2020). For this purpose, particle size in the diet and digesta samples were initially reduced to 500 microns by grinding in a hammer mill. These samples were then treated with performic acid in order to convert cysteine and methionine into their oxidized forms for greater stability. The samples were treated with 6 M hydrochloric acid/phenol for 24 hours and pH was thereafter fixed at 2.2. These samples were then filtered and placed in vials for quantification of AA by ion-exchange chromatography.

Histo-morphological measurements of the intestine

For measurement of the intestinal morphology, a 2 cm sample was taken from the middle portion of the duodenum. The collected samples were subsequently dipped in cold normal saline (0.9% NaCl) and preserved in a plastic container with 10% formaline solution for fixation. For histological examination, these samples were removed from the plastic bottles and transferred into an ethanol solution (70%) for 24 h. The samples were then put in paraffin and different segments of 5µm thickness were cut using a microtome, which were subsequently stained with hematoxylin–eosin for evaluation under a microscope (Labomed T121100, Los Angeles, CA, USA) (Gopinger *et al*., 2014). Various intestinal morphological parameters including VH and crypt depth (CD) were observed on 10 intact villi per sample, following the method outlined by Liaqat *et al*. (2023), and measurements were taken using the ImageJ software.

Determination of cecal microbial population

On the 35th d of age, to quantify the microbiome, the cecal contents from the two slaughtered birds (described above) were collected aseptically in a sterile container separately for each treatment. These containers were placed on ice cubes and transferred to laboratory, where these preserved cecal contents (2 g) were diluted and homogenized in a ratio of 1:10 followed by serial decimal dilution. A 0.1 ml sample from each dilution was plated on selective media. The *E. Coli* colonies were incubated (at 37°C for 24-48 hrs.) on Eosin Methylene Blue agar (Sozcu 2019). The *Salmonella* colonies were cultured on Bismuth Sulfite agar at 37°C for 24 hrs. (Chen *et al*., 2017). The *Lactobacillus* colonies were incubated at 30°C for 48 hours on De Man, Rogosa and Sharpe (MRS) agar (Sozcu 2019). All the cultured plates with countable growth were estimated using a colony counter. The average values were expressed as a log CFU /g of cecal contents.

pH of the digestive organs

The pH of the proventriculus and gizzard was recorded (slaughtered birds; 2 from each replicate) by inserting the probe of pH meter (Model-507, Crisone. Instrument) into each of these organs after incising them from the middle.

Data Analysis

The SAS PROC MIXED (version 9.1; SAS Inst. Inc., Cary, NC, USA) was used with a generalized linear model to analyze the data. Data analysis was performed following Alburih & Hasan (2024), according to the following statistical model:

$$Y_{ijkl} = \mu + FF_i + FS_j + FL_k + (FF_i \times FS_j) + (FF_i \times FL_k) + (FS_j \times FL_k) + (FF_i \times FS_j \times FL_k) + e_{ijkl}$$

Where,

Y= Any of the dependent variables tested in study

μ= Overall mean

FF_i= Feed form (either pellets or mash)

FS_j= Insoluble fiber source (either OH or SCB)

FL_k= Insoluble fiber level (either 3 or 5%)

$FF_i \times FS_j$= The interaction between feed form and fiber source

$FF_i \times FL_k$= The interaction between feed form and fiber level

$FS_j \times FL_k$= The interaction between fiber source and fiber level

$FF_i \times FS_j \times FL_k$= The interaction between feed form, fiber source and fiber levels

E_{ijkl}= Residual error

The mean differences between treatment groups were compared at a probability level of 5% or lower.

RESULTS

Live performance

The experimental diet influenced the live production performance of the broilers (Table 4). In the starter phase (0 to 21 days), finisher phase (22 to 35 days) and overall (0 to 35 days), feeding pelleted diets to the broilers influenced (p<0.05) the production performance (FI, BWG and FCR) in comparison to the feeding of mash diets. During the starter phase (0 to 21 days), regardless of FL and FF, the FS did not influence (p>0.05) the production performance of the broilers. Moreover, during the finisher and overall phase, the OH-supplemented diet increased (p<0.05) the FI and BWG, with improved FCR compared with broilers fed SCB-based diets. During the finisher phase (22-35 days), an interaction between FS and FF was observed for FI (p=0.039), BWG (p=0.012) and FCR (p=0.044), showing that broilers fed OH pelleted diets showed higher FI, and greater BWG, with improved FCR. In addition, regardless of the FL, an interaction between FS and FF was observed during the overall phase (0-35 days) for FI (p=0.045), BWG (p=0.023) and FCR (p=0.022), indicating that the broilers fed OH pelleted diets exhibited greater FI and BWG, with better FCR. However, interactions between FS×FL and FL×FF were not detected (p>0.05) for the production performance in broilers.

