A Dissertation

for the Degree of Doctor of Philosophy

Effects of Feed Form and Particle Size on Physiology and Productivity in Growing-Finishing Pigs

사료의 형태 및 입자도가 육성비육돈의 생리와 생산성에 미치는 영향

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By

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Overall Summary

Effects of Feed Form and Particle Size on Physiology and Productivity in Growing-Finishing Pigs

The objectives of these experiments were 1) to determine the effects of particle size of swine feed on plant productivity and pellet quality of diets for growing and finishing pigs, 2) to investigate the effects of different particle size of swine feed on ileal amino acid digestibility of growing pigs, and 3) to evaluate the effects of feed form and particle size on growth performance, nutrient digestibility, carcass characteristics, and gastric health.

Experiment I. Effects of Particle Size of Swine Feed on Plant Productivity and Pellet Quality

This study was conducted to evaluate the effects of particle size on plant productivity and pellet quality of diets for growing and finishing pigs. Dietary treatments were particle size (600, 750 or 900 μm) and experimental diets were ground by hammer mill (ANDRITZ Feed & Biofuel, Denmark) equipped with screen size of 3.6, 2.6 or 1.6mm. Major ingredients were corn, wheat and soybean meal, and grower diet contained 3,300 kcal of ME/kg, 15.00% crude protein, 1.11% total lysine, 0.66% Ca, and 0.56% total P, respectively. Finisher diet contained 3,275 kcal of ME/kg, 14.00% crude protein, 1.01% total lysine, 0.52% Ca, and 0.47% total P, respectively, and all other nutrients were met or exceeded requirements of NRC (2012). Pellet durability and hardness were measured for evaluating the effects of particle size on pellet quality. And, energy usage and production rate of feed were checked to evaluate plant productivity. Standard deviation of geometric weight (SGW) was reduced as decreasing particle size in both growing and finishing diets. Pellet durability was decreased significantly when pigs were fed diet for 750 μm

particle size (P<0.01), and there was no significant difference in pellet hardness. In finishing diet, pellet durability was the highest at diet for small particle size (600 μm) compared with other treatment diets (P<0.01), and pellet hardness was improved significantly as decreasing particle size of feed (P<0.01, linear and quadratic responses). The grinding energy for low particle size diets was higher than those for large particle size diet, but different particle size had no effects on energy consumption of pelleting process. Grinding production rate was the highest when diet was ground to 900 μm, and it was reduced as particle size was decreased. Production rate for pelleting was not changed by particle size. Consequently, pellet durability and hardness were improved with reduced particle size. However, high energy was needed for fine ground diet with low grinding production rate.

Experiment II. Effects of Particle Size on Ileal Amino Acid Digestibility in Growing Pigs

This experiment was done to analyze the effects of particle size of swine feed on ileal amino acid digestibility of growing pigs. A total of 12 growing barrows ([Yorkshire × Landrace] × Duroc), with an initial BW of 23.7 ± 0.75 kg, were allotted to 3 treatment diets and a N-free diet in a completely randomized design (CRD), and T-cannula was fitted to distal ileum of each pig. Dietary treatments were different particle size (600, 750, or 900 μm) and experimental diets for growing pigs were containing 3,300 kcal of ME/kg, 15.00% crude protein, 1.11% total lysine, 0.66% Ca, and 0.56% total P, respectively. Other nutrients were met or exceeded the requirements of NRC (2012). N-free diet was used for calculating basal endogenous AA losses, and major ingredients were tapioca starch, glucose, sucrose and soy oil. All diets contained 0.5% chromic oxide as an indicator of fecal sample. Experimental diets were fed to pigs with 2.0 times of the maintenance requirement for ME (NRC, 2012), and there was no significant difference on apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of amino acids. In diets of 600 or 900 μm particle size, there were no differences in amino acid digestibility.

In conclusion, different particle size ranged from 600 to 900 μm had no detrimental effects on AID and SID of amino acids in growing pigs.

Experiment III. Effects of Feed Form and Particle Size on Growth Performance, Nutrient Digestibility, Carcass Characteristics, and Gastric Health in Growing-Finishing Pigs

This study was conducted for evaluating the effects of feed form and particle size on growth performance, nutrient digestibility, carcass characteristics, and gastric health. A total of 360 growing pigs ([Yorkshire × Landrace] × Duroc; 22.64 ± 0.014 kg initial BW) were allocated to one of six treatments in 6 replicates by body weight and gender, and 10 pigs were housed in a metabolic crate in a randomized complete block design (RCBD). Body weight and feed intake were recorded at initial, 3rd, 6th, 10th and 12th wk to calculate the average daily gain (ADG), average daily feed intake (ADFI) and gain-to-feed ratio (G/F ratio). Main factors for experiment were particle size (600, 750, or 900 μm) and feed form (mash or pellet) of diet, and pigs were split based on a 2 × 3 factorial arrangement. Grower diets were containing 3,300 kcal of ME/kg, 15.00% crude protein, 1.11% total lysine, 0.66% Ca, and 0.56% total P, respectively. Finisher diets were also formulated to contain 3,275 kcal of ME/kg, 14.00% crude protein, 1.01% total lysine, 0.52% Ca, and 0.47% total P, respectively. All other nutrients were met or exceeded requirements of NRC (2012). During the whole experimental period, there was no significant difference in the results of BW and ADG. Feed intake of growing pigs was not affected by dietary treatment, but ADFI of finishing pigs was increased with mash diet ($P<0.05$). For overall period, there was a tendency for improved feed intake when pigs were fed mash diet ($P=0.09$), but different particle size had no significant effects on ADFI. Feed efficiency of pigs was improved with pellet diet ($P<0.01$) and reduced particle size ($P<0.01$), and there was no significant interaction between two factors (particle size and feed form) for all parameters of growth trial. Pelleting had no effects on DM and crude protein digestibility, but it resulted in

improved crude fat digestibility compared with mash diet ($P<0.01$). In carcass characteristics, there was no significant difference by dietary treatments. For evaluating gut health, tendency for increased incidence of keratinization in the esophageal region was observed as particle size was decreased ($P=0.07$). Consequently, pellet diet improved gain to feed ratio and fat digestibility and lower particle size could induce increased feed efficiency and incidence of keratinization in the esophageal region.

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List of Abbreviation

ADFI	average daily feed intake
ADG	average daily gain
BFT	backfat thickness
BUN	blood urea nitrogen
BW	body weight
CP	crude protein
DE	digestible energy
GE	gross energy
ME	metaboilzable energy
NE	net energy
GLM	general linear model
DM	dry matter
SBM	soybean meal
FCR	feed conversion ratio
MDCP	mono di-calcium phosphate
AA	amino acid
AID	apparent ileal digestibility
SID	standardized ileal digestibility
ATTD	apparent total tract digestibility
NRC	national research council

Chapter I. General Introduction

Corn-wheat-soybean meal based swine diet is the most popular in South Korea, and more than 90% of feed ingredients have to be imported from foreign countries because of limited production of grains in domestic area. A number of factors including biofuel demand and climate change result in suddenly increased price of feed ingredients, and it may induce more severe problems in swine farms as well as feed industries of South Korea. Based on this situation, the concerns for optimizing feed cost and improving feed efficiency have been increased annually. Practical approach for reducing feed cost is use of cheap ingredients, such as CM (copra meal), PKM (palm kernel meal), RSM (rapeseed meal), and so on. However, high inclusion level of those ingredients is not feasible due to the poor digestibility, decreased feed intake, and individual anti-nutritional factors. For reducing the risk of cheap ingredients, many approaches have been applied for swine feed such as ingredient processing quality control, pelleting of diet, application of enzyme, palatability enhancer and mycotoxin binder. Among these strategies, feed processing and optimization of particle size were the most popular application in feed industries.

Improved feed efficiency and growth performance of pigs by pelleting diets have been reported by previous studies (Fastinger et al., 2003; Rojas et al., 2016). Pelleting induced a change of physical properties and increased starch gelatinization of ingredients, resulting in increased surface area for enzyme digestion and improved nutrient digestibility (Jensen et al., 1965). Ulens et al. (2015) demonstrated that feeding pellet diet improved feed efficiency of the pigs relative to that of mash diet, and Steidinger et al. (2000) also reported increased feed intake by this approach. In some cases, the findings for evaluating the effects of feed form had inconsistent results because of un-expected factors, including type of feed ingredients, different facilities, and handling skills of operators (Mahan et al., 1966; Reimann et al., 1968; Pickett et al., 1969; Maxwell et al., 1970; Mavromichalis et al., 2000). Therefore, further studies will be needed to evaluate different responses of feed form in individual situation.

Optimal particle size of ingredients is one of the most important factors for determining animal performance, and there were many studies reporting positive effects of reduced particle size (Mavromichalis et al., 2000; Kim et al., 2002; Fastinger et al., 2003). The main reason for those responses was improved nutrient digestibility of pigs by increased surface area for enzyme digestion (Rojaset al., 2015). Kim et al. (2005) found that apparent total tract digestibility (ATTD) of starch was improved with decreased particle size from 920 to 580 μm, and Oryschak et al. (2002) demonstrated that reduced particle size had effects on increasing ATTD of GE and crude protein. However, reduced particle size may decrease production rate of feed in feed company (Healy et al., 1994), and Wondra et al. (1995) also presented slightly decreased production rate when particle size was reduced from 1,000 to 600 μm. Although applying small particle size results in improved nutrient digestibility and growth performance, the concern for balancing plant productivity and optimal particle size is needed to make ideal standard. For energy digestibilities (DE and ME), reduced particle has consistently positive effects, but there were inconsistent results associated with amino acid digestibility and other nutrients (Wondra et al., 1995; Liu et al., 2012). The reason for this difference could be explained by fiber fraction of ingredients (Rojas et al., 2015). All of feed ingredients have fiber fractions and the fiber digestibility could be increased highly by reduced particle size relative to other nutrient. Increased fiber digestibility may induce improved energy digestibility, resulted in consistent response with previous researches. Rojas et al. (2015) reported that standardized ileal digestibilities (SID) of amino acids were not changed by different particle size, and Giesemann et al. (1990) demonstrated that reduced particle size had no effects on digestibility of crude protein as well as amino acids. It is hard to find possible approach to resolve inconsistent result associated with amino acid digestibility, because there is limited information on the effects of particle size on AID and SID in growing pigs.

