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Article in *World's Poultry Science Journal* · October 2007

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Feed particle size: Implications on the digestion and performance of poultry

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This review highlights the limited amount of research conducted regarding the optimum particle size of different feeds for efficient poultry production. The current industry practice of using highly processed, pelleted diets masks the influence of particle size, but some reports suggest that the effects of feed particle size on performance may be maintained even after pelleting. There appears to be a general consensus that particle sizes of broiler diets based on maize or sorghum, optimum particle size should be between 600 and 900 μm . Available data clearly show that grain particle size is more critical in mash diets than in pelleted or crumble diets. Although it has been postulated that finer grinding increases substrate availability for enzymatic digestion, there is evidence that coarser grinding to a more uniform particle size improves the performance of birds maintained on mash diets. This counter-intuitive effect may result from the positive effect of feed particle size on gizzard development. A more developed gizzard is associated with increased grinding activity, resulting in increased gut motility and greater digestion of nutrients. Although grinding to fine particle size is thought to improve pellet quality, it will markedly increase energy consumption during milling. Systematic investigations on the relationships of feed particle size and diet uniformity with bird performance, gut health and pellet quality are warranted if efficiency is to be optimised in respect of the energy expenditure of grinding.

Keywords: particle size; feed form; gizzard development; pellet quality; poultry

Introduction

The first stage in the manufacture of commercial poultry feed involves the blending of ground seeds with protein meals. The feed industry has little control over the particle size of protein meals, such as soybean meal and meat meal, as they are supplied pre-ground by the processor. However, the particle size of seeds, including cereals and legumes, may vary at the feed mill.

Particle size reduction is a two-step process involving the disruption of outer seed coat and the exposure of endosperm. Continued reduction increases both the number of particles and the surface area per unit volume allowing greater access to digestive enzymes (Goodband *et al.*, 2002). Other benefits include increased ease of handling and easier mixing of the ingredients (Koch, 1996). However, there are practical limits to the degree of particle size reduction, as the birds may encounter difficulties in consuming very coarse or very fine particles.

In recent years, the interest in feed particle size has increased, as the industry continues to search for ways of optimising feed utilisation and improving production efficiency. Recommendations regarding optimum particle size, however, have been contradictory, as the results from feeding trials are confounded by a number of factors including feed physical form, complexity of the diet, grain type, endosperm hardness, grinding method, pellet quality and particle size distribution.

The extent of milling these seeds is known to influence a number of aspects of poultry production, including bird performance and digestive tract development. The aim of this paper is to review the published data on the influence of feed particle size on these aspects and, to highlight its implications for gut health and functionality. Data regarding the quantitative effects of degree of grinding on energy cost and pellet quality are also discussed.

Measurement of particle size

Size can be defined as the average diameter of individual particles of feed or simply the “fineness of grind” of the feed. Early researchers (Eley and Bell, 1948; Davis *et al.*, 1951) used the general terms ‘fine, medium and coarse’ to describe particle size, but these terms prevent meaningful comparisons of data. To overcome these limitations, the American Society of Agricultural Engineers (1983) developed methods to describe particle sizes more specifically. The average particle size is given as geometric mean diameter (GMD), expressed in mm or microns (μm) and the range of variation is described by geometric standard deviation (GSD), with a larger GSD representing lower uniformity. GMD and GSD are accurate descriptors only when particle size distribution, expressed as log data, are distributed parametrically, *i.e.* log normally (Lucas, 2004).

Feed particle size is typically determined by dry sieving of a 100-gram representative sample (Baker and Herrman, 2002). The feed sample is passed through a sieve stack on a shaker for 10 minutes. The amount of particles retained on each screen size is then determined, and the GMD and GSD of the sample calculated using standard formula or computer software. Particle size distribution may also be determined by wet sieving, but this method is used more often on digesta and excreta samples. In the wet sieving method, feed samples are suspended in 50 ml of water and left to stand for 30 min prior to sieving to ensure adequate hydration (Lentle *et al.*, 2006). The sample is then washed through a set of sieves and the material retained on each sieve, plus a representative sample of elute, is subsequently filtered and dried for 24h at 80°C. The weight of the retained particles from each sieve are then expressed as percent of total dry matter recovered.

Methods of particle size reduction

Two processing methods are commonly used to reduce the particle size of the grains; the hammer mill and the roller mill (Koch, 1996; Waldroup, 1997).

HAMMER MILL

This mill comprises a set of hammers moving at high speed in a grinding chamber, which reduce the size of the grains until the particles are able to pass through a screen of designated size. Thus, the size and spectrum of particles produced depends on the screen size and the hammer speed (Koch, 1996). The efficiency of the hammer mill is influenced by a number of factors, including grain type, grain moisture content, screen size, screen area, peripheral speed, hammer width and design, number of hammers, hammer tip to screen clearance, feed rate, power of the motor and speed of air flow through the mill (Martin, 1985).

ROLLER MILL

The roller mill comprises of one or more pairs of horizontal rollers in a supporting frame, the distance between which may be varied according to the particle size required. The grains size is reduced by a constant compression force as they pass between the rotating rollers.

Roller mills are more efficient and require less energy for grinding than the hammer mill. The roller mill produces a more uniform particle size distribution with lower a proportion of fines (GMD, < 500 μm) than the hammer mill (Nir and Ptichi, 2001), although the particle size and spectrum may vary with the type of corrugation on the rollers and the type of the grain (Martin, 1985). Undersized grains may escape the grinding process in the roller mill (Douglas *et al.*, 1990) and the shape of the particles produced is more irregular, being cubic or rectangular (Koch, 1996) compared to those from a hammer mill, which tend to be spherical with more uniform shape (Reece *et al.*, 1985). Commercially the hammer mill is more commonly used for grinding grains because it is easier to use and maintain.

The particle size of milled product is influenced by grain type. Several studies have shown that grinding different grains with the same mill under similar conditions would give products with different particle sizes (*Table 1*). These observations suggest that, during grinding, different screen sizes may have to be used according to the grain type to obtain the desired particle size distribution. But it must be noted that even within a grain type, grinding in the same mill type under similar conditions may result in different particle sizes due to variations in endosperm hardness. Lentle *et al.* (2006) reported that grinding grains from three cultivars of wheat in a hammer mill through the same sieve resulted in different particle size distributions.

Endosperm hardness and grain particle size

The hardness of a grain sample is related to the percentage of fine particles obtained after grinding, with a higher percentage of fine particles from lower hardness grains (Carre *et al.*, 2005). Endosperm hardness in wheat cultivars is known to influence the milling outcome. A harder endosperm gives larger particles with more irregular shapes, while a soft endosperm will produce smaller size particles (Rose *et al.*, 2001). This effect may be responsible for the better broiler performance reported with mash diets based on hard wheats (Rose *et al.*, 2001; Pirgozliev *et al.*, 2003).

Effect of grinding method on broiler performance

Hammer and roller mill grindings had no effect on broiler performance, when diets of similar geometric mean particle diameter were compared (Nir *et al.*, 1990). GMD is an

accurate descriptor of particle size distribution only when log particle size is normally distributed (Lucas, 2004) and as the hammer mill grinding produces a greater amount of fine particles (Reece *et al.*, 1985), which may confound results.