Apparent ileal digestibility of crude protein and amino acids

The dietary treatments influenced the AID of CP and AA (Table 5 a&b). The broilers consuming pelleted diets showed a higher (p<0.05) AID of CP and almost all AA (except for histidine, glutamine and alanine) than those in the mash groups. The broilers fed OH-based diets had an enhanced (p<0.05) digestibility of leucine, lysine, methionine, valine, arginine, and tyrosine I comparison to those fed the SCB-based diets. An interaction between FS and FF was detected for lysine (p=0.029), methionine (p=0.044), threonine (p=0.030), valine (p=0.038), arginine (p=0.041), and cysteine (p=0.023), indicating that supplementing OH in pelleted diets improved the AID in the broilers, compared with those fed SCB pelleted diets. An interaction between FL and FF was detected for methionine (p=0.027), serine (p=0.017) and cysteine (0.031), indicating that 3% OH in pelleted diets exhibited a higher AID of the aforementioned AA relative to those fed the 3% SCB pelleted diet. The AID of CP and AA, however, were not affected (p>0.05) by the interaction between FS×FL.

Gut histomorphology

The influence of dietary treatments on duodenal histomorphology is shown in Table 6. The broilers fed OH-based diets had greater (p<0.05) VH among the treatment groups, whereas the broilers consuming SCB diets had deeper (p<0.05) crypts compared with the OH groups. Similarly, broilers fed mash diets had 15% deeper CD compared with those that were fed the pelleted diets. A significant interaction between FS and FL was observed for VH (p=0.03), revealing that diet containing 3% OH resulted in improved VH. The FS× FF interaction was observed for VH (p=0.025) and VCR (p=0.011), revealing that broilers fed the OH pelleted diet had improved VH and VCR in comparison to those fed the SCB pelleted diet. The interaction between FL×FF did not alter the duodenal histomorphology in broilers.

Table 4 – Effects of feed form, and fiber source and levels on the production performance of broilers from 0 to 35th days of age[1].

Treatment[2]			Observations[3]								
			FI (g/bird/d)			BWG (g/bird/d)			FCR (g/g)		
FS	FL (%)	FF	0-21	22-35	0-35	0-21	22-35	0-35	0-21	22-35	0-35
OH											
	3	Mash	53.9	135.4^{b}	86.5^{b}	42.1	70.8^{bc}	53.6^{bc}	1.28	1.91^{a}	1.61^{bc}
		Pellet	57.6	144.3^{a}	92.8^{a}	46.0	82.1^{a}	60.5^{a}	1.25	1.75^{c}	1.52^{c}
	5	Mash	53.2	134.5^{b}	85.7^{b}	40.1	71.3^{bc}	52.5^{c}	1.33	1.88^{ab}	1.63^{a}
		Pellet	54.9	142.4^{a}	89.4^{a}	43.1	79.2^{a}	57.5^{b}	1.27	1.79^{c}	1.56^{c}
SCB											
	3	Mash	51.7	135.6^{c}	85.2^{bc}	39.0	68.2^{c}	50.6^{c}	1.32	1.98^{a}	1.68^{a}
		Pellet	58.5	138.5^{ab}	90.5^{a}	44.9	76.2^{b}	57.4^{a}	1.30	1.81^{c}	1.57^{c}
	5	Mash	51.4	129.5^{c}	82.6^{bc}	38.8	67.0^{c}	50.5^{c}	1.32	1.93^{a}	1.63^{a}
		Pellet	56.3	134.3^{b}	87.5^{b}	43.7	72.4^{c}	55.0^{b}	1.29	1.85^{bc}	1.59^{c}
Pooled *SEM*			1.98	1.93	1.34	1.42	1.23	1.16	0.057	0.004	0.002
Main Effects											
FS											
	OH		55.0	139.1^{a}	89.0^{a}	42.8	76.0^{a}	56.0^{a}	1.28	1.83	1.57^{b}
	SCB		54.5	134.4^{b}	86.4^{b}	41.7	71.1^{b}	53.2^{b}	1.30	1.89	1.61^{a}
FL											
	3		54.3	138.5	88.2	43.0	74.3	55.5	1.28	1.86	1.59
	5		54.0	135.0	86.3	41.4	72.4	54.0	1.30	1.86	1.60
FF											
	Mash		52.5^{b}	133.5^{b}	85.0^{b}	39.8^{b}	69.3^{b}	52.0^{b}	1.31^{b}	1.80^{a}	1.63^{a}
	Pellet		56.8^{a}	140.0^{a}	90.0^{a}	44.4^{a}	77.2^{a}	58.0^{a}	1.27^{a}	1.92^{b}	1.56^{b}
p-value											
FS			0.248	0.041	0.033	0.140	0.040	0.030	0.532	0.072	0.042
FL			0.441	0.508	0.090	0.451	0.209	0.134	0.540	0.425	0.093
FF			0.019	0.021	0.029	0.001	0.001	0.001	0.029	0.023	0.005
FS × FL			0.973	0.150	0.648	0.502	0.484	0.136	0.577	0.638	0.428
FS × FF			0.404	0.039	0.045	0.976	0.012	0.023	0.745	0.044	0.022
FL × FF			0.855	0.307	0.487	0.841	0.754	0.425	0.753	0.548	0.812

