Aguzey and Gao, Poult Fish Wildl Sci 2018, 6:2
DOI: 10.4172/2375-446X.1000196

Poultry, Fisheries & Wildlife Sciences

Review Article Open Access

Influence of Feed Form and Particle Size on Gizzard, Intestinal Morphology and Microbiota Composition of Broiler Chicken

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Received date: June 21, 2018; **Accepted date**: August 20, 2018; **Published date**: August 27, 2018

Abstract

Feed structure (particle size) and form (mash, pellets) play very important roles in ensuring the optimal utilization of nutrients by determining the level of feed intake. Modern meat type birds have high appetite for food therefore their FI should be well studied to ensure the realization of their full genetic potential. Pellets consist of ground feed that has been compressed and molded in a pellet mill. Pelleting binds the individual ingredients together to make a whole feed and prevents selective feeding therefore ensuring that all the animals are given well balanced diets. Mash is the nutritionally complete poultry diet in a ground form. The quality of the mash is assessed by the size and uniformity of its particles. Feeding broilers on mash diets have positive effect on gizzard development than feeding pelleted diets by increasing the relative weight. There is proper stimulation by the feed ensuring the optimum function of the gizzard when mash diets are fed. Birds fed pelleted diets have lower length and weight of the duodenum, jejunum, ileum and caeca than those fed mash diets but the villus height and crypt depth of birds fed pelleted diets are higher compared with those fed mash diet. The microbiota composition promotes healthy immune system and growth.

Keywords: Intestinal morphology; Feed form; Microbiota; Broilers; Coefficient of apparent ileal digestibility; Non-starch polysaccharides; Geometric mean diameter

Introduction

Chicken are omnivorous animals with simple, single-chambered stomach and are therefore termed monogastrics. Digestion is mostly carried out by enzymes residing in the gastro-intestinal tract. As a result, chicken require high quality feed which will provide readily available nutrients to the enzymes [1]. Besides feed composition as the most important factor that determines the efficiency of feed utilization by animals, feed structure (particle size) and feed form (mash, pellets) are also important for the optimal nutrient utilization [2-5]. The success or failure of any poultry industry depends to a large extent on feeding. The cost of feeding ranges between 60-70% of the total cost of production [6,7]. It is therefore imperative that much emphasis must be laid on the type and form of feed given to chicken with the ultimate aim of boosting production. Numerous researches have been done on the form of diet to be used in feeding broilers; the pelletized form and the mash form. Abdollahi et al. [8], 2014 reports that, because of the high appetite for food by modern meat-type birds, their feed intake (FI) must be tightly monitored in order to achieve their high genetic potential. It is also well documented that feeding pelleted diets results in marked performance improvement in fast growing birds mainly through increased feed consumption. Coffey et al. [9], reports that the pelleting process was introduced to the United States feed industry by Purina in the mid-1920s. The main reason of pelleting at the time was to convert fibrous, bulky, finely-ground and unpalatable blends of feed ingredients into a compact, free-flowing pellet that facilitate easy prehension [9,10]. Pelleting has become the most common and popular hydro-thermal process in broiler diet preparation worldwide. Recent studies on the management, nutrition, genetics and other husbandry practices has led to the shift from fibrous and poorly digestible feedstuffs to the use of low fibre, texture-less and diets enriched in nutrients. This change has affected the development, functionality and health of the gastrointestinal tract (GIT), which in turn affects nutrient digestibility and also limits the advantages generated by steam-pelleting [11,12]. Among the numerous advantages associated with pelleting are enhancement of feed intake and growth of animals as a result of the reduction in feed wastage, decreasing of energy used for consumption, improving palatability, and the reduction of dustiness of feed [8]. Pelleting is a costly process but considering the enhancement of growth performance it is a justified venture. Pelleting diets also eliminate the negative effects of feeding bulky, fibrous feedstuffs creating an avenue for the incorporation of more inexpensive and less palatable feedstuffs into practical broiler diets [13]. Pelleting as a feed form also has its own disadvantages, their physical quality and ability to withstand handling stresses also affects its use [14]. Mash diets, increase starch digestibility [15]. Feeding mashed diet of high density performs the same function like pelleted diets. Feeding mashed diets have the tendency of reducing feed intake, more time spent on feeding and energy lost as a result of that. Ferket and Gernat [16], reported that when viscous grains such as wheat are finely ground and not pelleted feed prehension is compromised and consumption becomes very difficult due to the formation of a viscous sticky saliva-food mass in bird's mouth and beak pasting caused by wheat gluten. Regarding feed particle size, there is an opinion that the smaller the particle size, the larger the surface area of the feed ingredient which would possibly result in higher digestibility in poultry due to a greater interaction with digestive enzymes in the gastrointestinal tract [17]. In more recent years, however, it is thought that a large particle size aided by some structural components is beneficial to gizzard functions and gut development [15,18,3]. The