Effect of particle size and particle size distribution on performance

It must be recognised that not only the size of the feed particles, but also uniformity of particles size, is relevant in determining the influence of particle size on bird performance. Both particle size and shape may influence bird performance (Axe, 1995). Birds distinguish the differences in feed particle size by mechanoreceptors located in the beak (Gentle, 1979). Chickens are known to have a preference for larger feed particles (Schiffman, 1968), which is observed at all ages (Portella *et al.*, 1988) and particle size preference is thought to increase with age (Nir *et al.*, 1994b). This may be related to the size of the bird's 'gape' (the width of the beak). Whilst beak width increases with age (Gentle, 1979), there are no published data relating preferred particle size to gape. It is possible that the particle size must be increased with age for optimum poultry performance.

A more uniform diet will reduce the time spent searching for and selecting larger particles, with beneficial effects on performance. Using maize-soy diets in mash form, Nir *et al.* (1994a) have shown that diets with lower GSD gave better weight gain and feed efficiency. Despite this importance, only limited studies have been carried out on the effects of particle size uniformity for different cereal grains in poultry feeds. This lack of interest may be due to the fact that the majority of the feed used in the production of broilers is fed as pelleted or crumbled feed, where there is no opportunity for selection of particles of different sizes (Reece *et al.*, 1986a).

Effect of physical form of feed - mash versus pellets

Interaction between particle size and feed physical form in broiler diets for weight gain and feed intake is well documented. Available data clearly suggest that grain particle size is more critical in mash feeds, than in pelleted or crumbled feeds (Reece *et al.*, 1985, 1986a; Cabrera, 1994; Hamilton and Proudfoot, 1995a; Nir *et al.*, 1995; Svihus *et al.*, 2004a; Peron *et al.*, 2005).

Pelleting is known to improve weight gain, feed intake and feed efficiency in broilers regardless of the grain source (Calet, 1965; Douglas *et al.*, 1990; Nir *et al.*, 1995; Jensen, 2000; Nir and Ptichi, 2001). These improvements have been attributed *inter alia* to higher density, improved starch digestibility resulting from chemical changes during pelleting, increased nutrient intake, changes in physical form, reduced feed wastage and decreased energy spent for eating (Calet, 1965; Jensen, 2000). Similar improvements have been reported in laying hens (Morgan and Heywang, 1941). In contrast, Hamilton and Proudfoot (1995b) reported that layers fed a mash diet performed better than those fed a crumbled diet.

Effect of grain particle size on bird performance in mash diets

Most studies on the effects of particle size reduction in mash diets have been conducted with maize or sorghum (*Table 2*). One of the earliest reports suggested that maize-based mash diets of larger particle size increased feed consumption and decreased feed wastage,

without influencing weight gain (Eley and Bell, 1948). In contrast, another early work showed that cracked maize are selected in preference to the rest of the ration, which resulted in significantly poorer growth and feed efficiency (Davis *et al.*, 1951). Subsequent studies, however, have confirmed the beneficial effects of medium or coarse grinding in mash diets (Reece *et al.*, 1985; Reece *et al.*, 1986a,b; Nir, 1987; Proudfoot and Hulan, 1989; Nir *et al.*, 1990; Nir *et al.*, 1994a,b; Hamilton and Proudfoot, 1995a; Nir *et al.*, 1995). Reece *et al.* (1985) fed mash diets based on maize ground by hammer mill (GMD, 814 μm) and roller mill (GMD, 1343 μm) to broiler starters, and observed better performance in birds fed coarse particle size in terms of weight gain and feed efficiency. Similar results have been reported by Proudfoot and Hulan (1989) and Hamilton and Proudfoot (1995a) who found that weight gain was improved when birds were fed mash diets containing coarse or very coarse maize particles compared to those containing fine particles.

Similar effects are reported with sorghum grain, ground in hammer and roller mills to produce particle size fractions with GMD of 536-574 μm (fine), 671-773 μm (medium) and 871-905 μm (coarse) which were fed as mash diets (Nir *et al.*, 1990). Feed intake increased on the coarser particle diets as did weight gain, with no deleterious effect on feed efficiency.

Nir *et al.* (1995) reported that broilers fed wheat and sorghum mash diets with coarser particles had heavier body weights and better feed efficiency compared to those fed the finely ground diets. Amerah *et al.* (2007a) also found that broilers fed fine particle wheat mash had lower weight gains and feed intake, and higher feed/gain than those fed medium or coarse particle mash diets. It was observed that the digestive tract of birds fed the fine particle mash diet became severely impacted, which may have been caused by highly viscous digesta from finely ground wheat. High digesta viscosity has been reported in birds fed fine mash diets compared to those fed medium or coarse wheat diets (Yasar, 2003).

In contrast, Douglas *et al.* (1990) reported that mash feeding of coarser particle diets of either sorghum or maize that were ground in a roller mill (GMD, 1470-1800 μm) depressed weight gain and feed efficiency in broilers compared with those fed diets with finely hammer milled grains (GMD, 833-947 μm). The poor performance of birds fed large particles was attributed to the preferential selection of large particles but, as noted previously, may equally have resulted from differences in the particulate spectra from the two methods of milling.

It appears that these effects of feed particle size may be influenced by age of birds. When Nir *et al.* (1994b) compared maize, wheat or sorghum based diets that were ground in a hammer mill to differing particle sizes but nearly similar GSD, no significant differences in performance were observed in 7-day old chicks, whilst performance was improved in 21-day old birds that consumed medium and coarse mash diets compared with those that were fed the fine mash diet.

There is some evidence that very coarse particles may adversely influence the performance in young birds. Particle sizes larger than 1000 μm are thought to be too large for chicks to utilise efficiently, as their passage through the gizzard is slower (Lott *et al.*, 1992), possibly because the undeveloped gizzard is physically unable to break down large grains (Covasa and Forbes, 1996). This may explain the poor performance observed when chicks are fed mash diets based on cracked maize (Davis *et al.*, 1951) and very coarse particles (Douglas *et al.*, 1990) from day 1 post hatch. A parallel situation occurs when whole grains are fed, and it has been observed by Ravindran *et al.* (2006) that young chicks have difficulties in swallowing whole wheat during the first few days of life. These researchers found that, when chicks are fed diets with whole wheat from day 1, the birds grow slower and eat less feed compared to those fed ground wheat diets. Thus, optimum

particle size probably varies with the rate of development of the digestive system, the beak dimensions and the gape (Portella *et al.*, 1988). Once adequate gizzard development is attained, improvements in performance associated with the feeding of coarser, more uniform particles may be partly explained by the lower energy input required by birds when they ingest coarser particles. It is known that the number of pecks to consume a given amount of feed is reduced when particle size increases (Jensen *et al.*, 1962). In general, published data suggest that medium and coarse grindings are advantageous to improve the performance of broilers fed mash diets and that these beneficial effects are greater in diets of better particle uniformity. General recommendations for final grain GMD from hatch to market weight for broilers have been suggested by Nir and Ptichi (2001), and these values are presented in *Table 3*. However, it should be noted that uniformity of the diet should also be considered and that fine particles less than 600 μm GMD should be avoided at all ages (Waldroup, 1997). Based on available published data, it may be concluded that the optimum feed particle size lies between 600 and 900 μm for broiler diets based on maize or sorghum.

Although laying hens are usually fed mash diets, studies that examine the effects of feed particle size on their performance are limited. Early work suggested that neither egg production nor body weight gain were influenced by the particle size (Berg and Bearnse, 1948). Subsequent work showed no difference in layer performance between hens fed hammer milled maize diets with particle GMD ranging from 814 to 873 μm or with roller milled maize diets with GMD ranging from 1343 to 1501 μm (Deaton *et al.*, 1989). Hamilton and Proudfoot (1995b) similarly found that the effect of grain particle size in layer diets was of lesser importance than the physical form of the feed. In contrast, Cabrera (1994) found that layers performed better on diets containing coarse maize, but the reverse was true for sorghum, suggesting a particle size x grain type interaction. Goodband *et al.* (2002) were also of the opinion that, for layers, medium and coarse grindings are preferable for maize and that there is no advantage in reducing particle size below 800 μm .