Different superscripts ($^{a-c}$) over means represent significant differences at (p<0.05). [1]The value of each treatment group is the mean of 6 replicates (10 birds per replicate). [2]F.S = Fiber source, OH= Oat hulls, SCB= Sugarcane bagasse, FL = Fiber level, F.F = Feed form [3]F.I= Feed intake, BWG = Body weight gain, FCR= Feed conversion ratio.

Table 5 (a) – Effects of dietary treatments on apparent ileal digestibility of essential amino acids (%) in broilers at the 35th day of age[1].

Treatment[2]			Observations[3] (%)									
FS	FL (%)	FF	CP	Iso	Leu	Lys	Meth	Phe	Thr	Val	His	Arg
OH												
	3	Mash	79.4	68.6^{b}	70.5^{b}	76.6^{c}	80.6^{c}	68.4	74.6^{c}	62.4^{c}	75.6	74.3^{cd}
		Pellet	81.1	75.4^{a}	75.1^{a}	83.1^{a}	87.4^{a}	76.2	81.3^{a}	71.6^{a}	78.3	84.0^{a}
	5	Mash	78.8	68.0^{b}	70.3^{b}	77.2^{bc}	80.0^{c}	68.3	74.3^{c}	62.2^{c}	79.5	73.8^{c}
		Pellet	82.0	75.1^{a}	74.8^{a}	82.6^{a}	88.5^{a}	76.0	80.6^{a}	70.9^{a}	80.5	83.8^{a}
SCB												
	3	Mash	78.9	67.5^{b}	69.6 ^{b}	75.2^{d}	76.7^{d}	67.7	74.1^{c}	61.9^{c}	80.4	73.0^{dc}
		Pellet	81.7	74.4^{a}	75.2^{a}	78.4^{b}	83.1^{b}	75.5	78.6^{ab}	67.1^{b}	78.5	79.4^{b}
	5	Mash	78.2	67.4^{b}	69.3^{b}	74.8^{d}	75.8^{d}	67.3	74.3^{c}	61.6^{c}	75.4	72.4^{e}
		Pellet	81.4	75.0^{a}	74.7^{a}	78.1^{b}	83.5^{b}	75.2	78.5^{ab}	67.1^{b}	79.5	78.8^{b}
Pooled *SEM*			0.368	0.282	0.364	0.304	0.420	0.179	0.414	0.223	0.157	0.23
Main Effects												
FS												
	OH		80.3	71.8	72.9^{a}	79.9^{a}	84.2^{a}	72.2	77.7	66.8^{a}	78.4	79.0^{a}
	SCB		78.9	69.5	69.1^{b}	76.7^{b}	79.8^{b}	71.4	76.4	64.4^{b}	77.1	75.9^{b}
FL												
	3		78.2	71.5	71.6	78.2	82.0	71.9	77.2	65.7	78.2	77.7
	5		76.4	70.4	69.9	75.6	80.5	70.7	76.9	65.4	79.2	74.2
FF												
	Mash		76.3^{b}	67.9^{b}	69.9^{b}	75.9^{b}	78.3^{b}	67.9^{b}	74.3^{b}	62.0^{a}	77.7	73.4^{b}
	Pellet		81.6a	75.0^{a}	75.2^{a}	80.6^{a}	85.8^{a}	75.7^{a}	79.8^{a}	69.2^{b}	79.2	81.5^{a}
p-value												
FS			0.298	0.558	0.040	0.025	0.035	0.349	0.110	0.001	0.455	0.001
FL			0.558	0.607	0.756	0.608	0.795	0.086	0.389	0.064	0.398	0.325
FF			0.001	0.001	0.011	0.021	0.039	0.045	0.035	0.001	0.145	0.021
FS × FL			0.255	0.096	0.254	0.582	0.571	0.370	0.389	0.261	0.452	0.438
FS × FF			0.336	0.525	0.333	0.029	0.044	0.877	0.030	0.038	0.858	0.041
FL × FF			0.088	0.258	0.515	0.353	0.027	0.830	0.554	0.871	0.622	0.676