chicken digestive system is an organ which performs numerous functions with great complexity and dynamics. Among the functions of the digestive system are the digestion of feed into smaller molecules by means of enzymes and microbial fermentation, which can then be absorbed into the body, the creation of barrier against antigens and pathogens as the GIT is the largest interface between the host and the environment and finally, the GIT is considered to be the largest organ of the immune system as more than 70% of the cells of the immune system can call the GIT home [19]. Ingested feed and by extension nutrients play a significant role in the development and functionality of the GIT, diet composition (ingredients, nutrients and additives) can influence the development and function of the digestive system, including the immune system and the microbiota [20]. The aim of the present article is to give an overview of the effects of feed forms on parts of the digestive tract of broiler chicken and ultimately evaluate their effects on broiler performance.

Pelleting

Pellets consist of a mash that has been pelletized, that is, compressed and molded into pellets in a pellet mill. Unlike mash, where the ingredients can separate and the poultry can pick and choose among the ingredients, the ingredients in a single pellet stay together, and the poultry eat the pellets whole. Pellets are often too large for newly hatched chicken. Chicken feed can be pelletized into different sizes and shapes. Basically, the purpose of pelleting is to take a finely divided, sometimes dusty, unpalatable and difficult-to-handle feed material and, by using heat, moisture and pressure, form it into larger particles. These larger particles are easier to handle, more palatable and usually result in improved feeding when compared to the non-pelleted feed. Many researches have been in favor of pelleting the diet of poultry because animals fed pelleted diets make better gains than those fed mash diets [21,18,22]. This is because, in conditioning and pelleting process the heat produced breaks down the starch making the feedstuffs more digestible, the feed is in concentrated form as a result of pelleting and minimization of waste during the eating process [23,24]. Feeding pelleted diet also ensures that every animal receives a well balance diet because it eliminates the process of selective picking and choosing between ingredients [25,26]. Several researches have proven the preference of pelleted diet over mash diet in most animal species when given the choice. When moisture, heat and pressure is applied on feed ingredients, it produces a level of gelatinization which helps animals to utilize the nutrients better [27]. There is also the prevention of individual nutrients being separated during mixing, handling and feeding. Pelleting prevents feed wastage since the animals pick it in whole and there is likelihood that all the animals would receive a balanced ration [28]. There is a better flow and handling of pelleted feed thereby ensuring that feed contamination is minimized. The process of producing feed pellets can roughly be described as assembling of various compounds such as proteins, acids, sugars, fibers, and minerals. In modern feed mills, the ingredients are usually stored in bins above a weighing system composed of one or more scales. Grinding of coarse textured ingredients such as whole grains and other fibrous materials are done to get fine meal which will enhance the mixing and pelleting process. Quantities of each ingredient are weighed and thoroughly mixed and then conveyed to a bin above the pellet mill. These products can be softened (conditioned) by the addition of heat and water. After which the conditioned feed ingredients are compressed to form a dense mass which shape conforms to the die against which they are pressed. It is then allowed to dry and cool to be used in future as a form of animal feed.

Mash

Mash refers to a nutritionally complete poultry diet in a ground form. When typical ingredients are ground and mixed into a complete diet and fed, this is mash feed. The quality of the mash is assessed by the size and uniformity of its particles. Several authors have demonstrated that there is a positive correlation between increase in feed particle size and broiler growth. It is therefore very important that uniformity of particle size is ensured in preparing mash diets because birds are known to favor bigger particles and the preferred particle size increases with age [29,30]. This will prevent the dominant birds from eating the bigger particles while the rest of the birds will eat the finer particles and this does not ensure each chicken getting a well balance diet. The uniformity in particle size promotes good performance because it eliminates the differences in energy expended in ingesting feed with lower energy being used to ingest bigger particles and energy used for ingesting smaller particles [21,31]. The number of pecks to eat one given feed amount is reduced when particle size increases. According to Savory [32], particle size and nutrient concentration of the feed are the two main factors determining FI of birds. Portella et al. [33] reported that altering feed particle size without changing diet composition affected FI in layers. Portella et al. [33] demonstrated that feed consumption of broilers was related directly to particle size, with only a weak correlation with nutrient composition. The uniformity affects FI and eventually affects the performance of the birds. The differences in the uniformity may likely be due to factors such as type and variety of cereal, particle characteristics of feed components, grinding method and age of the birds [8,11].