Consequently, 3 experiments were conducted 1) to determine the effects of particle size of feed on plant productivity and pellet quality of diets for growing and finishing pigs, 2) to investigate the effects of different particle size of feed on ileal amino acid digestibility of growing pigs, and 3) to evaluate the effects of feed form and particle size on growth performance, nutrient digestibility, carcass characteristics, and gastric health of growing-finishing pigs.

Chapter II. Literature Review

1. Feed Ingredients and Processing

1.1 Feed Ingredients Situation in South Korea

Corn and soybean meal have been widely used as feed ingredients in South Korea, and more than 90% of those ingredients have to be imported from foreign countries due to limited production in domestic area. A number of factors, such as increased biofuel demand, El Nino and La Nina phenomenon results in dramatically increased price of feed ingredients, and it could cause more severe problems in case of South Korea, because of high dependence on imported ingredients. Based on this situation, the concerns of swine producers and nutritionists for decreasing feed cost and improving feed efficiency was increasing annually.

Application of cheap ingredients (copra meal, palm kernel meal, and rapeseed meal) have been popular strategies for decreasing feed cost, but maximum addition level was limited because of growth check, poor digestibility, and low feed intake. Those negative responses could be derived from various anti-nutritional factors of cheap ingredients, and many strategies for decreasing ANF level of swine diet were applied by previous studies, such as pelleting of diet, application of enzyme and mycotoxin binder. In these approaches, pelleting diet is popularly applied for swine industry, and there were many reports for presenting positive response of pellet diet on nutrient digestibility and feed efficiency (Jensen, 1965; Xing et al., 2004; Lewis et al., 2015).

The pigs fed pellet diet showed high gain to feed ratio compared with the those fed mash diet (Ulens et al., 2015), and also resulted in improved feed intake (Steidinger et al., 2000). The possible explanation for these responses was high energy digestibility of processed cereals by increased gelatinization degree of starch and fiber fractions (Jensen et al., 1965). In many case, application of pellet diet had inconsistent results by un-expected factors, such as type of feed ingredients, different facilities, and handling skills of producers (Mahan et al., 1966; Reimann et al., 1968; Pickett et al., 1969; Maxwell et al., 1970; Mavromichalis et al., 2000). Therefore, there is need to establish individual standard of feed form and particle size of ingredient for improving productivity and reducing feed coast in swine industry.

1.2 Flow of Feed Processing

Individual ingredients have different physical properties and nutrient compositions, and have to be mixed with proper nutrient standard for maximizing animal performance. General feed manufacturing process could be divided as grinding, mixing, pelleting, crumbling and packaging, and there are two kinds of grinding process for individual feed mills, pre and post-grinding (Figure 1).

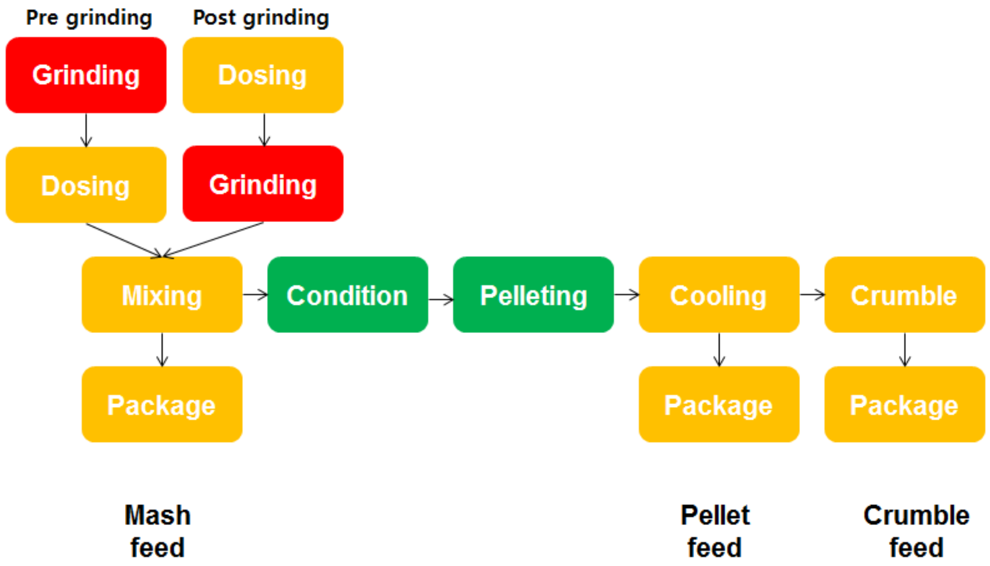

Figure 1. General manufacturing process of swine feed in feed mill

In pre-grinding process, ingredients could be grinded individually, based on ideal particle size and diet recipe, and the ordered feeds can be produced immediately, because already grinded ingredients were prepared in ingredient bins. However, ingredients have to be grinded after dosing process in post-grinding process, and feed nutritionist could use various cheap ingredients with different particle size. Generally, pre-grinding process is very popular in United State and South Korea, and sometimes, there are several feed mills which have both grinding system in one feed line. After grinding and dosing process, various ingredients could be mixed, and mash feed has to be packed immediately after filtering process. For producing pellet and crumble diets, mixed ingredients have to keep steam inside by conditioning process, and the steamed ingredients are pelleted with proper pressure. In a pelleting process, pellet diameter was determined by screen size, and the fines could be removed by filter screener. For reducing the temperature of pellet without any detrimental effect on pellet quality, the cooling process is applied, and the pellet diet could be packed immediately. Additionally, the diet has to be split for producing crumble diet.

1.3 Grinding Process

Grinding is the process for the particle size reduction of feed ingredients, and hammer mill and roller mill are commonly used in feed industry (Figure 2). The use of roller mills or hammer mills is affected by different preferences. These preferences are considered based on the production situation like grinding capacity, electricity efficiency and types of ingredient used (Hancock, 2001). Hammer mill is easy to operate for grinding and provides various sizes of ingredient particle. However, it needs more energy than roller mill. Roller mill requires complicated managing skills than hammer mill, but they provide a less particle size variation of ingredients compared with hammer mills (Vermeer et al., 1993).

1.3.1 Hammer Mill

Hammer mill is composed of delivery device, hammer tips, rotor and screen. After ingredients supply through delivery device into hammer mill, they are crushed by hammer tips rotating rapidly (Heiman, 2005). The grinding of ingredients in a hammer mill occurs as the particles are enough to exit through the holes of screen. During this process, particle size is controlled by the screen size, number of hammer tips, speed of tip rotation and feeding speed of delivery device.

Vermeer (1993) demonstrated that the equipment cost of hammer mill was half of roller mill system, but more electricity was needed to maintain hammer mill system. Generally, hammer mill resulted in higher variation of particle size relative to roller mill, especially when large screen was equipped, and number of hammer mill have been needed to achieve target particle size (Patience et al., 2012). The moisture content of ingredients could be decreased with hammer mill, and it was noisier than roller mill.

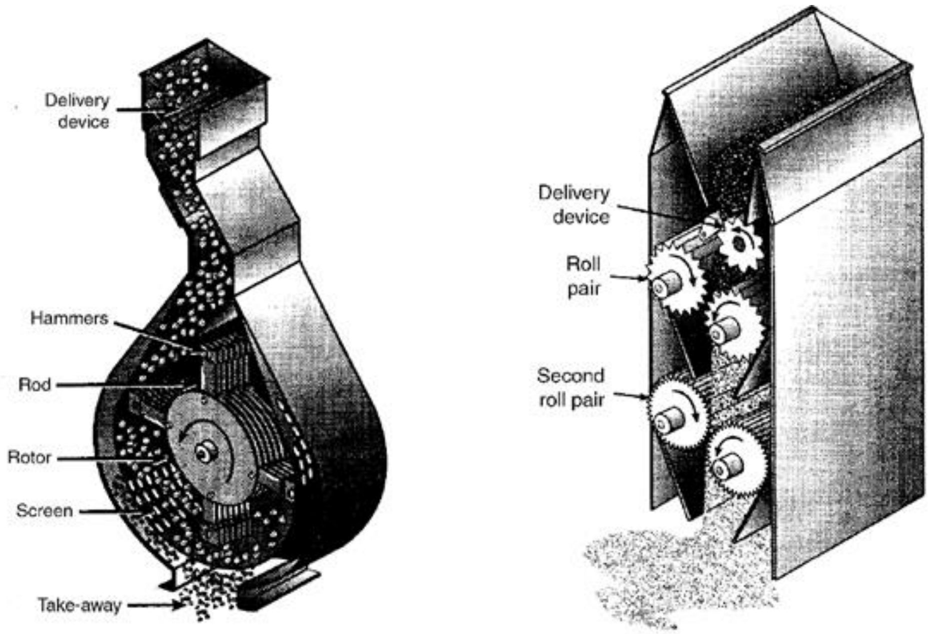

Figure 2. A basic design for hammer mill and roller mill (Koch et al., 1996)

1.3.2 Roller Mill

Roller mill is composed of delivery device and double layers of roll pair. Ingredients delivered are crushed by passing the gap between rolls horizontally located and rolling. The particle size of ingredients is controlled by width of the gap between rolls. Generally, roller mill resulted in low variation of particle size (Groesbeck et al., 2003), less heat while grinding (Heimann, 1983), and low energy requirement (McEllhiney, 1983) compared with hammer mill. Heiman (2005) suggested that application of roller mill had effects on improving production rate of the plant from 15% to 40% relative to hammer mill, and Wondra et al. (1995) reported that the digestibilities of DM, N, and GE were increased with roller mill grinding due to improved uniformity of particle size. Several findings (McEllhiney, 1983; Wondra et al., 1995) demonstrated different shape of particle in both grinding systems, round edges for hammer mill and sharp edge for roller mill, and Reece et al. (1985) suggested that the spherical shape by hammer mill might reduce surface area for enzyme action, and resulted in reduced digestibility and growth of broilers.

1.4 Pelleting Process

After mixing process, ingredients could be treated by many kinds of heat and pressure processing, including pelleting, steam flaking, extrusion and expansion. Ingredients have to keep steam inside and take pressure to be pelleted, and pellet quality would be affected by many factors such as diet recipe, particle size, conditioning process, and levels of liquid ingredients (Reimer, 1992; Traylor et al., 1999). Wondra et al. (1995) demonstrated that pellet durability was improved as particle size is decreased, and Stark (1994) suggested that low inclusion level of liquid ingredients resulted in poor-quality pellet. The responses on those treatments were inconsistent because of different plant facilities, and handling skills, so there is need to determine individual standard for each parameters.