Different superscripts ($^{a-e}$) over means represent significant differences at (p<0.05). [1]The value of each treatment group is the mean of 6 replicates (2 birds per replicate). [2]F.S = Fiber source, OH= Oat hulls, SCB= Sugarcane bagasse, FL = Fiber level, F.F = Feed form [3]CP=Crude protein, Iso = Isoleucine, Leu = Leucine, Lys = Lysine, Meth = Methionine, Phe = Phenylalanine, Thr = Threonine, Valine = Valine, His = Histidine, Arg = Arginine.

Table 5 (b) – Effects of dietary treatments on apparent ileal digestibility of non-essential amino acids (%) in broilers at the 35th day of age[1].

Treatment[2]			Observations[3] (%)								
FS	**FL (%)**	**FF**	**Asp**	**Ser**	**Glu**	**Gly**	**Ala**	**Cys**	**Pro**	**Tyr**	**Orn**
OH											
	3	Mash	59.4	55.1[bc]	84.2	58.5	72.2	68.0[b]	63.3	76.5	78.4
		Pellet	65.8	62.3[a]	87.2	64.1	75.3	72.3[a]	70.3	83.3	84.2
	5	Mash	58.8	53.9[c]	83.6	57.3	72.1	66.8[bc]	61.4	74.9	76.5
		Pellet	63.9	61.1[a]	86.0	64.0	74.9	72.2[a]	68.4	81.3	83.1
SCB											
	3	Mash	58.3	54.4[c]	82.5	58.0	72.4	65.3[bc]	62.7	76.1	78.2
		Pellet	64.8	58.5[b]	85.4	63.7	74.3	68.5[b]	69.3	81.9	83.4
	5	Mash	57.1	55.7[bc]	86.1	57.1	71.9	65.1[bc]	60.5	72.7	76.5
		Pellet	62.3	57.4[b]	84.5	62.4	72.9	68.2[b]	67.7	79.3	81.4
Pooled *SEM*			0.222	0.215	0.03	0.214	0.02	0.473	0.154	0.127	0.184
Main Effects											
FS											
	OH		61.9	58.1	85.2	61.1	73.6	69.3	66.0	79.0[a]	80.5
	SCB		60.6	57.3	84.6	60.3	72.8	67.5	65.0	77.5[b]	79.8
FL											
	3		62.1	57.1	84.8	61.0	73.5	68.5	66.4	79.4	81.1
	5		60.5	57.0	85.5	60.4	72.9	68.0	64.5	77.0	79.4
FF											
	Mash		58.4[b]	54.7[b]	84.1	57.9[b]	72.1	66.3[b]	61.9[b]	75.0[b]	77.4[b]
	Pellet		64.2[a]	59.5[a]	85.7	63.7[a]	74.3	70.3[a]	68.9[a]	81.4[a]	83.0[a]
p-value											
FS			0.303	0.291	0.445	0.267	0.397	0.379	0.124	0.001	0.441
FL			0.288	0.251	0.301	0.284	0.384	0.167	0.311	0.376	0.461
FF			0.033	0.010	0.588	0.027	0.358	0.001	0.011	0.001	0.001
FS × FL			0.572	0.122	0.334	0.163	0.998	0.693	0.348	0.720	0.137
FS × FF			0.320	0.321	0.357	0.987	0.160	0.023	0.754	0.232	0.217
FL × FF			0.420	0.017	0.340	0.253	0.323	0.031	0.396	0.436	0.587

Different superscripts ([a - c]) over means represent significant differences at ($p<0.05$). [1]The value of each treatment group is the mean of 6 replicates (2 birds per replicate). [2]F.S = Fiber source, OH= Oat hulls, SCB= Sugarcane bagasse, FL = Fiber level, F.F = Feed form [3]Asp= Aspartic acid, Ser= Serine, Glu= Glutamic acid, Gly= Glycine, Ala= Alanine, Cys= Cystine, Pro= Proline, Tyr= Tyrosine, Orn= Ornithine.

