Optimizing feed processing parameters and alternative ingredients for enhanced broiler performance and pellet quality

by

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Abstract

A sequence of experiments were conducted to optimize and evaluate effects of feed processing parameters and alternative ingredient use on broiler growth performance and pellet quality. When pelleting feed, several pellet mill factors influence the final quality of a pellet, and understanding their interactions is crucial to producing the highest quality product. Two experiments were conducted to determine the effect of conditioner retention time, conditioning temperature, and mixer added fat inclusion, on the final pellet durability of broiler feed. Exp. 1 analyzed the effects of conditioning temperature and conditioner retention time and Exp. 2 analyzed the effects of mixer added fat inclusion and conditioner retention time on pellet durability. Samples were obtained and pellet durability was measured using the modified tumble box pellet durability index (M-PDI; Exp. 1) and percent pellets surviving the New Holmen Pellet Tester (60 sec; H60-PDI; Exp. 1 & 2). Both experiments were analyzed using PROC GLIMMIX in SAS v. 9.4 (Cary, NC). In Exp. 1, increasing conditioner retention time from 30 to 90 seconds increased (linear, $P < 0.001$) M-PDI and H60-PDI. As conditioning temperature increased from 74 to 85°C, there was no difference in H60-PDI but M-PDI improved ($P < 0.01$). In Exp. 2, there was a fat inclusion × conditioner retention time interaction ($P = 0.019$) for H60-PDI. Increasing conditioner retention time from 30 to 90 sec improved H60-PDI in diets containing 1.5 or 2% fat but not in diets containing 0.5 and 1.0% fat. Overall, these results emphasize the importance of better understanding the effects of changing pelleting process parameters and dietary fat inclusion levels have on pellet durability.

When altering processing parameters in feed manufacturing, it is imperative to assess the impact those changes can have on feed quality and broiler growth performance. Therefore, two experiments (Exp. 3 and 4) evaluated the effects of pellet die diameter and pellet fines inclusion

on broiler growth performance. Exp. 3 used a 3 x 2 factorial design with 3 pellet die diameters (4.0 mm, 4.8 mm, and 6.4 mm) and 2 fines inclusions (0% and 30%) fed from d 12-47. Exp. 4 used as a 2 x 3 factorial with 2 pellet die diameters (4.8 mm and 6.4 mm) and 3 fines inclusions (0%, 30%, and 60%), fed from d 14-49, with a crumble (4.8 mm or 6.4 mm) being fed from d 0-14. Data were analyzed using PROC GLIMMIX in SAS v. 9.4 (Cary, NC). In Exp 3., overall growth interactions were observed for both FI ($P = 0.015$) and BWG ($P = 0.013$), where fines reduced performance in 4.0 and 4.8 mm pellet diets, but improved FI and BWG with 6.4 mm pellets. In Exp. 4, the 4.8 mm pellet die diameter, increased FI ($P = 0.003$), BWG ($P < 0.001$), and improved FCR ($P = 0.002$) in the starter phase. From d 0-49, increasing fines improved (linearly, $P < 0.05$) FCR, though no interactions were observed for FI and BWG. These results suggest that while increased fines generally impair broiler growth performance, their inclusion alongside a 6.4 mm pellet may help mitigate the typical negative impacts associated with higher pellet fines.

When implementing alternative ingredients into broiler diets, an ingredient in the process of being researched for its use as an alternative ingredient is CoverCress Whole Grain (CCWG). CCWG is a variety of pennycress with low erucic acid and reduced fiber content, was developed as a cover crop. It is designed to be planted in the fall following corn harvest and harvested in the spring before planting soybeans. The objective of this experiment was to determine the effect of including up to 6% CCWG seed in diets on broiler chicken growth performance over 49 days. Dietary treatments were established using a control basal diet fed over four feeding phases and treatments were allocated as additional inclusion of 2%, 4%, or 6% CCWG added to the diet. On d 12, 28, 39, and 49, birds and feeders were weighed to determine feed intake (FI), body weight gain (BWG), feed conversion ratio (FCR), and mortality corrected FCR (adj. FCR). At d 0-12, d

0-28, d 0-39, and d 0-49, birds performed below the Cobb 500 objectives for body weight gain, feed intake and feed conversion. For d 0-12, d 0-28, and d 0-39 increasing CCWG in the diet showed no effect on FI, BWG, FCR, or adj. FCR. For d 0-49, no differences were observed for FI, BWG or FCR. However, birds fed the 6% CCWG in the diet had poorer ($P = 0.019$) adjusted FCR as compared to broilers fed the 0 and 4% CCWG diets which may have been due to the 6% inclusion finisher diet being less nutrient dense as compared to the other treatments. In conclusion, CCWG can be safely included into broiler diets up to 6% inclusion through 49 days without negatively affecting BWG, FI, and FCR, and up to 4% inclusion to 49 days without negatively impacting adj. FCR.

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Dedication

This thesis is dedicated to all my friends and family who have supported me throughout my time at K-State. I am blessed to have such a great support system.

Chapter 1 - Effect of conditioning temperature and steam conditioning parameters during the pelleting process and dietary fat inclusion on pellet durability of broiler diets

Abstract

Several pellet mill factors influence the final quality of a pellet, and understanding their interactions is crucial to producing the highest quality product. Two experiments were conducted to determine the effect of conditioner retention time, conditioning temperature, and mixer added fat inclusion, on the final pellet durability of broiler feed. Exp. 1 analyzed the effects of conditioning temperature and conditioner retention time and Exp. 2 analyzed the effects of mixer added fat inclusion and conditioner retention time on pellet durability. Samples were obtained and pellet durability was measured using the modified tumble box pellet durability index (M-PDI; Exp. 1) and percent pellets surviving the New Holmen Pellet Tester (60 sec; H60-PDI; Exp. 1 & 2). Both experiments were analyzed using PROC GLIMMIX in SAS v. 9.4 (Cary, NC). In Exp. 1, increasing conditioner retention time from 30 to 90 seconds increased (linear, $P < 0.001$) M-PDI and H60-PDI. As conditioning temperature increased from 74 to 85°C, there was no difference in H60-PDI but M-PDI improved ($P < 0.01$). In Exp. 2, there was a fat inclusion ´ conditioner retention time interaction ($P = 0.019$) for H60-PDI. Increasing conditioner retention time from 30 to 90 sec improved H60-PDI in diets containing 1.5 or 2% fat but not in diets containing 0.5 and 1.0% fat. Overall, these results emphasize the importance of better understanding the effects of changing pelleting process parameters and dietary fat inclusion levels have on pellet durability.

Introduction

Pelleting feed offers several benefits, including improved palatability and flowability, reduced feed wastage, minimized ingredient segregation, and pathogen destruction (Behnke, 1994). Although pelleting incurs additional costs, these can often be offset by improved animal performance. When formulating pelleted diets, feed mills must establish a target pellet quality or durability. Factors such as ingredient composition, equipment design, and manufacturing parameters significantly impact pellet durability. For swine and poultry feeds, minimizing fines at the feeder is a key objective in producing high-quality pellets. Within the pelleting process, several chemical changes take place due to heat, water, and pressure applied directly to the feed molecules that subsequently affect pellet durability (Abdollahi, et al., 2013).

A main processing parameter that can influence the final durability of the pellet is the steam conditioning parameters. The conditioning of feed allows for heat and moisture to be added, in a homogenized fashion, to the mash feed before it is pelleted. Within the conditioning process, there are factors that can be changed to alter the overall effect the conditioning process will have on moisture absorption. The first factor is the conditioning temperature. As conditioning temperature is increased within the conditioner, more heat and steam are applied to the feed particles. This addition of steam allows particles to conglomerate in the pellet die and leads to an improvement in pellet durability index (Boltz et al., 2020; Santos et al., 2020).

In addition to conditioning temperature, the amount of time the feed can spend in the conditioner, can be adjusted based on equipment design and operational settings. Adjusting the conditioning time allows for mash feed to be exposed to the heat and moisture, from the steam, for varying amounts of time. Previous research has demonstrated varying results on how conditioning time influences subsequent pellet durability (Boltz et al., 2020; Santos et al., 2020).

Ingredients and nutrient composition, in addition to processing parameters, play a significant role in pellet durability. For example, adding fat to the mixer can act as a lubricant while feed is being extruded through the pellet die, improving production rates. However, increasing fat levels can lead to over-lubrication, decreasing the time feed spends in the die and weakening inter-particle bonding leading to reduced pellet durability. When formulating diets to meet energy requirements using formulation software, it is essential to account for differences in fat concentrations. According to Fahrenholz, 2005, as fat level is increased from 1% to 3% in the diet, there will be a reduction in pellet durability. This agrees with Briggs et al., 1999, who observed PDI ranges from 82.0 to 49.2 when added fat levels ranged from 3.9% to 7.9% respectively. Previous research has demonstrated that for every 1% increase in added fat, pellet durability index (PDI) decreased by 10 to 14% (Dunmire et al., 2020; Truelock et al., 2020). However, this response is influenced by pelleting parameters such as conditioning temperature, conditioning time, and die specifications.

Therefore, considering the range of parameters that can affect the final quality of the pellet, two studies were conducted to evaluate the effects of conditioning temperature, retention time in the conditioner, and mixer added dietary fat on subsequent processing parameters and pellet quality.

Materials and Methods

Feed Manufacturing

For Exp. 1, a corn and soybean meal-based diet (Table 1) was pelleted to determine the effects of conditioner retention time and conditioning temperature on pellet durability. Treatments were arranged in a 3 × 2 factorial with 3 feed conditioning times of 30, 60, or 90 seconds and 2 conditioning temperatures of either 74 or 85°C. Treatments were pelleted at 3 separate time points to provide 3 replicates per treatment.

A total of 5 separate 907-kg batches were mixed in a 1.63 m^3 twin shaft counterpose mixer (Hayes and Stolz, model TRDB63-0152, Fort Worth, TX). All dry ingredients were mixed for 60 seconds prior to liquid fat being applied. After fat application, the feed was mixed for an additional 120 seconds. After batching, all feed was sacked, and treatments were created by portioning the 5 separate 907-kg batches into 6 separate 756-kg treatment batches. To create replicate treatments, the 6 treatment batches were divided into 3 separate 252-kg replication batches.

Each replication batch of mash feed (252-kg) was conditioned at either 74 or 85°C in a twin-shaft conditioner (10 × 55 in. Wenger twin staff conditioner, Model 150) for 30, 60, or 90 seconds depending on treatment specifications. All diets were pelleted on a 1-ton 30-horsepower pellet mill (1012-2 Master Model, California Pellet Mill) equipped with a 4.4 mm × 35.2 mm (length: diameter 8) pellet die. Each treatment was pelleted on three separate days. Within each day, treatment pelleting order was randomized within temperature, with the lower temperature of 74°C being pelleted first, to minimize residual changes in die temperature. Once conditioner temperature and retention time were stabilized, conditioned mash, hot pellet temperatures, production rate, and pellet samples were collected every 3 minutes, with a total of 3 samples being collected per replicate. Conditioned mash samples were placed directly into a freezer upon collection to prevent any potential moisture loss. Hot pellet temperature measurements were taken using a pre-warmed double-wall thermos equipped with a digital thermometer. Production rate was monitored to ensure production consistency throughout the pelleting run. Pellet samples were placed into a laboratory cooler affixed with a 153 mm axial fan, for 10 minutes, to facilitate uniform cooling. Hot pellet temperature was used to calculate ΔT.

For Exp. 2, a corn soybean meal-based diet (Table 2) was pelleted to determine the effect of feed retention time in the conditioner and mixer added dietary fat inclusion on pellet durability. Treatments were arranged in a 3 × 4 factorial with 3 conditioning times of 30, 60, or 90 seconds and 4 mixer added dietary fat inclusion levels of 0.5, 1.0, 1.5, or 2.0% of the total diet. All treatments were steam conditioned at 85°C and were pelleted at 3 separate time points (days) to provide 3 replicates per treatment.

A total of 3 separate 907-kg batches were mixed per fat inclusion treatment level using a 1.63 m^3 twin shaft counterpose mixer (Hayes and Stolz, model TRDB63-0152, Fort Worth, TX). All dry ingredients were mixed for 60 seconds before liquid fat application. After fat was applied, mixing continued for an additional 120 seconds. After batching, each 907-kg batch of feed was subdivided into 3 separate, 302-kg batches, creating 3 treatment replications per batch.

Each replication batch of mash feed (302-kg) was conditioned at 85°C in a twin shaft conditioner (10 × 55 in. Wenger twin shaft conditioner, Model 150) for 30, 60, or 90 seconds depending on treatment specifications. All diets were pelleted on a 1-ton 30-horsepower pellet mill (1012-2 Master Model, California Pellet Mill) equipped with a 4.4 mm × 35.2 mm (length: diameter 8) pellet die. Treatment replication was blocked by day of manufacturing to account for any environmental differences that may influence the pelleting process. Within each manufacturing day, the pelleting order was randomized within fat inclusion level. However, to minimize the lubricating effect of higher fat inclusion levels on the pellet die, the 0.5% fat inclusion level was always processed first, followed by the 1.0%, 1.5%, and 2.0% levels. Once retention time was stabilized, conditioned mash, hot pellet temperatures, production rate, and pellet samples were collected every 3 minutes, with a total of 3 samples being collected per replicate. Conditioned mash samples were placed directly into a freezer upon collection to prevent any potential moisture loss. Hot pellet temperature measurements were taken using a pre-warmed double-wall thermos equipped with a digital thermometer. Production rate was monitored to ensure production consistency throughout the pelleting run. Pellet samples were placed into a laboratory cooler affixed with a 153 mm axial fan, for 10 minutes, to facilitate uniform cooling. Hot pellet temperature was used to calculate ΔT as previously described.