1.4.1 Advantages of Pelleting

Various benefits of pellet diet have been demonstrated by previous studies, including improved ingredient uniformity, increased bulk density, reduced dust levels, high nutrients digestibility and performance (Amerah et al., 2007).

In a physical aspect, pellet diet improved flowability, segregation of mixed feed ingredients, fine levels, and feed density, and had effects on solving problems by different feed appearance. For a growth performance, increased feed intake (Steidinger et al., 2000), advanced ADG and feed efficiency (Ulens et al., 2015) were observed when pigs fed pellet diet. The main reasons for these responses were improved starch digestibility of cereal grains due to increased gelatinization degree of starch (Jensen, 1965).

Sometimes, the response of pellet diet was inconsistent, because of age difference, environment and factors affecting feed intake (Patience, 2012). In the later contents, there is detailed review of literature associated with those parameters.

1.4.2 Other Factors in Pelleting Process

Pellet quality are controlled by formulation (40%), fineness of grind (20%), steam conditioning (20%), die selection (15%), cooling and drying (5%) (Reimer, 1992). Conditioner is a part of the pellet mill, and the major function is providing steam with a high temperature to produce more durable pellet. Generally, the heating temperature for swine diets is ranged from 75 to 85 ℃, and the retention time is only a few seconds. In case of long-term conditioners, the retention time could be longer than several minutes, and it may induce increased starch gelatinization. This system is widely used in the aquaculture industry for maintaining feed shape in the water.

For improving pellet quality, sometimes, feed producers applied pellet binder in the mixer, and it may induce improved pellet durability. There are many kinds of pellet binders including lignosulfonates, calcium and sodium bentonites, and sugar molasses and high starch ingredients also have been used frequently. Addition of fat in the mixer had effects on increasing pelleting productivity, but Pacheco and Stark (2009) suggested poor pellet quality by this treatment. It was hard to induce proper temperature and level of gelatinization in the pelleting process, when excess fat was added to the mixer, and it was main reason for poor pellet quality.

1.5 Feed Production Cost

1.5.1 Energy Consumption in Feed Processing

Reducing energy consumption is most important for improving operation cost of the feed mill, and there were many factors which can affect energy consumption, including grinding and pelleting energy. Anderson (2010) demonstrated that 2.5 times increase of energy consumption by hammer mill resulted in 24% increment of total operating cost in the plant, and it means grinding energy is dominant factor for the plant productivity. Generally, it is well known that roller mills had higher energy efficiency and uniform particle size relative to hammer mill, but the equipment cost was higher than that of hammer mill. The energy consumption of hammer mill could be changed by the condition of the hammers and screens, because it has the highest efficiency when the edge of the hammer is sharp. However, frequent renewal of hammer can cause cost problem, so there is need to make an optimized plan for handling hammer mill based on grinding efficiency and equipment cost.

Increasing particle size is easily available for reducing grinding energy, but many findings showed negative effects of large particle size on growth performance of the pigs (Ohh et al., 1983; Goodband and Hines, 1987; Wondra et al., 1995; Mavromichalis et al., 2000). Wondra et al. (1995) suggested that reduced particle size from 1,000 to 600 μm had effects on decreasing the energy usage almost 2.5 times, and the type of grains also had considerable effect on grinding energy. Feed producers may have their own standard of particle size for optimizing animal growth and plant productivity, and grinding energy could be optimized followed by this internal standard.

Limited information is available for the effects of particle size on pelleting energy. Generally, pelleting process could be controlled by many factors, such as conditioner process, temperature, moisture content, use of pellet binder, pelleting and cooling time, and it means that classifying factors of pelleting energy and efficiency by different particle size is very hard due to other factors. Individual research and observation were needed to determine the effects of particle size on pelleting energy.

1.5.2 Feed Plant Productivity

Improving plant productivity is very important for reducing operation cost, and there are many factors affecting plant productivity, such as product number, particle size of ingredient, manufacturing process, and so on. In these parameters, grinding and pelleting efficiencies were dominant factors, however, there are few researches recently for evaluating the effects of particle size on those parameters (Beyer, 2003).

Healy et al. (1994) suggested that reduced particle size may decrease production rate (ton/h), and Wondra et al. (1995) reported similar observation that production rate was slightly decreased when particle size was reduced from 1,000 to 600 μm. Although applying large particle size results in high production rate, growth check and decreased nutrient digestibility could be induced as particle size increasing. Therefore, the concerns for evaluating optimal particle size based on plant productivity and growth performance have been increased annually.

In addition, nutrient composition and specific additives had effects on production rate. Stark et al. (1994) found that pelleting efficiency was improved as dietary level of calcium lignosulfonate is increasing from 0 to 2%, and liquid ingredients had positive effects on production rate. Sometimes, increased rate of liquid ingredients could be a reason for high feed cost, so the final decision is depend on each ingredient's price, operating cost and handling skills in the plant.

2. Feed Processing and Particle Size on Nutrient Digestibility of Growing Pigs

2.1 Ileal Amino Acid Digestibility

Protein digestibility has a crucial role for evaluating protein quality of ingredients, and the methods for measuring these parameters could be classified to direct and indirect methods. Total collection method can be classified as a direct method, and is measuring protein digestibility from nitrogen differences between feed and feces. However, amino acid composition of digesta could be changed by intestinal micro-organism, and it means that other method was needed to measure amino acid digestibility. For solving this problem, ileal digestibility method was adapted, and there are many type of cannulation method, including T-cannula injection and re-entrant cannula. The ileal digestibility can be expressed as an apparent ileal digestibility (AID) and standardized ileal digestibility (SID) based on a consideration of basal endogenous amino acid losses (BEAL). AID is measured by amino acid differences between ileal digesta and feed, and BEAL is not used for calculation. If there are many un-expected factors including age difference, dietary nutrient levels, and physical properties of feeds, BEAL would be useful options for reducing variance and classifying treatment effects. However, the risk for exclusion of BEAL in AID could be reduced when the trial was conducted in well-controlled environment. For measuring SID of amino acids, the pigs fed nitrogen free diet is needed to calculate BEAL. In this case, agreed assumption is that amino acid from the feed is totally digested, and amino acids in the ileal digest just came from gut of animals. Generally, chromic oxide and ferric oxide have been used as a marker for amino acids, and SID is measured by amino acid differences between ileal digesta and feed with a consideration of BEAL. Detailed equation for AID and SID is presented below (Stein, 2001).

(i) Apparent ileal digestibility (%) = 100 - [(ND / NF) x (CrF / CrD) x 100]

* ND = AA level in ileal digesta

* NF = AA level in diet

* CrD = Chrome level in ileal digesta

* CrF = Chrome level in feed

(ii) Basal endogenous AA losses (BAL) = ND x (CrF / CrD)

* BAL was calculated by N-free diet.

(iii) Standardized ileal digestibility (%) = [AID + (EAL/NF)] x 100

There were many results to present the effects of different particle size on AID and SID of pigs, however the observation was not consistent among the experiments. Kim et al. (2009) reported that CP and SID of amino acids were increased as particle size of lupins is decreasing from 1,304 to 567 μm, and Fastinger and Mahan (2003) demonstrated that the pigs fed diet containing soybean meal of 600 μm particle size showed the highest AA digestibility relative to those of 900 μm. However, Rojas et al. (2015) had no effects on SID AA by reduced particle size of corn, and decreased particle size of soybean meal ranged from 949 to 185 μm also had no effects on SID of indispensable and dispensable AA, only with numerically increased levels for SID of isoleucine, methionine, phenylalanine, and valine. Many factors had influence on the response of different particle size in AID and SID of AAs. Liu et al. (2012) found that higher fiber fractions of diet can cause different response of reduced particle size, and Seerley et al. (1988) demonstrated that different feed intake could be a reason for inconsistent results by reduced particle size. Reduced particle size had great impact on digestibility of amino acids as crude fiber level is increasing, and had no impact in restricted feeding condition because the pigs already had higher digestibility.

Rojas et al. (2016) indicated that pelleting improved AID of indispensable AA, and similar observations of improved AA were presented with experimental diets containing wheat-canola meal (Lahaye et al., 2008), and soybean meal (Ginste et al., 1998). The consistent results associated with pelleting were derived from increased gelatinization degree and changed protein structure in these findings. Protein denaturation by pelleting of ingredients increased surface area for protein enzyme, and results in improved AID and SID of AAs.

2.2 Nutrient Digestibility

Positive effects of reduced particle size on energy and nutrients digestibility of the pigs were suggested in previous findings (Wondra et al., 1995; Lawrence et al., 2003; Amaral et al., 2015). Rojas et al. (2015) indicated that a reduction of mean particle size from 600 to 485 μm improved energy and nutrients digestibility, and Kim et al. (2005) found that starch digestibility was increased as the particle size of wheat is decreasing from 920 to 580 μm. Improved energy digestibility by reduced particle size was also observed in other findings. Oryschak et al. (2002) demonstrated that the pigs fed diet of 400 μm showed higher apparent total tract digestibility (ATTD) of GE and DM compared with those of 700 μm, and Liu et al. (2012) reported that ATTD of DM, GE, and ME were improved when the pigs fed diet of small particle size. The main reason for these considerable changes of energy digestibility was increased gelatinization degree of starch (Jensen, 1965), and the difference was elevated when the level of crude fiber was increased, because changed fiber structure can induce increased digestibility of other nutrients (Liu et al., 2012). For other nutrients, the inconsistent results were reported in previous studies. Improved crude protein digestibility by reduced particle size was presented in the experiment of Kim et al. (2009), but not for that of Medel et al. (2000). Rojas et al. (2015) reported that reduced particle size had effects on increasing phosphorus digestibility, but Liu et al. (2012) demonstrated that there was no significant difference on phosphorus digestibility by different particle size. Further studies would be needed to evaluate the effects of different particle size on those parameters.