Table 6 – Effects of feed form, and fiber source and levels on duodenal histomorphology in broilers at the 35th day of age[1].

Treatment[2]			Observations[3] (%)		
FS	**FL (%)**	**FF**	**VH (µm)**	**CD (µm)**	**VCR**
OH					
	3	Mash	1530[c]	228[b]	6.70[c]
		Pellet	1663[a]	203[d]	8.20[a]
	5	Mash	1520[c]	229[b]	6.64[c]
		Pellet	1643[a]	196[d]	8.37[a]
SCB					
	3	Mash	1425[d]	247[a]	5.76[d]
		Pellet	1567[b]	216[c]	7.23[b]
	5	Mash	1446[d]	249[a]	5.79[d]
		Pellet	1571[b]	213[c]	7.37[b]
Pooled *SEM*			6.26	2.02	0.21
Main Effects					
FS					
	OH		1589[a]	214[b]	7.48[a]
	SCB		1502[b]	231[a]	6.54[b]
FL					
	3		1546	223	6.97
	5		1545	222	7.04
FF					
	Mash		1480[b]	238[a]	6.22[b]
	Pellet		1611[a]	207[b]	7.79[a]
p-value					
FS			0.020	0.013	0.001
FL			0.729	0.197	0.128
FF			0.001	0.001	0.001
FS × FL			0.003	0.424	0.724
FS × FF			0.025	0.112	0.011
FL × FF			0.126	0.245	0.071

Different superscripts ([a - d]) over means represent significant differences at ($p<0.05$). [1]The value of each treatment group is the mean of 6 replicates each containing 2 birds (2 birds per replicate). [2]F.S = Fiber source, OH= Oat hulls, SCB= Sugarcane bagasse, FL = Fiber level, F.F = Feed form [3]VH= Villus height, CD = Crypt depth, VCR= Villus height to crypt depth ratio.

Relative empty digestive organ weights and pH

The impacts of experimental diets on the relative empty digestive organ weight of the broilers and pH are shown in Table 7. The dietary treatments influenced (p<0.05) the relative empty organ weights of the proventriculus and gizzard. The empty relative weight of the proventriculus and gizzard of broilers fed pelleted diets were respectively 27% and 10% lower than those of broilers fed mash diets. In average, OH supplementation increased the relative empty weight of the proventriculus and gizzard up to 6% than those fed SCB-based diets. However, no significant interactions were found for the relative empty weights of the proventriculus and gizzard.

Dietary treatments influenced (p<0.05) the pH of the proventriculus and gizzard. Supplementing broiler diets with 5% fiber, regardless of the FS and FF, reduced (p<0.05) the pH in the proventriculus and gizzard as compared with those fed diets containing 3% fiber. No interactions between FS×FL, FF×FS or FL×FF were detected (p>0.05) for the pH in the proventriculus and gizzard.

Table 7 – Effects of feed form, and fiber source and level on the relative empty organ weight and pH of broilers at the 35th day of age[1].

Treatment[2]			Relative organ weight (g/100g)		pH of the digestive organ	
FS	FL (%)	FF	Proventriculus	Gizzard	Proventriculus	Gizzard
OH						
	3	Mash	0.42	1.29	3.50	3.37
		Pellet	0.37	1.23	3.39	3.38
	5	Mash	0.43	1.35	3.03	3.04
		Pellet	0.35	1.24	3.02	3.03
SCB						
	3	Mash	0.40	1.30	3.45	3.24
		Pellet	0.36	1.10	3.46	3.43
	5	Mash	0.40	1.26	2.97	2.95
		Pellet	0.35	1.15	3.12	2.90
Pooled *SEM*			0.01	0.027	0.02	0.040
Main Effects						
FS						
	OH		0.39^{a}	1.28^{a}	3.23	3.21
	SCB		0.37^{b}	1.20^{b}	3.25	3.13
FL						
	3		0.38	1.24	3.45^{a}	3.35^{a}
	5		0.37	1.23	3.03^{b}	2.98^{b}
FF						
	Mash		0.41^{a}	1.30^{a}	3.23	3.15
	Pellet		0.36^{b}	1.18^{b}	3.24	3.19
p-value						
FS			0.028	0.024	0.963	0.432
FL			0.066	0.953	0.001	0.001
FF			0.041	0.037	0.512	0.234
FS × FL			0.093	0.076	0.743	0.240
FS × FF			0.214	0.325	0.239	0.218
FL × FF			0.119	0.729	0.304	0.213

Different superscripts ($^{a-b}$) over means represent significant differences at (p<0.05). [1]The value of each treatment group is the mean of 6 replicates (2 birds per replicate). [2]F.S = Fiber source, OH= Oat hulls, SCB= Sugarcane bagasse, FL = Fiber level, F.F = Feed form.