Sample analyses

Conditioned mash samples were taken at the end of the conditioner (conditioned mash) for determination of moisture content of the feed after it was steam conditioned. Upon collection of the sample, bags were immediately sealed and placed in a freezer to prevent any potential moisture loss. Triplicate samples were taken and were analyzed according to AOAC 930.15. and can be found in Tables 3 and 4, for experiments 1 and 2, respectively.

Pellet samples were collected directly off the pellet die and placed into a counter-flow laboratory cooler for 10 minutes. Samples were then transferred and stored in commercial bi-layer paper feed sacked for 24 hours before analysis. Three samples per replicate were obtained. All samples were subsampled and analyzed for pellet durability using the modified tumble box method (M-PDI; Exp. 1) and percent pellets surviving the New Holmen Pellet Tester (60 sec; H60-PDI; Exp. 1 & 2).

For the modified tumble box method (M-PDI), pellets were initially sifted using a No. 5 (3.9 mm) sieve for removal of fines (Schofield and American Feed Industry Association, 2005).

A 500-g sample of sifted pellets was then placed into the tumble box along with 3 19-mm hex-nuts to increase the agitation of the pellets. The tumble box rotated for 10 min. After tumbling, the sample was collected and sifted again for the removal of fines. PDI was calculated according to S269.5 (ASAE, 2012).

For the H60-PDI method, pellets were sifted prior to testing, using a No. 5 (3.9 mm) sieve for the removal of fines (Schofield and American Feed Industry Association, 2005). A 100-g subsample was then placed into the chamber of the Holmen NHP100 (TekPro Ltd, Norfolk, UK). The machine was set to 60 second agitation at 70 mbar of pressure. After testing, samples were once again sifted for the removal of fines. PDI was calculated according to S269.4. (ASAE, 2012). All samples were analyzed in triplicates and the results were averaged. Results can be found in Tables 2 and 4, for Exp. 1 and 2, respectively.

Statistical analysis

Experiment 1

All data was analyzed using the PROC GLIMMIX procedure in SAS 9.4 (Cary, NC) with means separated by least square means procedure. Treatments were arranged in a 3 × 2 factorial of conditioner retention time (30, 60, and 90 seconds) and conditioning temperature (74 and 85°C). Fixed effects included temperature, retention time, and their interaction. For retention time, polynomial contrasts were used to assess linear and quadratic effects. Date of manufacture served as a random effect to account for any possible environmental differences that may affect the pelleting process. Treatments were replicated 3 times each. Results were considered significant at $P \leq 0.05$.

Experiment 2

All data was analyzed using the PROC GLIMMIX procedure in SAS 9.4 (Cary, NC) with means separated by least square means procedure. Treatments were arranged in a 3 × 4 factorial of conditioner retention time (30, 60, and 90 seconds) and mixer added dietary fat inclusion level (0.5, 1.0, 1.5, and 2.0%). Fixed effects included retention time, fat inclusion level, and their interaction. For both retention time and fat inclusion level, polynomial contrasts were used to assess linear and quadratic effects. Date of manufacture served as a random effect to account for any possible environmental differences that may affect the pelleting process. Treatments were replicated 3 times each. Results were considered significant at $P \leq 0.05$.

Results and Discussion

Experiment 1

When analyzing conditioned mash moisture percentage, no interaction was observed between retention time and conditioning temperature. There was no evidence of difference in conditioned mash moisture when increasing conditioning retention time. Increasing conditioning temperature from 74°C to 85°C increased ($P < 0.05$) conditioned mash moisture (Table 3). This agrees with Truelock et al., 2019, who observed that increasing conditioning temperature led to an increase in conditioned mash moisture percentage. Pope and Fahrenholz, 2020, also observed a similar trend when comparing the moisture content at different conditioning temperatures, observing that as conditioning temperature was increased from 80°C to 92°C there was an increase in the moisture content of the conditioned mash from added steam. Increasing the temperature inside the conditioner requires an increased amount of steam to be injected into the conditioning chamber leading to increases in conditioned mash moisture content.

For ΔT, no interaction was observed between retention time of the feed in the conditioner and conditioning temperature. However, increasing the conditioning temperature from 74°C to 85°C led to a decreased ($P < 0.05$) ΔT value. When increasing retention time from 30 seconds to 60 and 90 seconds, an increase (linear, $P < 0.05$) in ΔT was observed. For pellet durability, the H60-PDI method resulted in no interaction between retention time of feed in the conditioner and conditioning temperature. However, increasing retention time improved (linearly, $P < 0.05$) H60-PDI as it was increased from 30 to 90 seconds. When increasing the conditioning temperature from 74°C to 85°C no difference in H60-PDI was observed. For M-PDI, no interaction was observed between retention time and conditioning temperature. When retention time was increased, a linear increase ($P < 0.05$) was observed for M-PDI. Additionally, increasing conditioning temperature from 74°C to 85°C led to an increase ($P < 0.05$) in M-PDI. No interaction being observed for conditioning temperature and retention time for H60-PDI agrees with Boltz et al., 2020, who did not find a conditioning temperature by retention time interaction on pellet quality when using the New Holmen Pellet Tester 30 second method. The improvement observed in H60-PDI as retention time was increased is consistent with Massuquetto et al., 2018, who observed a quadratic increase in pellet quality at up to 80 seconds of retention time in the conditioner. One possible reason for the improvement in pellet quality is the increased time of exposure to moisture and heat, which promotes starch granule swelling and enhances the formation of bonds during the compression of feed through the pellet die. The increase in M-PDI as retention time was increased is supported by Gilpin, 2001, who observed an increase in M-PDI as retention time was increased. Additionally, the positive effect of increased conditioning temperature on M-PDI agrees with Boney and Moritz, 2017, who observed similar results, showing that as conditioning temperature increased from 74°C to 91°C, PDI subsequently increased.

Experiment 2

In the second experiment, no interaction was observed between retention time and dietary fat inclusion on conditioned mash moisture percentage. Fat inclusion and conditioner retention time showed no effect on mash moisture percentage. This demonstrates that increasing mixer added dietary fat at up to 2% does not influence the conditioned mash moisture content of the feed. ForΔT, no interaction was observed between retention time and dietary fat inclusion. However, increasing the conditioning temperature from 0.5% to 2.0% led to a decreased (linearly, $P < 0.05$) ΔT value. This response is most likely due to the lubricative effects of fat leading to less friction as the feed is forced through the die. When increasing retention time from 30 to 90 seconds, no difference was in ΔT was observed. The H60-PDI was the only method used to analyze pellet durability in this experiment. An interaction was detected between retention time and fat inclusion level (linearly, $P < 0.05$). As fat inclusion level in the diet increased from 0.5% to 2%, the effect of extended retention time became more pronounced. For diets containing 0.5% fat, increasing the feed retention time in the conditioner from 30 seconds to 60 seconds led to an increase of 2% points in H60-PDI; however, there was no further improvement in H60-PDI when increasing the conditioning retention time from 60 to 90 sec. In comparison, when diets contained 2% added fat, H60-PDI increased by approximately 7% points when conditioner retention time was increased from 30 to 90 seconds. This difference may be attributed to the increased conditioning time, which likely allowed for enhanced starch gelatinization and improved pellet binding (Lewis et al., 2015). Additionally, since fat is hydrophobic, the extended exposure to heat and moisture during the longer conditioning time may have allowed the moisture to overcome the fat’s hydrophobic effects, facilitating increased moisture penetration into the starch granules. For diets conditioned at 30 sec, increasing fat from 0.5 to 2.0% reduced H60-PDI by 7% points. For diets conditioned at 60 sec H60-PDI was reduced by 5% points. For diets conditioned at 90 sec H60-PDI was reduced by 2% points. Abadi et al. (2019) conditioned diets for 10 seconds and observed a 12% point decrease in H60-PDI as soy oil inclusion was increased from 1.5 to 3% of the diet.

These findings demonstrate that minor adjustments made to pelleting process, such as increased retention time can significantly enhance pellet quality. Increasing retention time can positively influence pellet durability and can mitigate the negative effect of increased fat inclusion, which typically reduces pellet quality. While increasing conditioning temperature may also have a beneficial impact on pellet quality, the extent of this effect can be dependent upon the magnitude of the temperature increase. However, the results also underscore the complexity of the pelleting process, emphasizing that altering a single factor alone is not a comprehensive solution for optimizing pellet quality.

Conclusion and Applications

1. Increased conditioner retention time led to increased pellet quality for Exp. 1
2. Increased conditioning temperature leads to increased conditioned mash moisture content
3. The negative effects of dietary fat inclusion on pellet quality can be mitigated by extending retention time.

Table 1. Diet Composition[1]

Ingredient, % as fed	Basal Diet
Ground corn	69.09
Soybean meal	25.75
Soy oil	2.12
Limestone	0.99
Dicalcium phosphate, 18%	0.88
Salt	0.41
L-Lysine, 78%	0.17
DL-Methionine	0.22
L-Threonine	0.07
Phytase[2]	0.01
Choline Chloride	0.04
Vitamin trace mineral premix[3]	0.25
Total	100.00

[1] A poultry diet composed of corn (1200 µm) and soybean meal was manufactured. Diets were steam conditioned (25.4 × 139.7 cm length Wenger twin staff conditioner, Model 150) for approximately 30, 60, or 90 seconds at either 74℃ or 85℃ depending on treatment specifications. Diets were then pelleted on a 22-kilowatt pellet mill (1012-2 Master Model, California Pellet Mill) equipped with a 4.4 × 22.2-mm pellet die (L:D 8).

[2] Quantum Blue (AB Vista, Plantation, FL) Phytase, 10,000 FTU/g

[3] Provided per kg of premix: 40 g Zn, 20 g Fe, 40 g Mn, 4500 ppm Cu, 600 ppm I, 60 ppm Se, 3.087,000 IU vitamin A, 1,102,500 ICU vitamin D3, 6615 IU vitamin E, 4.41 mg vitamin B12, 331 mg menadione, 2646 mg riboflavin, 441 mg thiamine, 2646 mg pantothenic acid, 11023 mg niacin, 154,323 mg choline, , 276 mg folic acid, 551 mg pyridoxine, and 13 mg biotin

Table 2. Diet Composition[1]

	Mixer Added Fat			
Ingredient, % as fed	0.5%	1.0%	1.5%	2.0%
Ground corn	70.86	70.30	69.73	69.22
Soybean meal	25.55	25.61	25.68	25.73
Limestone	1.00	1.00	1.00	1.00
Dicalcium phosphate, 18%	0.87	0.87	0.87	0.87
Salt	0.46	0.46	0.46	0.46
L-Lysine, 78%	0.17	0.17	0.17	0.17
DL-Methionine	0.22	0.22	0.22	0.22
L-Threonine	0.07	0.07	0.07	0.07
Phytase[2]	0.01	0.01	0.01	0.01
Choline Chloride	0.04	0.04	0.04	0.04
Vitamin Trace Mineral Premix[3]	0.25	0.25	0.25	0.25
Soy Oil	0.50	1.00	1.50	2.00
Total	100.00	100.00	100.00	100.00

[1] A poultry diet composed of corn (1200 µm) and soybean meal was manufactured. Diets were steam conditioned (25.4 × 139.7 cm length Wenger twin staff conditioner, Model 150) for approximately 30, 60, or 90 seconds at 85°C depending on treatment specifications. Diets were the pelleted on a 22-kilowatt pellet mill (1012-2 Master Model, California Pellet Mill) with a 4.4 × 22.2-mm pellet die (L:D 8).

[2] Quantum Blue (AB Vista, Plantation, FL) Phytase, 10,000 FTU/g

[3] Provided per kg of premix: 40 g Zn, 20 g Fe, 40 g Mn, 4500 ppm Cu, 600 ppm I, 60 ppm Se, 3.087,000 IU vitamin A, 1,102,500 ICU vitamin D3, 6615 IU vitamin E, 4.41 mg vitamin B12, 331 mg menadione, 2646 mg riboflavin, 441 mg thiamine, 2646 mg pantothenic acid, 11023 mg niacin, 154,323 mg choline, , 276 mg folic acid, 551 mg pyridoxine, and 13 mg biotin.

Table 3. Influence of conditioning temperature and feed retention time in the conditioner on pellet durability as measured by modified pellet durability index (M-PDI) and New Holmen pellet tester (H60-PDI)[1]

Conditioning Temp	Retention Time	Measured Conditioning Temp, °C	Conditioned Mash Moisture, %	Production Rate[2], kg/hr	Δ Δ T, °C	H-60 PDI, %	M-60 PDI, %
74°C	30 sec	74.4	15.1	1041.9	8.93	58.0	59.4
	60 sec	74.3	15.4	1041.0	9.96	61.1	65.3
	90 sec	74.0	15.2	1036.0	10.33	68.8	67.4
85°C	30 sec	85.3	16.0	1041.4	3.85	61.2	65.8
	60 sec	84.8	16.1	1049.2	4.65	62.2	69.0
	90 sec	84.9	15.8	1044.6	4.49	66.9	69.0
SEM	-	-	0.18	-	0.34	1.97	2.03
Conditioning Temp Means							
74°C	-	-	15.2^{b}	-	9.74^{a}	62.6	64.0^{b}
85°C	-	-	15.9^{a}	-	4.33^{b}	63.4	67.9^{a}
Retention Time Means							
-	30 sec	-	15.5	-	6.39^{b}	59.6^{b}	62.6^{b}
-	60 sec	-	15.8	-	7.31^{a}	61.7^{b}	67.2^{a}
-	90 sec	-	15.5	-	7.41^{a}	67.9^{a}	68.2^{a}
Interaction[3], *P* =		-	0.500	-	0.541	0.200	0.093
Retention Time, *P* =							
Linear		-	0.685	-	0.014	0.001	0.001
Quadratic		-	0.122	-	0.203	0.220	0.150
Temperature, *P* =		-	0.007	-	0.001	0.600	0.004

[1] A poultry diet composed of corn (1200 µm) and soybean meal was manufactured. Diets were steam conditioned (25.4 × 139.7 cm length Wenger twin staff preconditioner, Model 150) for approximately 30, 60, or 90 seconds at either 74°C or 85°C depending on treatment specifications on a 22-kilowatt pellet mill (1012-2 Master Model, California Pellet Mill) equipped with a 4.4 × 22.2-mm pellet die (L:D 8).