Effect of grain particle size on broiler performance in pelleted diets

Although there is a degree of inconsistency, most data suggest that any effect of feed particle size on broiler performance is reduced when offered in the crumble or pelleted diets (*Table 4*). However, there has been sustained interest in studying the effects of particle size in pelleted feeds on the basis that the pellets dissolve in the crop after consumption and hence that the effect of feed particle size may be maintained even after pelleting (Nir *et al.*, 1995).

A number of studies have shown that feed particle size has no significant effect on broiler performance in pelleted feeds. Reece *et al.* (1986a) found no effect on performance using maize of differing particle sizes to formulate broiler starter diets in crumble form. Similarly, Svihus *et al.* (2004a) showed no difference in any of the performance parameter when broilers were fed pelleted feeds made from wheat ground in hammer and roller mills to a range of particle sizes, and concluded that pelleting evened out differences in particle size distribution. Peron *et al.* (2005) also found no effect on the performance of broilers fed pelleted diets made from wheat of two particle sizes (GMD, 380 and 955 μm), although differences in particle size distribution persisted after pelleting.

In contrast, a number of researchers have demonstrated effects of particle size in pelleted feeds that suggest variation between grain types. Lentle *et al.* (2006) fed broilers with pelleted feeds based on three cultivars of wheat that each produced different particle size spectra as a result of hammer milling, and found that diets with a higher relative proportion of coarser particles resulted in better feed efficiency. Other investigators, using

maize-based pelleted diets, have suggested that fine grinding has beneficial effect on performance compared to coarse grinding. Lott *et al.* (1992) found that broilers fed pelleted feeds made from coarse hammer mill ground maize (GMD, 1196 μm) had a significantly lower weight gain and poor feed efficiency at 21 days as compared with those fed pellets made from finer ground maize (GMD, 679 μm). Similarly, Kilburn and Edwards (2001) reported that performance and true metabolisable energy were improved when the broilers were fed pelleted diets that included fine maize (GMD, 869 μm) compared to that made from coarse maize (GMD, 2897 μm).

On the other hand, Reece *et al.* (1986b), in an extensive comparison between maize based diets, found that both fine (GMD, 679 μm) and coarse (GMD, 1289 μm) grindings improved both weight gain and feed efficiency, relative to those fed medium ground maize (GMD, 987 μm) even though there was no differences in feed intake. No significant difference was observed between performances of the birds maintained on the former two diets. However, birds maintained on pellets formulated with one-half of finely ground maize and one-half of coarse maize, with an average GMD 908 μm , performed better than those maintained on medium ground maize, although the GMD was somewhat similar.

Such contradictory evidence from comparisons of pelleted diets formulated from different grain particle sizes may be related, in part, to changes in size distribution following pelleting. These changes appear to be dependent on grain type and cultivars. Particle size of milled products is known to be affected by grain hardness (Dobraszczyk *et al.*, 2002; Carre, 2004). However, the effect of grain hardness on particle size distribution after pelleting remains to be investigated. When particle size differences persisted in wheat-based diets after pelleting, those with coarser particles were found to improve feed efficiency of broilers (Lentle *et al.*, 2006). On the other hand, no effect on performance was observed when pelleting evened out any differences in particle size distribution (Engberg *et al.*, 2002; Svihus *et al.*, 2004a).

Effect of particle size on digestive tract development and physiology

The development of digestive tract of poultry, especially the gizzard, is known to be influenced by feed particle size, which is evident in chickens at 7 days of age. Nir *et al.* (1994b) reported greater gizzard development and lower gizzard pH in 7-day old chicks fed medium or coarse particle size diets compared with those fine particulate diets.

The gizzard is a muscular organ that reduces the particle size of ingested foods and mixes them with digestive enzymes (Duke, 1986). The mechanical pressure applied in grinding by the gizzard may exceed 585 kg/cm² (Cabrera, 1994). When such grinding is carried out by feed mills, this has negative effects on gizzard size and gut function. As a result, the gizzard is relatively underdeveloped and the proventriculus becomes enlarged when broilers are fed finely ground, processed diets (Taylor and Jones, 2004). Under these conditions, the gizzard functions as a transit rather than a grinding organ (Cummings, 1994). The relative weights of both the gizzard (Nir *et al.*, 1995; Engberg *et al.*, 2002) and the small intestine (Nir *et al.*, 1995) have been shown to decrease when birds are fed pelleted rather than mash diets.

Feed particle size is positively related to the relative gizzard weight (Nir and Ptichi, 2001) when diets are fed as mash. In pelleted diets, however, this is likely to depend on the particle size distribution after dissolution in the crop. Svihus *et al.* (2004a) found no effect of particle size pre-pelleting on gizzard weight when a hard wheat (hardness index 64), with GMD varying between 600 and 1700 μm , was used. The explanation for this finding probably lies in the lack of differences in particle size distribution after pelleting in this study. In contrast, Peron *et al.* (2005) found that particle size differences remained even

after pelleting in wheat-based diets made from a very hard wheat (hardness value, 83), with GMD values of 380 and 955 μm , and that pelleted diets made from coarse particles significantly increased gizzard weights compared to those made from fine wheat. This was probably due to resistance of the hard particulate material to reduction by the pelleting process.

A large, well-developed gizzard improves gut motility (Ferket, 2000) through increasing the levels of cholecystokinin release (Svihus *et al.*, 2004b), which stimulates the secretion of pancreatic enzymes and the gastro-duodenal refluxes (Duke, 1992; Li and Owyang, 1993). Coarse particles may slow the passage rate of digesta through the gizzard (Nir *et al.*, 1994b), increasing the exposure time of nutrients to digestive enzymes, which in turn, may improve energy utilisation and nutrient digestibility (Carre, 2000). It has been reported that a lower pH of gizzard contents may increase pepsin activity (Gabriel *et al.*, 2003) and improve protein digestion. It has also been suggested that lower pH of gizzard contents may reduce the risk of coccidiosis (Cumming, 1994) and feed-borne pathogens (Engberg *et al.*, 2002).

Feed particle size has been shown to influence the development of other segments of digestive tract in birds fed mash diets. Nir *et al.* (1994b) reported the hypertrophy of the small intestine and lowering of intestinal pH when fine mash diets were fed. Similar results were reported by Nir *et al.* (1995), who found lower relative duodenal weights in birds fed coarse particle diets compared to those fed fine particle diets. Interestingly, a similar pattern was also been recorded in the birds fed whole-wheat diets (Gabriel *et al.*, 2003). The significance of lower duodenal weights associated with coarse feed particles is unclear.

Effect of feed particle size on digesta particle size

Data on the effect of feed particle size on its subsequent distribution in poultry digesta are scanty. Hetland *et al.* (2004) stated that the gizzard has a remarkable ability to grind all organic constituents of feed to a consistently fine size regardless of the original particle size of the feed. The digesta passing through the gizzard had a consistent particle size distribution, with the majority of particles being smaller than 40 (μm in size regardless of the original feed structure (Hetland *et al.*, 2002). In contrast, Lentle (2005) speculated that an increase in the proportion of coarser particles in the diet caused greater amounts of coarser particles to transit the gizzard but that these particles increased digestive efficiency as a result of increasing the permeability of digesta to digestive enzymes. This speculation was based on the observations that digesta contains a mixture of large and small particles, with small particles occupying the spaces between larger particles, which resulted in a reduction of mean void space radius available for permeation (Wise, 1952; Deresiewicz, 1958). Thus an increase in the numbers of coarser particles may lead to a local increase in permeation of digestive fluids through sites where there is a greater proportion of larger particles (Lentle, 2005; Lentle *et al.*, 2006).