Cecal microbiota

The experimental diets influenced the cecal microbiota profile of broilers (Table 8). An interaction between FS and FF was detected for *Lactobacillus* spp. (p=0.025) and *E. Coli* (p=0.011) counts, indicating that, regardless of the FL, broilers fed the OH pelleted diet had an increased count of *Lactobacillus* spp. and a decreased count of *E. Coli* relative to those fed SCB pelleted diet. Similarly, there were no FS×FL or FL×FF interactions detected (p>0.05) for cecal microbiota counts in broilers. Regardless of the FL, OH supplementation decreased (p<0.05) the population of *Salmonella* spp. compared to the SCB-based diets. Nevertheless, no interactions were found between the dietary treatments for cecal *Salmonella* spp.

Table 8 – Effects of feed form, and fiber source and levels on the cecal microbial population (log10 cfu/g) of broilers at the 35th day of age[1].

Treatment[2]			Observations		
FS	FL (%)	FF	*Lactobacillus* spp	*E.coli*	*Salmonella*
OH					
	3	Mash	9.7^{b}	7.5^{c}	5.7
		Pellet	10.5^{a}	7.3^{c}	5.4
	5	Mash	8.8^{c}	8.1^{bc}	6.2
		Pellet	9.8^{b}	7.4^{c}	6.0
SCB					
	3	Mash	8.0^{cd}	9.3^{a}	7.1
		Pellet	7.9^{d}	9.1^{a}	6.5
	5	Mash	7.3^{d}	8.7^{b}	7.4
		Pellet	8.1^{cd}	8.5^{b}	6.7
Pooled *SEM*			0.03	0.04	0.035
Main Effects					
FS					
	OH		9.7^{a}	7.5^{b}	5.8^{b}
	SCB		7.8^{b}	8.9^{a}	6.9^{a}
FL					
	3		9.0	8.3	6.1
	5		8.5	8.1	6.5
FF					
	Mash		8.4	8.4	6.6
	Pellet		9.0	8.0	6.1
p-value					
FS			0.01	0.01	0.01
FL			0.13	0.25	0.40
FF			0.28	0.60	0.31
FS × FL			0.138	0.140	0.190
FS × FF			0.025	0.011	0.220
FL × FF			0.114	0.210	0.121

Different superscripts ($^{a-d}$) over means represent significant differences at (p<0.05). [1]The value of each treatment group is the mean of 6 replicates (2 birds per replicate). [2]F.S=Fiber source, OH=Oat hulls, SCB=Sugarcane bagasse, FL=Fiber level, F.F=Feed form.

DISCUSSION

The current experiment was conducted to evaluate the interactive effects of feed form, and fiber source and level on production performance, intestinal histomorphology, foregut development and nutrients digestibility in broilers. The hypothesis was that dietary inclusion of OH or SCB at a moderate level in pelleted diets could exert significant positive effects on various production traits and the cecal microbiota profile of broilers.

The positive interaction observed between feed form and fiber source in the present study is in agreement with the findings of Itani *et al*. (2024). These authors observed a 7% increase in FI, with improved FCR in the broilers fed ground OH in a SBM-oat pelleted diet. Similarly, Boazar *et al*. (2021) found a positive interaction between feed form and fiber source in broilers regarding FI and BWG during the overall phase. These authors documented that wheat bran in pelleted diets increased the FI in up to 14%, and BWG by 15% in comparison to wheat bran in a mash-based diet. In contrast, Jimenez-Moreno *et al*. (2013b) reported the negative influence of OH (7.5%) inclusion on the production efficiency of broilers. Potential reasons for these discrepancies could be the type of fiber and its level, feed form, ingredient types, and the age of the birds.