[2] Production rate was aimed to be kept constant throughout all pelleting runs

[3] Linear and quadratic contrasts testing the response of increasing conditioning temperature and increasing retention time are considered significant at $P \leq 0.05$

Table 4. The influence of dietary fat inclusion and feed retention time in the conditioner on pellet durability as measured by the New Holmen pellet tester (H60-PDI)[1,3]

Fat Inclusion (%)	Retention Time, sec	Conditioned Mash Moisture, %	Production Rate[2], kg/hr	Δ T, °C	H60-PDI, %
0.5	30	16.95	1176.6	4.17	77.62^{abcd}
	60	17.22	1167.6	4.58	80.35^{a}
	90	17.25	1160.9	3.88	79.74^{ab}
1.0	30	16.86	1145.8	2.82	76.52^{cd}
	60	17.37	1160.3	2.68	79.04^{abc}
	90	17.10	1163.9	3.57	78.45^{abc}
1.5	30	16.89	1154.3	2.64	72.77^{ef}
	60	17.23	1178.5	3.23	76.21^{cd}
	90	17.14	1163.7	3.37	77.64^{abcd}
2.0	30	16.96	1182.7	2.09	70.85^{f}
	60	17.00	1147.0	2.62	75.22^{de}
	90	17.24	1186.3	3.49	77.25^{bcd}
SEM	-	0.27	-	0.53	1.88
Fat Inclusion Means					
0.5 %	-	17.14	-	4.21^{a}	79.24^{a}
1.0 %	-	17.11	-	3.02^{b}	78.00^{a}
1.5 %	-	17.09	-	3.08^{b}	75.54^{b}
2.0 %	-	17.07	-	2.73^{b}	74.44^{b}
Retention Time Means					
-	30 sec	16.91	-	2.93	74.44^{b}
-	60 sec	17.18	-	3.28	77.71^{a}
-	90 sec	17.21	-	3.58	78.27^{a}
Linear Interaction, *P* =	-	0.958	-	0.140	0.019
Quadratic Interaction, *P* =	-	0.305	-	0.602	0.918
Fat Inclusion					
Linear, *P* =	-	0.691	-	0.004	<0.001
Quadratic, *P* =	-	0.966	-	0.183	0.912
Retention Time					
Linear, *P* =	-	0.109	-	0.094	<0.001
Quadratic, *P* =	-	0.271	-	0.941	0.037

[1] A common poultry diet composed of corn (1200 µm) and soybean meal was manufactured. Diets were steam conditioned (25.4 × 139.7 cm length Wenger twin staff conditioner, Model 150) for approximately 30, 60, or 90 seconds at 85°C depending on treatment specifications. Diets were the

pelleted on a 22-kilowatt pellet mill (1012-2 Master Model, California Pellet Mill) with a 4.4 × 22.2-mm pellet die (L:D 8).

[2] Production rate was aimed to be kept constant throughout all pelleting runs

[3] Linear and quadratic contrasts testing the response of increasing conditioning temperature and increasing retention time are considered significant at $P \leq 0.05$

[a,b,c,d,e,f] Means lacking a common superscript differ ($P < 0.05$)

Chapter 2 - Impact of pellet die diameter and pellet fines on broiler growth performance

Abstract

Altering processing parameters in feed manufacturing can impact feed quality and broiler growth. Two experiments evaluated the effects of pellet die diameter and pellet fines inclusion on broiler growth performance. Exp. 1 used a 3 x 2 factorial design with 3 pellet die diameters (4.0 mm, 4.8 mm, and 6.4 mm) and 2 fines inclusions (0% and 30%) fed from d 12-47. Exp. 2 used as a 2 x 3 factorial with 2 pellet die diameters (4.8 mm and 6.4 mm) and 3 fines inclusions (0%, 30%, and 60%), fed from d 14-49, with a crumble (4.8 mm or 6.4 mm) being fed from d 0-14. Data were analyzed using PROC GLIMMIX in SAS v. 9.4 (Cary, NC). In Exp 1. overall growth interactions were observed for both FI ($P = 0.015$) and BWG ($P = 0.013$), where fines reduced performance in 4.0 and 4.8 mm pellet diets, but improved FI and BWG with 6.4 mm pellets. In Exp. 2, the 4.8 mm pellet die diameter, increased FI ($P = 0.003$), BWG ($P < 0.001$), and improved FCR ($P = 0.002$) in the starter phase. From d 0-49, increasing fines improved (linearly, $P < 0.05$) FCR, though no interactions were observed for FI and BWG. These results suggest that while increased fines generally impair broiler growth performance, their inclusion alongside a 6.4 mm pellet may help mitigate the typical negative impacts associated with higher pellet fines.

Introduction

Pelleting feed is a common practice in the broiler industry. It is accepted that there are benefits of feeding pellets such as decreased feed wastage, less time spent for prehension, and improved palatability (Behnke, 1994), however, there are current questions about the pelleting process and what factors can be adjusted to improve economic return for integrated broiler producers. Many factors within the pelleting process can be adjusted to affect the production rate, energy usage, and subsequent quality of the pellet fed to the bird. All three of these factors combine to influence the economic return for integrated producers.

Increasing pellet mill efficiency on a tons per hour (TPH) basis can lead to a reduction in feed cost for integrated feed mills. Many factors can influence the efficiency of a pellet mill such as design characteristics, conditioned feed temperature and moisture, diet formulation, and pellet die specifications. A commonly adjusted parameter, besides conditioning temperature, is the pellet die specifications. There are two main factors on a pellet die that can be altered. When aiming for a higher quality pellet, manufacturers often increase the length:diameter **(L:D)** ratio of die. This leads to using a thicker die that causes the feed to spend a longer amount of time in the die and improves binding properties of the feed material. Previous research has demonstrated this improvement in pellet durability while increasing pellet die thickness (Truelock et al., 2020). In addition to altering pellet die thickness or length, pellet die diameter can be changed resulting to different size pellets. Within the broiler industry, common die diameters range anywhere from 3-5 mm, with anywhere from 4.0 mm to 4.8 mm being the most common. Die selection plays a large role in the total efficiency (productivity) of the pellet mill each day. Truelock (2019) found that the use of a thicker die enhances pellet durability, however, increases total energy consumption, leading to a less efficient pellet mill. This is due to the increased compression of the feed and increased length of the die hole that the feed must pass through before exiting the die. However, it has been hypothesized that as we alter the diameter of the die hole, the open area, or area on the die that feed can pass through, is increased, leading to less compression of the pellets. This decrease in compression and increased area for passage should lead to an increase in production rate. As production rate increases with a larger open area of the die, this leads to more efficient mills for integrated producers on a TPH basis. However, a drawback of increasing die hole diameter is the detrimental effect to pellet quality. As stated previously, a larger die hole will lead to less compression of the feed while in the die, leading to decreased inter-particle bonding. This has potential of lowering the quality of the pellets. However, pellet quality can also be dependent upon the final length of the pellet as well, along with the die diameter (Abdollahi et al., 2013).

Although production rate increase can be beneficial it does have its drawbacks. Stark (2009) reported a linear decrease in pellet durability as the throughput of the pellet mill increased. As the pellet durability decreases, there is increased breakage of pellets and increased fines creation. This leads to another factor in the feed manufacturing process that can impact pellet mill efficiency and broiler performance, the creation of fine material after pelleting. Increased pellet fines can potentially lead to poorer flowability of the feed at the farm, nutrient segregation (Sellers et al., 2020) and can negatively affect broiler growth performance (Corzo et al., 2013). Therefore, two studies were conducted to determine the effects of feeding varying pellet diameters and fines inclusion levels on growth performance of broilers.

Materials and Methods

Two experiments were conducted at the Tom Avery Poultry Research Farm, Animal Science and Industry Department, Kansas State University, Manhattan, KS. All experimental procedures were approved by the Institutional Animal Care and Use Committee (IACUC #4850) of Kansas State University, Manhattan, KS.

Dietary Treatments and Feed Manufacture

Feed was manufactured in accordance with Current Good Manufacturing Practices at the Kansas State University O.H. Kruse Technology Innovation Center, Manhattan, KS.

Experiment 1

Treatments were arranged in a 3 × 2 factorial of pellet diameter (4.0, 4.8, and 6.4 mm) and fines inclusion (0 or 30%). Three corn-soy based diets, depending on phase of broiler production, were formulated to meet the nutritional recommendations of Ross 708 broilers (Table 5). All birds were initially fed a common starter diet fed in crumble form. Subsequently, treatment diets were provided during grower and finisher phases (d 12-47). The corn used for the diets was ground using a 25-horsepower hammermill (Model 22115, Bliss Industries LLC., Ponca City, OK). Corn was ground to an average particle size of 1000 µm for grower and finisher phases. All mash diets were mixed on a 909-kg twin shaft counterpoise mixer (Hayes and Stoltz, Model TRDB63-0152, Fort Worth, TX). After mixing, the diets were steam conditioned for approximately 30 seconds at 82°C in a single pass conditioner prior to being pelleted on a 5-Ton 100-HP (Model 3016-4 Master, California Pellet Mill Co., Crawfordsville, IN) pellet mill. Within pellet manufacturing, the diameter of the pellets was determined by using 3 different pellet dies. Die hole length and pellet die hole diameters (**L:D**) ratios were as follows: 4.0 mm pellet (35 mm: 4.0 mm, 8.75 L:D), 4.8 mm pellet (45 mm: 4.8 mm, 9.38 L:D), 6.4 mm (51 mm: 6.4 mm, 7.96 L:D). After production of pellets, ambient air was used to cool pellets in a counterflow cooler to room temperature and pellet samples were collected to analyze pellet durability.

After diets were pelleted and cooled, pellets were sifted using a Gentle Roll (Model 24S-1-HB-F-FF, EBM Manufacturing Inc., Norfolk, NE) equipped with 3.88 mm wire mesh screen, to remove and collect fines. After screening all diets, fines were mixed in a 226-kg horizontal paddle mixer (Model S3, H.C. Davis Sons Mfg. Co. Inc., Bonner Springs, KS) to form a homogenous mixture of the fines material to be included back into pellets to create treatment diets. Pellet fines were added to specified diets at a 30% inclusion rate and mixed to create a homogenous form of feed. After manufacturing, the grower diets were fed from d 12-26 and the finisher diets from d 26-47.

Experiment 2

Treatments were arranged in a 2 × 3 factorial of pellet die diameter (4.8 and 6.4 mm) and fines inclusion (0, 30, or 60%). Treatments were randomly assigned to pen within location block and balanced by initial body weight on d 0. Three corn-soy based diets, depending on phase of broiler production, were formulated to meet the nutritional recommendations of Cobb 500 broilers (Table 6). The corn used for the diets was ground using a 25-horsepower hammermill (Model 22115, Bliss Industries LLC., Ponca City, OK). Corn was ground to an average particle size of 700 µm for all phases. All mash diets were mixed on a 909-kg twin shaft counterpoise mixer (Hayes and Stoltz, Model TRDB63-0152, Fort Worth, TX). After mixing, the diets were then pelleted on a 5-Ton 100-HP (Model 3016-4 Master, California Pellet Mill Co., Crawfordsville, IN). Within pellet manufacturing, diameter of the pellets was determined by using 2 different pellet dies. Die hole length and pellet die hole diameters (**L:D**) ratios were as follows: 4.8 mm pellet (45 mm: 4.8 mm, 9.38 L:D) and 6.4 mm (51 mm: 6.4 mm, 7.96 L:D). After production of pellets, ambient air was used to cool pellets in a counterflow cooler to room temperature and pellet samples were collected to analyze pellet durability.

After diets were pelleted and cooled, pellets were sifted using a Gentle Roll (Model 24S-1-HB-F-FF, EBM Manufacturing Inc., Norfolk, NE) equipped with 3.88 mm wire mesh screen, to remove and collect fines. After screening all diets, fines were mixed in a 226-kg horizontal paddle mixer (Model S3, H.C. Davis Sons Mfg. Co. Inc., Bonner Springs, KS) to form a homogenous mixture of the fines material to be included back into the treatment diets. Pellet fines were added to specified diets at 30 or 60% inclusion rate and mixed to create a homogenous form of feed. After manufacturing, the starter crumble diets were fed from d 0-14, grower diets were fed from d 14-28, and the finisher diets from d 28-49.