Effects on gizzard

The gizzard, also known as the muscular stomach or ventriculus serves as the grinding mill of birds. The gizzard can grind the food with previously swallowed stones and pass it back to the true stomach, and vice versa. Bird gizzards are lined with a tough layer made of the carbohydrate-protein complex koilin to protect the muscles in the gizzard. Diet form (e.g., structure: pellets vs. mash) can have a significant impact on gizzard functionality. It basically serves as the teeth of chicken. A large and well-developed gizzard is able to grind feed particles more thoroughly [34], to elevate pancreatic enzyme secretion through increased release of cholecystokinin [11], to increase proteolysis by pepsin, trypsin and other endogenous proteases in the small intestine, to improve gastrointestinal tract motility and to improve nutrient digestibility [35]. Thus, gut development and health can be enhanced. It is therefore very important that the promotion of the health and development of the gizzard should be of importance in the broiler industry. Nir et al. [36] reports of a positive relationship between gizzard weight and particle size which can be achieved by manipulating feed particle size. Svihus et al. [18] reported that feed form had a great effect on gizzard development emphasizing that there was a remarkable gizzard relative weight reduction when broiler mash diets were replaced by whole wheat diets or pelleted diets. This reduction of gizzard weight could be attributable to the lack of mechanical stimulation by the feed. Pelleting reduced feed particle size, and small particles are retained in the gizzard for less time than coarse particles, resulting in less mechanical stimulation [12] and reduced organ size [11]. There have been various studies on the effect of particle size of feed on the gizzard. Chewning et al. [29] reported that feeding smaller particle size (1.6-mm screen) of maize compared to coarse particles (7.9 mm screen) in mash form, reduced feed per unit gain by 31 and 17 points during 0 to 21 and 0 to 44 day, respectively.

Charbeneau and Roberson [37] reported that in turkey poults, there was a linear decrease in weight gain when the size of maize grain was increased, due mainly to decrease FI. Jacobs et al. [38] however reported that in broilers, when the particle size of maize was increased it resulted in a linear decrease in weight gain and feed efficiency. Numerous researchers have reported that in young birds fed large particle size of maize, when fed mash diets there is a negative effect because of the poorly developed gizzard which cannot grind coarse particles [30,39-41]. When fed pelleted diets, replacing half of finely-ground maize with coarse maize, from day 14 to 49, increased body weight (day 35) and feed efficiency at 35 and 49 day of age but at day 1 when the same feed was fed FI and weight gain decreased [42]. It was therefore concluded that young broilers are not able to utilize larger particles of feedstuffs efficiently because of the poorly developed nature of the gizzard. This situation exerts much pressure on the gizzard which will have to use more energy to perform its grinding function. The healthy growth and development of the gizzard to a greater extent affects the performance of the birds [30,43]. According to Abdollahi and Ravindran [44], when the gizzard is under-developed, there is a short retention time of digesta and an elevated pH and this condition leads to a possible minimization of the digestion process in boiler chicken. These conditions (pH and retention time) becomes more limiting when birds are fed diets in pelleted form [8]. Engberg et al. [22], Huang et al. [45], Frikha et al. [46] reported that when birds are fed pelleted diets, the pH is higher than those fed mash diets and this was assigned mainly to the high intake of feed by those fed pelleted diets and possibly a lower secretion of hydrochloric acid, [11]. Available literature favors the use of mash diets for proper gizzard growth than pelleted diets.