Pelleting improved starch digestibility of cereal grains due to high gelatinization degree of starch (Jensen et al., 1965), and Wondra et al. (1995) found that pelleting had effects on increasing digestibilities of dry matter, nitrogen and GE. For the fat digestibility, Noblet et al. (2004) showed higher digestibility of the pigs fed pellet diet relative to those fed mash diet, but also there were studies indicating no response of pelleting on this parameters (Kim et al., 2013). Inconsistent results with fat digestibility could be derived from endogenous fat losses by intestinal microflora, and formation of Ca-lipid complex in the gut (Rojas et al., 2017). Therefore, acid hydrolysis for the fat analysis is needed to measure accurate fat digestibility.

3. Feed Processing and Particle Size on Growth Performance of Growing Pigs

3.1 Feed Intake

Generally, growing-finishing pigs are provided feed with *ad libitum* access, and the strategies for increasing feed intake is really important for improving growth performance. Feed intake of animals could be controlled by the central nervous system and metabolites in the body. Mayer (1953) and Martin et al. (1989) demonstrated that blood glucose level had effects on feed intake of animals by neurons in hypothalamus. Also, Houseknecht et al. (1998) found the role of leptin in the brain for decreasing feed intake and controlling steady energy intake, and many other findings have indicated regulation mechanisms of feed intake by various hormones and neurotransmitters (Houpt, 1985; Scharrer, 1991). Although there were many studies for control mechanisms of feed intake in animal body, limited information is available for the effects of dietary physical properties and feed form on feed intake of growing pigs.

Seerley et al. (1988) reported that reduced particle size from 1,200 to 980 μm had effects on increasing feed intake, but Wondra et al. (1995) demonstrated that the pigs fed diet of 400 μm particle size showed lower feed intake than that of 1,000 μm particle size. Based on previous studies, it is clear that both lower and higher particle size have negative effects on feed intake of pigs. If pigs are fed diet of low particle size, it can cause gastric ulcer, and delayed passage rate of digesta, resulted in intake problem. However, low nutrient digestibility derived from large particle size also may cause poor feed intake. Optimum particle size would be determined by age difference, environmental condition, and farm management (Patience, 2012), therefore, individual validation process is needed to set ideal standard for particle size.

Amerah et al. (2007) indicated that pelleting decreased feed intake because of reduced feed waste, and Steidinger et al. (2000) demonstrated that pellet diet improved feed intake of weanling pigs compared with mash diet. However, Potter et al. (2009) reported that feed intake was not affected by feed form. In well-managed environment, the feed intake of animals would be increased regardless of feed form, and finding treatment effects by pelleting is hard due to high influence of environment.

3.2 Feed Efficiency and Growth

Many positive effects of reduced particle size on feed efficiency and growth were demonstrated in previous studies (Table 1). Fine grinding of corn and sorghum had positive effects on improving FCR of starter pigs, and Healy et al.

(1994) reported reduced particle size of corn from 1,000 to 500 μm improved growth of starter pigs. Wondra et al. (1995) reported that reduced particle size of corn from 1,000 to 400 μm increased 8% of G:F ratio, and reduced particle size of wheat from 1,380 to 387 μm also had effects on improving FCR of starter pigs (Mavromichalis et al., 2000). Likewise, Hancock and Behnke (2001) found that G:F ratio of growing pigs was increased when the pigs fed diet containing fine grinded corn, and Amaral et al. (2015) and Rojas et al. (2016) agreed with this observation. For the finishing pigs, reduced particle size of ingredients ranged from 1,200 to 400 μm also improved FCR (Goodband et al., 2002).

Even though the effects of reduced particle size were evaluated many times for various ingredients, there were inconstant responses followed by the type of ingredient (Kim et al. 2005), especially for soybean meal. Fastinger and Mahan (2003) demonstrated that feed efficiency of pigs fed diet containing fine grinded SBM was higher than those fed diet containing coarse grinded SBM, however Lawrence et al. (2003) indicated that there was no significant change of ADG and

Table 1. Effects of pellet diet on growth performance of pigs

References	Periods	Improved ratio relative to mash diet	
		Growth	Feed efficiency
Hanke et al. (1972)	Finisher	6.7%	6.9%
Baird (1973)	Grower-finisher	4.3%	8.1%
Harris et al. (1979)	Finisher	8.2%	8.0%
Skoch et al. (1983)	Nursery pigs	9.8%	8.8%
Hanarahan (1984)	Grower-finisher	Not presented	1.3%
Wondra et al. (1995)	Grower-finisher	4.2%	6.0%
Steidinger et al. (2000)	Nursery pigs	Not presented	3.0%

FCR by reduced particle size of SBM. Based on these findings, feed producer must conduct individual test for optimal standard of particle size, because the responses could be changed by many other factors.

Pelleting improved gelatinization degree of starch in ingredients, and resulted in improved starch digestibility of the pigs (Jensen, 1965). Many studies indicated improved feed conversion ratio ranged from 4 to 12% by applying pellet diet (Walker et al., 1989; Xing et al., 2004; Lewis et al., 2015; Paulk et al., 2016). Ulens et al. (2015) reported that the pigs fed pellet diet had higher ADG compared with those fed mash diet, and Overholt et al. (2016) showed improved feed efficiency and energy digestibility by providing pellet diet. The main reason for these effects of pelleting was increased surface area for enzyme reaction (Mavromichalis et al., 2000). In nursery pigs, feeding pellet diet have benefits to improve ADG and FCR (Skoch et al., 1983), and Stark (1994) also agreed with this observation. Sometimes, there were inconsistent results, and one of the reasons was fines derived from pellet affecting feed intake of animals. Hanrahan (1984) demonstrated that there was no significant difference by providing pellet diet due to high fine levels of 60%, and Harris et al. (1979) reported the pigs fed high quality pellet showed improved feed efficiency, compared with those fed poor quality pellet containing high level of fines. Feed efficiency was reduced as the level of fines is increasing (Schell and Heugten, 1998), and it means fine levels have to be considered as one of affecting factors for measurement in experiments for evaluating effects of pellet diet. Also, different feed intake, environmental conditions, and type of feed provider were factors for inconsistent response of providing pellet diet (Rojas and Stein, 2017).

4. Feed Processing and Particle Size on Gut Health and Carcass Characteristics of Growing Pigs

4.1 Prevalence of Gastric Ulcer

The stomach of the pigs could be divided to 4 regions including esophageal, cardiac, fundic and pyloric regions, and the esophageal region is most weak at developing gastric ulcer (Yen et al., 2001). Stomach regions are covered by thick layer of mucus excepting esophageal region covered by epithelium cell layer (Lawrence et al., 1996). In the stomach, mucus has a role for protecting internal wall of stomach, but this function is not working with high secretion level of hydrogen chloride. Because reduced particle size of ingredients can stimulate secretion of hydrogen chloride, incidence of gastric ulcer by different particle size was reported in previous studies (Mahan et al., 1966; Reimann et al., 1968; Pickett et al., 1969; Maxwell et al., 1970). Development of ulcer in stomach is derived from keratinization of esophageal region. Frequent peristalsis of gut stimulates the hardening of the epithelium cells and that region of keratinization was stained by bile from small intestine. That region absorbs stains and the color is changed to yellow. Swelling and erosion the area of keratinization is the following step of ulceration (Lawrence et al., 1996). Wondra et al. (1995) demonstrated that the pigs fed pellet diet of small particle size showed higher incidence of gastric ulcer relative to those fed non-pelleted diet. Sometimes, the responses of reduced particle size on developing gastric ulcer were inconsistent because of different management methods and type of housing (Kowalczyk et al., 1969; Ramis et al., 2004).

4.2 Carcass Characteristics

Generally, it is well known that the digestive organ of the pigs fed pellet diet could be decreased due to improved DM digestibility, and this action can induce improved carcass yield. Potter et al. (2009) found that carcass yield and backfat thickness after slaughter were improved by providing pellet diet, and the main reason for this was increased energy digestibility and reduced organ weight. Rojas et al. (2015) also demonstrated increased carcass yield as corn particle size is decreasing from 865 to 339 μm, and reduced organ weight was detected, and Wondra et al. (1995) reported same observation associated with carcass yield. However, Mavromichalis et al. (2000) indicated no effect on dressing percentage by providing fine wheat, so further studies would be needed to evaluate the different responses of various ingredients on carcass characteristics of the pigs.

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Chapter III. Effects of Particle Size of Swine Feed on Plant Productivity and Pellet Quality

ABSTRACT: This study was conducted to evaluate the effects of particle size on plant productivity and pellet quality of diets based on corn, wheat and soybean meal for growing and finishing pigs. Dietary treatments were particle size (600, 750 and 900 μm) and experimental diets were grinded by hammer mill (ANDRITZ Feed & Biofuel, Denmark) equipped with screen size of 3.6, 2.6 and 1.6-mm. Major ingredients were corn, wheat and soybean meal, and grower diet contained 3,300 kcal of ME/kg, 15.00% crude protein, 1.11% total lysine, 0.66% Ca, and 0.56% total P, respectively. Finisher diet contained 3,275 kcal of ME/kg, 14.00% crude protein, 1.01% total lysine, 0.52% Ca, and 0.47% total P, respectively, and all other nutrients were met or exceeded requirements. Pellet durability and hardness were measured for evaluating the effects of particle size on pellet quality. Energy usage and production rate were calculated to evaluate plant productivity. Standard deviation of geometric weight (SGW) was reduced as particle size was decreased in both growing and finishing diets. Pellet durability was decreased significantly when the pigs fed diet for 750 μm particle size ($P<0.01$), and there was no significant difference in pellet hardness. In finishing diet, pellet durability was the highest at diet for small particle size (600 μm) compared with other diets ($P<0.01$), and pellet hardness was improved significantly as particle size was decreased ($P<0.01$, linear and quadratic responses). The grinding energy for low particle size diets was higher than those for large particle size diet, but particle size had no effects on pelleting energy consumption. Grinding production rate was the highest when diet was grinded to 900 μm, and it was reduced as particle size decreased. Production rate for pelleting was not affected by different particle size. Consequently, pellet durability and hardness were improved with reduced particle size. However, high level of grinding energy was needed for fine grinded diet with low grinding production rate.

Key words: Particle Size, Plant Productivity, Pellet Quality, Growing Pigs

INTRODUCTION

The strategies for improving plant productivity is very important for reducing production cost, and there are many factors affecting plant productivity, such as number of feed product, particle size of ingredient, manufacturing process, and so on. Within these factors, major difference could be derived from grinding process of individual ingredients, because plant productivity could be highly decreased by fine grinding process. Large particle size can improve production rate, but the performance and nutrient digestibility of animals could be reduced by decreased surface area for digestion (Ohh et al., 1983; Goodband and Hines, 1987; Wondra et al., 1995; Mavromichalis et al., 2000). For improving feed quality with an acceptable production cost, there is need to make ideal standard for particle size. However, there is lack of information about ideal standard.