Pellet Quality

Pellets were collected and analyzed using a New Holmen Portable Pellet Durability Tester (Model NHP 100, TekPro, Ltd., Norfolk, UK) to analyze percent pellets survivability (H30-PDI). A 100 g sample was screened to remove fines created using a No. 6, 5, or 3.5 screen (Schofield and American Feed Industry Association, 2005) for the 4.0 mm, 4.8 mm, or 6.4 mm pellets, respectively. After screening, the pellets were placed into the chamber and were air agitated for 30 seconds at 70 mbar of pressure. Following the agitation, the pellets remaining in the chamber were sifted again on the required screen before being weighed back. The final weight of the pellets was then used in the equation below to calculate PDI, %.

$$PDI, \% = \frac{Final\ Weight}{Initial\ Weight} \times 100$$

Bird Husbandry

Experiment 1

A total of 650 male one-day old broiler chick (Ross 708 Byproduct Broiler, Sallisaw, OK, Initial BW 42.8 g) were obtained from a commercial hatchery and brought to the Kansas State University Poultry Unit. Birds were randomly placed in pens and fed a common crumble diet from d 0-12. On d 12, a total of 600 birds were placed into 60-floor pens (2.3 × 1.5 m) resulting in 10 birds per pen. Floor pens were divided into 10 location blocks and 1 of 6 dietary treatments were randomly assigned within each block. Each pen was equipped with 6 nipple drinkers (Chore-Time Steadi-FLOW, Milford, Indiana) and a plastic tube feeder affixed to a Model C2 Plus broiler feed pan (Chore-Time, Milford, Indiana). The lighting procedure was as follows: 23 hours of light and 1 hour of darkness for the first 12 days, from d 13-47, 18 hours of light and 6 hours of darkness. The temperature of the house was set at 30°C from d 0-12; 27°C from d 13-26; and 25°C from d 27-47. All birds were provided ad-libitum access to feed and water throughout the study and feeders were shaken twice a day to promote feed intake.

Experiment 2

A total of 720 male one-day old broiler chick (Cobb breeder by-product, C500 off-sex males; Siloam Springs, AR, Initial BW 49.1 g) were obtained from a commercial hatchery and brought to the Kansas State University Poultry Unit. Birds were randomly placed into 60-floor pens (2.3 × 1.5 m) on d 0, resulting in 12 birds per pen to begin the experimental procedure. Floor pens were divided into 10 location blocks. On d 0, one of two treatments, based upon pellet die diameter (4.8 mm or 6.4 mm), were assigned to all pens and were fed in crumble form. On d 14, 1 of 6 dietary treatments were assigned consisting of 2 different pellet die diameters (4.8 mm and 6.4 mm) and 3 fines inclusion levels (0, 30, and 60%). Pellet fines treatments were randomly assigned to pens within previously fed pellet die diameter treatments. Each pen was equipped with 6 nipple drinkers (Chore-Time Steadi-FLOW, Milford, Indiana) and a plastic tube feeder affixed to a Model C2 Plus broiler feed pan (Chore-Time, Milford, Indiana). The lighting procedure was as follows: 23 hours of light and 1 hour of darkness for the first 14 days, from d 14-49, 18 hours of light and 6 hours of darkness. The temperature of the house was set at 30°C from d 0-12; 27°C from d 12-28; and 25°C from d 28-49. All birds were provided ad-libitum access to feed and water throughout the study and feeders were shaken twice a day to promote feed intake.

Data Collection

Experiment 1

On d 12, birds were weighed, and treatments were randomly assigned to pen within location block and balanced by average pen BW. On d 26 and d 47, birds and feeders were weighed to calculate pen body weight gain (**BWG**) and total feed intake (**FI**). Mortality was observed twice daily, if found, birds were removed and weighed. The mortality weight was then added to the pen body weight and used to adjust pen BWG and feed conversion ratio (**FCR**).

Experiment 2

On d 0, birds were weighed, and pellet die diameter treatments (4.8 mm or 6.4 mm) were randomly assigned to pen within location block and balanced by average pen BW. On d 14, birds were assigned treatment diets consisting of 2 pellet die diameters (4.8 mm and 6.4 mm) and 3 fines inclusion levels (0%, 30%, and 60%). All treatment diets on d 14 were assigned within previously fed die diameter from d 0-14. On d 14, d 28, and d 49, birds and feeders were weighed to calculate pen body weight gain (**BWG**) and total feed intake (**FI**). Mortality was observed twice daily, if found, birds were removed and weighed. The mortality weight was then added to the pen body weight and used to adjust pen BWG and feed conversion ratio (**FCR**).

Statistical Analysis

Experiment 1

The experiment was arranged as a 3 × 2 factorial with pellet die diameters of 4.0, 4.8, and 6.4 mm and fines inclusion levels of 0 and 30%. All experimental data collected were analyzed using the GLIMMIX procedure of SAS 9.4 (Cary, NC). Pen was considered the experimental unit and block was a random effect. The statistical model included treatment as fixed effect. Pairwise comparison of least square means was performed using Tukey's HSD test and were considered significantly different at $P \leq 0.05$.

Experiment 2

The experiment was arranged as a 2 × 3 factorial with pellet die diameters of 4.8 and 6.4 mm and fines inclusion levels of 0, 30, or 60%. All experimental data collected were analyzed using the GLIMMIX procedure of SAS 9.4 (Cary, NC). Pen was the experimental unit and block was a random effect. The statistical model included treatment as fixed effect. Polynomial contrasts were used to evaluate linear and quadratic effect of fines inclusion as well as their interactions. Pairwise comparison of least square means was performed using Tukey's HSD test and were considered significantly different at $P \leq 0.05$.

Results and Discussion

Experiment 1

Performance results from Exp. 1 are displayed in Table 7. For d 12-26, there was a die diameter and pellet fines inclusion interaction ($P < 0.002$) for FI. For the 0% fines treatments, as die diameter increased from 4.0 mm to 6.4 mm, there was a decrease in FI. However, as 30% fines were included, all three die diameters performed similarly. For d 12-26 BWG, there was a die diameter and pellet fines interaction ($P < 0.025$). For the 0% fines treatments, there was a decrease in BWG as the die diameter increased from 4.0 mm to 6.4 mm, respectively. However, as 30% fines were included, no differences in BWG were observed between the 3 varying die diameters. For d 12-26 FCR, there was no evidence of an interaction, however, main effects of both die diameter ($P < 0.006$) and pellet fines ($P < 0.001$) were observed. Broilers fed diets pelleted using the 4.0 mm diameter die had improved FCR compared to those fed diets pelleted using the 4.8 mm diameter die, with those fed diets pelleted using the 6.4 mm diameter die being intermediate. For the main effect of fines percentage, broiler fed diets containing 30% added fines had poorer FCR compared to those fed the diets containing 0% added fines. For d 26-47, FI was similar across all treatments, with no differences being observed for the various die diameters or pellet fines inclusion levels. For d 26-47 BWG, an interaction ($P < 0.046$) was observed between die diameter and pellet fines inclusion. As treatments were fed with 0% pellet fines, BWG decreased as the larger die diameter was fed. However, as 30% pellet fines were added, all die diameters performed similarly. For d 26-47 FCR, no interaction was observed between die diameter and pellet fines inclusion. However, main effects for both die diameter ($P < 0.019$) and pellet fines ($P < 0.004$) were present. Broilers fed die diameters of 4.0 and 4.8 mm showed improved FCR when compared to broilers fed the 6.4 mm die diameter. As for pellet fines inclusion, as fines were included in the diet at 30%, FCR worsened for the broilers. For d 12-47 FI, an interaction ($P < 0.015$) between die diameter and pellet fines inclusion was observed. As broilers were fed diets containing 0% fines, increased die diameter led to poorer FI; however, as 30% fines were included, broilers performed similarly, regardless of die diameter. For d 12-47 BWG, an interaction ($P < 0.013$) was observed between die diameter and pellet fines inclusion. As fines were absent from the treatments, increased die diameter led to lower BWG; however, as 30% fines were included, all die diameters observed similar BWG. For d 12-47 FCR, no interaction was observed, however, main effects for both die diameter ($P < 0.013$) and pellet fines ($P < 0.001$) were observed. As die diameter was increased from 4.0 and 4.8 mm to 6.4 mm, a decrease was observed in FCR. For pellet fines inclusion, the absence of pellet fines led to improved FCR when compared to treatments fed 30% pellet fines.

Experiment 2

Performance results from Exp. 2 are displayed in Tables 8 & 9. Due to the similarities between the 4.0 mm and 4.8 mm die diameter treatments from the previous experiment, Exp. 2 was conducted to further understand the effects of increased fines inclusion on growth performance with an industry common (4.8 mm) and enlarged (6.4 mm) die diameters being used.

For d 0-14, broilers consuming the 4.8 mm crumble, had increased FI ($P < 0.003$) and BWG ($P < 0.001$) compared to broilers fed the 6.4 mm crumble. For FCR from d 0-14, the smaller die diameter of 4.8 mm led in improved FCR ($P < 0.002$) when compared to the 6.4 mm crumble. For d 14-28 FI, no interaction was observed between die diameter and pellet fines, however, a decrease (linearly, $P < 0.002$) was observed for increasing fines inclusion. For d 14-28 BWG, no interaction was observed; however, main effects of both die diameter ($P < 0.007$) and fines (linear, $P < 0.001$) were observed. As broilers were fed the 4.8 mm die diameter, an increase in BWG was observed for all 3 treatments when compared to the 6.4 mm treatments. As for fines inclusion, as fines increased in the diet, there was a linear decrease observed in BWG. For d 14-28 FCR, an interaction ($P < 0.044$) was observed between die diameter and fines inclusion. When broilers were fed diets produced using a 4.8 mm die diameter, FCR remained consistent across the three treatments. However, when diets were produced with a 6.4 mm die diameter, there was a numerical increase, or worsening, in FCR with the 6.4 mm die diameter combined with 60% fines resulting in the highest FCR value. For d 28-49, FI and BWG observed no interactions, or main effects were observed for FI or BWG. However, a decrease (linearly, $P < 0.003$) in FCR was observed for fines inclusion. As fines inclusion increased from 0 to 60%, an improvement in FCR was observed, with the 30% treatment serving as an intermediary. For d 14-49, no interaction or main effects were observed for FI and BWG. As for FCR, a decrease (linearly, $P < 0.009$) was observed for fines inclusion. As fines inclusion increased from 0 to

60%, an improvement in FCR was observed, with the 30% treatment serving as an intermediary. For overall d 0-49, no interactions or main effects were observed for both FI and BWG, however, the same trend followed with a decrease (linearly, $P < 0.009$) in FCR being observed for fines inclusion. As fines inclusion increased from 0 to 60%, an improvement in FCR was observed, with the 30% treatment serving as an intermediary.

Discussion

Across both experiments, feeding diets pelleted with a larger die diameter appeared to reduce FI and BWG when no fines were included, particularly early in the bird's life. This result aligns with previous findings (Neves et al. 2014), which suggest that broiler prehension is influenced by particle size, with younger birds preferring particles that align with the size of their beak. Similarly, Nir et al. (1994), found that smaller particles are easier for young birds to consume and digest, which supports the observed reduction in BWG when birds were fed pellets from larger die diameters early in life. In Exp 1. including fines into the diet led to worsened FCR values, consistent with previous research (Lemons & Moritz, 2016; Glover et al., 2016). However, in Exp 2., increasing fines inclusion in the later life stages (d 28-49) and across the overall experimental period (d 0-49) led to improvements in FCR values. Although this response is not commonly reported in the literature, Dozier et al., (2010) reported a numerical increase in FCR when birds were fed low-quality pellets compared to high-quality pellets. Similarly, McCafferty & Purswell (2023) found no significant difference in FCR when broilers were fed diets with varying levels of fines inclusion. A possible explanation for this response is enhanced digestibility of fines when included in diets containing increased die diameter pellets. The gizzard plays a crucial role in poultry digestion, by breaking down coarse materials. Research has shown that stimulating the gizzard by providing larger particles, promotes gastric function and motility, leading to benefits in nutrient digestibility (Mtei et al., 2019). Therefore, it is possible that the presence of larger die diameter pellets (6.4 mm) stimulated gizzard activity, increasing retention time and digestive enzyme secretion, which enhanced the digestion of fines, or smaller particles, included in the diet. As a result, the negative effects typically associated with higher fines inclusion may have been mitigated when feeding larger diameter pellets (6.4 mm).

In conclusion, the results from both Exp. 1 and 2 highlight the complex interactions between die diameter, fines inclusion, and their effect on broiler growth performance. The inclusion of fines in the diet has the potential to affect FI, BWG, and FCR. However, if larger die diameters are used to produce pellets fed to broilers, the negative effects of increased fines in the diet have the potential to be mitigated.

Conclusions and Applications

1. Fines inclusion has the potential to mitigate the negative effects of the larger die diameter. Therefore, if a larger die diameter is going to be used, allowing for pellet fines could allow for easier prehension of feed for the broiler.
2. A larger die diameter negatively affects the performance of young birds; however, later life stages of the broiler have the capability to adapt to the larger die diameter.
3. Fines in feed manufacturing can positively impact bird efficiency if the feed particle size is not appropriately matched to the age and prehension ability of the bird.

Table 5. Ingredient composition of experimental diet (as-fed basis)[1]

Ingredient, % as fed	Starter[2]	Grower[3]	Finisher[3]
Ground corn	56.87	59.45	64.29
Soybean meal	38.48	35.81	31.31
Limestone	0.91	0.81	0.73
Dicalcium phosphate	1.48	1.17	0.81
Salt	0.35	0.41	0.40
L-Lysine	0.17	0.14	0.11
DL-Methionine	0.34	0.31	0.27
L-Threonine	0.08	0.10	0.07
Phytase[4]	0.01	0.01	0.01
Vitamin trace mineral premix[5]	0.25	0.25	0.25
Choline chloride	0.06	0.04	0.04
Soy oil	1.00	1.51	1.71
Total	100.00	100.00	100.00
Calculated Composition			
Metabolize Energy, kcal/kg	2914	2978	3044
Crude Protein	24.2	23.0	21.1
Calcium	0.88	0.77	0.65
Phosphorus	0.64	0.57	0.49
Standarized ileal digestible AA,			
Arginine	1.45	1.37	1.24
Histidine	0.57	0.54	0.50
Isoleucine	0.91	0.87	0.79
Leucine	1.77	1.70	1.59
Lysine	1.33	1.37	1.11
Methionine	0.65	0.60	0.55
Phenylalanine	1.05	1.00	0.91
Threonine	0.85	0.84	0.75
Tryptophan	0.27	0.25	0.23
Valine	0.97	0.92	0.85

[1] A total of 600 one-day old (Ross 708 byproduct) broiler chick were placed into 60-floor pens with 10 birds per pen. Floor pens were divided into 10 location blocks and 1 of 6 dietary treatments were randomly assigned within each block.