Effects on intestinal morphology

Feeding plays very important role in the life of every organism and has direct relationship with the gastro-intestinal tract. The growth and development of the gastrointestinal tract is vital for broiler chickens as it helps to effectively utilize nutrients in their diet [47]. The size, morphology and how the digestive system functions is very important in helping broiler chicken to adapt to the various conditions it will be subjected to. Therefore measures that would help in the post hatch period are necessary to ensure the proper growth of the chicken [48,47]. Lim and Low [49] reports that the gastrointestinal tract of chicks develops at the embryonic stage but undergoes rapid morphological changes at the onset of feeding. Researches have shown that within 48 h post hatch, the weight of the small intestine, which is the primary site of digestion and absorption, doubles, reiterating the presence of specific components in the diet affecting intestinal morphology [50]. When pelleted diets are fed to chicken, there is increased excreta score and reduced excreta dry matter (DM). The site for the reabsorption and recycling of water in the GIT is the caeca, studies have shown that the length and weight of the caeca is lower in birds fed pelleted diets than those fed mash diets and this might be the reason for the greater loss of water through the excreta in pellet-fed birds [8]. Several study have also reported of lower relative length of the different segments of the digestive tract of birds fed pelleted diets compared to those fed mash diets [8,22,36,51,52]. Although several studies have reported that the length and weight of the segments of the GIT are lowered in pellet-fed birds, Amerah et al. [51], Zang et al. [53] reported of an increase in the villus height and crypt depth of birds fed pelleted diets compared with mash diet. The villi serve as the direct surface for absorption. For absorption to occur, the nutrient must come into contact with the epithelial cells lining the small intestine which consists of circular folds known as mucosal folds and tiny finger-like projections known as villi lining the walls of the small intestine. The villi increase the surface area of the small intestine which greatly increases the amount of nutrients to be absorbed. The increased villus height may increase total luminal villus absorptive area and subsequently result in greater digestive enzyme action and enhanced transport of nutrients at the villus surface [54,55]. Study shows that when there is over feeding of wheat-based pelleted diet, digestibility of starch is impaired [56]. Diet form, type and particle size also has effect on ileal digestibility of nutrients [57]. These researchers reported of lower N digestibility in wheat-based pellets compared to mash diets. Abdollahi et al. [8] showed that feeding pelleted diets either had no effect on N and starch or improve fat, Ca and P ileal digestibility in maize-based diets, whereas pellet feeding reduced the digestibility of all nutrients in wheat-based diets. Selle et al. [58] reported that feed form had no influence on ileal starch digestibility while Abdollahi et al. [59] showed that the effect of feed form on starch digestibility depends on the grain type; while pelleting had no effect on ileal digestibility of starch in maize-based diets it decreased starch digestibility in wheat-based diets. To this, de Vries et al. [60] reported that the rise in concentration of high molecular weight of soluble NSP and digesta viscosity in the small intestine may be responsible for the poor digestibility of starch in pelleted wheat based diet. Svihus and Hetland [56], also reported that there is an overload of wheat starch in the small intestine and this may account for the poor digestibility of pelleted wheat based diet. The endosperm of sorghum grains contain kafirin proteins which surround starch granules with both embedded in the glutelin protein matrix [61]. There is the possibility that during steam-pelleting, an interactions occurs between kafirin-glutelin-starch that promote polymerisation of the kafirin protein to high molecular weight polymers that may eventually impede starch digestion. Abdollahi et al. [62], reported of a reduction of the CAID of Ca, P and fat of wheat- based diets when they are pelleted whiles the pelleting of maize-based diets improved digestibility of Ca, P and fat compared to mash diet. Intact pellets when fed led to a reduction in the relative length of small intestine and caeca, [52,36]. The ileum functions mainly in the absorption of vitamin B12 and bile salts and any other products of digestion which were not absorbed by the jejunum. The wall is made up of folds, each of which has many tiny finger-like projections known as villi on its surface. The jejunum, along with the other areas of the small intestine, is responsible for absorbing nutrients from digested food into the bloodstream. The duodenum is the section of the intestines that connects to the stomach and pancreas and it is the site for digestion. It accepts chyme from the stomach and completes the digestion of food [63-67]. Feed form and its characteristics also influence the microbiota composition and function in the GIT. The presence of these microbiota play very crucial role by stimulating the development of the digestive tract to enable it perform functions of nutrient digestion, gut mucosal proliferations, growth of digestive enzymes, synthesis and utilization of vitamins and fermentation processes [68,69]. Short-chain fatty acids (SCFA) are produced through fermentation and this stimulates the development of the digestive system through the increase in size and tissue components of the guts (Table 1). Fermentation in the hindgut by microbes yields mainly lactic acid like acetate, propionate and butyrate which are produced in the cecal digesta [69]. These appear to accelerate gut epithelial cell proliferation, thereby increasing intestinal tissue weight [70-74]. Mucosa development is retarded in chicks if feeding is delayed therefore the form and particle size must be considered in relation to the age of the broiler [16,75-77]. The compositions of the diet and the microbiota and their interactions also affect the intestinal

development, mucosal architecture and the mucus composition of the lower digestive tract [69]. The microbiota also help in the building of a strong immune system and since there is a strong relationship between diet form and microbiota development, the health of the broilers are also improved [65,69].