The improved production performance (BWG and FCR) in the broilers fed OH-based rations compared to those fed the SCB-based diets is in line with the findings of Jimenez-Moreno *et al*. (2009). These authors reported a 6% increase in BWG and a 5% improvement in FCR during the grower phase (0-21 d) in the broilers that consumed 3% OH-based ration relative to the control diet. This enhanced BWG may be associated with the fusiform structure of OH, which tends to stay in the gizzard for longer, and improves the motility of gut, which in turn improves the utilization of nutrients through the prolonged mixing of enzymes with digesta (Jimenez-Moreno *et al*., 2019; Kakhki *et al*., 2024). Berrocoso *et al*. (2020) also observed a higher average daily FI (36.6 *vs*. 34.9 g/d) and average daily gain (27.5 *vs*. 26.5 g/d) in broilers fed a 3% OH-based ration compared to those fed the control diet. Naeem *et al*. (2024), however, found no significant differences in BWG and FI among broilers fed a 5% OH-based ration.

In the current experiment, the pelleted diet increased the digestibility of CP and AA, which is in line with the findings of da Silva *et al*. (2018). These authors documented that feeding a pelleted diet (particle size of 650 microns and 1.6% of moisture) to the broilers increased the coefficients of ileal digestibility of lysine (84.4 *vs*.82.8%) and glycine (77.16 *vs*. 74.47%). Pelleting requires higher temperature, pressure and moisture that may dissolve the cell wall of grains, thus facilitating the penetration of digestive enzymes into cell contents (Lundblad *et al*., 2011). Moreover, the application of heat during the pelleting process denatures proteins and inactivates enzyme inhibitors present in dietary nutrients. This denaturing and inactivation of anti-nutritional factors creates more sites for enzymatic digestion, leading to better digestibility of crude protein and AAs in broilers (Lv *et al*., 2015). Contrary to the present findings, Saldana *et al*. (2015) observed reduced nutrient digestibility of starch (up to 3%) and fat (9%) in broilers fed pelleted diets compared to those fed mash diets. More recently, Jimenez-Moreno *et al*. (2019) documented that a pelleted feed did not influence the dry matter, CP, and organic matter digestibilities. These inconsistencies regarding the effects of pelleted diet on nutrients digestibility may be associated with differences in the pelleting process (e.g. pelleting temperature), voluntary feed intake, and composition of the diet (Pourazadi *et al*., 2024).

The improved nutrients digestibility observed in the broilers fed the pelleted OH-based diet was in line with the findings of Moradi *et al*. (2021), who concluded that a 3% OH pelleted diet increased the coefficient of apparent ileal digestibility of CP and fat by 7% relative to the control diet. This higher digestibility may be associated with an improved grinding capacity of the gizzard, enhanced secretion of HCl from the proventriculus, and increased enzymatic activity of pepsin. A better enzymatic activity, in turn, enhances the utilization of protein, leading to an improved digestibility of nutrients in broilers (Gabriel *et al*., 2003; Naeem *et al*., 2024). In contrast, Scholey *et al*. (2019) reported that OH inclusion (7 and 17%) in a wheat-based diet reduced the digestibility of cysteine, aspartic acid, methionine, serine, glutamine, and tyrosine in comparison to broilers fed the control diet.

The greater VH and VCR observed in the current study by feeding a pelleted fibrous diet is an indicator of better nutrients absorption and utilization, evidenced by the production performance and nutrients digestibility outcomes. In agreement with the present findings regarding gut morphology, Moradi *et al*. (2021) observed a 6% increase in VH, whereas VCR and CD remained the same after the dietary inclusion of 3% OH in a pelleted diet relative to the results from the control diet without fiber source. Recently, the inclusion of sunflower hulls (3%) in a pelleted diet increased the duodenal VH and VCR by respectively 20 and 18% relative to those of broilers fed sunflower hulls in mash diets (Pourazadi *et al*., 2024). The improved duodenal VH may be associated with a higher nutrients availability, which in turn enhances the surface area and absorption of the small intestine

(Wan *et al*., 2021; Moradi *et al*., 2024). In contrast to the present findings, Abdollahi *et al*. (2019) found no statistical differences with the dietary inclusion of 3% OH on the gut morphology of broilers fed the wheat-based mash feed. These contradictions between different studies may be due to the varying effects of insoluble fiber types, their water holding and swelling capacities, feed form, age of the birds, and types of the basal feeds used.