Improved feed efficiency and growth performance of pigs by pelleting corn and soybean meal have been demonstrated by previous findings (Walker et al., 1989; Xing et al., 2004; Lewis et al., 2015; Paulk et al., 2016; Rojas et al., 2016). Pelleting induced changed physical properties and increased starch gelatinization of ingredients, and results in increased surface area for enzyme digestion and improved nutrient digestibility.

For evaluating pellet quality, pellet durability and hardness have been used frequently, because of its effects on animal performance. Particle size of ingredient has effects on these parameters, and pellet durability and hardness were improved by reduce particle size (Behnke, 1994). The effects of particle size on pellet quality could be influenced by various feed ingredients, and different facilities in plant, so establishing individual standard of particle size is very important for ideal pellet quality.

Therefore, the present study was conducted to determine the effects of particle size on plant productivity and pellet quality in diets for growing and finishing pigs.

MATERIALS AND METHODS

Plant Facility Management

Experimental diet was grinded by a hammer mill (ANDRITZ Feed & Biofuel, Denmark) equipped with screen size of 3.6, 2.6 and 1.6mm. Average production volume was 4 ton, and hammer mill screen was changed to control particle size. Electrical energy consumption for grinding and production rate were calculated by the initial and final records of electric meter and time. The pelleted diets were produced by a 400-horsepower pellet mill (7730-8, CPM, Denmark, 80-mm thick die with 4.2mm diameter holes). Before pelleting process, steam was used for conditioning the diets to 75°C, and electrical energy consumption for pelleting and production rate were determined by the initial and final records of electric meter, steam usage and time.

Experimental Design and Diets

Treatments were particle size (600, 750 and 900μm) and experimental diets were corn-wheat-soybean meal based diet. Grower diet was containing 3,300 kcal of ME/kg, 15.00% crude protein, 1.11% total lysine, 0.66% Ca, and 0.56% total P, respectively and finisher diet was containing 3,275 kcal of ME/kg, 14.00% crude protein, 1.01% total lysine, 0.52% Ca, and 0.47% total P, respectively. All other nutrients were met or exceeded requirements of NRC (2012). The formula and chemical composition of experimental diets are presented in Table 1.

Sample Collections

Six samples for mash and pellet form of each treatment were collected for chemical and physical analysis. Mash diets were collected after mixing process, and pellet diets were collected after cooling process.

Physical Analysis

Particle size of diets were determined using US sieves of numbers 6, 8, 12, 16, 20, 30, 40, 50, 70, 100, 140, 200, 270 and a pan. A Ro-Tap shaker was used to sift the 100-g samples for 10 min. The geometric mean particle size (dgw) and the log normal standard deviation (sgw) were calculated by measuring the amount of diet remaining on each screen (ASAE 2008). For pelleted diets, ten pellets were analyzed from pellet samples of each treatment. Pellets were chosen that were between 10mm and 12mm in length, in order to minimize the effects of pellet length. Pellet durability index (PDI) was determined using a Holmen NHP100 (Tekpro Limited, Norfolk, United Kingdom) for 30s. Pellet hardness was determined by measuring the force of first fracture of individual pellets using a particle hardness tester (KQ-3Ex, Clover technology group). The force (kg) required to crush a pellet was determined by evaluating the peak amount of force applied before the first fracture occurred.

Calculations and Statistical Analysis

Individual diet was experimental unit, and all data were carried out by the General Linear Model (GLM) procedure of SAS (SAS Institute, 2004). Orthogonal polynomial contrasts were used for analyzing linear and quadratic responses of particle size, and differences were determined significant at $P<0.05$ and highly significant at $P<0.01$.

RESULTS

Analyzed particle size and standard deviation of geometric weight of experimental diets were presented in Table 2. Analyzed particle sizes of each treatment were in a range of ± 30 μm from target particle size of treatments. Even though statistical analysis was not performed for evaluating significant difference of particle characteristics, lower average particle size and standard deviation were observed when screen size was decreased. Both growing and finishing diets showed same trend for these parameters.

The effects of particle size on pellet durability and hardness were evaluated in growing and finishing diets (Table 3 and 4). For a growing diet, pellet durability was significantly reduced when diet was grinded to 750 μm ($P<0.01$), and there was no significant difference in pellet hardness. Similarly, finishing diet for 750 μm particle size also showed the lowest pellet durability compared with other diets ($P<0.01$). In finishing diet, pellet hardness was significantly increased by decreasing particle size ($P<0.01$, linear and quadratic responses).

For evaluating productivity of feed processing, used energy and production rate were calculated in grinding and pelleting process (Table 5). Low particle size diets showed higher grinding energy consumption compared with those of high particle size diets, but energy used for pelleting was not affected by different particle size. Grinding production rate was the highest when diet was grinded to 900 μm, and it was reduced as particle size decreased. Pelleting production rate was not affected by different particle size.

DISCUSSION

In a feed industry, particle size is an important factor for improving physical properties of feed and plant productivity. However, there are few researches recently for evaluating the effects of particle size on those parameters (Beyer, 2003). Generally, the range of variation for particle size could be measured by standard deviation of geometric weight (SGW), and a small SGW means higher uniformity. There is report that improved feed efficiency by high uniformity (Healy et al., 1994), and in this experiment, reduced particle size resulted in lower SGW in both growing and finishing diets.

Pellet durability and pellet hardness were major parameters for evaluating pellet quality, and the positive effects of reduced particle size have been demonstrated in previous finding (Behnke, 1994). In the present study, pellet durability of finishing diet was increased when the particle size was reduced, but there was no response in the result of growing diet. In pellet hardness, higher values were observed in diet for small particle size with an agreement of previous research (Behnke, 1994).

Feed processing is most important for improving plant productivity, because it has effects on energy use and production rate of feed. The energy usage could be increased almost 2.5 times when particle size was reduced from 1,000 to 600 μm (Wondra et al., 1995). In this experiment, grinding energy was increased 2.75 times for grower diet and 2.54 times for finisher diet when particle size was decreased from 900 to 600 μm. However, pelleting energy was not changed highly by different particle size. In the previous study, the production rate (ton/h) was reduced as decreasing particle size (Hearly et al., 1994), and there was same trend in this experiment (77% decreased production rate for grower and finisher diet). In pre-grinding system of feed mill, decreased grinding production rate could be solved by additional investment of grinding facility. It only affects to efficiency of grinding process. Whereas decreased production rate in grinding process delay whole process of feed processing in post-grinding system of feed mill.

CONCLUSION

Pellet durability and pellet hardness were improved significantly as particle size decreased ($P<0.01$, linear and quadratic responses), and the grinding energy for low particle size diets was higher than those for large particle size diet. However, different particle size had no effects on the energy consumption and production rate for pelleting process.

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Table 1. The formulas and chemical composition of growing and finishing diet

Items	Growing diets, %	Finishing diets, %
Corn	40.57	45.81
Wheat	35.00	35.00
Soybean meal	16.70	13.66
Mixed animal fat	3.84	2.30
MDCP	1.24	0.82
Limestone	0.76	0.68
Salt	0.40	0.40
L-Lysine HCl (78%)	0.57	0.55
DL-Methionine (99%)	0.20	0.18
L-Tryptophan (99%)	0.05	0.05
L-Threonine (99%)	0.23	0.22
Vitamin Mix[1]	0.05	0.05
Mineral Mix[2]	0.34	0.23
Choline Cl (50%)	0.05	0.05
Total	100.00	100.00
Chemical composition[3]		
ME, kcal/kg	3,300.00	3,275.00
CP, %	15.00	14.00
Lys, %	1.11	1.01
Met, %	0.43	0.39
Ca, %	0.66	0.52
Total P, %	0.56	0.47

[1]Provided per kg of diet: vitamin A, 12,000 IU; vitamin D_3, 2,400 IU; vitamin E, 10 IU; vitamin K, 5.6 mg; vitamin B_2, 4 mg; vitamin B_6, 2 mg; vitamin B_{12}, 40 μg; pantothenic acid, 16 mg; biotin, 100 μg; niacin, 20 mg; folic acid 1 mg

[2]Provided per kg of diet: Fe, 65 mg; Mn, 30 mg; Zn, 30 mg; Cu, 50 mg; Se, 500 μg; I, 1.24 mg.

[3]Calculated values.

Table 2. Particle size characteristics of experimental diet

Items	Growing diet			Finishing diet		
Particle size, μm	600	750	900	600	750	900
DGW, μm[1]	620	750	920	630	760	910
SGW[2]	1.48	1.63	1.73	1.46	1.59	1.72

[1] Diameter of geometric weight (ASAE, 1983).
[2] Standard deviation of geometric weight (ASAE, 1983).

Table 3. Pellet quality characteristics of growing diet

Items	Growing diet			SEM[1]	P-value		
Particle size, µm	600	750	900		ANOVA	Linear	Quadra.
Pellet durability, %	93.33^{A}	91.67^{B}	92.92^{A}	0.209	<0.01	0.20	<0.01
Pellet hardness, kg/cm	4.60	4.46	4.48	0.067	0.70	0.52	0.61

[1] Standard error of means

Table 4. Pellet quality characteristics of finishing diet

Items	Finishing diet			SEM[1]	P-value		
Particle size, µm	600	750	900		ANOVA	Linear	Quadra.
Pellet durability, %	93.92^{A}	91.25^{C}	92.83^{B}	0.280	<0.01	<0.01	<0.01
Pellet hardness, kg/cm	6.23^{A}	5.12^{B}	4.77^{C}	0.185	<0.01	<0.01	0.21

[1] Standard error of means

Table 5. Effects of particle size on productivity in feed processing

Items	Growing diet			Finishing diet		
Particle size, µm	600	750	900	600	750	900
Grinding process						
Grinding energy, kWh/t	16.24	8.17	5.88	12.38	7.50	4.88
Grinding production rate, t/h	10.61	27.01	45.22	9.99	21.16	48.32
Pelleting process						
Pelleting energy, kWh/t	68.30	70.08	70.66	67.78	69.22	70.28
Pelleting production rate, t/h	12.50	12.50	13.20	11.71	11.63	11.71

Chapter IV. Effects of Particle Size on Ileal Amino Acid Digestibility in Growing Pigs

ABSTRACT: This experiment was done to analyze the effects of particle size on ileal amino acid digestibility of growing pigs. A total of 12 weaning barrows ([Yorkshire × Landrace] × Duroc) with an initial BW of 23.66 ± 0.75 kg were allotted to 3 experimental diets and a N-free diet in a completely randomized design (CRD), and T-cannula was fitted to distal ileum of each pigs followed by Stein et al. (2007). Dietary treatments were three different particle sizes (600, 750, and 900 μm) and experimental diets were containing 3,300 kcal of ME/kg**,** 15.00% crude protein, 1.11% total lysine, 0.66% Ca, and 0.56% total P, respectively. Other nutrients were met or exceeded the requirements. N-free diet was used for calculating basal endogenous AA losses, and major ingredients were tapioca starch, glucose, sucrose and soy oil. All diets contained 0.5% chromic oxide as an indicator of nutrients. Experimental diets were fed to pigs with 2.0 times of the maintenance requirement for ME, and there were no significant differences on AID and SID of amino acids. Although there was no significant effect, the pigs fed diet of 750 μm particle size showed lower AID and SID of amino acids than those fed other diets. In diets for 600 and 900 μm particle size, there was no difference on amino acid digestibility. In conclusion, different particle size ranged from 600 to 900 μm had no effects on AID and SID of amino acids in growing pigs.