Parameters		Feed Structure (Particle size)		Feed form	
		Big	Small	Pellets	Mash
Gizzard		Increase organ size/More mechanical stimulation	Reduce organ size/ Less mechanical stimulation	Higher pH Decrease in weight	Lower pH Increase in weight
Intestinal morphology	Length/ Weight of Caeca	-	-	Short/Low	Long/ High
	Length/weight of duodenum	-	-	Short/Low	Long/ High
	Length and weigh of Ileum	-	-	Short/Low	Long/ High
	Length and weigh of jejunum	-	-	Short/Low	Long/ High
	Villus height and Crypt depth			High	Low

Table 1: Effect of feed form and particle size on gizzard, Intestinal morphology and microbiota composition of broiler chicken.

Conclusion

It can therefore be concluded that diet form (mash or pelleted), type of grain and level of non-starch polysaccharides have various impacts on the function, shape and overall morphology of the gizzard and the intestines with mash diets being recommended for proper gizzard function and weight. Using less expensive, bulky, fibrous feed ingredients and by-products to prepare feed in pellet form is also a good way to maximize productivity in a broiler enterprise.

References

1. Kersten J, Rohde HR, Nef E (2005) Principles of Mixed Feed Production. Agrimedia, Bergen, Germany.
2. Wondra KJ, Hancock JD, Behnke KC, Hines RH, Stark CR (1995) Effects of particle size and pelleting on growth performance, nutrient digestibility and stomach morphology in finishing pigs. J Anim Sci 73: 757-763.
3. Choct M, Selby EAD, Cadogan DJ, Campbell RG (2004) Effect of particle size, processing, and dry or liquid feeding on performance of piglets. Aust J Agric Res 55: 237-245.
4. Thorsten L (2011) Stage grinding with hammer mill and crushing roller mill. Feed Compounder 22-26.
5. Ball MEE, Magowan E, McCracken KJ, Beattie VE, Bradford R, et al. (2015) An investigation into the effect of dietary particle size and pelleting of diets for finishing pigs. Livest Sci 173: 48-54.
6. Aliakbarpour HR, Chamani M, Rahimi G, Sadeghi AA, Qujeq D (2013) Inter-mittent feeding programme and addition of Bacillus subtilis based probiotics to the diet of growing broiler chickens: influence on growth, hepatic enzymes and serum lipid metabolites profile. Arch Anim Breed 56: 410-422.
7. Willems OW, Miller SP, Wood BJ (2003) Aspects of selection for feed efficiency in meat producing poultry. Worlds Poult Sci J 69: 77-88.
8. Abdollahi MR, Ravindran V, Svihus B, (2013) Influence of grain type and feed form on performance, apparent metabolisable energy and ileal digestibility of nitrogen, starch, fat, calcium and phosphorus in broiler starters. Anim Feed Sci Technol 186: 193-203.
9. Coffey D, Dawson KA, Ferket P, Connolly A (2016) Review of the feed industry from a historical perspective and implications for its future. J Appl Anim Nutr 4: 1-11.
10. Brickett KE, Dahiya JP, Classen HL, Gomis S (2007) Influence of dietary nutrient density, feed form, and lighting on growth and meat yield of broiler chickens. Poult Sci 86: 2172-2181.
11. Svihus B (2011) The gizzard: function, influence of diet structure and effect on nutrient availability. World's Poult Sci J 67: 207-224.
12. Mateos GG, Jimenez-Moreno E, Serrano MP, Lazaro R (2012) Poultry response to high levels of dietary fibre sources varying in physical and chemical characteristics. J Appl Poult Res 21: 156-174.
13. Abdollahi MR, Ravindran V, Wester TJ, Ravindran G, Thomas DV (2010) Influence of conditioning temperature on performance, apparent metabolisable energy, ileal digestibility of starch and nitrogen and the quality of pellets, in broiler starters fed maize- and sorghum- based diets. Anim Feed Sci Technol 162: 106-115.
14. Biggs P, Parsons CM (2009) The effects of whole grains on nutrient digestibilities, growth performance, and cecal short-chain fatty acid concentrations in young chicks fed ground corn-soybean meal diets. Poult Sci 88: 1893-1905.
15. Hetland H, Svihus B (2001) Effect of oat hulls on performance, gut capacity and feed passing time in broiler chickens. Br Poult Sci 42: 354-361.
16. Ferket PR, Gernat AG (2006) Factors that affect feed intake of meat birds: a review. Int J Poult Sci 5: 905-911.
17. Preston CM, McCracken KJ, McAllister A (2000) Effect of diet form and enzyme supplementation on growth, efficiency and energy utilisation of wheat-based diets for broilers. Br Poult Sci 41: 324-331.
18. Svihus B, Klovstad KH, Perez V, Zimonja O, Sahlstrom S, et al. (2004) Physical and nutritional effects of pelleting of broiler chicken diets made fromwheat ground to different coarsenesses by the use of roller mill and hammer mill. Anim Feed Sci Technol 117: 281-293.
19. Sergeant MJ, Constantinidou C, Cogan TA, Bedford MR, Penn CW.et al. (2014) Extensive microbial and functional diversity within the chicken cecal microbiome. PLoS ONE 9: 91941.
20. Borda-Molina D, Jana S, Camarinha-Silva A, 2018. Current perspective of the chicken gastrointestinal tract and its microbiome. Comput Struct Biotechnol J 16: 131-139.
21. Abdollahi MR, Zaefariana F, Ravindrana V, Selle PH (2018) The interactive influence of dietary nutrient density and feed form on the performance of broiler chickens. Anim Feed Sci Technol 239: 33-43.
22. Engberg RM, Hedemann MS, Jensen BB (2002) The influence of grinding and pelleting of feed on the microbial composition and activity in the digestive tract of broiler chickens. Br Poult Sci 43: 569-579.
23. Kenny M, Flemming E (2006) Optimising broiler performance - The role of physical feed quality. Aust Poult Sci Symp 18: 25-29.
24. Creswell D, Bedford M (2006) High pelleting temperatures reduce broiler performance. Proceedings of the 18th Australian Poultry Science Symposium, Sydney, Australia.
25. Jensen LS (2000) Influence of pelleting on the nutritional needs of poultry. Asian-Aust J Anim Sci 13: 35-46.
26. Thomas M, Van der poel AFB (1996) Physical quality of pelleted animal feed. 1. Criteria for pellet quality. Anim Feed Sci Technol 61: 89-112.
27. Silversides FG, Bedford MR (1999) Effect of pelleting temperature on the recovery and efficacy of a xylanase enzyme in wheat-based diets. Poult Sci 78: 1184-1190.