The decreased pH of the digestive organs (proventriculus and gizzard) by fiber addition, regardless of the fiber source, is in line with the study of Itani *et al*. (2024). These authors reported a significant reduction (2.31 *vs*. 3.48) in pH of the gizzard by increasing the OH level (29.5, 65, 96, 114g/kg) in the broilers' diet. Jiminez-Moreno *et al*. (2019) also observed a 2.5% decrease in gizzard pH with increasing (2.5 *vs*. 5.0%) OH dietary levels. Moreover, Kheravii *et al*. (2017b) documented a reduced (3.67 *vs*. 4.03) pH of the gizzard by feeding SCB. Dietary inclusion of insoluble fiber enhances the secretion of HCl from the proventriculus, which in turn is responsible for a reduced pH in the proventriculus and gizzard. In addition to reducing pH, this increased HCl secretion stimulates the activity of various digestive enzymes and enhances the proliferation of beneficial microbes, ultimately leading to an increase in broiler production performance (Sozcu, 2019). However, another recent study by Rybicka *et al*. (2024) found no significant differences in the pH of digestive organs (proventriculus, gizzard and ceaca) with the inclusion of insoluble fiber sources (almond shell and lignocellulose;1.5% each) in the diets of broilers.

Despite the beneficial effects on production performance and other traits, certain negative impacts of pelleted diets on the relative empty weight of the proventriculus and gizzard in broilers were reported in the present study, which are consistent with previous studies. Abdollahi *et al*. (2011) reported a decreased proventriculus (3.88 *vs*. 4.27g/kg of BW) and gizzard weight (10.3 *vs*. 15.2 27g/kg of BW) in broilers fed a pelleted, wheat-based diet compared to those fed mash. Moreover, pelleting, including grinding and passing the ingredients through dye, causes a significant reduction in the size of feed particles, which in turn reduces the staying time of feed in the gizzard. This decreased staying time is responsible for the reduced relative empty weight of the proventriculus and gizzard in the broilers fed pelleted diets. Mirghelenj and Golian (2009), however, did not observe changes in relative empty weights of the digestive organs (crop, proventriculus and gizzard) among the broilers fed diets in pelleted and mash forms.

The increased gizzard and proventriculus weights with the dietary inclusion of OH in broilers in the current study is in line with the findings of Hikawczuk *et al*. (2023). These authors reported significant improvements of up to 14% in the gizzard weight of broilers fed OH as lingo-cellulose complex (30g/kg of the diet) relative to those fed the control diet without fiber sources. This higher weight may be associated with the higher lignin contents of OH, which in turn increases the feed retention time in the gizzard and enhances its grinding activity. This increased activity is responsible for an improved development of the muscular layer that leads to a heavier gizzard (Habibi *et al*., 2024).

In line with the current findings, Moradi *et al*. (2021) reported an increased cecal *Lactobacillus* spp. count by feeding an OH pelleted diet. In another experiment conducted by Boazar *et al*. (2021), the inclusion of wheat bran and sunflower hulls in pelleted diets significantly reduced the cecal *E. Coli* spp. and Coliform counts. In another recent study with broilers, the inclusion of 3% of sunflower hulls in barley-based diets increased the *Lactobacillus* spp. cecal population and decreased the *E. Coli* spp. and *Coliforms* counts (Pourazadi *et al*. (2024). In contrast, Kheravii *et al*. (2017b) concluded that a 2% SCB inclusion did not influence the ileal *Lactobacillus* spp. count. The observed effect of OH on the beneficial cecal microbiome can be explained by a few reasons. The developed gizzard and reduced pH through the increased secretion of HCl in the proventriculus with the use of an OH-based diet facilitates the seeding of a beneficial microbiome, including *Lactobacillus* spp.; while also preventing the entry of pathogenic microbes such as *E. Coli* spp. and *Salmonella* spp. into the distal part of the GIT (Mahmood & Guo, 2020). Another potential explanation could be the competitive exclusion mechanism, which may promote the proliferation of beneficial microbiome and reduce the proliferation of harmful microbiome (Karunaratne *et al*., 2023; Wu *et al*., 2023) However, possible discrepancies among studies can be attributed to the complex composition of the microbiome and the fermentable substrate, specifically monomers of the fiber present in the dietary fiber source used.

CONCLUSION

In summary, the pelleted diet containing 3% OH led to an improved production performance, with better duodenal morphology and enhanced nutrients utilization. Moreover, the dietary inclusion of OH improved foregut development and increased the cecal *Lactobacillus* spp. count. Furthermore, the addition of SCB in pelleted or mash diets exerted negative effects on several production parameters. In conclusion, 3% OH in pelleted diets may potentially be used in broiler diets to enhance duodenal histomorphology, nutrients digestibility, beneficial cecal microbiota counts and, ultimately, the production performance.

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The data will be provided by the corresponding authors upon reasonable request.

CONFLICT OF INTEREST

It is certified that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

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