Key words: Particle size, Ileal digestibility, SID, AID, Growing Pigs

INTRODUCTION

Physical property of diet is one of important factors for determining animal performance, and optimal particle size have been popular research topics based on this background (Rojas et al., 2017). Reduced particle size may increase surface area for enzyme digestion, and there are many results about the positive effects of reduced particle size on nutrient digestibility of pigs (Mavromichalis et al., 2000; Kim et al., 2002; Fastinger et al., 2003; Rojas et al., 2015). Apparent total tract digestibility (ATTD) of starch was improved with decreased particle size from 920 to 580 μm (Kim et al., 2005), and reduced particle size had effects on increasing ATTD of GE and crude protein (Oryschak et al., 2002).

For energy digestibilities (DE and ME), reduced particle size has consistently positive effects, but there were inconsistent results associated with amino acid and other nutrients digestibility (Wondra et al., 1995; Liu et al., 2012). The reason for this difference could be explained by fiber fraction of ingredients. All of feed ingredients have fiber fractions and the fiber digestibility could be increased highly by reduced particle size relative to other nutrient. Increased fiber digestibility may induce improved energy digestibility, and results in consistent response with previous researches. However, particle size had no effects on standardized ileal digestibilities of amino acids (Rojas et al., 2015), and digestibility of crude protein and amino acids was not changed by different particle size (Giesemann et al., 1990). It is hard to find possible approach for inconsistent result associated with amino acid digestibility, because there is limited information on the effects of particle size on AID and SID of amino acids in growing pigs.

Consequently, the aim of this study was to evaluate the effects of different particle size on ileal amino acid digestibilities of growing pigs.

MATERIALS AND METHODS

Experimental Design and Diets

A total of 12 weaning barrows ([Yorkshire × Landrace] × Duroc; average BW of 23.66 ± 0.75 kg) were allotted to 3 experimental diets and a N-free diet in a completely randomized design (CRD), and T-cannula was equipped to distal ileum of each pigs followed by Stein et al. (2007). The experimental treatments were different particle size (600, 750, and 900 μm) of growing diets, and experimental diets were corn-wheat-soybean meal based diet containing 3,300 kcal of ME/kg**,** 15.00% crude protein, 1.11% total lysine, 0.66% Ca, and 0.56% total P, respectively. Other nutrients were met or exceeded the requirements of NRC (2012) (Table1). Major ingredients of N-free diet were tapioca starch, glucose, sucrose and soy oil, and experimental and N-free diets were formulated to contain same level of vitamin and minerals (Table1). Chromic oxide was supplemented to all diets at 0.5% as an indicator of nutrients.

Animal Management, Digesta Sampling and Chemical Analyses

After T-cannula injection, all pigs had 2 weeks recuperation periods in individual metabolic crates (0.93 × 1.53 m) with controlled temperature (27 ℃), and commercial diet and water were provided *ad libitum*. The experimental period was consisted of 5 d adaptation phase and 3 d collection phase, and ileal digesta samples were collected during 12 h from 0800 to 2000 by the procedure of Jorgensen et al. (1984). Experimental diets and N-free diet were provided twice a day at 0700 and 1900 with 2.0 times of the maintenance requirement for ME (NRC, 2012), and collected digesta were immediately stored in deep freezer, at -60 ℃ for preventing bacterial degradation of amino acids. After collection, ileal digesta were freeze-dried to make a solid form, and grinded by 2 mm screen Wiley mill. Chrome level was determined according to Williams method (1962), and amino acid levels were analyzed by the Beckman 6300 AA Analyzer (Beckman Instruments Corp., Palo Alto, CA) with ninhydrin method. As a reagent, the hydrochloric acid was used as for analyzing stable amino acids, and the performic acid was used for oxidation of sulfur containing amino acids.

Calculations and Statistical Analysis

Apparent ileal digestibility and standardized ileal digestibility of growing pigs were determined by the calculation method of Stein (1999a, 2001). Chromic oxide was used for calculating the AID of AAs by the indirect method, and ileal endogenous AA losses was used for determining the SID of AAs. Detailed equation was presented below.

(i) Apparent ileal digestibility (%) = 100 - [(ND / NF) x (CrF / CrD) x 100]

* ND = AA level in ileal digesta
* NF = AA level in diet
* CrD = Chrome level in ileal digesta
* CrF = Chrome level in feed

(ii) Basal endogenous AA losses (BAL) = ND x (CrF / CrD)

* BAL was calculated by N-free diet.

(iii) Standardized ileal digestibility (%) = [AID + (EAL/NF)] x 100

Individual growing pig was experimental unit, and all data were carried out by the General Linear Model (GLM) procedure of SAS (SAS Institute, 2004). Orthogonal polynomial contrasts were used for analyzing linear and quadratic responses of particle size, and differences were determined significant at $P<0.05$ and highly significant at $P<0.01$.

RESULTS

The effects of particle size on apparent ileal amino acid digestibilities (AID) of growing pigs were presented in Table 2. Although there was no significant difference on AID of amino acids with different particle size, the pigs fed diet for 750 μm particle size had lower AID of amino acids than those fed diets for 600 and 900 μm particle size, numerically. Pigs for 600 and 900 μm particle size showed similar AID of amino acids.

To calculate standardized ileal amino acid digestibilities, ileal endogenous AA losses were used, and the results were shown in Table 3. Dietary treatments of particle size had no significant differences on the SID of essential and non-essential amino acids, but numerically lower SID of amino acids was detected in the pigs fed diet for 750 μm particle size compared with other pigs fed diets for 650 and 900 μm particle size. For evaluating linear and quadratics responses by different particle size, orthogonal polynormial contrasts was performed, but there was no significant difference for AID and SID digestibility of all amino acids.

DISCUSSION

Many findings demonstrated increased nutrients digestibilities by applying reduced particle size in growing pigs, and the optimal particle size was ranged from 485 to 600 μm (Wondra et al., 1995; Rojas et al., 2015). The major reasons for this positive effect were increased surface area for digestion and increased digestibility by reducing particle size (Owens and Heimann, 1994; Patience, 2012).

In the previous finding, the amino acid digestibility of pigs was improved when the particle size of SBM was reduced from 900 to 600 μm (Fastinger and Mahan, 2003), but also there is study reporting no difference by reduced particle size of SBM (Lawrence et al., 2003). In this experiment, AID and SID of growing pigs was not changed significantly by different particle size. For analyzing these results, two explanations could be suggested, and first one is different grinding results for ingredients. Particle size could be different by ingredients even though same screen size of hammer mill was applied (Ghaid et al., 2013). In fact, the particle size of experimental diet by applying 3.6 mm screen size of hammer mill was 900 μm in this experiment, but that of SBM was 720 μm in the previous test. In a same condition of grinding, SBM was ground into smaller particles than grains because SBM is a processing byproduct. This difference could induce inconsistent results associated with various nutrients including CP, amino acids and energy digestibility. Second possible approach is reduced treatment effect on AID and SID of growing pigs by well-managed environment and restricted feeding program. In fact, the responses on digestibility by reduced particle size were inconsistent when the pigs had good conditions and restricted feeding program for improving digestibility (Rojas and Stein, 2017). In this trial, the experimental diets were supplied to the pigs according to the rate of 2.0 times of the maintenance requirement for ME (106 kcal of ME per kg of BW 0.75; NRC, 1998), and temperature and other environmental condition were maintained stably. Therefore, AID and SID of growing pigs were maintained highly in all treatments, and it was hard to find treatment effect by reduced particle size.

Besides, there were several findings for reporting different response of reduced particle size on individual nutrients, such as energy and amino acid digestibility. In many cases, energy digestibility (DE and ME) was improved, and AID and SID of amino acids were not changed by different particle size (Giesemann et al., 1990; Rojas et al., 2015). The major reasons for this difference is highly improved digestibility of fiber by reduced particle size, and the improvement of energy digestibility was higher than those of amino acids (Liu et al., 2012).

CONCLUSION

Different particle size had no considerable effects on AID and SID of amino acids, and the pigs fed diet of 750 μm particle size showed numerically lower AID and SID of amino acids than those fed other diets. In diets for 600 and 900 μm particle size, there was no difference on amino acid digestibility.