28. Moritz JS, Beyer RS, Wilson KJ, Cramer KR (2001) Effect of moisture addition at the mixer to a corn-soybean-based diet on broiler performance. J Appl Poult Res 10: 347-353.
29. Chewning CG, Stark CR, Brake J (2012) Effects of particle size and feed form on broiler performance. J Appl Poult Res 21: 830-837.
30. Parsons AS, Buchanan NP, Blemings KP, Wilson ME, Moritz JS (2006) Effect of corn particle size and pellet texture on broiler performance in the growing phase. J Appl Poult Res 15: 245-255.
31. Amerah AM, Ravindran V (2009) Influence of maize particle size and microbial phytase supplementation on the performance, nutrient utilisation and digestive tract parameters of broiler starters. Anim Prod Sci 49: 704-710.
32. Savory CJ (1980) Diurnal feeding patterns in domestic fowls: a review. Appl Anim Ethol 6: 71-82.
33. Portella FJ, Caston LJ, Leeson S (1988) Apparent feed particle size preference by broilers. Can J Anim Sci 68: 923-930.
34. Amerah, A.M., Ravindran, V., Lentle, R.G., Thomas, D.G., 2007. Influence of feed particle size and feed form on the performance, energy utilisation, digestive tract development, and digesta parameters of broiler starters. Poult. Sci. 86, 2615-2623.
35. Amerah AM, Ravindran V (2008). Influence of method of whole-wheat feeding on the performance, digestive tract development and carcass traits of broiler chickens. Anim Feed Sci Technol 147: 326-339.
36. Nir I, Twina Y, Grossman E, Nitsan Z (1994c) Quantitative effects of pelleting on performance, gastrointestinal tract and behaviour of meat-type chickens. Br Poult Sci 35: 589-602.
37. Charbeneau RA, Roberson KD (2004) Effect of corn and soybean meal particle size on phosphorus use in Turkey poults. J Appl Poult Res 13: 302-310.
38. Jacobs CM, Utterback PL, Parsons CM (2010) Effect of corn particle size on growth performance and nutrient utilisation in young chicks. Poult Sci 89: 539-544.
39. Douglas JH, Sullivan TW, Bond PL, Struwe FJ, Baier JG, et al. (1990). Influence of grinding, rolling, and pelleting on the nutritional-value of grain sorghums and yellow corn for broilers. Poult Sci 69: 2150-2156.
40. Lott BD, Day EJ, Deaton JW, May JD (1992) The effect of temperature, dietary energy level, and corn particle size on broiler performance. Poult Sci 71: 618-624.
41. Xu Y, Stark CR, Ferket PR, Williams CM, Brake J (2015c) Effects of feed form and dietary coarse ground corn on broiler live performance body weight uniformity, relative gizzard weight, excreta nitrogen, and particle size preference behaviors. Poult Sci 94: 1549-1556.
42. Xu Y, Stark CR, Ferket PR, Williams CM, Auttawong S, Brake J (2015a) Effects of dietary coarsely ground corn and litter type on broiler live performance litter characteristics, gastrointestinal tract development, apparent ileal digestibility of energy and nitrogen, and intestinal morphology. Poult Sci 94: 353-361.
43. Pacheco WJ, Stark CR, PR, Brake J (2013) Evaluation of soybean meal source and particle size on broiler performance nutrient digestibility, and gizzard development. Poult Sci 92: 2914-2922.
44. Abdollahi MR, Ravindran V (2013) Influence of pellet length on pellet quality and performance of broiler starters. J Appl Poult Res 22: 516-522.
45. Huang DS, Li DF, Xing JJ, Ma YX, Li ZJ, et al. (2006) Effects of feed particle size and feed form on survival of Salmonella typhimurium in the alimentary tract and cecal S typhimurium reduction in growing broilers. Poult Sci 85: 831-836.
46. Frikha M, Safaa HM, Serrano MP, Arbe X, Mateos GG (2009) Influence of the main cereal and feed form of the diet on performance and digestive tract traits of brown-egg laying pullets. Poult Sci 88: 994-1002.
47. Uni Z, Ganto S, Sklan D (1998) Post hatch development of mucosal function in the broiler small intestine. Poult Sci 77: 75-82.
48. Iji PA, Saki A, Tivey DR (2001a) Body and intestinal growth of broiler chicks on a commercial starter diet. 1. Intestinal weight and mucosal development. Br Poult Sci 42: 505-513.