In a recent study (Amerah *et al.*, 2007c), it was found that gizzard mass was greater in birds fed mash diets and that the duodenal digesta contained a higher proportion of large particles (1000-2000 μm) compared with those fed pelleted diets. In this study, whilst the gizzard enlarged in response to an increase in the coarse fraction of the diet, it did not uniformly reduce particle size. It should be noted that Hetland *et al.* (2002) used a laser diffraction method, which only determined changes in the size spectrum of particles less than 880 μm , whereas the methodology of Lentle *et al.* (2006) determined changes in particles over the range from less than 75 μm to over 2000 μm . Hence, as discussed above, the increase in starch digestibility associated with increased gizzard size of birds

fed diets containing whole cereals (Hetland *et al.*, 2002) may have resulted from changes in permeability from an undetected increase in the proportion of coarse particles.

Effect of particle size on nutrient utilisation

Although particle size reduction is said to improve digestion of nutrients by increasing the surface area available to digestive enzymes, studies which relate particle size to digestibility of nutrients are limited and, in the case of grains, equivocal. Kilburn and Edwards (2001) reported that fine grinding of maize increased the true metabolisable energy values in mash diets, but the opposite effect was observed with pelleted diets. Peron *et al.* (2005) found that fine grinding wheat improved starch digestibility and the apparent metabolisable energy (AME) compared to coarse grinding. On the other hand, coarse grinding of maize has been reported to increase the efficiency of nitrogen and lysine retention in broilers fed mash diets (Parsons *et al.*, 2006). Amerah *et al.* (2007b) reported that coarse grinding tended to improve the AME in wheat-based diets, but not in maize-based diets. In contrast, Svihus *et al.* (2004a) found no effect of wheat particle size on the AME.

A negative relationship between wheat hardness and the digestibility of starch in pelleted diets has been reported (Carre *et al.*, 2002; 2005). This effect of hardness was attributed to larger particulate size reducing the surface area and accessibility to digestive enzymes (Carre *et al.*, 2005). Conversely, Uddin *et al.* (1996) found that AME of pelleted wheat diets was not affected by endosperm hardness. Lack of relationship between grain hardness and AME or starch digestibility in wheat-based mash diets has been reported by several other workers (Rogel *et al.*, 1987; Rose *et al.*, 2001; Pirgozliev *et al.*, 2003).

The results for dicotyledonous seeds are less equivocal. Coarse grinding of grain legumes has been shown to lower energy utilisation and, digestibility coefficients of nutrients. A discussion on the effects of particle size on starch digestibility in grain legumes has been published (Carre, 2004). In general, fine grinding of peas was reported to improve the total tract digestibility of starch and protein when they are fed as mash diets (Carre *et al.*, 1998; Daveby *et al.*, 1998; Carre, 2000). Similarly, fine grinding of peas has been shown to improve the apparent ileal protein digestibility (Crevieu *et al.*, 1997). Similar positive effects were found for AME and apparent ileal protein acid digestibility when sweet lupine seeds were finely ground (Table 5). All of these effects may be attributed to the basis of increased accessibility of nutrients in fine legume particles. Fine grinding of faba beans had no effect on the total tract digestibility of protein (Lacassagne *et al.*, 1991), but these contradictory results on the effects of feed particle size on nutrient digestibility are possibly related to the differences in site of measurement (ileal *versus* total tract). The variable and modifying effects of caecal microflora on protein digestion have been recognised in recent years (Ravindran *et al.*, 1999) and it is now generally agreed that the analysis of ileal digesta rather than excreta is the preferred method for assessing nutrient digestibility in poultry (Ravindran and Bryden, 1999).

Interestingly, in terms of mineral availability, coarse grinding appears preferable over fine grinding. Large maize particle size has been shown to significantly improve calcium, total phosphorus and phytate phosphorus utilisation in broilers (Kasim and Edwards, 2000; Kilburn and Edwards, 2001). Bone ash and plasma phosphorus levels of broilers were improved after the feeding of coarse (GMD, 1239 μm) rather than fine (GMD, 891 μm) soybean meal (Kilburn and Edwards, 2004). Similar findings have been reported with maize-soy diets by Carlos and Edwards (1997). It was hypothesised that larger particle size led to longer transit time allowing more time for mineral digestion and absorption. These benefits were reduced when the diet was fed in pelleted or crumbled form (Kilburn

and Edwards, 2004) presumably as a result of concomitant degradation of larger particles during the pelleting process.

Effect of particle size on passage rate

It is hypothesised that rapid passage rate reduces the time available for digestion and absorption, whilst slow passage rate limits the intake of feed (Svihus *et al.*, 2002). The passage rate of the digesta is usually measured using insoluble (solid phase) coloured markers such as chromic or ferric oxide, but it must be borne in mind that results may be confounded by preferential retention of particles of particular size in particular segments of the gut, by adherence to other particles or by dissolution. Furthermore, in a number of species, soluble nutrients traverse the gut at faster rates than particulate matter (Lentle, 2005).

In broiler chickens, solid phase markers appear in the excreta 1.6 to 2.6 hr after ingestion (Denbow, 2000). Several factors are known to affect the passage rate of solid phase markers, including the strain of the chicken (Denbow, 2000), age of the bird (Shires *et al.*, 1987), dietary content of non-starch polysaccharides (Almirall and Esteve-Garcia, 1994), the fraction of water insoluble non-starch polysaccharides (Hetland and Svihus, 2001), dietary fat level (Sell *et al.*, 1983) and environmental temperature (Denbow, 2000). In general, larger particles are retained longer than finer particles in the digestive tract (Nir *et al.*, 1994b; Denbow, 2000), prolonging mean residence time. Thus the proportion of coarse fibre in the gizzard is double that in the feed (Hetland *et al.*, 2005) possibly reflecting selective retention of coarse particles (Hetland *et al.*, 2004; 2005).

It should also be mentioned, however, that overall retention time does not increase when birds are fed whole grains (Svihus *et al.*, 2002; Svihus *et al.*, 2004a; Wu and Ravindran, 2004). Hetland *et al.* (2005) speculated that there is rapid dissolution of starch granule and protein of whole grains in the low pH environment of the gizzard so that the particle size is rapidly reduced with no effect on passage rate.

Effect of particle size on pellet quality

Good pellet quality is defined as the ability to withstand mechanical handling (bagging, transport etc) without breaking up, and to reach feeders without generating a high proportion of fines. Pellet quality is determined by two physical parameters, the pellet durability index (PDI) and pellet hardness. The PDI measures the proportion of fines generated during standardized mechanical handling (Behnke, 2001), typically in a tumbling can (ASAE, 1987) or Holman Pellet Tester (Holman Chemical Ltd, United Kingdom). Pellet hardness is determined, in a spring hardness tester, as the static force (in kg) required to break the pellet.

