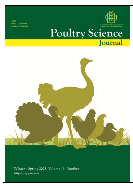

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# A Review on Feed Particle Size and Form: Implications on the Performance and Gut Health of Poultry

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## Abstract

Feed ingredients, particle size, and texture are well-acknowledged factors affecting nutrient digestibility, feed utilization, gut health development, and overall production performance of poultry birds. Therefore, it has been a topic of interest for nutritionists and feed producers to optimize poultry production efficiency. Grinding, the second most expensive process during feed manufacturing, has been proposed to modify ingredient particle size. It is investigated that changes in the feed ingredients' particle size can significantly affect poultry birds' production, thus increasing particle size to the recommended level for improving poultry performance and saving costs from over-grinding. Providing feed in pelleted form is an advanced form of feeding with many benefits compared to mash, such as improved nutrient digestibility, feed palatability, and reduced ingredient segregation. The modern poultry industry has traditionally fed birds with pelleted diets.Moreover, pellet quality and conditioning temperature significantly impact bird production performance. The feed form and feed ingredient particle size also significantly influence digestive system development and intestinal microflora, affecting birds' overall performance. This review paper will discuss the published literature on feed form and particle size on bird performance, passage rate, gut development, feed intake, and nutrient digestibility.

## Introduction

The poultry industry has become one of the most crucial sectors due to the pivotal role of food provision worldwide (Mottet and Tempio, 2017). Although this sector has grown hugely, it is facing many challenges, such as high feed prices, shortage of feed ingredients, and irregular supply and import of conventional feed ingredients. Economical and efficient poultry production is directly related to quality feed production, raising the effect and impacting birds' health. One of the most important issues is feeding birds with optimal feed particle size.

In the past, particle size had no impact on the production performance of birds. Still, it has been proved that changes in the particle size of the feed ingredients may significantly affect the production performance (Xu *et al.*, 2015a) and nutrient digestibility of poultry birds (Kiarie and Mills, 2019). Altering the particle size of feed ingredients is known to affect several features of the poultry, including

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digesta passage rate, gut development, and performance. Particle size and diet form mainly affect the physiology of the digestive system and feed intake (FI) of poultry birds, respectively (Zaefarian *et al.,* 2016). To achieve their maximum genetic potential, poultry birds require highly digestible feed because of the short permanence time of feed in the digestive tract. To modify the particle size, grinding, the second most expensive process during feed manufacturing (Rubio *et al.*, 2020), is performed during feed processing. After grinding, digestion enzymes and digesta may interact more easily with ingredients, resulting in improved digestion and bird performance (Xu *et al.,* 2015a). Other advantages of decreasing the particle size include increased pellet quality, handling, and materials mixing ease. The particle size reduction has its practical limits since very fine particles may be difficult to be consumed by birds. Considering its importance, in recent years, the feed particle size of ingredients in poultry feed has been a topic that deserves scientific attention (Saldana *et al.,* 2015; Ege *et al.,* 2019). An optimum particle size may maximize nutritional and economic benefits. Conversely, recommendations concerning optimal particle size are contradictory because outcomes from different experiments are confounded by some factors such as physical feed form, diet complexity, grains type, particle size distribution, pellet quality, grinding methods, and endosperm hardness (Amerah *et al.,* 2007).

When birds are fed on fine particles, their digesta enters the duodenum more quickly and spends less time in the gizzard, where digesta is exposed to low pH and enzymes. Consequently, a comparatively higher undigested material may be found in the intestine (Kheravii *et al.*, 2018a). Moreover, fine grinding boosts energy intake by the grinding mill and declines grinding equipment capacity and flow ability, increasing dust problems (Kiarie and Mills, 2019). In contrast to fine grinding, coarsely ground particles in diets are responsible for enhancing feed utilization, production efficiency, and gut health which can be achieved by increasing gizzard and crop activity and stimulating digestive enzymes (Kheravii *et al.,* 2018a). The genetic potential of poultry birds has improved, so nutritionists focus on improving the feed forms to achieve maximum production. To achieve maximal efficiency from feed, feeding forms are improved to modify the digestive system to make it more efficient. Therefore, it is recommended to use advanced pelleted or crumbled diets instead of simply mixed mash diets (Rueda *et al.,* 2022). Based on scientific studies, it is evident that particle size and diet form have deep effects on poultry growth performance.