[2] Starter diet was fed as a common crumble

[3] Grower and finisher diets were manufactured with three different pellet diameters of 4.0, 4.8 or 6.4 mm. After manufacturing, pellets were sifted, and pellet fines were mixed with sifted pellets depending on treatment specified inclusion level of 0 or 30% fines.

[4] Quantum Blue (AB Vista, Plantation, FL) Phytase, 10,000 FTU/g

[5] Provided per kg of premix: Provided per kg of premix: 40 g Zn, 20 g Fe, 40 g Mn, 4500 ppm Cu, 600 ppm I, 60 ppm Se, 3.087,000 IU vitamin A, 1,102,500 ICU vitamin D_3, 6615 IU vitamin E, 4.41 mg vitamin B_{12}, 331 mg menadione, 2646 mg riboflavin, 441 mg thiamine, 2646 mg

pantothenic acid, 11023 mg niacin, 154,323 mg choline, , 276 mg folic acid, 551 mg pyridoxine, and 13 mg biotin

Table 6. Ingredient composition of experimental diet (as-fed basis)[1]

Ingredient, %	Starter[2]	Grower[3]	Finisher[3]
Ground corn	56.80	62.33	68.94
Soybean meal	38.18	33.45	27.14
Limestone	0.85	1.03	0.97
Dicalcium phosphate	1.87	0.92	0.79
Salt	0.40	0.40	0.40
L-Lysine	0.13	0.15	0.16
DL-Methionine	0.30	0.28	0.23
L-Threonine	0.10	0.09	0.06
Phytase[4]	0.01	0.01	0.01
Vitamin trace mineral premix[5]	0.25	0.25	0.25
Choline chloride	0.06	0.06	0.06
Zoamix[6]	0.05	0.05	0.00
Soy oil	1.00	1.00	1.00
Total	100.00	100.00	100.00
Calculated Composition			
Metabolize Energy	1343.64	1375.34	1404.42
Crude Protein	24.05	22.10	19.41
Crude Fat	3.60	3.76	3.96
Crude Fiber	2.23	2.19	2.12
Calcium	0.96	0.80	0.73
Phosphorus	0.68	0.49	0.44
Total AA,			
Arginine	1.44	1.31	1.12
Histidine	0.57	0.53	0.47
Isoleucine	0.89	0.81	0.71
Leucine	1.79	1.69	1.54
Lysine	1.26	1.16	1.01
Methionine	0.60	0.56	0.49
Phenylalanine	1.05	0.96	0.84
Threonine	0.86	0.78	0.67
Tryptophan	0.26	0.23	0.20
Valine	0.96	0.88	0.78

[1] A total of 720 one-day old broiler chick (Cobb breeder by-product (C500 off-sex males)) were placed into 60-floor pens with 12 birds per pen. Floor pens were divided into 10 location blocks. Treatments from d 0-14 consisted of 2 crumble treatments based on pellet diameter (4.8 mm or 6.4 mm). From d 14-49 (Grower and Finisher), 1 of 6 dietary treatments were randomly assigned within each block.

[2] Starter diet was fed as a crumble with two different pellet diameters of either 4.8 or 6.4 mm

[3] Grower and finisher diets were manufactured with two different pellet diameters of 4.8 or 6.4 mm. After manufacturing, pellets were sifted, and pellet fines were mixed with sifted pellets depending on treatment specified inclusion level of 0, 30, or 60% fines.

[4] Quantum Blue (AB Vista, Plantation, FL) Phytase, 10,000 FTU/g

[5] Provided per kg of premix: Provided per kg of premix: 40 g Zn, 20 g Fe, 40 g Mn, 4500 ppm Cu, 600 ppm I, 60 ppm Se, 3.087,000 IU vitamin A, 1,102,500 ICU vitamin D_3, 6615 IU vitamin E, 4.41 mg vitamin B_{12}, 331 mg menadione, 2646 mg riboflavin, 441 mg thiamine, 2646 mg pantothenic acid, 11023 mg niacin, 154,323 mg choline, , 276 mg folic acid, 551 mg pyridoxine, and 13 mg biotin

[6] Zoamix 25% (Zoetis Inc., Parsippany, NJ) include per kg of diet; Zoalene, 125 mg

Table 7. Effect of varying pellet diameters and fines inclusion on broiler growth performance[1]

	Grower (d 12-26)			Finisher (d 26-47)			Overall (d 12-47)		
	FI	BWG	FCR	FI	BWG	FCR	FI	BWG	FCR
Interaction[2]									
4.0, 0%	1.46^{a}	1.22^{a}	1.20	3.67	2.40^{a}	1.53	5.12^{a}	3.61^{a}	1.42
4.8, 0%	1.44^{ab}	1.19^{ab}	1.22	3.57	2.36^{ab}	1.52	5.00^{ab}	3.54^{ab}	1.41
6.4, 0%	1.39^{c}	1.16^{bc}	1.21	3.50	2.25^{c}	1.56	4.88^{b}	3.40^{c}	1.44
4.0, 30%	1.44^{ab}	1.18^{abc}	1.22	3.52	2.27^{bc}	1.55	4.96^{b}	3.45^{bc}	1.44
4.8, 30%	1.42^{bc}	1.15^{c}	1.24	3.45	2.22^{c}	1.56	4.86^{b}	3.36^{c}	1.45
6.4, 30%	1.46^{ab}	1.18^{abc}	1.23	3.56	2.25^{c}	1.58	5.01^{ab}	3.43^{bc}	1.46
SEM	0.016	0.016	0.006	0.060	0.040	0.012	0.070	0.051	0.007
Die Diameter Means[2]									
4.0	1.45	1.20^{a}	1.21^{b}	3.60	2.33^{a}	1.54^{b}	5.04	3.53^{a}	1.43^{b}
4.8	1.43	1.17^{b}	1.23^{a}	3.51	2.29^{ab}	1.54^{b}	4.93	3.45^{b}	1.43^{b}
6.4	1.43	1.17^{b}	1.22^{ab}	3.53	2.25^{b}	1.57^{a}	4.94	3.42^{b}	1.45^{a}
SEM	0.013	0.014	0.004	0.051	0.034	0.008	0.060	0.044	0.005
Fines Means[2]									
0	1.43	1.19	1.21^{b}	3.58	2.34^{a}	1.53^{b}	5.00	3.52^{a}	1.42^{b}
30	1.44	1.17	1.23^{a}	3.51	2.25^{b}	1.56^{a}	4.94	3.42^{b}	1.45^{a}
SEM	0.012	0.012	0.004	0.047	0.032	0.007	0.056	0.041	0.004
Interaction, *P* =	0.002	0.025	0.401	0.063	0.046	0.712	0.015	0.013	0.579
Die Diameter, *P* =	0.167	0.024	0.006	0.162	0.032	0.019	0.085	0.010	0.013
Fines, %, *P* =	0.617	0.145	<0.001	0.071	0.001	0.004	0.182	0.002	<0.001

[1] A total of 600 one-day old broiler chick were placed into 60-floor pens with 10 birds per pen. Floor pens were divided into 10 location blocks and 1 of 6 dietary treatments were randomly assigned within each block. A total of six dietary treatments were offered from d 12-47. Treatments consisted of 3 different pellet diameters (4.0 mm, 4.8 mm, and 6.4 mm) and 2 fines inclusion levels (0% and 30%). A common starter crumble was fed from d 0-12.

[2] Means within a column followed by a different letter$^{(a\text{-}c)}$ are significantly different ($P \leq 0.05$).

Table 8. Influence of varying pellet die diameter and pellet fines inclusion level of broiler growth performance parameters in the starter phase (d 0-14)[1]

Die Diameter	4.8 mm	6.4 mm	SEM	*P*-value[2]
Starter (d 0-14)				
FI	0.535^{a}	0.517^{b}	0.005	0.003
BWG	0.472^{a}	0.448^{b}	0.006	0.001
FCR	1.134^{b}	1.155^{a}	0.005	0.002

[1] A total of 720 one-day old broiler chick (Cobb breeder by-product (C500 off-sex males)) were placed into 60-floor pens with 12 birds per pen. Floor pens were divided into 10 location blocks. Treatments from d 0-14 consisted of 2 crumble treatments based on pellet diameter (4.8 mm or 6.4 mm). From d 14-49 (Grower and Finisher), 1 of 6 dietary treatments were randomly assigned within each block.

[2] Means within a row followed by a different letter$^{(a\text{-}b)}$ are significantly different ($P \leq 0.05$)

Table 9. Influence of varying pellet die diameter and pellet fines inclusion level on broiler growth performance parameters in the grower and finisher phase[1,2,3]

	Grower (d 14-28)			Finisher (d 28-49)			Grower & Finisher (d 14-49)			Overall (d 0-49)		
	FI	BWG	FCR	FI	BWG	FCR	FI	BWG	FCR	FI	BWG	FCR
Interaction[2]												
4.8 mm, 0%	2.021	1.486	1.360^{d}	4.195	2.248	1.885	6.205	3.734	1.669	6.696	4.220	1.593
4.8 mm, 30%	2.010	1.458	1.378^{bcd}	4.220	2.366	1.797	6.229	3.823	1.634	6.740	4.281	1.578
4.8 mm, 60%	1.957	1.427	1.372^{cd}	4.135	2.369	1.751	6.081	3.794	1.605	6.550	4.230	1.550
6.4 mm, 0%	2.003	1.438	1.393^{ab}	4.210	2.352	1.796	6.212	3.791	1.639	6.678	4.206	1.588
6.4 mm, 30%	1.991	1.437	1.387^{bc}	4.247	2.408	1.770	6.217	3.839	1.621	6.626	4.267	1.555
6.4 mm, 60%	1.943	1.380	1.409^{a}	4.129	2.402	1.721	6.056	3.777	1.604	6.523	4.199	1.554
SEM	0.032	0.019	0.016	0.084	0.076	0.036	0.103	0.088	0.020	0.111	0.097	0.017
Die Diameter Means[2]												
4.8 mm	1.996	1.457^{a}	1.396^{a}	4.184	2.328	1.811	6.172	3.784	1.636	6.662	4.244	1.574
6.4 mm	1.979	1.418^{b}	1.370^{b}	4.195	2.387	1.762	6.162	3.803	1.621	6.609	4.224	1.566
SEM	0.029	0.013	0.015	0.065	0.061	0.024	0.082	0.071	0.014	0.087	0.079	0.013
Fines Means[2]												
0%	2.012^{a}	1.462^{a}	1.376	4.203	2.300	1.840^{a}	6.208	3.763	1.654^{a}	6.686	4.213	1.591^{a}
30%	2.001^{a}	1.447^{a}	1.383	4.234	2.387	1.783^{ab}	6.223	3.831	1.627^{ab}	6.683	4.274	1.566^{ab}
60%	1.950^{b}	1.403^{b}	1.390	4.132	2.385	1.736^{b}	6.068	3.786	1.605^{b}	6.537	4.215	1.552^{b}
SEM	0.030	0.015	0.016	0.071	0.066	0.028	0.089	0.076	0.018	0.094	0.084	0.014
Interaction[3], *P* =	0.911^{*}	0.366^{*}	0.044^{*}	0.845^{*}	0.548^{+}	0.383^{+}	0.844^{+}	0.564^{+}	0.428^{+}	0.540^{*}	0.902^{+}	0.345^{*}
Die Diameter, *P* =	0.266	0.007	<0.001	0.832	0.209	0.078	0.878	0.721	0.336	0.451	0.729	0.495
Fines, %, *P* =												

Linear	0.002	0.001	0.059	0.302	0.144	0.003	0.082	0.723	0.009	0.090	0.980	0.009
Quadratic	0.240	0.332	0.918	0.258	0.373	0.867	0.217	0.303	0.910	0.342	0.324	0.668

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[1] A total of 720 one-day old broiler chick (Cobb breeder by-product (C500 off-sex males)) were placed into 60-floor pens with 12 birds per pen. Floor pens were divided into 10 location blocks. Treatments from d 0-14 consisted of 2 crumble treatments based on pellet diameter (4.8 mm or 6.4 mm). From d 14-49 (Grower and Finisher), 1 of 6 dietary treatments were randomly assigned within each block with treatments consisting of 2 pellet die diameters (4.0 mm and 6.4 mm) and 3 fines inclusion levels (0%, 30%, and 60%)

[2] Means within a row followed by a different letter$^{(a\text{-}d)}$ are significantly different ($P \leq 0.05$).

[3] Interaction Response: + = Linear, * = Quadratic

Chapter 3 - Influence of low erucic acid, lower fiber pennycress (CoverCress®) inclusion on broiler growth performance

Abstract

CoverCress Whole Grain (CCWG), a variety of pennycress with low erucic acid and reduced fiber content, was developed as a cover crop. It is designed to be planted in the fall following corn harvest and harvested in the spring before planting soybeans. The objective of this experiment was to determine the effect of including up to 6% CCWG seed in diets on broiler chicken growth performance over 49 days. Dietary treatments were established using a control basal diet fed over four feeding phases and treatments were allocated as additional inclusion of 2%, 4%, or 6% CCWG added to the diet. On d 12, 28, 39, and 49, birds and feeders were weighed to determine feed intake (FI), body weight gain (BWG), feed conversion ratio (FCR), and mortality corrected FCR (adj. FCR). At d 0-12, d 0-28, d 0-39, and d 0-49, birds performed below the Cobb 500 objectives for body weight gain, feed intake and feed conversion. For d 0-12, d 0-28, and d 0-39 increasing CCWG in the diet showed no effect on FI, BWG, FCR, or adj. FCR. For d 0-49, no differences were observed for FI, BWG or FCR. However, birds fed the 6% CCWG in the diet had poorer ($P = 0.019$) adjusted FCR as compared to broilers fed the 0 and 4% CCWG diets which may have been due to the 6% inclusion finisher diet being less nutrient dense as compared to the other treatments. In conclusion, CCWG can be safely included into broiler diets up to 6% inclusion through 49 days without negatively affecting BWG, FI, and FCR, and up to 4% inclusion to 49 days without negatively impacting adj. FCR.