There is a positive correlation between pellet durability and feed efficiency (Carre *et al.*, 2005). Higher pellet durability lowered the formation of fines and, reduces feed wastage and selection for larger particles by the birds. Pellet durability is thought to be inversely related to particle size (Angulo *et al.*, 1996), based on the fact that smaller particles have more contact points with each other because of their larger surface area per unit volume (Behnke, 2001). However, there is little scientific evidence to support this, and a number of studies having shown that fineness of grind of grain has no effect on pellet durability (Reece *et al.*, 1986b; Koch, 1996). Moreover, contradictory results have been obtained from the limited studies that relate particle size to pellet durability (Table 6).

Carre *et al.* (2005) reported a positive correlation between pellet durability and wheat hardness. It was stated that this hardness effect is independent of the particle size. Other

factors affecting pellet durability include dietary protein and oil contents (Briggs *et al.*, 1999), mash conditioning, die specifications, and cooling and drying (Behnke, 1996). Thus, any effect of particle size on pellet durability may be confounded by that of other dietary or milling parameters.

High starch gelatinisation has also been reported to improve pellet durability (Carmer *et al.*, 2003). Therefore, it has been suggested that poor quality of the pellets associated with coarse particles is due to the low starch gelatinisation in coarse particles compared to pellets made with fine particles (Svihus *et al.*, 2004a).

Effect of particle size on energy cost

Feed constitutes the greatest single cost in poultry production. The reduction of feed particle size is the second largest energy cost after that of pelleting in the broiler industry (Reece *et al.*, 1985) and likely to be the largest user of energy in the layer industry where pelleting is not performed (Deaton *et al.*, 1989). Dozier (2002) estimated that the utility usage comprised 25 to 30% of the manufacturing cost of broiler feed. Reducing feed particles to a finer size requires greater energy use and lowers production rate. Thus, any reduction in energy consumption from grinding could significantly lower feed cost.

Reece *et al.* (1986a) reported that energy savings of 27% could be achieved by increasing the screen size of a hammer mill from 4.76 to 6.35 mm. However, the relationship between screen size and energy consumption is not linear. The energy consumption during milling of maize with a hammer mill from a GMD of 600 μm to one of 400 μm is double that required to reduce particle size from 1,000 to 600 μm (Wondra *et al.*, 1995). Production rates are similarly non-linear (Wondra *et al.*, 1995). Moreover, several studies have shown that fineness of grind of grain has no effect on the rate/efficiency of pelleting (Martin, 1985) or power consumption during pelleting (Martin, 1985; Svihus *et al.*, 2004a). Hence, any gain in productivity of birds from the reduction of particle size must be sufficient to offset the higher cost of fine grinding.

Conclusions

This review highlights the limited amount of research conducted regarding the optimum particle size of different grains for efficient poultry production. This is likely to be due to the current industry practice of using highly processed, pelleted diets, which clearly masks the influence of particle size.

Available data clearly show that grain particle size is more critical in mash diets than in pelleted or crumble diets. Although it is generally believed that finer grinding will increase, and coarse grinding will decrease, the substrate surface area for enzymatic digestion, data reviewed herein suggest that coarser grinding to a more uniform particle size improves the performance of birds maintained on mash diets. This counter-intuitive effect may result from the positive effect of feed particle size on gizzard development. A well developed gizzard is associated with increased grinding activity, resulting in not only increased gut motility and greater digestion of nutrients, but also in greater reduction in particle size entering the small intestine and increasing the accessibility to digestive enzymes. It must be noted that both GMD and GSD are important to maintain bird performance on mash diets. The effects of particle size on pellet quality remain unexplored and warrant urgent attention. Further systematic investigations on the relationship of feed particle size with bird performance, gut health, and pellet quality are required if production efficiency are to be optimised in respect of the energy expenditure of grinding.

References

- ALMIRAL, M. and ESTEVE-GARCIA, E. (1994) Rate of passage of barley diets with chromium oxide: influence of age and poultry strain and effect of β -glucanase supplementation. *Poultry Science* **73**: 1433-1440.
- AMERAH, A.M., RAVINDRAN, V., LENTLE, R.G. and THOMAS, D.G. (2007a) Performance and digestive tract characteristics of broilers as influenced by particle size and feed form. *Proceedings of the Australian Poultry Science Symposium* **19**: 85-88.
- AMERAH, A.M., RAVINDRAN, V., LENTLE, R.G. and THOMAS, D.G. (2007b) Influence of particle size on the performance, digesta characteristics and energy utilisation of broilers fed maize and wheat based diets. *Proceedings of the Australian Poultry Science Symposium* **19**: 89-92.
- AMERAH, A.M., RAVINDRAN, V. and LENTLE, R.G. (2007c) Influence of feed form on gizzard morphology and particle size spectra of duodenal digesta in broiler chickens. *Journal of Poultry Science* **44**: 175-181.
- ANGULO, E., BRUFAU, J. and ESTEVE-GARCIA, E. (1996) Effect of a sepiolite product on pellet durability in pig diets differing in particle size and in broiler starter and finisher diets. *Animal Feed Science and Technology* **63**: 25-34.
- ASAE (1983) Method of determining and expressing fineness of feed materials by sieving. American Society of Agricultural Engineers Standard S319.2. Yearbook of Standards, American Society of Agricultural Engineers, St. Joseph, MO.
- ASAE (1987) Wafers, pellets, crumbles-definitions and methods for determining density, durability, and moisture content. American Society of Agricultural Engineers Standard S269.3. Yearbook of Standards, American Society of Agricultural Engineers, St. Joseph, MO.
- AXE, D.E. (1995) Factors affecting uniformity of a mix. *Animal Feed Science and Technology* **53**: 211-220.
- BAKER, S. and HERMAN, T. (2002) Evaluating Particle Size. MF-2051 Feed Manufacturing, Department of Grain Science and Industry, Kansas State University. 5 pp.
- BEHNKE, K.C. (1996) Feed manufacturing technology: current issues and challenges. *Animal Feed Science and Technology* **62**: 49-57.
- BEHNKE, K.C. (2001) Factors influencing pellet quality. *Feed Technology* **5**: 19-22.
- BERG, L.R. and BEARSE, G.E. (1948) Studies on the granulation of chicken laying mash. *Poultry Science* **27**: 653.
- BRIGGS, J.L., MAIER, D.E., WATKINS, B.A. and BENHKE, K.C. (1999) Effect of ingredients and processing parameters on pellet quality. *Poultry Science* **78**: 1464-1471.
- CABRERA, M.R. (1994) Effects of sorghum genotype and particle size on milling characteristics and performance of finishing pigs, broiler chicks, and laying hens. Masters Thesis, Kansas State University.
- CALET, C. (1965) The relative value of pellets versus mash and grain in poultry nutrition. *World's Poultry Science Journal* **21**: 23-52.
- CARLOS, A.B. and EDWARDS Jr., H.M. (1997) Influence of soybean particle size and chlortetracycline on the utilization of phytate phosphorus by broilers. *Poultry Science* **76**(Suppl): 234.
- CARRE, B. (2000) Effects de la taille des particules alimentaires sur les processus digestifs chez les oiseaux élevage. *INRA Productions Animales* **13**: 131-136.
- CARRE, B. (2004) Causes for variation in digestibility of starch among feedstuffs. *World's Poultry Science Journal* **60**: 76-89.
- CARRE, B., MAISONNIER, MELCION, J.P., OURYT FX, GOMEZ, J. and PLUCHARD, P. (2002) Relationships between digestibilities of food components and characteristics of wheats (*Triticum aestivum*) introduced as the only cereal source in a broiler chicken diet. *British Poultry Science* **43**: 404-415.
- CARRE, B., MECION, J.P. WIDEZ J.L. AND BIOT, P. (1998) Effects of various processes of fractionation, grinding and storage of peas on the digestibility of pea starch in chickens. *Animal Feed Science and Technology* **71**: 19-33.
- CARRE, B., MULEY, N., GOMEZ, J., OURYT, FX, LAFFITTE, E. GUILLOU, D. and SIGNORET, C. (2005) Soft wheat instead of hard wheat in pelleted diets results in high starch digestibility in broiler chickens. *British Poultry Science* **46**: 66-74.
- COVASA, M. and FORBES, J.M. (1996) Effect of prior experience and training on diet selection of broiler chicken using wheat. *Applied Animal Behaviour Science* **46**: 229-242.
- CRAMER, K.R., WILSON, K.J., MORITZ, J.S. AND BEYER, R.S. (2003) Effect of sorghum-based diets subjected to various manufacturing procedures on broiler performance. *Journal of Applied Poultry Research* **12**: 404-410.
- CREVIEU, I., CARRC B., CHAGNEAU, A.M., GUEGUEN, J. and MELCION, J.P. (1997) Effect of particle size of pea flours on the digestion of proteins in the digestive tract of broilers. *Journal of the Science of Food and Agriculture* **75**: 217-226.
- CUMMING, R.B. (1994) Opportunities for whole grain feeding. *Proceedings of the 9th European Poultry Conference*, Vol. 2, pp. 219-222, World Poultry Science Association, Glasgow, United Kingdom.