49. Lim SS, Low FN (1977) Scanning electron microscopy of the developing alimentary canal in the chick. Am J Anat 150: 149-174.
50. Sklan D, Noy Y (2000) Hydrolysis and absorption in the small intestines of post hatch chicks. Poult Sci 79: 1306-1310.
51. Amerah AM, Ravindran V, Lentle RG (2007a) Feed particle size: implications on the digestion and performance in poultry. World's Poult Sci J 63: 439-455.
52. Abdollahi MR, Ravindran V, Wester TJ, Ravindran G, Thomas DV (2011) Influence of feed form and conditioning temperature on performance, apparent metabolisable energy and ileal digestibility of starch and nitrogen in broiler starters fed wheat-based diet. Anim Feed Sci Technol 168: 88-99.
53. Zang JJ, Piao XS, Huang DS, Wang JJ, Ma X, et al. (2009) Effects of feed particle size and feed form on growth performance: nutrient metabolisability and intestinal morphology in broiler chickens. Asian-Aust J Anim Sci 22: 107-112.
54. Naderinejad S, Zaefarian F, Abdollahi MR, Hassanabadi A, Kermanshahi H, Ravindran V (2016) Influence of feed form and particle size on performance nutrient utilisation, and gastrointestinal tract development and morphometry in broiler starters fed maize-based diets. Anim Feed Sci Technol 215: 92-104.
55. Cera KR, Mahan DC, Cross RF (1988) Effect of age, weaning and post weaning diet on small intestinal growth and jejunal morphology in young swine. J Anim Sci 66: 574-584.
56. Svihus B, Hetland H (2001) Ileal starch digestibility in growing broiler chickens fed on a wheat-based diet is improved by mash feeding, dilution with cellulose or whole wheat inclusion. Br Poult Sci 42: 633-637.
57. Lentle RG, Ravindran V, Ravindran G, Thomas DV (2006) Influence of feed particle size on the efficiency of broiler chickens fed wheat based diets. J Poult Sci 43: 135-142.
58. Selle PH, Liu SY, Cai J, Cowieson AJ (2013) Steam-pelleting temperatures, grain variety, feed form and protease supplementation of mediumly ground, sorghum-based broiler diets: influences on growth performance, relative gizzard weights, nutrient utilisation, starch and nitrogen digestibility. Anim Prod Sci 53: 378-387.
59. Abdollahi MR, Ravindran V, Wester TJ, Ravindran G, Thomas DV (2013b) The effect of manipulation of pellet size (diameter and length) on pellet quality and performance, apparent metabolisable energy and ileal nutrient digestibility in broilers fed maize-based diets. Anim Prod Sci 53: 114-120.
60. de Vries S, Pustjens AM, Schols HA, Hendriks WH, Gerrits WJJ (2012) Improving digestive utilisation of fiber-rich feedstuffs in pigs and poultry by processing and enzyme technologies: a review. Anim Feed Sci Technol 178: 123-138.
61. Liu SY, Selle PH, Cowieson AJ (2013) Strategies to enhance the performance of pigs and poultry on sorghum-based diets. Anim Feed Sci Technol 181: 1-14.
62. Abdollahi MR, Ravindran V, Wester TJ, Ravindran G, Thomas DV (2013a) Influence of pellet diameter and length on the quality of pellets and performance: nutrient utilisation and digestive tract development of broilers fed on wheat-based diets. Br Poult Sci 54: 337-345.
63. Abdollahi MR, Ravindran V (2014) Influence of pellet length changes at 4, 5 and 6 weeks of age and two pellet diameters on growth performance and carcass characteristics of broiler finishers. Anim Prod Sci 54: 950-955.
64. Abdollahi MR, Ravindran V, Svihus B (2014) Influence of feed form on growth performance, ileal nutrient digestibility, and energy utilisation in broiler starters fed a sorghum-based diet. Livestock Sci, 165: 80-86.
65. Amerah AM, Ravindran V, Lentle RG, Thomas DG (2008a) Influence of feed particle size on the performance, energy utilisation, digestive tract development, and digesta parameters of broiler starters fed wheat- and corn-based diets. Poult Sci 87: 2320-2328.
66. Amerah AM, Ravindran V, Lentle RG, Thomas DG (2008b) Influence of particle size and enzyme supplementation on the performance energy utilisation, digestive tract parameters and digesta viscosity of broiler starters. Br Poult Sci 49: 455-462.