**Impacts on poultry production**

A balanced diet may provide all essential nutrients according to the bird's requirement; however, it is necessary to understand the impact of feed form and particle size on poultry growth performance to gain the maximum productive potential of birds. The feed conversion ratio (FCR) improvement was reported as the corn particle size increased in the pelleted broiler diet. Aged birds' response to an increase in particle size is more pronounced than younger birds (Xu *et al.*, 2015a). For instance, a 987 µm-sized coarse corn can promote better performance in broilers than a 908 µm-sized one, possibly due to its possible developing activity of the digestive system. In addition, it remains in the birds’ digestive system for more extended periods than fine particles and is therefore used more efficiently. Feeding coarse maize particles (6 mm) rather than fine particles (2 mm) increased growth performance in broilers during 25-42 days of age, with European production efficiency factors of 622 and 553, respectively (Abadi *et al.,* 2019). Conversely, in younger birds, the digestive system cannot fully use the feed containing coarse grains; therefore, particle sizes either have no (Xu *et al.*, 2015a) or an inverse effect (Jacobs *et al.,* 2010) on production performance. During the first 16 days of life, broiler chicks fed a fine maize-based diet of (geometric mean diameters (GMD) of 869 µm) experienced an FCR improvement as compared to coarse maize (2897 µm) (Kilburn and Edwards, 2001). Broiler chicks fed a pelleted diet composed of fine corn particles (534 µm) during the first 21 days of age had a significantly improved FCR than those, of course, corn particles (1071 µm) (Moradi *et al.*, 2021). However, Oppong-Sekyere *et al.* (2012) worked on different particle sizes of corn for 4-weeks-old broilers and classified as “smooth” those with a size of 713.82 µm, “coarse” with a size of 1462 µm, and “very coarse” those with a size of 1506.8 µm. The highest body weight and weight gain were observed in birds fed on a smooth particle-containing diet, while those receiving very coarse particles showed a decline in efficiency. The most obvious reason for this inefficiency was that the birds could not digest very coarse particles properly. Reducing particle size to the optimum level could help to improve poultry performance (Healy *et al.*, 1994) and save costs from over-grinding (Oppong-Sekyere *et al.*, 2012). Nevertheless, it has been observed that feeding mixed particle sizes of corn (coarse and fine) could have better production in broilers (Reece *et al.*, 1986; Xu *et al.*, 2015a). Reece *et al.* (1986) found that providing broiler chickens from 0-42 days with a diet with fine (679 µm), coarse (1289 µm), or mixed size (50% fine and 50% coarse corn) had a better performance compared to medium grounded corn (987 µm). Inclusion of course corn (1,314 µm) by 50% in a diet for 21-42-days-old broiler chickens decreased FI and body weight gain without affecting FCR (Wang-Li *et al.,* 2020). On another side, unusual findings regarding sorghum and corn of different sizes exhibiting no influence on the performance of broilers (live weight, FCR, and FI) were reported (Murta *et al.,* 2004; Fernandes *et al.,* 2013).

The physical feed form could confuse the impact of particle size on birds' performance. It is suggested that a pellet diet with coarsely ground ingredients could be an alternative nutritional strategy in the poultry sector to improve production efficiency and save energy (Zang *et al.,* 2009). Pelletizing corn-soybean meals, including 15% intact flaxseeds, was found to be very effective in achieving optimal growth performance in broiler chickens, implying that the use of whole seeds in pelleted diets is a viable option (Jia and Slominski, 2010).

The production performance of a broiler is directly related to fulfilling its nutritional requirements that, in turn, depend, in part, on the bird's feed intake and composition. The feed intake is significantly influenced by feed form. Mash feed has several benefits uniform growth, decreased bird mortality, and cost-effectiveness. However, the component grinding results in reduced palatability and obtaining the lowest weight and highest FCR values compared to crumble and pellet feed supplementation for broilers from 21 to 56 days of age (Jahan *et al.,* 2006). FCR in broilers fed a pelleted diet was improved when compared to the mash diet (Jahan *et al.,* 2006; Amerah *et al.,* 2008; Gracia *et al.,* 2016; Abadi *et al.,* 2019). Broiler chicks fed crumple pre-stater feed showed a 35% greater BWG and a 30% higher feed intake at 10 days of age than birds fed mash feed (Mahdavi *et al.,* 2018). Enhancing performance might be attributed to improved digestibility and palatability, reduced ingredient segregation and feed wastage, destruction of pathogenic microorganisms, and inactivation of various antinutritional components like trypsin inhibitors by heat during pelleting (Feng *et al.,* 2003). For these reasons, the modern poultry industry has traditionally fed birds with pelleted diets.

More in detail, pellet quality has the potential to have a significant impact on bird production performance. Pellets formed at 82 °C temperature improved broilers' FCR compared to pellets prepared at 92 °C or 72 °C (Rueda *et al.,* 2022). FCR rose in diet-fed broilers as conditioning temperature increased from 65 °C to 95 °C without influencing feed intake (Selle *et al.,* 2013). The metabolizable energy content of the diet was improved due to pelleting (Zang *et al.,* 2009). Kilburn and Edwards (2001) investigated the effect of feed pelleting on phytate phosphorus availability in broilers and discovered lower bone ash due to decreased phytate phosphorus retention (PPR). In contrast, other scientists found that pelleting the broiler diet either improved phytate phosphorus availability (Bayley *et al.,* 1968) or had a lesser influence on the PPR (Edwards *et al.,* 1999).

In the case of layer hens, the response of the birds due to changes in particle size may not be as pronounced as shown by the broilers (Frikha *et al.,* 2011; Ege *et al.,* 2019). Instead, the feed form (pellet or mash) could influence the laying hens' performance (Wahlstrom *et al.,* 1999; Kocer *et al.,* 2016; Bozkurt *et al.,* 2019). In the studies of Safaa *et al.* (2009) and; Herrera *et al.* (2017), the main ingredients of the diet were milled to pass from different screen sizes, no effect was found on the production traits like egg production, egg mass, egg weight, feed intake, body weight, or FCR. The reason could be a preferred selection of the coarse ingredients and thus devoicing themselves from essential amino acids, vitamins, and minerals present in the fine fraction of the diet (Ege *et al.,* 2019).