- DAVEBY, G.D., RAZDAN, A. and AMAN, P.** (1998) Effect of particle size and enzyme supplementation of diets based on dehulled peas on the nutritive value of broiler chickens. *Animal Feed Science and Technology* **74**: 229–239.
- DAVIS, R.L., HILL, E.G., SLOAN, H.J. and BRIGGS, G.M.** (1951) Detrimental effect of corn of coarse particle size in rations for chicks. *Poultry Science* **30**: 325-328.
- DEATON, J.W., LOTT, B.D. and SIMMONS, J.D.** (1989) Hammer mill versus roller mill grinding of corn for commercial egg layers. *Poultry Science* **68**: 1342-1344.
- DENBOW, D.M.** (2000) Gastrointestinal anatomy and physiology. In: Sturkie's Avian Physiology, 5th edition. (G. C. Whittow, ed.). San Diego: Academic Press, pp. 299-325.
- DERESIEWICZ, H.** (1958) Mechanics of granular matter. *Advances in Applied Mechanics* **5**: 233-306.
- DOBRSZCZYK, B.J., WHITWORTH, M.B., VINCENT, J.F.V. AND KHAN, A.A.** (2002) Single kernel wheat hardness and fracture properties in relation to density and the modelling of fracture in wheat endosperm. *Journal of Cereal Science* **35**: 245–263.
- DOUGLAS, J.H., SULLIVAN, T.W., BOND, P.L., STRUWE, F.J., BAIER, J.G. and ROBESON, L.G.** (1990) Influence of grinding, rolling, and pelleting on the nutritional-value of grain sorghums and yellow corn for broilers. *Poultry Science* **69**: 2150-2156.
- DOZIER, W.A., III** (2002) Reducing utility cost in the feed mill. *Watt Poultry USA* **53**:40-44.
- DUKE, G.E.** (1986) Alimentary canal: Anatomy, regulation of feeding and motility. In: *Avian Physiology*, (P.D. Sturkie, ed.). New York: Springer Verlag, pp. 269-288.
- DUKE, G.E.** (1992) Recent studies on regulation of gastric motility in turkeys. *Poultry Science* **81**: 1-8.
- ELEY, P. and BELL, J.C.** (1948) Particle of broiler food as a factor in the consumption and excretion of water. *Poultry Science* **27**: 660. (Abstract)
- ENGBERG, R.M., HEDEMANN, M.S. and JENSEN, B.B.** (2002) The influence of grinding and pelleting of feed on the microbial composition and activity in the digestive tract of broiler chickens. *British Poultry Science* **43**: 569-579.
- FERKET, P.** (2000) Feeding whole grains to poultry improves gut health. *Feedstuffs USA* September 04, pp. 12-14.
- GABRIEL, I., MALLET, S. and LECONTE, M.** (2003) Differences in the digestive tract characteristics of broiler chickens fed on complete pelleted diet or on whole wheat added to pelleted protein concentrate. *British Poultry Science* **44**: 283-290.
- GENTLE, M.J.** (1979) Sensory control of feed intake. In: *Food Intake Regulation in Poultry*, (K.N. Boorman and B.M. Freeman, eds.). Edinburg: British Poultry Science Ltd, pp. 259-273.
- GOODBAND, R.D., TOKACH, M.D. and NELSEN, J.L.** (2002) The effects of diet particle size on animal performance. MF-2050 Feed Manufacturing, Department of Grain Science and Industry, Kansas State University. 6 pp.
- HAMILTON, R.M.G. and PROUDFOOT, F.G.** (1995a) Ingredient particle size and feed texture effects on the performance of broiler chickens. *Animal Feed Science and Technology* **51**: 203-210.
- HAMILTON, R.M.G. and PROUDFOOT, F.G.** (1995b) Effects of ingredient particle size and feed form on the performance of leghorn hens. *Canadian Journal of Animal Science* **75**: 109-114.
- HETLAND, H., CHOCT, M. and SVIHUS, B.** (2004) Role of insoluble non-starch polysaccharides in poultry nutrition. *World's Poultry Science Journal* **60**: 415-422.
- HETLAND, H. AND SVIHUS, B.** (2001) Effect of oat hulls on performance, gut capacity and feed passage time in broiler chickens. *British Poultry Science* **42**: 354-361.
- HETLAND, H., SVIHUS, B. and CHOCT, M.** (2005) Role of insoluble fiber on gizzard activity in layers. *Journal of Applied Poultry Research* **14**: 38-46.
- HETLAND, H., SVIHUS, B. AND OLAISEN, V.** (2002) Effect of feeding whole cereals on performance, starch digestibility and duodenal particle size distribution in broiler chickens. *British Poultry Science* **43**: 416-423.
- JENSEN, L.S.** (2000) Influence of pelleting on the nutritional needs of poultry. *Asian-Australasian Journal of Animal Science* **13**: 35-46.
- JENSEN, L.S., MERILL, H., REDDY, C.V. and MCGINNIS, J.** (1962) Observation on eating patterns and rate of passage of birds fed pelleted and unpelleted diets. *Poultry Science* **41**: 1414-1419.
- KASIM, A.B. and EDWARDS, H.M.** (2000) Effect of sources of maize and maize particle sizes on the utilisation of phytate phosphorus in broiler chicks. *Animal Feed Science and Technology* **86**: 15-26.
- KILBURN, J. and EDWARDS, H.M.** (2001) The response of broilers to the feeding of mash or pelleted diets containing maize of varying particle sizes. *British Poultry Science* **42**: 484-492.
- KILBURN, J. and EDWARDS, H.M.** (2004) The effect of particle size of commercial soybean meal on performance and nutrient utilization of broiler chicks. *Poultry Science* **83**: 428-432.
- KOCH, K.** (1996) Hammermills and roller mills. MF-2048 Feed Manufacturing, Department of Grain Science and Industry, Kansas State University. 8 pp.
- LACASSAGNE, L., MELCION, J.P., DE MONREDON, F. and CARRE, B.** (1991) The nutritional values of faba bean flours varying in their mean particle size in young chickens. *Animal Feed Science and Technology* **34**: 11-19.