67. Amerah AM, Ravindran V, Lentle RG (2009) Influence of insoluble fibre and whole wheat inclusion on the performance: digestive tract development and ileal microbial profile of broiler chickens. Br Poult Sci 50: 366-375.
68. Gabriel I, Mallet S, Leconte M (2003) Differences in the digestive tract characteristics of broiler chickens fed on complete pelleted diet or whole wheat added to pelleted protein concentrate. Br Poult Sci 44: 283-290.
69. Lan Y, Williams BA, Tamminga S, Boer H, Akkermans A, et al. (2005) In vitro fermentation kinetics of some non-digestible carbohydrates by the caecal microbial community of broilers. Anim Feed Sci Technol 123-124, 687-702.
70. Gabriel I, Mallet S, Leconte M, Travel A, Lalles JP (2008) Effects of whole wheat feeding on the development of the digestive tract of broiler chickens. Anim Feed Sci Technol 142: 144-162.
71. Amerah AM, Ravindran V (2009) Influence of particle size and microbial phytase supplementation on the performance: nutrient utilisation and digestive tract parameters of broiler starters. Anim Prod Sci 49: 704-710.
72. Amerah AM (2015) Interactions between wheat characteristics and feed enzyme supplementation in broiler diets. Anim Feed Sci Technol 199: 1-9.
73. Fujita H (1973) Quantitative studies on the variations in feeding activity of chickens: ii: Effect of the physical form of the feed on the feeding activity of laying hens. Jpn Poult Sci 10: 47-55.
74. Pacheco WJ, Stark CR, Ferket PR, Brake J (2014) Effects of trypsin inhibitor and particle size of expeller-extracted soybean meal on broiler live performance and weight of gizzard and pancreas. Poult Sci 93: 2245-2252.
75. Ravindran V (2013) Feed enzymes: the science, practice, and metabolic realities. J Appl Poult Res 22: 628-636.
76. Svihus B (2001) Research note: a consistent low starch digestibility observed in pelleted broiler chicken diets containing high levels of different wheat varieties. Anim Feed Sci Technol 92: 45-49.
77. Thomas DG (2007b) Influence of feed particle size and feed form on the performance energy utilisation, digestive tract development, and digesta parameters of broiler starters. Poult Sci 86: 2615-2623.