**Impacts on gastrointestinal tract development**

The feed particle size may affect birds' gastrointestinal tract (GIT). The coarse feed particles may enhance the function of certain parts of GIT, like the gizzard and small intestine (SI), while feeding fine particles may develop proventriculus more prominently. Herrera *et al.* (2017) experienced a linear increasing effect between the relative weights of GIT, gizzard, and liver and the screening size (2, 4, 6, 8, 10, and 12 mm) used for grinding the ingredients. The increased weight of the gizzard owing to the increasing maize particle size is a logical result of the improved mechanical grinding activity (Dahlke *et al.,* 2003; Parsons *et al.,* 2006). Pancreas and gizzard weight dropped significantly after cereals were ground finely (4 mm) compared to after cereals were ground coarsely (8 mm) for laying chickens (from 21-52 weeks) (Ege *et al.,* 2019). A positive correlation between the relative weights of the pancreas and gizzard was stated by Liu *et al.* (2015). Adding 50% course ground corn to the diet raised relative gizzard weight while decreasing relative proventriculus weight at 49 days of age (Xu *et al.,* 2015b). The association between proventriculus and gizzard weight could indicate that broilers' enzymatic digestive and mechanical functions have evolved in response to physical feed structure (Svihus, 2011). In addition, the coarse ground feed remains longer in the GIT, resulting in prolonged exposure to feed with digestive enzymes and, thus, better digestion (Carre, 2000). Therefore, coarse grinding of maize was favorable to broilers' energy and nutrient utilization and growth performance through improved gizzard functionality and development (Naderinejad *et al.,* 2016).

Even though thermal processing of feed may affect feed structure and reduce particle size and therefore the feed form containing course or fine ground grains (particle size distribution), as well as the type of grains, may have an impact on the GIT development, not only the diameter of particle size. For instance, the relative weight of the gizzard was not affected by the coarse maize percentage in the crumble diet, while it increased linearly with the increase of coarse maize addition in the mash diet (Xu *et al.*, 2015c). In addition, while testing the impact of particle size, maize showed a higher effect on the gizzard size than soybean meal (Pacheco *et al.*, 2013).

Particle size manipulation (4, 2.5, 2.0, 1.6, 1.25, 1.0, 0.63, 0.40, or 0.15 mm) did not significantly affect the weights of the small intestine of laying hens at 23 weeks of age (Rohe *et al.*, 2014). The same was reported by particle sizes 4 and 8 mm on the relative length of the small intestine (SI) and caecum of laying chickens at 52 weeks of age (Ege *et al.*, 2019). However, Frikha *et al.* (2011) reported that the weight of the digestive system and the length of jejunum were increased in pullets fed coarser feeds (10 mm) when compared to pullets fed finer diets (6 mm) during 1-45 days of age. Interestingly, the small intestine length was not affected by the whole-grain inclusion in the diet, but GIT weight and cecum length were increased when birds were fed with whole-grain sorghum in the diet. The increase in GIT weight could be due to the more significant development of mucosa of the intestine to digest whole grains in the diet (Fernandes *et al.*, 2013)

However, contrast results were obtained in broilers fed whole wheat grains from 7-29 days of age, resulting in lower duodenal weight (Gabriel *et al.*, 2003). Likewise, the relative length of SI was decreased in broilers fed coarse ground maize (7-mm screen) compared to fine ground maize (1-mm screen) (Amerah *et al.*, 2008). Nir *et al.* (1995) reported lower GIT weight and that its content in broilers by a coarse particle diet (1.413 mm for sorghum and 2.174 mm for wheat) than a fine particle diet (0.628 mm for sorghum and 0.681 mm for wheat). These inconsistent findings among research can be likely related to variations in the final particle size and ingredient composition of the meals among studies.

Although Mirghelenj and Golian (2009) and Ege *et al.* (2019) indicated that feed form (crumble vs. mash) did not affect the relative weights of proventriculus and crop. Mash feed also resulted in heavier gizzard than crumple feed in laying hens (Ege *et al.*, 2019). Additionally, during the first 10 days of the age of broilers, mash pre-starter feed increased relatively small intestinal length (cm/kg BW) considerably vs. crumple feed (Mahdavi *et al.*, 2018). That is attributed to the prolonged retention of mash feed in the gizzard; hence both the activity of the gizzard and intestinal reflux are improved. Conversely, highly processed pellet feed does not fully allow birds to develop their upper GIT.

In a study by Abdollahi *et al.* (2011), pellet-fed chicks had a significantly lower proventriculus and gizzard weight than mash-fed chicks. The authors explained that pellet feeding results in a smaller gizzard due to reduced grinding activity and finer particle size resulting from pelletizing. Using pellets to reduce feed particle size and evenly distribute finely and coarsely ground meals in wheat-based diets has been reported by Engberg *et al.* (2002). Their study found that pelleting decreased the fraction of feed particles larger than 1.0 mm from 209 g/kg to 135 g/kg for finely ground feed and from 262 g/kg to 149 g/kg for coarsely ground feed pelleting. The relative pancreas weight (Agah and Norollahi, 2008), pancreatic weights, and activity (Ravindran, 2013) in chicks fed the pelleted diet had lowered compared to those fed the mash diet. Abadi *et al.* (2019) found that pellet diets result in 17.8% lower pancreas and, 28% lower gizzard weights, and 10.6% heavier liver weights. Liu *et al.* (2015) stated that there was a negative correlation between the gizzard's pH and the relative weight of the gizzard. They indicated the significance of heavier gizzard weight in increasing grinding activity. The reduction of the grinding requirement of pelleted feed results in a lack of mechanical stimulation of gizzards and, thus, poor development in pellet-fed birds.

Interestingly, in contrast to the outcomes reported by the above studies, Ege *et al.* (2019) experimented with the impact of feed form on GIT traits of laying hens reared in cages and concluded that the liver weight and small intestine length were more significant by feeding crumble diet than mash diet. According to the authors, crumbling reduced the gizzard's need for grinding and, as a result, its function and feed transit time. Therefore, crumble-fed laying hens may lengthen their small intestine and liver to compensate for the effects of rapid feed passage on nutritional absorption and digestion.