- LENTLE, R.G.** (2005) The macrobiophysics of digestion: Implications for the poultry industry. *Proceedings of the Australian Poultry Science Symposium* **17**: 163-170.
- LENTLE, R.G., RAVINDRAN, V., RAVINDRAN, G. and THOMAS, D.V.** (2006) Influence of feed particle size on the efficiency of broiler chickens fed wheat based diets. *Journal of Poultry Science* **43**:135-142.
- LI, Y. and OWYANG, C.** (1993) Vagal afferent pathway mediates physiological action of Cholecystokinin on pancreatic enzyme secretion. *Journal of Clinical Investigation* **92**: 418-424.
- LOTT, B.D., DAY, E.J., DEATON, J.W. and MAY, J.D.** (1992) The effect of temperature, dietary energy level, and corn particle size on broiler performance. *Poultry Science* **71**: 618-624.
- LUCAS G.M.** (2004) Dental Functional Morphology. Cambridge University Press. Cambridge, UK.
- MARTIN, S.** (1985) Comparison of hammer mill and roller mill grinding and the effect of grain particle size on mixing and pelleting. Masters Thesis, Kansas State University, Kansas.
- MCINTOSH, J.I., SLINGER, S.J., SIBBALD, I.R. and ASHTON, G.C.** (1962) Factors affecting the metabolisable energy content of poultry feeds. 7. The effects of grinding, pelleting and grit feeding on the availability of the energy of wheat, corn, oats and barley. *Poultry Science* **41**: 445 -456.
- MORGAN, R.B. and HEYWANG, B.W.** (1941) A comparison of a pelleted and unpelleted all-mash diet for laying hens. *Poultry Science* **20**: 62-65.
- NIR, I.** (1987) The Influence of the degree and method of grinding on the performance of broiler chicks. *In: Proceedings of the 6th European Symposium on Poultry Nutrition*. Konigslutter, Germany, pp. 21-25.
- NIR, I., HILLEL, R., PTICHI, I. and SHEFET, G.** (1995) Effect of particle size on performance .3. Grinding pelleting interactions. *Poultry Science* **74**: 771-783.
- NIR, I., HILLEL, R., SHEFET, G. and NITSAN, Z.** (1994a) Effect of grain particle size on performance. 2. Grain texture interactions. *Poultry Science* **73**: 781-791.
- NIR, I., MELCION, J.P. and PICARD, M.** (1990) Effect of particle size of sorghum grains on feed intake and performance of young broilers. *Poultry Science* **69**: 2177-2184.
- NIR, I., SHEFET, G. and AARONI, Y.** (1994b) Effect of particle size on performance. 1. Corn. *Poultry Science* **73**: 45-49.
- NIR, I. and PTICHI, I.** (2001) Feed particle size and hardness: Influence on performance, nutritional, behavioral and metabolic aspects. *In: Proceedings of the 1st World Feed Conference*, Utrecht, the Netherlands, pp. 157-186.
- PARSONS, A.S., BUCHANAN, N.P., BLEMINGS, K.P., WILSON, M.E. and MORTIZ, J.S.** (2006) Effect of corn particle size and pellet texture on broiler performance in the growing phase. *Journal of Applied Poultry Research* **15**: 245-255.
- PERON, A., BASTIANELLI, D., OURY, F.X., GOMEZ, J. and CARRE, B.** (2005) Effects of food deprivation and particle size of ground wheat on digestibility of food components in broilers fed on a pelleted diet. *British Poultry Science* **46**: 223-230.
- PIRGOZLIEV, V.R., BIRCH, C.L., ROSE, S.P., KETTLEWELL, P.S. and BEDFORD, M.R.** (2003) Chemical composition and the nutritive quality of different wheat cultivars for broiler chickens. *British Poultry Science* **44**: 464-475.
- PORTELLA, F.J., CASTON, L.J. and LEESON, S.** (1988) Apparent feed particle size preference by laying hens. *Canadian Journal of Animal Science* **68**: 915-922.
- PRESTON, C.M., MCCRACKEN, K.J. and MCALLISTER, A.** (2000) Effect of diet form and enzyme supplementation on growth, efficiency and energy utilisation of wheat-based diets for broilers. *British Poultry Science* **41**: 324-331.
- PROUDFOOT, F.G. and HULAN, H.W.** (1989) Feed texture effects on the performance of roaster chickens. *Canadian Journal of Animal Science* **69**: 801-807.
- RAVINDRAN, V. and BRYDEN, W.L.** (1999) Amino acid availability in poultry - *in vitro* and *in vivo* measurements. *Australian Journal of Agricultural Research* **50**: 889-908.
- RAVINDRAN, V., HEW, L.I., RAVINDRAN, G. and BRYDEN, W.L.** (1999) A comparison of ileal digesta and excreta analysis for the determination of amino acid digestibility in feed ingredients for poultry. *British Poultry Science* **40**: 266-274.
- RAVINDRAN, V., WU, Y.B., THOMAS, D.G. and MOREL, P.C.H.** (2006) Influence of whole wheat feeding on the development of gastrointestinal tract and performance of broiler chickens. *Australian Journal of Agricultural Research* **57**: 21-26.
- REECE, F.N., LOTT, B.D. and DEATON, J.W.** (1985) The effects of feed form, grinding method, energy level, and gender on broiler performance in a moderate (21oC) environment. *Poultry Science* **64**: 1834-1839.
- REECE, F.N., LOTT, B.D. and DEATON, J.W.** (1986a) Effects of environmental temperature and corn particle size on response of broilers to pelleted feed. *Poultry Science* **65**: 636-641.
- REECE, F.N., LOTT, B.D. and DEATON, J.W.** (1986b) The effects of hammer mill screen size on ground corn particle size, pellet durability, and broiler performance. *Poultry Science* **65**: 1257-1261.
- ROGEL, A.M., ANNISON, E.F., BRYDEN, W.L. and BALNAVE, D.** (1987) The digestion of wheat starch in broiler chickens. *Australian Journal of Agricultural Research* **38**: 639-649.
- ROSE, S.P., TUCKER, L.A., KETTLEWELL, P.S. and COLLIER, J.D.A.** (2001) Rapid tests of wheat nutritive value for growing chickens. *Journal of Cereal Science* **34**: 181-190.