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Table 1. The formulas and chemical composition of experimental diet and N-free diet

Ingredients	Experimental diet, %	N-free diet, %
Corn	40.57	
Wheat	35.00	
Soybean meal	16.70	
Tapioca starch		65.90
Mixed animal fat	3.84	
Soy oil		10.85
Sucrose		10.00
Glucose		10.00
MDCP	1.24	2.41
Limestone	0.76	
Salt	0.40	0.40
L-Lysine HCl (78%)	0.57	
DL-Methionine (99%)	0.20	
L-Tryptophan (99%)	0.05	
L-Threonine (99%)	0.23	
Vitamin Mix[1]	0.05	0.05
Mineral Mix[2]	0.34	0.34
Choline Cl (50%)	0.05	0.05
Total	100.00	100.00
Chemical composition[3]		
ME, kcal/kg	3,300.00	3,300.00
CP, %	15.00	0.00
Lys, %	1.11	0.00
Met, %	0.43	0.00
Ca, %	0.66	0.66
Total P, %	0.56	0.56

[1]Provided per kg of diet: vitamin A, 12,000 IU; vitamin D_3, 2,400 IU; vitamin E, 10 IU; vitamin K, 5.6 mg; vitamin B_2, 4 mg; vitamin B_6, 2 mg; vitamin B_{12}, 40 μg; pantothenic acid, 16 mg; biotin, 100 μg; niacin, 20 mg; folic acid 1 mg

[2]Provided per kg of diet: Fe, 65 mg; Mn, 30 mg; Zn, 30 mg; Cu, 50 mg; Se, 500 μg; I, 1.24 mg.

[3]Calculated values.

Table 2. The effect of particle size of diet on apparent ileal digestibility of amino acid in growing pigs

Item	Growing diet			SEM[1]	P-value	
Particle size, µm	600	750	900		Linear	Quadratic
Total amino acid, %						
	88.50	86.71	88.98	1.330	0.47	0.14
Essential amino acid, %						
LYS	88.60	87.27	89.11	1.177	0.51	0.34
MET	89.08	88.57	89.56	0.609	0.37	0.37
THR	88.60	86.62	88.91	1.450	0.35	0.19
VAL	87.94	86.21	88.67	1.702	0.46	0.44
ILE	87.85	86.17	88.70	1.564	0.41	0.31
LEU	88.39	87.02	88.92	1.297	0.51	0.42
PHE	88.33	86.83	88.97	1.365	0.50	0.36
HIS	88.72	87.07	89.02	1.268	0.59	0.19
ARG	88.90	87.51	89.32	1.028	0.35	0.09
Non-essential amino acid, %						
ASP	88.10	85.93	88.79	1.688	0.48	0.18
SER	88.53	86.47	88.86	1.457	0.51	0.14
GLU	88.95	87.79	89.32	0.926	0.50	0.22
GLY	87.88	84.66	88.49	2.165	0.48	0.06
ALA	87.53	85.06	88.11	2.124	0.65	0.41
TYR	88.06	86.21	88.73	1.510	0.53	0.27
PRO	87.96	86.29	89.17	1.476	0.48	0.05
CYS	88.85	87.00	89.07	1.240	0.64	0.08
ASP	88.10	85.93	88.79	1.688	0.48	0.18

[1] Standard error of means

Table 3. The effect of particle size of diet on standardized ileal digestibility of amino acid in growing pigs

Item	Growing diet			SEM[1]	P-value	
Particle size, μm	600	750	900		Linear	Quadratic
Total amino acid, %						
	88.72	86.87	89.18	1.370	0.49	0.14
Essential amino acid, %						
LYS	88.70	87.35	89.21	1.197	0.51	0.34
MET	89.15	88.60	89.62	0.618	0.37	0.37
THR	88.77	86.75	89.07	1.484	0.67	0.20
VAL	88.12	86.35	88.83	1.732	0.47	0.45
ILE	88.09	86.36	88.92	1.596	0.50	0.09
LEU	88.55	87.11	89.06	1.330	0.53	0.42
PHE	88.45	86.91	89.09	1.388	0.51	0.36
HIS	88.86	87.16	89.14	1.296	0.61	0.19
ARG	89.06	87.62	89.45	1.055	0.37	0.09
Non-essential amino acid, %						
ASP	88.29	86.06	88.95	1.719	0.49	0.19
SER	88.75	86.61	89.05	1.498	0.64	0.14
GLU	89.06	87.87	89.41	0.942	0.51	0.22
GLY	88.42	85.04	88.95	2.256	0.64	0.08
ALA	87.78	85.22	88.33	2.173	0.67	0.41
TYR	88.35	86.39	88.98	1.571	0.64	0.16
PRO	89.59	86.75	89.77	1.659	0.80	0.28
CYS	89.03	87.12	89.25	1.273	0.65	0.08
ASP	88.29	86.06	88.95	1.719	0.49	0.19

[1] Standard error of means

Chapter V. Effects of Feed Form and Particle Size on Growth Performance, Nutrient Digestibility, Carcass Characteristics, and Gastric Health in Growing-Finishing Pigs

ABSTRACT: This study was conducted for evaluating the effects of feed processing and particle size on growth performance, nutrient digestibility, carcass characteristics, and gastric health. A total of 360 growing pigs ([Yorkshire × Landrace] × Duroc; 22.64 ± 0.014 kg initial BW) were allocated to one of six treatments in 6 replicates by body weight and gender, and 10 pigs were housed in one pen in a randomized complete block design (RCBD) (Kim and Lindemann, 2007). Body weight and feed intake were recorded at 0, 3rd, 6th, 10^{th} and 12th wk to calculate the average daily gain (ADG), average daily feed intake (ADFI) and gain-to-feed ratio (G/F ratio). Main factors for experiment were particle size (600, 750, 900 μm) and feed form (mash and pellet) of diet, and pigs were split based on a 2 x 3 factorial arrangement. Grower diets were containing 3,300 kcal of ME/kg, 15.00% crude protein, 1.11% total lysine, 0.66% Ca, and 0.56% total P, respectively, and finisher diets were formulated to contain 3,275 kcal of ME/kg, 14.00% crude protein, 1.01% total lysine, 0.52% Ca, and 0.47% total P, respectively. All other nutrients were met or exceeded requirements. During the whole experimental period, there was no significant difference in BW and ADG. But, the pigs fed diet for 600 μm particle size had numerically higher ADG than those fed other diets. Feed intake of growing pigs was not affected by dietary treatment, but ADFI of finishing pigs was increased with mash diet ($P<0.05$). For overall period, there was a tendency for improved feed intake when the pigs fed mash diet ($P=0.09$), and different particle size had no significant effects on ADFI. Feed efficiency of pigs was improved with pellet diet ($P<0.01$) and reduced particle size ($P<0.01$), and there was no considerable interaction between two factors (particle size and feed form) for all parameters of growth. Pelleting had no effects on DM and crude protein digestibilities, but resulted in improved crude fat digestibility relative to mash diet ($P<0.01$). In carcass characteristics, there was no considerable change by dietary treatments, but the pigs fed pellet diet showed numerically higher backfat thickness compared with those fed mash diet. In evaluation of gut health, tendency for increased incidence of keratinization in the esophageal region was observed as particle size decreased ($P=0.07$). Consequently, pellet diet improved feed efficiency and fat digestibility and reduced particle size could induce increased feed efficiency and incidence of keratinization in the esophageal region.

Key words: Feed Processing, Pellet Diet, Particle Size, Growth Performance, Nutrient Digestibility, Carcass Characteristics, Gastric Ulcer, Growing Pigs

INTRODUCTION

The benefits of reduced particle size of feed ingredients have been reported in previous findings (Goodband and Hines, 1987; Healy et al., 1994). However, there were many inconsistent results, because of change of feed intake (Mavromichalis et al., 2000), increased incidence of gastric ulcer (Mahan et al., 1966; Reimann et al., 1968; Pickett et al., 1969; Maxwell et al., 1970), and various environmental condition (Rojas et al., 2017). Although feed producers have their own standard for particle size, the main concern was plant productivity. Therefore, there is need to determine optimal particle size for improving growth performance of pigs.

Pelleting a corn-soybean meal diet had positive effects on improving growth performance, nutrient digestibility, and feed efficiency (Jensen, 1965; Xing et al., 2004; Lewis et al., 2015). Feed efficiency of the pigs fed pellet diet was increased relative to those fed mash diet (Ulens et al., 2015), and pelleting of feed ingredients improved feed intake of weaning pigs (Steidinger et al., 2000). The major reason for these responses was improved gelatinization of starch fraction in feed ingredients (Jensen et al., 1965). Although there were many finding associated with the effects of pellet diet on pigs, limited information was available for interaction between feed form and particle size of feed ingredients.

Consequently, this study was conducted to determine the effects of feed processing and particle size on growth performance, nutrient digestibility, carcass characteristics, and gastric health in pigs.

MATERIALS AND METHODS

Animal and Management

All of procedure of experiment with animals was conducted based on standard of Institutional Animal Ethics Committee provided from Seoul National University (SNUIACUC; SNU-171203-03). A total of 360 growing pigs ([Yorkshire × Landrace] × Duroc; 22.64 ± 0.014 kg initial BW) were used for a 12-wk growth trial, at a research farm located in Jincheon, South Korea. Pigs were allocated to one of six treatments in 6 replicates by body weight and gender, and 10 pigs were housed in one pen in a randomized complete block design (RCBD) (Kim and Lindemann, 2007). Each pen was equipped with half-slotted concrete floors (1.60 x 3.00 m), a feeder and a nipple drinker to provide water and feed with *ad libitum* access, and room temperature was controlled stably at 24℃ for growing period for 6wks and 22℃ for finishing period for 6wks. Body weight and feed intake were recorded at 0, 3rd, 6th, 10th and 12th wk to calculate the average daily gain (ADG), average daily feed intake (ADFI) and gain-to-feed ratio (G/F ratio).

Experimental Design and Diets

The experiment was designed as a 2 x 3 factorial arrangement of treatments, and main factors were particle size (600, 750, 900 μm) and feed form (mash and pellet) of diet. Experimental diets for growing pigs were contained 3,300 kcal of ME/kg, 15.00% crude protein, 1.11% total lysine, 0.66% Ca, and 0.56% total P, respectively, and major ingredients were corn, wheat and soybean meal. For the finishing period, experimental diet was formulated to 3,275 kcal of ME/kg, 14.00% crude protein, 1.01% total lysine, 0.52% Ca, and 0.47% total P, respectively, and all other nutrients were met or exceeded requirements of NRC (2012). The formula and chemical composition of experimental diets were shown in Table 1.

Chemical Analysis

All of experimental diets were analyzed for DM (AOAC 934.01, 2006), crude protein (AOAC 990.03, 2006), ether extract (AOAC 920.39 A, 2006), crude fiber (AOAC 978.10, 2006), ash (AOAC 942.05, 2006), Ca (AOAC 965.14/985.01, 2006) and P (AOAC 965.17/985.01, 2006). Starch contents of diets were analyzed by polarimetric method according to the Commission Directive 1999/79/EC, and the degree of gelatinization was measured by using a glucose analyzer (Model 2700, YSI). The proximate composition of growing and finishing diet were presented in Table 2.