Introduction

CoverCress, Inc. has developed CoverCress Whole Grain (CCWG), a low erucic acid pennycress (Thalaspi arvense L.) whole grain that includes a lower seed coat fiber trait. CCWG was developed using gene editing technology to introduce base changes to two pennycress coding sequences, resulting in loss of function mutations in the fatty acid elongation enzyme (FAE1) and transcription factor TT8. CCWG is a variety of field pennycress (Thlaspi arvense L.) that can be planted and cultivated as an annual cover crop during crop rotations between corn and soybeans. The target planting season is in the fall after corn harvest, with cultivation taking place in the spring prior to soybean planting. It is a member of the Brassicaceae family, which is best known for mustard seeds. Pennycress has been evaluated and shown to produce similar properties to canola, which is commonly used in biodiesel production (Moser et al., 2009). This is due to its high oil content of approximately 36%, nearly twice the oil level of soybeans (Fan et al., 2023).

The increased oil level allows CCWG to be considered as an alternative energy source for animals due to its characteristics being similar to rapeseeds and canola (Hartnell et al., 2023). However, a significant difference between canola and pennycress is the higher presence of glucosinolates and erucic acid.

Glucosinolates are secondary plant metabolites found in Brassica-origin feedstocks. The negative effects of glucosinolates on livestock production include decreased palatability, growth, and overall production, as well as adverse impacts on kidney and liver function (Tripathi and Mishra, 2007). Erucic acid is associated with myocardial lipidosis, which involves the accumulation of triacylglycerols in the myocardium of the heart, leading to reduced contractile force (EFSA Panel on Contaminants in the Food Chain (CONTAM) et al., 2016).

Another characteristic of pennycress is its high fiber content, which can negatively affect nutrient digestibility in broilers. To address these challenges, genetic mutations have been developed to reduce the levels of erucic acid and fiber content in pennycress. CoverCress, Inc. has created CoverCress Whole Grain (CCWG), a low-erucic acid pennycress whole grain that incorporates a reduced seed coat fiber trait. CCWG was developed using gene-editing technology to introduce base changes to two pennycress coding sequences, resulting in loss-of-function mutations in the fatty acid elongation enzyme (FAE1) and the transcription factor TT8.

Previous research has assessed the effects of varying inclusion levels of mutation-bred pennycress (CCWG-1), mutation-bred pennycress treated with copper sulfate (CCWG-1-CuSO4), and gene-edited pennycress (CCWG-2) on the performance and health of broiler chickens (Hartnell et al., 2023). CCWG is being considered as an alternative energy source for animals because of its similarities to rapeseeds and canola (Hartnell et al., 2023).

In earlier research, it was concluded that broilers performed similarly at a 4% inclusion of CCWG, regardless of copper sulfate treatment. Additionally, no differences were observed at a 4% inclusion level between the mutant (CCWG-1) and gene-edited (CCWG-2) varieties. The study concluded that CCWG could be safely fed to broilers when dietary glucosinolate levels did not exceed 4.9 µmol/g.

The current study aims to expand upon previous research by determining the effects of including up to 6% CCWG-2 in diets on broiler chicken growth performance from 0 to 49 days of age.

Materials and Methods

Test Material

CCWG was grown and harvested by CoverCress Inc. (St. Louis, MO). Grain was then shipped to Kansas State University to be used in diet formulation.

Diet Formulation and Dietary Treatments

All diets were corn and soybean meal based. All diets were formulated to meet or exceed the nutritional requirements stated in the Nutrition Requirements of Poultry: Ninth Revised Edition (1994), Washington, D.C., National Academies Press (NRC, 1994) and/or based on industry practices. Diets were formulated to be isocaloric and isodigestible for lysine and methionine. Diets contained added phytase and iodine levels were approximately ~1 ppm in all diets as recommended for Cobb 500 broilers (Cobb 500 Broiler Performance and Nutrition Supplement).

Treatments were arranged as a randomized complete block design with 4 different treatments of increasing CCWG inclusion, %, of the total diet. Treatments were as follows: 0% (Control), 2%, 4%, and 6%.

Manufacturing of Diets/Feed Processing

Feed was manufactured in accordance with Current Good Manufacturing Practices at the Kansas State University O.H. Kruse Technology Innovation Center (Manhattan, KS).

Starter, Grower I, Grower II, and Finisher diets were manufactured one to two weeks prior to the start of each phase. A total of 10 feed samples, per diet, were collected from the feed mill during manufacturing. All 10 samples were homogenized and pooled into a single sample of each diet. Samples were sent to the University of Missouri Agriculture Experiment Station Chemical Laboratory (Columbia, MO) to be analyzed for proximate analysis, amino acids, Ca, P, Mg, K, Na, Cl, S, Cu, Mn, Fe, and Zn. A sample of CCWG was sent to the University of Missouri Agriculture Experiment Station for analysis of dry matter, crude protein, amino acids, fat (acid hydrolysis) and fatty acid analysis. A sample was also sent to Dairyland Laboratories (Arcadia, WI) for analyses of dry matter, crude protein, fat (acid hydrolysis), ADF, NDF, crude fiber, ash, Ca, P, Mg, K, Na, Cl, S, Cu, Mn, Fe, Zn, and mycotoxins.

All diets were manufactured with approximately 900-micron ground corn and mixed in a 909-kg counterpoise mixer (Hayes and Stoltz, Model TRDB63-0152, Fort Worth, TX). After mixing, diets were pelleted on a 1-ton 30-horsepower pellet mill (1012-2 Master Model, California Pellet Mill) equipped with a 4.4 mm × 35.2 mm (length: diameter 8) pellet die. Diets will be conditioned at a target of 85°C with a retention time of 30 seconds. After cooling, starter diets were crumbled.

Pellet Durability Index

Pellets were collected and analyzed using a New Holmen Portable Pellet Durability Tester (Model NHP 100, TekPro, Ltd., Norfolk, UK) to analyze percent pellets survivability. A 100 g sample was screened to remove fines created using a No. 5 screen (Schofield and American Feed Industry Association, 2005). After screening, the pellets were placed into the chamber and were air agitated for 60 seconds at 70 mbar of pressure for the starter, grower I, and grower II treatments (H60-PDI). Pellets were air agitated at 30 seconds at 70 mbar of pressure for the finisher treatments (H30-PDI). Following the agitation, the pellets remaining in the chamber were sifted again on the required screen before being weighed back. The final weight of the pellets was then used in the equation below to calculate PDI, %.

$$PDI, \% = \frac{Final\ Weight}{Initial\ Weight} \times 100$$

Broiler Housing and Management

The experiment was conducted at the Tom Avery Poultry Research Farm, Kansas State University, Manhattan, KS. The broiler genetic strain used was Cobb breeder by-product (C500 off-sex males, Siloam Springs, AR). All experimental procedures were approved by the Institutional Animal Care and Use Committee (IACUC #4850) of Kansas State University, Manhattan, KS.

Birds were housed in an environmentally controlled barn with concrete floor pens, bedded with fresh wooden shavings (~2.4 x 1.2 m minus 0.2 m^2 of feeder space) to ensure chick comfortability. A total of 15 broilers were each randomly assigned to 76 floor pens, blocked by location and balanced on d 0 body weight. Resulting in a total of 19 location blocks throughout the barn.

Temperature, humidity, lighting, feeder, and water space were similar for all test groups. All pens were affixed with equipped with 6 nipple drinkers (Chore-Time Steadi-FLOW, Milford, Indiana) and a plastic tube feeder affixed to a Model C2 Plus broiler feed pan (Chore-Time, Milford, Indiana). A chick feeder tray was placed into each pen for the first 5 days. Broilers were placed on their respective treatment diets upon placement. Feed added and removed from pens from d 0 to the end of the study was weighed and recorded on a pen basis. All feed and water were provided *ad-libitum* throughout the entirety of the study.

The facility, all pens, and all birds were observed twice daily for flock condition, lighting, water, feed, ventilation, and unanticipated events. For lighting procedures, birds were subjected to fluorescent light for the first 3 days of the study and then incandescent lights were used for the remainder of the study. Birds were given 6 hours of darkness from d 3-35, however, on d 36, darkness was adjusted to potentially combat issues with kinky back in the birds. Therefore, from d 36-49, birds were given 8 hours of darkness per day. As for temperature of the barn, the Cobb 500 Broiler Management guide was followed. From d 0-7, the temperature was set at 33°C (91.4°F). From d 7-14, the temperature was set at 31°C (87.8°F). From d 14-28, the temperature was set at 28°C (82.4°F). From d 29-49, the temperature was set at 26°C (78.8°F). Birds and feed were weighed on d 12, 28, 39, and 49 to calculate body weight gain, feed intake, and feed conversion ratio.

Data Collection

Experimental unit was set to pen, and data was collected by weighing birds and feeders on d 0, 14, 28, 39, and 49 to calculate pen body weight gain (**BWG**) and total feed intake (**FI**). Mortality and culled birds were weighed and recorded. Feed conversion ratio (**FCR**) was calculated using FI and BWG, not accounting for mortality bird weight. The mortality weight was then added to the pen body weight and used to adjust pen BWG and calculate (**Adj. FCR**).

Statistical Analysis

The experiment was arranged as a randomized complete block design (RCBD) with 4 various CCWG inclusions of 0%, 2%, 4%, and 6% of the total diet. All growth performance experimental data collected was analyzed using the GLIMMIX procedure of SAS 9.4 (SAS Institute, Kerry, NC). Pen was considered the experimental unit and pen location was considered the blocking factor. Results were analyzed as a RCBD with linear and quadratic contrasts. Results were considered significant a $P < 0.05$, and tendencies between $0.05 < P < 0.1$.

Results and Discussion

Test Material

The contents of nutrients and glucosinolates for the CCWG used in the experiments are presented in Table 10. Mycotoxin and mold results for the CCWG are presented in Table 11. Results of analysis show no mold or mycotoxin were present. When comparing values to Hartnell et al., 2023, values of the current CCWG tend to be lower, such as, moisture, crude protein, and crude fat. Crude fiber, however, showed an elevated value of 19.54%, when compared to 16.0% in the previous study. The current study also observed lower values of glucosinolate values, an anti-nutritional factor, when compared to previous research by Hartnell et al., (2023). Glucosinolate levels in the current study were 0, 1.8, 3.6, and 5.4 µmoles/g of the diet for the 0, 2, 4, and 6% inclusion levels, respectively.

Diets

Ingredient formulation and calculated nutrient composition of all diets can be found in Tables 12 and 13. All diets, within growth phase, were formulated to be balanced for ME, digestible AA, total Ca and total P. Tables 14-17 contain the analyzed values of the diets. In general, the nutrients contents for the diets within growth phase were similar, except for the 6% CCWG diet in the finisher phase (d 39-49). Phosphorus, magnesium, potassium, protein, fat, and many of the amino acids are lower than the other three diets within the finisher phase. As expected, sulfur levels are increased for diets containing the CCWG, due to the higher sulfur content of the ingredient.

Feed Manufacture

Results of the diet production measurements are presented in Tables 18 and 19. Conditioning temperature, hot pellet temperature, Δ T, and pellet quality appeared to be similar among diets within the various growth phases. Lower numeric values were observed for pellet quality in the finisher phase, when compared to the previous 3 phases, however, remained consistent within phase.

Mortality and Culls

Table 20 summarizes the mortality and culling data for birds from d 0-49, with no evidence of treatment-related effects. Of the total affected birds, 26.80% were mortalities, while culling accounted for the remaining 73.20%. Altogether, 153 birds were either lost to mortality or culled during the experiment.

Growth Performance

Growth performance results can be found in Table 21. During the initial phase (d 0-12), no differences were observed for feed intake (FI), body weight gain (BWG), feed conversion ratio (FCR), or adjusted feed conversion ratio (adj. FCR), which includes data from culled birds and mortalities. For d 12-28, FI, BWG, FCR, and adj. FCR remained similar across treatments. For d 28-39, a difference was observed for FI ($P = 0.050$), where birds fed the control and 6%, CCWG diets had higher FI than those receiving the 2% CCWG diet. However, BWG, FCR, and adj. FCR did not differ among treatments. For d 39-49, no differences were found for FI, BWG, or FCR. However, adj. FCR for the birds fed the 6% inclusion CCWG was poorer than from the control ($P = 0.046$). The 6% CCWG finisher diet contained less protein, fat, and indispensable amino acids than the control, 2 and 4% CCWG inclusion diets (Table 6) which may have contributed to this difference. For d 0-28, no differences were observed for FI, BWG, FCR, or adj. FCR. When compared to Hartnell et al., 2023, all treatments exhibited increased FI and BWG, along with a slight improvement in FCR. For d 12-39, FI, BWG, FCR, and adj. FCR remained unaffected by treatment. For d 0-39, no differences were observed for FI, BWG, FCR, or adj. FCR. For D0-49, no differences were observed for FI, BWG, or FCR among treatments; however, adj. FCR was poorer for the birds consuming the 6% CCWG diet ($P = 0.019$).