- SCHIFFMAN, H.R.** (1968) Texture preference in the domestic chick. *Journal of Comparative and Physiological Psychology* **66**: 540.
- SELL, J. L., EASTWOOD, J.A. and MATEOS, G.G.** (1983) Influence of supplemental fat on diet metabolisable energy and ingest a transit time in laying hens. *Nutrition Reports International* **28**: 487-495.
- SHIRES, A., THOMPSON, J.R., TURNER, B.V., KENNEDY, P.M. and GOH, Y.K.** (1987) Rate of passage of corn-canola meal and corn-soybean meal diets through the gastrointestinal tract of broiler and leghorn chickens. *Poultry Science* **66**: 289-298.
- SVIHUS, B., HETLAND, H., CHOCT, M. and SUNDBY, F.** (2002) Passage rate through the anterior digestive tract of broiler chickens fed on diets with ground and whole wheat. *British Poultry Science* **43**: 662-668.
- SVIHUS, B., KLOVSTAD, K.H., PEREZ, V., ZIMONJA, O., SAHLSTROM, S. and SCHULLER, R.B.** (2004a) Physical and nutritional effects of pelleting of broiler chicken diets made from wheat ground to different coarsenesses by the use of roller mill and hammer mill. *Animal Feed Science and Technology* **117**: 281-293.
- SVIHUS, B., JUVIK, E., HETLAND, H. and KROGDAHL, A.** (2004b) Causes for improvement in nutritive value of broiler chicken diets with whole wheat instead of ground wheat. *British Poultry Science* **45**: 55-60.
- TAYLOR, R.D. and JONES, G.P.D.** (2004) The incorporation of whole grain into pelleted broiler chicken diet. 2. Gastrointestinal and digesta characteristics. *British Poultry Science* **45**: 237-246.
- UDDIN, M.S., ROSE, S.P., HISCOCK, T.A. and BONNET, S.** (1996) A comparison of the energy availability for chickens of ground and whole grain samples of two wheat varieties. *British Poultry Science* **37**: 347-357.
- WALDROUP, P.W.** (1997) Particle Size Reduction of Cereal Grains and its Significance in Poultry Nutrition. Technical Bulletin PO34-1997, American Soybean Association, Singapore. 14 pp.
- WISE, M.E.** (1952) Dense random packing of unequal spheres. *Philips Research Report* **7**: 321-343.
- WONDRA, K.J., HANCOCK, J.D., BEHNKE, K.C., HINES, R.H. and STARK, C.R.** (1995) Effects of particle size and pelleting on growth performance, nutrient digestibility, and stomach morphology in finishing pigs. *Journal of Animal Science* **73**: 757-763.
- WU, Y.B. and RAVINDRAN V.** (2004) Influence of whole-wheat inclusion and xylanase supplementation on the performance, digestive tract measurements and carcass characteristics of broiler chickens. *Animal Feed Science and Technology* **116**: 129-139.
- YASAR, S.** (2003) Performance, gut size and ileal digesta viscosity of broiler chickens fed with a whole wheat added diet and the diets with different wheat particle sizes. *International Journal of Poultry Science* **2**: 75-82.

Table 1 The effect of grain type on particle size analysis¹.

Grain	GMD (µm)	GSD	Reference
Hammer mill			
Maize	947	2.07	Douglas <i>et al.</i> (1990)
Sorghum	841	1.77	
Sorghum	628	1.88	Nir <i>et al.</i> (1995)
Wheat	681	2.29	
Roller mill			
Maize	1470	1.82	Douglas <i>et al.</i> (1990)
Sorghum	1800	1.40	
Sorghum	1413	1.76	Nir <i>et al.</i> (1995)
Wheat	2170	1.65	

¹In each study, the grains were ground in the same mill under similar conditions.

Table 2 Effect of particle size on the performance of broiler fed mash diets.

Grain	Age (days)	Particle size (µm)	Gain (g/bird)	Feed intake (g/bird)	Feed/gain (g/g)	Reference
Maize	1-21	814	582 ^a	-	1.43 ^a	Reece <i>et al.</i> (1985)
		1343	635 ^b	-	1.40 ^b	
Maize	1-21	947	521 ^a	-	1.49 ^a	Douglas <i>et al.</i> (1990)
		1470	488 ^b	-	1.55 ^b	
		1470	488 ^b	-	1.55 ^b	
Sorghum	7-21	Fine	364 ^b	532 ^b	1.46 ^a	Nir <i>et al.</i> (1990)
		Medium	376 ^a	548 ^{ab}	1.46 ^a	
		Coarse	382 ^a	561 ^a	1.47 ^a	
Maize	7-21	897	522 ^a	725	1.37 ^a	Nir <i>et al.</i> (1994a)
		1102	463 ^b	716	1.54 ^b	
		2010	473 ^b	740	1.60 ^b	
Maize, wheat and sorghum	1-21	Fine	357 ^b	591 ^b	1.65 ^b	Nir <i>et al.</i> (1994b)
		Medium	427 ^a	662 ^a	1.55 ^a	
		Coarse	401 ^a	645 ^a	1.60 ^{ab}	
Maize and wheat	7-42	Fine	1942 ^a	-	1.91 ^a	Hamilton and Proudfoot (1995)
		Medium	1982 ^b	-	1.92 ^a	
		Coarse	2004 ^c	-	1.92 ^a	

^{a,b,c}Within each reference, values in a column with different superscripts are significantly different (P < 0.05).

Table 3 Suggested GMD of cereal grains for broiler chickens¹.

Age (days)	GMD (µm)
1-7	900-1100
7-21	1100-1300
21-market	1300-1500

¹Adapted from Nir and Ptichi (2001).

Table 4 Effect of particle size on the performance of broiler fed pelleted diets.

Grain	Age (days)	Particle size (µm)	Gain (g/bird)	Feed intake (g/bird)	Feed/gain (g/g)	Reference
Maize	0-46	910	1998 ^a	-	1.934 ^a	Reece et al. (1986a)
		1024	2001 ^a	-	1.931 ^a	
Maize	0-42	679	1820 ^a	3447 ^b	1.894 ^a	Reece et al. (1986b)
		987	1754 ^b	3347 ^a	1.908 ^b	
		1289	1800 ^a	3400 ^{ab}	1.889 ^a	
Maize	1-21	679	748 ^a	1048 ^a	1.40 ^a	Lott et al. (1992)
		1289	729 ^b	1032 ^a	1.42 ^b	
Maize	0-16	869	386 ^a	-	1.35 ^a	Kilburn & Edwards (2001)
		2897	382 ^b	-	1.39 ^b	
Wheat	1-42	Fine	2007 ^a	3512 ^a	1.78 ^a	Engberg et al. (2002)
		Coarse	1997 ^a	3478 ^a	1.78 ^a	
Wheat	11-30	600	1361 ^a	2133 ^a	1.57 ^a	Svihus et al. (2004)
		1700	1315 ^a	2114 ^a	1.58 ^a	
Wheat	7-15	300	440 ^a	380 ^a	1.28 ^a	Peron et al. (2005)
		955	444 ^a	375 ^a	1.25 ^a	

^{a,b}Within each reference, values in a column with different superscripts are significantly different (P < 0.05).

Table 5 Influence of particle size on the apparent metabolisable energy and protein digestibility of Australian sweet lupine (*Lupinus angustifolius*) seeds (Ravindran, unpublished data)¹.

Parameter	Coarse grinding	Medium grinding	Fine grinding	Pooled SEM
AME, MJ/kg DM	8.83 ^a	9.67 ^b	9.35 ^{ab}	0.23
Ileal crude protein digestibility	0.745 ^a	0.796 ^c	0.771 ^b	0.007

^{a,b}Values in a row with different superscripts are significantly different (P < 0.05).

¹Seeds were ground by hammer mill to pass through 3 mm (fine), 5 mm (medium) or 7 mm (coarse) sieve.

Table 6 Effect of particle size on pellet durability.

Grain	GMD (µm)	Pellet durability index	Reference
Maize	910	91 ^a	Reece et al. (1986a) ¹
	1024	91 ^a	
Maize	679	91 ^a	Reece et al. (1986b) ¹
	987	91.3 ^a	
	1289	92.5 ^b	
Wheat	600	88 ^a	Svihus et al. (2004a) ¹
	930	81.2 ^a	
	1700	80.2 ^a	
Wheat	380	25 ^a	Peron et al. (2005) ²
	955	25 ^a	

¹Pellet durability was measured using Holmen Pellet Tester.

²Pellet durability was measured using Euortest rotary mill.

^{a,b}Within each reference, values in a column with different superscripts are significantly different (P < 0.05)