**Impacts on gastric pH and digestive enzymes**

The crop is moderately acidic (pH = 5.5), the gizzard and proventriculus are acidic (pH = 2.5-3.5), and the intestine is moderately neutral to moderately alkaline (pH = 5.0-7.5). A 24-week feeding period on Lohmann LSL hens failed to significantly modify pH in GIT sections in response to the particle size of 5 and 8 mm (Kocer *et al.*, 2016). Similarly, crop, gizzard, small intestines, and caecum pH in laying hens did not significantly change when the screen size was raised from 4 to 8 mm (Ege *et al.*, 2019). Also, when feeding maize with particle sizes ranging from 557 to 1387 µm, the gizzard pH remained unchanged (Jacobs *et al.*, 2010). The pH of the digesta of 19 weeks laying hens was unaffected by the different feed particle sizes for 21 days (Ruhnke *et al.,* 2015). It appears unlikely that the differences in feed particle sizes between the different diets would result in any observable variations in the GIT PH.

Nevertheless, the pH of digestive organs displayed significant responses to the interaction between particle size and thermal treatment. Particle size in mash diets had no effect on gizzard pH; however, in pelleted diets, fine grinding (2 mm) raised gizzard pH relative to medium (5mm) and coarse (8mm) grinding (pH: 3.43 vs. 2.92 and 2.9, respectively) (Naderinejad *et al.,* 2016). Contrarily, fine expandate causes the pH of digesta in the lower GIT (ileum and excreta) to decrease (Ruhnke *et al.,* 2015). The authors attributed this effect to less stimulation of gizzard activity, resulting in a larger proportion of coarse particles in the lower part of the gastrointestinal tract.

Crumbling increased pancreatic amylase activities, while the manipulations in feed form and screen size (4 or 8 mm) did not affect lipase secretion (Ege *et al.,* 2019). Likewise, compared to mash feed, pancreatic protease and amylase activities were significantly increased in the broilers fed crumple pre-starter feed during the first 10 days of age. Still, lipase activity was not influenced in broiler chicks (Mahdavi *et al.,* 2018). Amylase activity and concurrent starch digestion may be anticipated to increase in crumbled diets because starch gelatinization occurs during the pelleting process, and exposure to steam conditioning enhances the availability of starch for enzymatic destruction (Svihus *et al.,* 2005; Abdollahi *et al.,* 2013b). The expression of genes for duodenal amino peptidase N was increased in broilers due to the coarse grain size of maize (3576 µm vs. fine, 1113 µm) in the pelleted diet (Kheravii *et al.,* 2018b). Additionally, Kheravii *et al.* (2018b) reported that the addition of dietary fiber (2% sugarcane bagasse) with coarse corn increased the expression of genes for pepsinogens A and C, pancreatic amylase (AMY2A), and intestinal cationic amino acid transporter-1 (CAT1). Enhanced gut motility and digestion retention time brought on by coarse feed component particles, particularly in the upper region of the GIT, have increased the production of digestive enzymes and nutrient transporters that encourage the digestion of nutrients and benefit the birds' growth and performance.

**Impacts on histomorphology of intestine**

Higher duodenal villi and deeper crypts were observed when the particle size of the feed ingredients was raised as well as in birds received pelleted feed compared to those received mash feed, indicating that the particle size and physical form influenced the microstructures of the small intestine in the feed (Dahlke *et al.,* 2003). Coarsely ground corn and wheat-based feed significantly increased the height or number of villi (Rohe *et al.,* 2014). Likewise, coarse ground corn (8mm vs. fine corn (2mm)) increased villus height (VH) and crypt depth (CD) of duodenum without any change of those of jejunum in broiler chickens fed pelleted diet during 1$^{st}$ 20 days of age (Moradi *et al.,* 2021). The longest duodenal villus was seen in broiler birds that were fed a corn-soybean-based diet containing dietary fiber (4% Soyhulls with a coarse particle size of 600 µm) from 1-20 days of age while the group that consumed 8% cellulose as a dietary fiber in the form of fine particles 100 µm had the least jejunal villus height (Tejeda and Kim, 2021). Numerous experiments have determined that the longer VH indicates a greater luminal surface area for the absorption of nutrients. Finer feed particles may significantly alter the morphology of the intestine, which can influence the function and secretion of digestive enzymes and consequently affect feed digestibility (Zang *et al.,* 2009).

But conversely, there was no significant difference between broilers fed the coarse diet and fine diet regarding CD, VH, and VH/CD ratio within the ileum, jejunum, or duodenum (Zang *et al.,* 2009). Similarly, layer birds' villus parameters (VH, VH/CD ratio, and villus surface area) are unresponsive to the particle size of the diet (Ege *et al.,* 2019). Table 1 shows the effect of feed particle sizes on the GIT in poultry.

CD and VH were significantly higher in broilers fed crumple pre-starter feed during 1$^{st}$ 10 days of age than those fed mash feed, but villus width (VW), villus surface area (VSA), and VH/CD were not influenced by feed forms, suggesting that feeding crumble meal during the first 10 days of life improved intestinal histomorphology (Mahdavi *et al.,* 2018).