When comparing growth performance results to targeted values for Cobb 500 males (Cobb-Vantress, 2022) various results were observed, with most time frames performing under the Cobb 500 target values. For d 0-12, all treatments exhibited lower FI, BWG, and FCR values. For d 12-28, FI decreased, while BWG and FCR improved compared to targeted values. For d

28-39, d 39-49, and d 0-28, FI, BWG, and FCR underperformed targets regardless of treatment. For d 12-39, FI was lower, with BWG and FCR showing improved values when compared to Cobb 500 targets. For d 0-39 and d 0-49, FI, BWG, and FCR all remained below Cobb 500 targeted values. This result in underperformance can be attributed to the use of a by-product Cobb 500 male, rather than pure Cobb 500 males.

The previous study conducted by Hartnell et al. (2023) observed decreased FI in young broilers as CCWG inclusion increased in the diet from 0% to 4%. In contrast, the current study found no differences in FI across all treatments, including up to 6% CCWG inclusion. For BWG, Hartnell et al. (2023) reported decreased values as CCWG inclusion increased up to 4%. However, the current study observed no differences in BWG when CCWG was included at levels up to 6% of the diet. Regarding adj. FCR, Hartnell et al. (2023) noted worsened values as CCWG inclusion increased up to 4%. Conversely, the current study found no differences in adj. FCR with CCWG inclusion levels up to 6% up to 39 d of age. The differences between the two studies may be attributed to several factors. One potential explanation is the difference in stocking density. Hartnell et al. (2023) housed 19 birds per pen from D0-7 and 17 birds per pen from D7-42, whereas the current study housed 15 birds per pen from D0-49. This reduced stocking density in the current study may have provided more feeder space per bird, reducing competition and mitigating the effects of dietary treatments. Another possible explanation is the difference in glucosinolate content between the two studies. Hartnell et al. (2023) reported glucosinolate levels of 97.3 and 103.3 µmoles/g, whereas the current study observed lower levels at 91.0 µmoles/g. Glucosinolates are known to decrease FI, which could explain the reduced performance observed in Hartnell et al. (2023) compared to the current study.

When comparing the growth performance of mature broilers, Hartnell et al. (2023) observed a decrease in FI as CCWG inclusion increased from 0% and 2% to 4% in the diet. In contrast, the current study found no differences in FI across any of the four treatments. For BWG, Hartnell et al. (2023) reported no differences as CCWG inclusion increased up to 4%, which aligns with the current study, where no differences in BWG were observed with inclusion levels up to 6%. For adj. FCR, Hartnell et al. (2023) observed improved feed conversion as CCWG inclusion increased to 4%. Conversely, the current study found worsened adj. FCR values with higher CCWG inclusion of up to 6%, with the control diet having the lowest adj. FCR value. The differing results for adj. FCR between the two studies may be explained by the discrepancies in the calculated vs. analyzed nutrient composition within the 6% CCWG finisher diet, as the analyzed nutrient composition was lower than what was calculated when formulating the diets. In conclusion, CCWG can be safely included into broiler diets up to 6% inclusion through 49 days without negatively affecting BWG, FI, and FCR and up to 4% inclusion through 49 days without negatively impacting adjusted FCR.

Conclusions and Applications

1. CCWG can be safely fed to broilers when dietary glucosinolate levels do not exceed 5.4 umoles/g.
2. CCWG can be included up to 6% in broiler diets at 39 days of age without adverse growth performance effects
3. CCWG can be included up to 4% in broiler diets at 49 days of age without adverse growth performance effects.

Table 10. Chemical analysis of CCWG (as-is basis)[1]

Analyte	
Moisture	7.61
ME, kcal/kg calculated	4006
Crude protein, %	20.90
Crude fat, %	32.11
Crude Fiber, %	19.54
Acid detergent fiber, %	11.27
Neutral detergent fiber, %	18.02
Carbohydrates, %	6.79
Ash, %	5.90
Calcium, %	0.99
Phosphorus, %	0.77
Magnesium, %	0.77
Potassium, %	0.86
Sodium, %	0.00
Sulfur, %	0.63
Chloride, %	0.06
Iron, ppm	43.82
Manganese, ppm	29.01
Zinc, ppm	34.56
Indispensable Amino Acids	
Arginine	1.42
Histidine	0.51
Isoleucine	0.92
Leucine	1.54
Lysine	1.18
Methionine	0.33
Phenylalanine	1.00
Threonine	0.98
Tryptophan	0.16
Valine	1.22
Dispensable Amio Acids	
Alanine	1.01
Aspartic Acid	1.88
Cysteine	0.34
Glutamic Acid	3.09
Glycine	1.37
Proline	1.06
Tyrosine	0.71
Serine	0.82

Glucosinolates, µmoles g	91.0

[1] Samples were analyzed for 1) amino acids at the University of Missouri Agricultural Experiment Station Chemical Laboratories in Columbia, MO; 2) glucosinolates at EPL Bio Analytical Services (Niantic, IL); and 3) remaining nutrients at Dairyland Laboratories in Arcadia, WI.

Table 11. Mold and Mycotoxin results of CCWG[1]

Mold/Mycotoxin	Units	Detection Limit	Detection
Aflatoxin B1	ppb	1	None
Aflatoxin B2	ppb	1	None
Aflatoxin G1	ppb	1	None
Aflatoxin G2	ppb	1	None
Vomitoxin (DON)	ppm	0.1	None
3 Acetyl DON	ppm	0.1	None
15 Acetyl DON	ppm	0.1	None
Zearalenone	ppb	10	None
T2	ppb	5	None
HT2	ppb	5	None
Fumonisin B1	ppm	0.1	None
Fumonisin B2	ppm	0.1	None
Fumonisin B3	ppm	0.1	None
Ochratoxin A	ppb	1.1	None
Fusaric Acid	ppm	0.1	None
Citrinin	ppb	5	None
Patulin	ppb	200	None
Fusarenon X	ppm	0.1	None
Nivalenol	ppm	0.1	None
Neosolaniol	ppb	100	None
DAS	ppb	100	None
Roquefortine C	ppb	1	None

[1] Samples were analyzed at Dairyland Laoratories, Arcadia, WI

Table 12. Starter and Grower I ingredient composition and calculated analysis of diets (as-fed basis)[1]

	Starter				**Grower 1**			
	CCWG, %				CCWG, %			
Ingredient, %	0	2	4	6	0	2	4	6
Ground Corn	58.61	57.99	57.36	56.66	65.03	64.40	63.77	63.14
Soybean Meal	36.13	35.25	34.37	33.51	30.46	29.58	28.70	27.82
Limestone	0.85	0.83	0.82	0.80	1.04	1.02	1.01	0.99
Dicalcium phosphate	1.91	1.86	1.81	1.76	0.94	0.89	0.84	0.79
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Soy oil	1.25	0.82	0.38	0.00	1.31	0.87	0.43	0.00
L-Lysine	0.14	0.15	0.16	0.17	0.16	0.17	0.18	0.19
DL-Methionine	0.29	0.29	0.29	0.29	0.25	0.26	0.26	0.26
L-Threonine	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.08
Vitamin trace mineral premix[2]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Phytase[3]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Choline Chloride	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
CCWG[4]	0.00	2.00	4.00	6.00	0.00	2.00	4.00	6.00
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Calculated composition								
ME, Kcal/lb	1350	1350	1350	1351	1394	1394	1394	1394
Crude protein, %	23.3	23.2	23.1	23.1	20.9	20.9	20.8	20.7
Crude fat, %	3.95	4.12	4.29	4.52	4.20	4.38	4.55	4.72
Ca	0.96	0.96	0.96	0.96	0.80	0.80	0.80	0.80
P	0.68	0.68	0.68	0.68	0.48	0.48	0.48	0.48
Digestible AA, %								
Arg	1.39	1.38	1.38	1.37	1.22	1.21	1.21	1.21
His	0.55	0.55	0.55	0.55	0.50	0.50	0.50	0.49
Ile	0.86	0.86	0.85	0.85	0.76	0.76	0.76	0.75
Leu	1.75	1.74	1.74	1.73	1.63	1.62	1.61	1.60
Lys	1.22	1.22	1.22	1.22	1.10	1.10	1.10	1.10
Met	0.58	0.58	0.59	0.59	0.53	0.53	0.53	0.53
Phe	1.01	1.01	1.00	1.00	0.91	0.91	0.90	0.90
Thr	0.83	0.83	0.83	0.83	0.74	0.74	0.74	0.74
Trp	0.25	0.25	0.24	0.24	0.22	0.22	0.21	0.21
Val	0.93	0.93	0.93	0.93	0.84	0.84	0.84	0.84

[1] A total of 1,140 one-day old male broilers (Cobb breeder by-product, C500 off-sex males, Cobb-Vantress, Siloam Springs, AR) were placed in floor pens with 15 broilers per cage and 19 replicates per treatment. Treatment diets were as a basal diet and CCWG inclusions of 2, 4, and 6%.

[2] Provided per kg of premix: 40 g Zn, 20 g Fe, 40 g Mn, 4500 ppm Cu, 600 ppm I, 60 ppm Se, 3.087,000 IU vitamin A, 1,102,500 ICU vitamin D_3, 6615 IU vitamin E, 4.41 mg vitamin B_{12}, 331 mg menadione, 2646 mg riboflavin, 441 mg thiamine, 2646 mg pantothenic acid, 11023 mg niacin, 154,323 mg choline, , 276 mg folic acid, 551 mg pyridoxine, and 13 mg biotin.

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[3] Quantum Blue (AB Vista, Plantation, FL) Phytase, 10,000 FTU/g.

[4] CoverCress Whole Grain (CCWG), St. Louis, MO

Table 13. Grower II and Finisher ingredient composition and calculated analysis of diets (as-fed basis)[1]

	Grower 2				**Finisher**			
	CCWG, %				CCWG, %			
Ingredient, %	0	2	4	6	0	2	4	6
Ground Corn	69.87	69.06	68.25	67.37	72.93	72.12	71.31	70.37
Soybean Meal	26.00	25.28	24.56	23.85	23.03	22.31	21.59	20.88
Limestone	1.01	0.99	0.98	0.96	0.99	0.97	0.95	0.99
Dicalcium phosphate	0.78	0.73	0.68	0.63	0.77	0.72	0.67	0.62
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Soy Oil	1.15	0.74	0.34	0.00	1.15	0.74	0.34	0.00
L-Lysine	0.18	0.18	0.19	0.19	0.17	0.18	0.18	0.18
DL-Methionine	0.23	0.23	0.23	0.23	0.19	0.19	0.19	0.19
L-Threonine	0.07	0.07	0.06	0.06	0.06	0.05	0.05	0.05
Vitamin trace mineral premix[2]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Phytase[3]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Choline Chloride	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
CCWG[4]	0.00	2.00	4.00	6.00	0.00	2.00	4.00	6.00
Total	100	100	100	100	100	100	100	100
Calculated composition								
ME, Kcal/lb	1418	1418	1418	1419	1435	1435	1435	1435
Crude Protein, %	19.1	19.1	19.1	19.0	17.8	17.8	17.8	17.8
Crude Fat, %	4.19	4.39	4.59	4.85	4.28	4.48	4.68	4.93
Ca, %	0.74	0.74	0.74	0.74	0.72	0.72	0.72	0.74
P, %	0.43	0.43	0.43	0.43	0.42	0.42	0.42	0.42
Digestible AA,%								
Arg	1.09	1.09	1.09	1.09	1.00	1.00	1.00	1.00
His	0.46	0.46	0.46	0.46	0.43	0.43	0.43	0.43
Ile	0.69	0.69	0.69	0.69	0.64	0.64	0.64	0.64
Leu	1.52	1.52	1.51	1.51	1.45	1.45	1.44	1.44
Lys	1.00	1.00	1.00	1.00	0.92	0.92	0.92	0.92
Met	0.48	0.48	0.49	0.49	0.43	0.44	0.44	0.44
Phe	0.83	0.83	0.82	0.82	0.77	0.77	0.77	0.77
Thr	0.66	0.66	0.66	0.66	0.61	0.61	0.61	0.61
Trp	0.19	0.19	0.19	0.19	0.18	0.18	0.17	0.17
Val	0.76	0.77	0.77	0.77	0.72	0.72	0.72	0.72

[1] A total of 1,140 one-day old male broilers (Cobb breeder by-product, C500 off-sex males, Cobb-Vantress, Siloam Springs, AR) were placed in floor pens with 15 broilers per cage and 19 replicates per treatment. Treatment diets were as a basal diet and CCWG inclusions of 2, 4, and 6%.

[2] Provided per kg of premix: 40 g Zn, 20 g Fe, 40 g Mn, 4500 ppm Cu, 600 ppm I, 60 ppm Se, 3.087,000 IU vitamin A, 1,102,500 ICU vitamin D_3, 6615 IU vitamin E, 4.41 mg vitamin B_{12}, 331 mg menadione, 2646 mg riboflavin, 441 mg thiamine, 2646 mg pantothenic acid, 11023 mg niacin, 154,323 mg choline, , 276 mg folic acid, 551 mg pyridoxine, and 13 mg biotin.