Abadi *et al.* (2019) evaluated the effect of pellet binder, particle size, and feed form on growth indices, intestinal morphology digestive tract parameters of broilers aged 25-42 days. They reported that birds fed pellets had higher VH to CD ratio in the jejunum and duodenum sections when compared to those fed mash diets. The effect of feed form on intestinal morphology parameters has been evaluated in a corn-based diet (Zang *et al.*, 2009; Naderinejad *et al.,* 2016) and indicated increasing VH and VH/CD of pellet-fed broilers. This increase in VH/CD ratio resulted in improved nutrient digestibility and growth performance in broiler chickens (Zang *et al.*, 2009). These results are a general response of the absorptive and digestive capacity to the better load of nutrients in birds receiving the pelleted feed. The longer the villi, the bigger the VSA acquired and the more intestinal enzyme release, resulting in high intestine digestion and absorption function. Table 2 shows the impact of feed form on GIT in poultry.

**Table 1.** Effect of feed particle sizes on poultry's gastrointestinal tract (GIT)

| Bird type | Grain type | Particle size | Results | Reference |
|---|---|---|---|---|
| Broiler | Wheat | 0.839 - 1.164 mm | Increased gut component weight | Amerah *et al.* (2007) |
| Layer | Corn & wheat | 1.8 mm | Coarse grinding increased the gizzard and pancreas weight | Ege *et al.* (2019) |
| Broiler | Corn & rice | 0.29 – 1.36 mm | Intestinal length not affected | Xu *et al.* (2015a) |
| Broiler | Wheat & barley | Whole | Increased gizzard proportional mass and digesta viscosity and decreased proventriculus proportional mass | Taylor *et al.* (2010) |
| Broiler | Corn | 0.46, 0.73 & 0.87 mm | Fine ground maize Decreased gizzard and proventriculus weight | Benedetti *et al.* (2011) |
| Broiler | Corn & wheat | 1.17, 0.74 &0.57 mm | Increasing the particle size increased the gizzard's weight | Arce-Menocal *et al.* (2020) |
| Broiler | Corn | 0.79 & 1.40 mm | Fine particle size decreased the gizzard's weight | Selle *et al.* (2019) |
| Broiler | Corn | 2.0, 5.0 & 8.0 mm | Coarse grinding increased gizzard weight ,villi height and feed intake Fine grinding increase gizzard pH | Naderinejad *et al.* (2016) |
| Layer | Corn & wheat | 4, 2.5, 2.0, 1.6, 1.25, 1.0, 0.63, 0.40, & 0.15 mm | Higher proventriculus, gizzard and pancreas weights and higher villi height feeding coarsely-ground feed | Rohe *et al.* (2014) |
| Layer | Corn | 5 & 8 mm | Cracked-broken egg rate, egg weight, and egg production rate were not affected by particle size | Kocer *et al.* (2016) |
| Broiler | Corn & wheat | 0.59-0.95 mm | Increased gizzard weight | Kiarie and Mills (2019) |
| Broiler | Corn | 0.65-1.3 mm | Weight of small intestine and gizzard was not affected | Rezaeipour and Gazani (2014) |
| Layer | Corn & barley | 4, 6, 8, 10, & 12 mm | Increasing the screen size linearly augmented the relative weight of the gizzard, liver and GIT | Herrera *et al.* (2017) |

**Table 2.** Impact of feed form on GIT in poultry

| Bird type | Grain type | Feed Form | Effect | Reference |
|---|---|---|---|---|
| Broiler | Sorghum | Mash, pellet | Pellet-fed chicks had a significantly lower proventriculus and gizzard weight than mash-fed chicks. | Abdollahi *et al.* (2014) |
| Broiler | Corn | Mash, pellet | Pellet-fed chicks had significantly lower intestinal pH and higher gizzard pH and weights of gizzard and pancreas than mash-fed chicks. | Engberg *et al.* (2002) |
| Broiler | Corn & wheat | Mash, pellet, crumbles | Pellet-fed chicks had significantly decreased pancreas and gizzard weights | Agah and Norollahi (2008) |
| Broiler | Corn | Mash, pellet | Pellet feed had significantly decreased gizzard and pancreas weights and intestinal length. | Abdollahi *et al.* (2013a) |
| Broiler | Corn | Mash, pellet | pelleted diets result in 28% lower gizzard and 17.8% lower pancreas weights, as well as 10.6% heavier liver weights | Abadi *et al.* (2019) |
| Broiler | Corn | Mash, pellet | Pellet-fed chicks had significantly decreased pancreas and gizzard weights | Naderinejad *et al.* (2016) |
| Layer | Corn | Mash, crumble | Length of the small intestines and liver weight were greater in crumble-fed hens than in mash-fed hens | Ege *et al.* (2019) |

**Impacts on intestinal microflora**

Numerous studies highlighted the feed particle size effects on intestinal microflora. A fully functional gizzard improves the gut environment through more efficient digestion and longer digesta retention time (Zaefarian *et al.,* 2016). The finer particles in the diet allow digesta to move more quickly into the duodenum and spend less period in the gizzard. Thus, a relatively more undigested material is revealed in the small intestine, which might increase the presence of pathogenic bacteria, for instance, *E. coli* and *C. perfringens* (Kheravii *et al.,* 2018a). High acidity increases the chances of harmful bacteria being suppressed in the intestinal tract. Huang *et al.* (2006) examined the influence of physical feed properties on *Salmonella* colonization in GIT of broilers using the *S. enterica* serovar Typhimurium DT12 model developed via Mikkelsen *et al.* (2004). The death rate of birds suffering from *S. enterica* serovar Typhimurium DT12 was lower in birds fed fine particles (0.3 mm) than in birds fed coarse particles (0.9 mm). Because of the relatively higher pH in the gizzard of birds feeding, a fine particle diet was associated with fewer deaths caused by *S. enterica* serovar Typhimurium DT12 in the gizzard contents of birds fed this diet. In terms of ceca and small intestine health and function, there are a few data regarding changes in gizzard ecology. Prescott *et al.* (2016) highlighted the connection between GIT ecology, which favors the growth of Necrotic enteritis (NE), and *C. perfringens*, the most severe disease among broilers worldwide. Prescott *et al.* (2016) reported characteristic necrotic lesions in the mid-GIT region during this disease, adversely affecting digestion and absorption. Accordingly, *Eimeria* and *C. perfringens* must be prevented from multiplying in GITs to control NE (Williams, 2005). In addition to the morphological and physiological characteristics of the gut, the particle size of the feed may also affect the microbial status of the gut, and small particles stimulate faster growth of *C. perfringens* than large particles (Engberg et al., 2002). This phenomenon is peculiar because large quantities of undigested protein form toxic compounds such as indoles, ammonia, amines, thiols, and phenols in the ceca. Most importantly, these substances increase the pH levels of the ceca, making it ideal for the propagation of pathogenic bacteria like *Clostridium spp.* (Timbermont *et al.,* 2011). Consequently, a well-developed gizzard, resulting from coarse grain particle size, will increase protein and amino digestion, causing pathogens in the lower digestive tract to be reduced. The coarsely or whole ground grain feed induces the foregut grinding activity and digesta retention period, thus enhancing the fermentation because of the availability of bacteria of the *Streptococci*, *Lactobacilli*, and *Coliform spp.* in the crop (Goodarzi *et al.,* 2016). In a study done by Yan *et al.* (2022), who investigated the effect of using a mixed regimen of particle size through starter, grower, and finisher diets for broiler for 37 days, the amount of *Lactobacillus* was improved. *Peptostreptococcus* and *Acinetobacter* were reduced in the ileum by feeding them finely ground corn between days 1 and 13 and coarsely ground corn between days 14 and 23 and between days 24 and 37**.** Nevertheless. neither coarse grinding (8mm) nor fine grinding (2mm) of corn in pelleted feed altered the caecal microbial population (*E. coli, Lactobacillus,* and total anaerobic bacteria) of Ross broiler starters on day 21. But the addition of dietary fiber (oat, rice, or sunflower hulls) to fine-ground corn increased counts of caecal Lactobacillus spp. and total anaerobic bacteria significantly compared to the control diet in fine-ground corn diets with no observable effect when added to course ground corn (Moradi *et al.*, 2021). However, Abadi *et al.* (2019) reported that coarse particles (6 mm) induced a higher cecal population of lactic acid and spore-forming bacteria spp. than fine particles (2mm) in the broiler at 42 days. Moreover, coarsely ground grain feed increases caecal beneficial bacteria, such as *Lactobacillus,* and decreases pathogenic bacteria, such as *Clostridium*, *E. coli,* and *Salmonella* spp. (Xu, 2014; Di Cerbo *et al.,* 2014). The feed form did not affect the cecal microflora population (Lactic acid bacteria, coliform spp., and *Clostridium* spp.) in broiler chickens on day 42, but spore-forming bacteria spp. population was significantly increased by pellet feed compared to mash feed and the lowest *Clostridium* spp. count was obtained by pellet course feed with a 3% binder (Abadi *et al.,* 2019). The mechanism of beneficial bacterial proliferation in response to particle size changes needs more investigation. In this way, the seeding of these bacteria in chickens' intestines and hind guts may be expected to increase. Having a high count of beneficial bacteria can induce the publication of health-promoting constituents, like flavonoids, which are said to contribute to bird health (Sulek *et al.,* 2014), provide intestinal protection, and enhance both innate and acquired immunity (Calixto *et al.*, 2004). Furthermore, the digestive enzyme activity of trypsin, proteases and lipases can be improved by promoting the growth of specific bacteria such as *Lactobacillus* and *Bifidobacterium* (Clavijo and Florez, 2018). Therefore, chicken diets consisting of coarse grains may develop good intestinal health, which is particularly beneficial when antibiotics are not supplemented with chicken feed (Palmieri *et al.,* 2014; Gallo *et al.*, 2017; Di Cerbo *et al*., 2020).

**Impacts on passage rate**

The digesta retention time affects the digestion of nutrients. Increased gizzard retention time elongates the time for the secretion of pepsin and HCl and the time for feed exposure to exogenous enzymes and increasing increase its efficiency (Svihus, 2011) as well as increases gastric refluxes that re-expose the digesta to pepsin enzyme (González-Alvarado *et al.*, 2008; Svihus, 2011) resulting in improved digestion. More mechanical stimulation occurs in the gizzard and the exposure time of nutrients to intestinal enzymes is increased because coarse particles prolong the digestive transit time in the gizzard (Zaefarian *et al.*, 2016). Transit time of digesta through the small intestine is increased for diets with ground wheat when compared with whole wheat (Svihus *et al.*, 2002). Xu *et al.* (2015a) interpreted the improved histomorphological structure of jejunum to feed course corn particle size that elongates the digesta retention period, thus enabling increased contact between the nutrients and villi and increasing absorption capacity.