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[3] Quantum Blue (AB Vista, Plantation, FL) Phytase, 10,000 FTU/g.
[4] CoverCress Whole Grain (CCWG), St. Louis, MO

Table 14. Chemical analysis of Starter and Grower I diets[1]

	Starter d 0-12				Grower I d 13-28			
		CCWG, %				CCWG, %		
Item, %	0	2	4	6	0	2	4	6
Moisture	13.62	13.18	13.19	13.07	13.04	12.46	12.63	12.82
Crude protein	22.43	21.94	22.38	21.68	19.93	19.36	19.41	20.25
Crude fat	2.91	3.55	3.66	4.44	3.51	2.85	3.03	3.01
Crude fiber	2.72	3.18	3.55	3.91	2.95	2.33	2.71	2.86
Ash	4.94	5.16	5.07	5.12	4.24	4.38	4.28	4.49
Indispensable AA								
Arginine	1.49	1.47	1.47	1.44	1.24	1.29	1.31	1.28
Histidine	0.64	0.63	0.63	0.61	0.56	0.57	0.58	0.56
Isoleucine	1.00	1.02	1.02	1.00	0.90	0.92	0.91	0.89
Leucine	1.91	1.90	1.92	1.89	1.83	1.80	1.78	1.75
Lysine	1.42	1.44	1.42	1.40	1.22	1.28	1.29	1.28
Methionine	0.52	0.53	0.54	0.55	0.46	0.56	0.52	0.51
Phenylalanine	1.14	1.13	1.14	1.12	1.03	1.04	1.04	1.02
Threonine	0.91	0.92	0.92	0.89	0.80	0.82	0.83	0.82
Tryptophan	0.24	0.24	0.24	0.25	0.21	0.22	0.22	0.22
Valine	1.10	1.11	1.11	1.10	0.97	0.99	0.99	0.97
Total Indispensable	10.37	10.39	10.41	10.25	9.22	9.49	9.47	9.30
Dispensable AA								
Alanine	1.11	1.11	1.11	1.10	0.97	0.99	0.99	0.97
Aspartic acid	2..29	2.29	2.28	2.22	1.99	2.04	2.06	2.00
Cystine	0.36	0.36	0.36	0.34	0.31	0.34	0.32	0.32
Glutamic acid	4.16	4.14	4.17	4.08	3.78	3.80	3.81	3.73
Glycine	0.93	0.93	0.93	0.92	0.79	0.82	0.84	0.83
Proline	1.27	1.26	1.28	1.25	1.20	1.19	1.18	1.16
Serine	0.95	0.92	0.91	0.91	0.84	0.85	0.87	0.84
Tyrosine	0.80	0.76	0.76	0.75	0.68	0.69	0.71	0.71
Total Dispensable	11.87	11.77	11.80	11.57	10.56	10.72	10.78	10.56
Total AA	22.24	22.16	22.21	21.82	19.78	20.21	20.25	19.86

[1] Samples were analyzed at the University of Missouri Agricultural Experiment Station Chemical Laboratories in Columbia, MO.

Table 15. Chemical analysis of Grower II and Finisher Diets[1]

	Grower II d 29-39				Finisher d 40-49			
		CCWG, %				CCWG, %		
Item, %	0	2	4	6	0	2	4	6
Moisture	12.56	12.24	12.23	12.37	12.01	11.83	12.03	12.68
Crude protein	17.78	18.31	17.65	17.98	17.38	17.63	17.31	16.48
Crude fat	3.66	3.55	3.98	4.18	5.57	5.57	5.62	4.40
Crude fiber	2.21	2.58	2.43	2.25	2.96	4.49	3.95	3.39
Ash	3.91	3.92	4.05	4.06	4.32	4.31	4.61	4.03
Indispensable AA								
Arginine	1.07	1.12	1.12	1.04	1.15	1.12	1.16	1.01
Histidine	0.50	0.52	0.52	0.50	0.52	0.51	0.53	0.50
Isoleucine	0.76	0.80	0.79	0.77	0.78	0.77	0.78	0.69
Leucine	1.61	1.69	1.66	1.62	1.61	1.61	1.59	1.45
Lysine	1.07	1.10	1.11	1.05	1.10	1.13	1.13	1.07
Methionine	0.43	0.47	0.45	0.44	0.44	0.45	0.46	0.42
Phenylalanine	0.89	0.93	0.92	0.88	0.90	0.89	0.90	0.81
Threonine	0.69	0.73	0.73	0.68	0.71	0.71	0.72	0.67
Tryptophan	0.20	0.18	0.19	0.19	0.19	0.18	0.19	0.17
Valine	0.82	0.87	0.87	0.86	0.89	0.88	0.90	0.79
Total Indispensable	8.04	8.41	8.36	8.03	8.29	8.25	8.36	7.58
Dispensable AA								
Alanine	0.93	0.97	0.96	0.94	0.98	0.97	0.97	0.87
Aspartic acid	1.70	1.76	1.76	1.63	1.73	1.71	1.73	1.56
Cystine	0.28	0.31	0.30	0.29	0.30	0.31	0.31	0.28
Glutamic acid	3.27	3.43	3.40	3.21	3.27	3.25	3.23	2.94
Glycine	0.68	0.73	0.74	0.71	0.75	0.76	0.78	0.71
Proline	1.07	1.11	1.10	1.06	1.08	1.08	1.08	0.99
Serine	0.75	0.81	0.79	0.72	0.75	0.75	0.75	0.71
Tyrosine	0.63	0.66	0.65	0.58	0.61	0.60	0.60	0.55
Total Dispensable	9.31	9.78	9.70	9.14	9.47	9.43	9.45	8.61
Total AA	17.35	18.19	18.06	17.17	17.76	17.68	17.81	16.19

[1] Samples were analyzed at the University of Missouri Agricultural Experiment Station Chemical Laboratories in Columbia, MO.

Table 16. Mineral analysis of Starter and Grower I diets[1]

	Starter d 0-12				Grower I d 13-28			
		CCWG, %				CCWG, %		
Item, %	0	2	4	6	0	2	4	6
Sulfur	0.22	0.24	0.25	0.25	0.21	0.23	0.24	0.26
Calcium	0.68	0.70	0.68	0.66	0.50	0.61	0.60	0.61
Phosphorus	0.65	0.67	0.64	0.65	0.49	0.47	0.44	0.43
Sodium	0.16	0.17	0.16	0.16	0.16	0.16	0.15	0.16
Magnesium	0.15	0.16	0.16	0.17	0.14	0.12	0.12	0.13
Potassium	1.00	1.02	1.00	1.00	0.93	0.86	0.85	0.85
Chloride	0.25	0.27	0.28	0.29	0.29	0.30	0.30	0.28
Item, ppm								
Manganese	80.90	94.40	149.00	111.00	75.30	111.00	84.10	97.40
Iron	195.00	198.00	189.00	185.00	147.00	154.00	139.00	139.00
Copper	15.80	15.10	19.50	14.80	14.30	14.70	14.00	14.50
Zinc	126.00	105.00	115.00	120.00	96.80	109.80	111.00	102.00

[1] Samples were analyzed at the University of Missouri Agricultural Experiment Station Chemical Laboratories in Columbia, MO.

Table 17. Mineral analysis of Grower II and Finisher diets[1]

	Grower II d 29-39				Finisher d 40-49			
		CCWG, %				CCWG, %		
Item, %	0	2	4	6	0	2	4	6
Sulfur	0.20	0.22	0.22	0.23	0.19	0.19	0.21	0.23
Calcium	0.54	0.55	0.53	0.55	0.48	0.54	0.58	0.58
Phosphorus	0.41	0.42	0.43	0.43	0.54	0.56	0.58	0.43
Sodium	0.15	0.15	0.16	0.16	0.15	0.15	0.16	0.17
Magnesium	0.12	0.13	0.13	0.14	0.17	0.17	0.18	0.13
Potassium	0.76	0.80	0.80	0.81	0.89	0.89	0.91	0.75
Chloride	0.29	0.29	0.27	0.29	0.29	0.31	0.31	0.28
Item, ppm								
Manganese	102.00	83.90	70.30	78.70	92.00	79.30	122.00	90.30
Iron	140.00	142.00	134.00	131.00	144.00	144.00	154.00	150.00
Copper	13.30	13.50	13.70	13.60	19.90	15.40	16.50	14.50
Zinc	153.00	366.00	96.10	74.90	104.00	80.30	106.00	174.00

[1] Samples were analyzed at the University of Missouri Agricultural Experiment Station Chemical Laboratories in Columbia, MO.

Table 18. Production Measurements of Starter and Grower I diets[1]

	Starter d 0-12				Grower I d 13-28			
		CCWG, %				CCWG, %		
Processing Parameter[1]	0	2	4	6	0	2	4	6
Cond. Temp., °C	84.3	84.5	84.3	84.8	83.69	83.13	83.41	83.39
Hot Pellet Temp., °C	86.3	86.8	87.3	87.5	87.30	91.07	89.50	89.11
Delta T, °C	2.0	2.3	3.0	2.7	3.61	7.94	6.09	5.72
PDI, %[2]	64.03[+]	61.99[+]	58.09[+]	62.78[+]	35.19[+]	54.07[+]	58.09[+]	46.57[+]

[1] Samples were taken and analyzed at the O.H. Kruse Feed Mill, Kansas State University, Manhattan, KS 66502

[2] All samples were analyzed in triplicate

[+] 60 second Holmen used to analyze PDI

Table 19. Production Measurements of Grower II and Finisher diets[1]

	Grower II d 29-39				Finisher d 40-49			
		CCWG, %				CCWG, %		
Processing Parameter[1]	0	2	4	6	0	2	4	6
Cond. Temp., °C	82.94	82.91	82.72	83.24	82.96	83.54	82.48	83.26
Hot Pellet Temp., °C	87.07	87.07	86.94	86.52	85.22	86.02	84.15	86.06
Delta T, °C	4.13	4.17	4.22	3.28	2.26	2.48	1.67	2.80
PDI, %[2]	69.41[+]	51.79[+]	47.89[+]	52.58[+]	37.01[*]	39.57[*]	26.34[*]	38.99[*]

[1] Samples were taken and analyzed at the O.H. Kruse Feed Mill, Kansas State University, Manhattan, KS 66502

[2] All samples were analyzed in triplicate

[+] 60 second Holmen used to analyze PDI

[*] 30 second Holmen used to analyze PDI

Table 20. Broiler mortality and removed birds recorded from d 0-49

Reason	Count of Reason	Percentage of total mortality/removed birds
Bad Leg[1]		
0%	13	8.50
2%	9	5.88
4%	6	3.92
6%	7	4.58
Kinky Back[1]		
0%	13	8.50
2%	11	7.19
4%	8	5.23
6%	7	4.58
Small Bird[1]		
0%	16	10.46
2%	10	6.54
4%	4	2.61
6%	8	5.23
Sudden Death Syndrome[2]		
0%	9	5.88
2%	9	5.88
4%	7	4.58
6%	5	3.27
Unknown[2]		
0%	3	1.96
2%	1	0.65
4%	2	1.31
6%	5	3.27
Total Mortality	41	26.80
Total Removal	112	73.20
Total	153	100.00

[1] Birds were removed from pen due to diagnosis

[2] Birds were found as a mortality within the pen

Table 21. Effects of CCWG inclusion on broiler growth performance from d 0-49[1]

Item, kg/bird	CCWG, % 0	2	4	6	SEM	P-Value
d 0-12						
FI	0.398	0.383	0.386	0.377	0.007	0.134
BWG	0.342	0.330	0.336	0.325	0.006	0.168
FCR	1.185	1.175	1.164	1.169	0.020	0.733
Adj. FCR	1.164	1.163	1.152	1.163	0.011	0.778
d 12-28						
FI	2.050	2.005	1.999	2.019	0.038	0.719
BWG	1.527	1.491	1.487	1.471	0.021	0.170
FCR	1.365	1.363	1.355	1.385	0.026	0.699
Adj. FCR	1.344	1.347	1.345	1.372	0.019	0.598
d 28-39						
FI	2.109[a]	2.024[b]	2.041[ab]	2.113[a]	0.037	0.050
BWG	1.229	1.186	1.195	1.239	0.032	0.391
FCR	1.872	1.820	1.824	1.818	0.051	0.853
Adj. FCR	1.722	1.718	1.715	1.713	0.020	0.985
d 39-49						
FI	2.047	2.048	2.030	2.089	0.043	0.597
BWG	0.977	0.939	0.930	0.934	0.031	0.606
FCR	2.489	2.500	2.418	2.612	0.179	0.831
Adj. FCR	2.108[b]	2.196[ab]	2.195[ab]	2.269[a]	0.040	0.046
d 0-28						
FI	2.447	2.389	2.385	2.396	0.042	0.608
BWG	1.869	1.821	1.822	1.796	0.024	0.102
FCR	1.331	1.327	1.319	1.345	0.016	0.685
Adj. FCR	1.311	1.312	1.309	1.334	0.015	0.552
d 12-39						
FI	4.155	4.030	4.040	4.131	0.064	0.179
BWG	2.756	2.677	2.682	2.710	0.046	0.411
FCR	1.571	1.552	1.548	1.567	0.021	0.823
Adj. FCR	1.511	1.508	1.508	1.526	0.013	0.688
d 0-39						
FI	4.552	4.413	4.426	4.509	0.067	0.184
BWG	3.097	3.007	3.017	3.035	0.048	0.354
FCR	1.523	1.507	1.503	1.522	0.018	0.792
Adj. FCR	1.473	1.469	1.468	1.487	0.011	0.590
d 0-49						
FI	6.598	6.461	6.456	6.598	0.100	0.285

BWG	4.073	3.946	3.948	3.969	0.067	0.213
FCR	1.696	1.726	1.682	1.719	0.025	0.526
Adj. FCR	1.622^{b}	1.640^{ab}	1.636^{b}	1.665^{a}	0.010	0.019

[1] A total of 1,140 one-day old male broilers (Cobb breeder by-product, C500 off-sex males, Cobb-Vantress, Siloam Springs, AR) were placed in floor pens with 15 broilers per cage and 19 replicates per treatment. Treatment diets were as a basal diet and CCWG inclusions of 2, 4, and 6%. Birds were weighed on d 12, 28, 39, and 49 to determine FI, BWG, FCR, and adj. FCR.

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