Nevertheless, fine-ground meals move through the digestive system more slowly than coarse-ground diets. Moradi *et al.* (2021) reported no difference in the transit time of digesta (162 min) by increasing the particle size of corn from 2mm to 8 mm in the broiler during 1st 21 days of age. Similarly, Naderinejad *et al.* (2016) reported that the digesta transit time did not vary by the mash feed composed of fine (2mm), medium (5mm), or course (8mm) maize particle size which was 162, 161, or 161 min, respectively and the pellet feed composed of fine, medium or coarse particle size which was 153, 154, or 163 min, respectively in broiler chickens throughout a 21- day trial. While laying chickens, no studies have investigated the effect of particle size of feed form on the passage time of digesta.

**Impacts on mineral retention**

Kilburn and Edwards (2001) studied the relationship between maize particle size and mineral retention in broilers. They observed that a coarse maize (GMD 2897 µm) diet boosted tibia ash, calcium, and phytate phosphorus retention in broilers. Conversely, lower dyschondroplasia of tibial incidence was seen when a diet containing fine maize. The coarse maize had enhanced bone ash when given to chicks fed phosphorus-deficient diets compared to fine maize, indicating that particle size and phosphorus concentration interact significantly. However, this result was not seen when both diets were phosphorus-adequate. Significant interactions were reported between forms of feed and corn particle size. When coarse maize diets were pelletized, calcium retention was reduced. The plasma dialysable phosphorus level increased in broilers rose on coarse maize feed when their diets were fed as a mash, but this response was eliminated when their diets were pelleted.

According to Parsons *et al.* (2006), broilers' efficiency at retaining nitrogen and lysine was improved by dietary course corn addition. Xu *et al.* (2015a) found that including course corn (630µm in grower and 651µm in finisher diets) in broiler diets for 0-49 days improved peptic digestion and amino acid absorption, as well as increased intestinal reverse peristalsis or morphology of gastrointestinal tract.

Some trace minerals in egg contents in laying hens were retained differently due to the interaction between particle size and thermal treatment. Hafeez *et al.* (2015) reported that the retention of a few trace elements (iron and zinc in egg contents) was improved when the coarse particle size was combined with both the mash and expandate forms when compared to fine feed particles with mash and expandate forms.

**Impacts on litter quality**

Many management and nutritional strategies, including bedding sources and coarse ingredients in chicken feed, were used to reduce the litter moisture during the chicken's lifespan (Kheravii *et al.*, 2017a,b). Literature regarding the impact of particle size on the quality of litter is rare. Xu *et al.* (2015c) and Xu *et al.* (2017) noted that replacing the finely grounded corn in a pellet form of broiler feed with coarse-ground corn significantly reduced moisture and nitrogen in the litter. They clarified that using about 50% of coarsely grounded maize decreased ammonia concentration and moisture content in the litter, but the mechanism for this phenomenon needs to be better understood. Nevertheless, Carre *et al.* (2002) found a negative correlation between water excretion and coarse wheat particles, indicating that increased digesta retention time in the GIT may allow for greater water reabsorption. More research is needed to understand the factors influencing litter quality improvement.

**Impacts on feed intake**

The impact of particle size of ingredients is different for pelleted and mash diets. Generally, it is believed that, due to the birds' sorting behavior, the particle size effect is more noticeable in mash feed than in a pelleted diet. However, researchers have also reported a significant impact of particle size on feed intake, even for pellet feed. For instance, Naderinejad *et al.* (2016) found that the pelletizing of the diet of different sizes has improved the performance of the birds. Pullets fed crumbles, for 1-112 days old, significantly consumed less feed (46.2 g) and had better FCR than those fed mashes (47.1 g) (Bozkurt *et al.*, 2019). However, compared to broilers fed crumbles or pellets from 1-25 days old, those fed mashes had significantly lower daily feed intake (52, 58.1, and 62.7 g, respectively) and daily weight gain and a poorer FCR (Serrano *et al.*, 2013). Course pelleting of diets (953 µm) resulted in greater average daily feed intake than course mash diet during starter (day 0-21: 54 vs. 48.2), grower (day 22-42: 160.1 vs.

152.4) and overall periods (day 0-42: 107.1 vs. 100.3) in broiler chickens. Also, the fine pellet diet (597µm) induced higher feed intake than the fine mash diet (Zang *et al.,* 2009). Attia *et al.* (2014) reported a decreasing level of FI by increasing the size of pellets in 21-day-old broilers till 37 days old where feeding mash, pellets 2-2mm, pellets 2-3 mm, and pellets 3-3.5mm induced feed consumption of 2439, 2232, 2211, and 2199 g/bird, respectively. Crumbling the feed (2- to 3-mm pieces) for laying hens during 21-52 weeks of age increased feed intake significantly (114.8 g/day) compared to those after mashing (107.8 g/day) (Ege *et al.,* 2019). Jia and Slominski (2010) found that finely ground flaxseed (15%) in a mashed corn-soybean diet for broiler chickens from day 5-18 decreased feed intake significantly compared to a pelleted diet whether containing ground [course (3.5 mm) or fine (2 mm)] or whole flaxseeds. However, the different particle sizes of corn (5 vs. 3 mm) in the mash or pellet diet didn't show a significant difference in the feed intake of broilers (Zang *et al.*, 2009). Likewise, Chewning *et al.* (2012) noticed no relation between particle size and feed intake when the feed was in pellet form. Coarse grinding cereals (8 mm) improved FCR without significant alterations in feed intake compared to that of fine grinding (4 mm) for pullets from (1-112 days of age) (Bozkurt *et al.,* 2019). In addition, Ege *et al.* (2019) reported that no effect was evident on the feed intake of laying hens during 21-52 weeks of age by increasing cereal particle size from 4 mm to 8 mm. Nevertheless, it was reported that increasing the particle size of corn or wheat from fine (6 mm) and medium (8 mm) to course (10 mm) size significantly increased the feed intake (107.9, 108, and 110.6 g/day, respectively) in layer hens in the period 20-48 weeks of age (Safaa *et al.,* 2009).

**Impacts on digestibility of feed**

Although the data regarding the impact of particle size on digestibility is scarce, some studies are available on this aspect. The logic hypothesis is that fine feed particle size has a greater surface area and may increase the contact of the digesta with digestive enzymes in the GIT, improving nutrient digestibility. In agreement with that, a reduction in feed particle size can significantly increase AME in 19 to 21-d broilers (Kilburn and Edwards, 2001; Zang *et al.*, 2009). The outcomes reported by Crevieu *et al.* (1997) showed that the fine-ground feed augmented the apparent crude protein digestibility compared with the coarse-ground meal. Digestion coefficients of protein and dry matter showed no response to changes in feed form (crumble or mash) and particle size (4 and 8 mm) in Hybrid layer hens from 21 to 52 weeks of age (Ege *et al.,* 2019). However, ileal gross energy and protein digestibility increased in broilers fed coarse corn particle size (2,982 µm) compared to those fed fine particles (941 µm) at d 24 (Kheravii *et al.,* 2017b). Likewise, in broilers at day 24, coarsely ground corn (3,576 µm) resulted in improved ileal protein digestibility more than finely ground corn (1,113 µm) (Kheravii *et al.,* 2018c).

The apparent digestibility % of dry matter, crude protein, ether extract, and crude fiber of broilers during days 21-37 of age was investigated by feeding mash vs pellets (2-2, 2-3, and 3-3.5mm) by Attia *et al.* (2014). They showed that any feed forms did not alter the digestibility of dry matter. In contrast, the lowest significant digestibility of crude protein, fiber, and ether extract was observed for mash feed without significant differences between different sizes of pellets.

Ileal digestibility of starch in 19 weeks aged layers in a 21 d- trial was significantly improved by feeding coarse compared to fine feed (96.9% vs. 95.7%, respectively) and by feeding mash compared to expandate (97.3% vs. 95.9%, respectively) (Ruhnke *et al.*, 2015). An interaction between particle size and thermal treatment was observed for starch digestibility (94.5% by fine particles of expandate compared to 97.0% by coarse mash) (Ruhnke *et al.*, 2015).

Fine particle size (4 mm) increased the digestibility coefficient of crude ash and ether extract (54.25 and 81.40, respectively) more than course particle size (8 mm) (50.12 and 77.17, respectively) in layer hens from 21 to 52 weeks of age, but neither crumble nor mash feed affected them (Ege *et al.,* 2019). Ileal fat digestibility was boosted by reducing flaxseed particle size through grinding (a course or fine). Still, it did not affect broiler chicken growth performance (from 5-18 days) in either mash or pelleted diets (Jia and Slominski, 2010).

Broiler chickens fed mash diets for 36 h (20–22 d of age) containing fine limestone (LM) (150 µm) showed lower standardized ileal digestibility (SID) of Ca (38.09%) than coarse LM (800 µm) (49.18%), regardless of phytase use as well as SID of P was lower with either 0 or 1,000 phytase U/kg (Li *et al.,* 2021). In a similar vein, Kim *et al.* (2019) found that, independent of phytase addition, smaller particle size LM milled from the same source had significantly lower apparent ileal Ca digestibility than bigger particle size LM. Whatever the ratio of calcium to phytate-P in the diet. Regardless of the diet Ca to phytate-P ratio, According to Anwar et al. (2016), an LM's Ca retention increased with larger particle size portions (1,000–2,000 µm) compared with smaller particle size portions (<500 µm). Therefore, increased LM solubility from the same LM source due to smaller LM particle size is not advantageous and is detrimental to Ca and P digestibility. Moradi *et al.* (2021) reported a higher coefficient of apparent ileal digestibility (CAID) of phosphorus in broiler chickens on day 21 by feeding course corn particles (1071 µm) than fine particles (534 µm) (CAID of

0.493 vs. 0.528, respectively), while CAID of protein, fat, ash, and ca did not show any alterations.

In 19-week-old layers, the apparent total digestibility (ATD) was higher for phosphorus and lower for iron by feeding fine feed particle size (<1.8 mm) than course feed particle size (>1.8mm), and the ATD of iron was higher in the mash feed composed of course particles compared to the mash contained fine particles (Hafeez *et al.,* 2015).

The possible causes for the difference between the investigations have yet to be clarified. For instance, the milling methods influenced the ATD of copper and iron but did not affect the ATD of other minerals and trace elements. Moreover, an interaction effect between the milling method and thermal treatment on the ATD of magnesium and iron was observed (Hafeez *et al.,* 2015). Other factors affecting the size distribution, size, and particle shape when feed ingredients are ground, like the content of dry matter of tested substance, may also vary. Furthermore, even though the geometric mean diameters were comparable, the particle size distribution might have been different (Kiarie and Mills, 2019).

**Conclusion**

It can be concluded that feed form and particle size have various impacts on the poultry gut function, shape, and overall morphology, with a promising effect on the poultry industry. Increasing the feed particle size as the chicks get older is recommended. In addition, pelleting is a trending field for use in poultry. However, increasing the particle size to the recommended level and using used in pellets requires a high quality of pelleting indicated by the pellet durability and hardness values. More attention should be paid to the use of pellet binders, their types, and their impacts on other nutrients and bird performance. The feed particle size that leads to better economy in mass egg production unit for modern laying hens should be studied.

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