Digestibility Trial

For evaluating total tract digestibility, a total of 24 growing pigs ([Yorkshire × Landrace] × Duroc; 33.65 ± 0.37 kg initial BW) were split into six treatments with completely randomized design (CRD). The experimental diets were supplied twice a day at 0700 and 1900 with *ad-libitum* access to water according to the rate of 2.0 times of the maintenance requirement for ME (106 kcal of ME per kg of BW0.75; NRC, 1998) based on initial BW of pigs. After 5 days of adaptation period, piglets were subjected to 5 days collection and chromic oxide and ferric oxide were used as initial and end marker, respectively. Collected excreta were stored at -20 ℃ during the collection period and dried (60 ℃, 72 h) and ground (5 mm screen, Wiley mill) for chemical analysis at the end of trial. Total urine was collected daily in plastic container containing 50ml of 10% H_2SO_4 to avoid evaporation of ammonia from urine. Glass wool was used as a filter to remove foreign materials and the urine collected massed up 4000ml with water. The samples were collected 50ml conical tube and stored at -20 ℃ during collecting period for nitrogen retention analysis.

Blood Urea Nitrogen (BUN)

For BUN analysis, blood samples were collected from anterior vena cava of 36 pigs (6 pigs for each treatment) at 0, 3th, 6th, 9th and 12th weeks for BUN analysis, and those were quickly centrifuged for 15 min at 3,000 rpm and 4 ℃. The serum was carefully removed to plastic vials and stored at -20 ℃ until BUN analysis, and total BUN concentrations were analyzed using blood analyzer (Ciba-Corning model, Express Plus, Ciba Corning Diagnostics Co.).

Carcass Traits

Carcass characteristics of 36 finishing pigs (6 pigs for each treatments) were measured after slaughter including carcass weight, percentage carcass yield and backfat thickness. Carcass yield was calculated by dividing the carcass weight at the abattoir by the live weight at the farm before transport to the abattoir. Backfat thickness was measured between the 11th and 12th point located vertically with the dorsal midline.

Keratinization and Ulcer Incidence

Stomachs were collected during evisceration and used for determining ulcer and keratinization score by the method of De Jong (2015). Keratinization scores were assigned on a scale from 1 to 4 with 1 being normal or no keratinization of the esophageal region; 2 being keratin covering < 25% of the esophageal region; 3 being keratin covering 25 to 75% of the esophageal region; and 4 being keratin covering >75% of the esophageal region. Ulcer scores were also assigned on a scale from 1 to 4 with 1 being no ulcers present; 2 being ulceration affecting <25% of the esophageal region; 3 ulceration affecting 25 to 75% of the esophageal region; and 4 being ulceration affecting >75% of the esophageal region (Figure 1).

Statistical Analysis

All collected data were carried out by least squares mean comparisons and were evaluated with the General Linear Model (GLM) procedure of SAS (SAS Institute, 2004). Experimental pen was used as an experimental unit for the performance data, whereas individual pig was served as the experimental unit to analyze nutrient digestibility, BUN, carcass traits, incidence of ulcer and keratinization in stomach. The experimental unit was analyzed as 2 x 3 factorial arrangements. Considering feed form and particle size as factors, the differences were declared significant at $P < 0.05$ or highly significant at $P < 0.01$ and the determination of tendency for all analysis was $P>0.05$ and $P<0.10$. The effect of particle size was also analyzed as linear and quadratic components by orthogonal polynomial contrasts.

RESULTS

The effect of feed form and particle size on growth performance of growing and finishing pigs was presented in Table 3. For overall periods, there was no significant difference in the results of body weight and daily gain. Feed intake of growing pigs was not affected by dietary treatment, but ADFI of finishing pigs was increased when they fed mash diet ($P<0.05$). Also for overall period, there was a tendency for improved ADFI when the pigs fed mash diet ($P=0.09$). During the whole experimental period, feed efficiency of pigs was subsequently shown to be improved when the pigs fed pellet diet ($P<0.01$) and as particle size was decreased ($P<0.01$). For all parameters of growth trial, there was no interaction between two factors (particle size and feed form).

To evaluate nitrogen utilization in the animal body, BUN was checked during the whole experimental periods (Table 4). As getting older, BUN was increased linearly, but there was no response by dietary treatments. The effects of feed form and particle size on nutrient digestibility and N retention of growing pigs were presented in Table 5. Dietary treatments had no effects for the total tract digestibilities of dry matter and crude protein, but feeding pellet diet improved crude fat digestibility relative to mash diet ($P<0.01$). Nitrogen retention was not changed by feed form and particle size, and there was no significant difference.

The live weight, carcass yield and backfat thickness were measured to evaluate treatment effects on carcass characteristics (Table 6). For all parameters, there was no considerable change by dietary treatments.

The effect of feed form and particle size on ulceration and keratinization of finishing pigs was shown in Table 7. Because of well-managed environment, there was no pig which have ulceration problem, and dietary feed form had no significant difference on keratinization of the esophageal region. However, a tendency for increased incidence of keratinization was observed as particle size decreased ($P=0.07$). There was no considerable interaction between two factors (particle size and feed form).

DISCUSSION

There were many studies to report decreased amounts of feed waste when pellet diet was provided to the pigs (Nir et al., 1995; Amerah et al., 2007). In the present study, feeding pellet diet resulted in decreased feed intake relative to mash diet during overall periods with an agreement of previous findings. For a feed consumption, improved intake of weanling pigs was reported compared with mash diet (Steidinger et al., 2000), but the response was inconsistent for finishing pigs (Potter et al., 2009). Different responses of feed intake by feed form could be induced by environmental condition and age of animals (Patience, 2012). In well-managed environment, animals can have maximum feed intake, and it is hard to improve feed intake by dietary treatments. In this experiment, pigs showed high feed intake during all periods compared with normal standard for feed intake curves, and there was no response by different feed form. Different feed intake by various particle size was observed in many findings (Seerley et al., 1988; Rojas et al., 2015), but the response was not consistent, because of age difference (Patience, 2012). In this experiment, different particle size had no considerable change on feed intake, and it means that there is no negative effect on feed intake if diet is grinded at below 900 μm.

Generally, it is well known that pelleting process could improve starch digestibility of cereal grains due to increased gelatinization degree of starch (Jensen, 1965). There were several reports for improved feed conversion ratio ranged from 4 to 12% by applying pellet diet (Walker et al., 1989; Xing et al., 2004; Lewis et al., 2015; Paulk et al., 2016). In this trial, improved G:F ratio was observed in pigs fed pellet diet during the whole experimental periods with an agreement of previous findings. The positive effects of particle size reduction on feed efficiency of swine have been reported (Goodband and Hines, 1987; Mavromichalis et al., 2000). Fine grinding process for corn and sorghum could improve feed efficiency in starter period (Ohh et al., 1983), and reduced particle size of corn resulted in an 8% improvement of feed efficiency in growing period (Wondra et al., 1995; 47.8 kg of initial BW). In the present study, the pigs fed diet for 900 μm particle size showed lower G:F ratio compared with those fed diets for 600 and 750 μm particle size, and it means reduced particle size below 750 μm could improve feed efficiency in both pellet and mash diet.

Pelleting often resulted in improved ADG and feed efficiency compared with mash diet, and it was derived from improved energy digestibility and reduced feed intake (Ulens et al., 2015; Overholt et al., 2016). Reduced particle size may improve enzyme surface reaction, and it could increase nutrient digestibility of nutrients (Mavromichalis et al., 2000). However, these responses of growth could be inconsistent due to changed digestibility by feed intake and environmental conditions (Rojas and Stein, 2017). In this trial, the pigs fed diet for pellet and reduced particle size showed numerically higher ADG than other treatments with a similar trend of previous researches, but there was no significant difference.

For evaluating the effects of dietary treatments on nutrient digestibility, BUN and total collection digestibility of growing pigs were analyzed. Several findings demonstrated that pelleting could improve digestibilities of DM. N, and energy ranged from 5 to 8% (Wondra et al., 1995), and increased AID of indispensable AA by application of pellet diet was also observed (Rojas et al., 2016). In the previous studies, the main reason for improved digestibility by pelleting was increased starch gelatinization and changed protein confirmation by steam conditioning process, however some findings demonstrated inconsistent results with N and AA digestibilties because of different pelleting and steam condition (Harris et al. 1979; Schell and van Heugten, 1998). In the present study, crude fat digestibility was improved by pelleting with agreement of previous findings (Jansen et al., 1965), but those for DM, BUN and crude protein were not changed by dietary treatments because of high digestibility in all treatments. During the experimental periods for digestibility trial, restricted feeding method was applied, and the pigs were housed in well-managed environment. Many experiments have been conducted to determine the effects of particle size on nutrient digestibility of pigs, and various positive effects were presented many times (Wondra et al., 1995; Lawrence et al., 2003; Amaral et al., 2015). Possible approach for this improvement is increased energy digestibility and prolonged passage rate of digesta. In the previous study, poor flowability of digesta was reduced as particle size decreasing (Appel, 1994), and reduced particle size may lead to improved energy digestibility (Jansen et al., 1965). However, there was no significant difference change of nutrient digestibility by different particle size in this trial, because of high digestibility in all experimental groups with an agreement of comparison result between pellet and mash diet. Consequently, the pigs showed high DM and crude protein digestibilities up to 94%, and it was hard to evaluate treatment effects. In a growth trial, *ad libitum* access to feed was applied and improved G:F ratio was observed. These different feeding programs could induce different digestibilities for various parameters.

In the previous study, carcass yield and backfat thickness after slaughter were increased when the pigs fed pellet diet relative to those fed mash diet, and the main reason for this change was improved energy digestibility and reduced organ weight (Potter et al., 2009). Even though there was no significant difference on the carcass characteristics in this trial, the pigs fed pellet diet showed numerically higher backfat thickness compared with those fed mash diet. In some case, carcass yield was increased by reduced particle size, because of decreased organ weight (Rojas et al., 2015). However, significant effect of carcass characteristics by different particle size was not observed in this experiment, and different particle size range would be a one of reason for this difference. In the previous experiment, the range for particle size was from 339 to 865 μm, and it was lower than 600 μm (Rojas et al., 2015).

The esophageal region is the most risky region at developing gastric ulcer, and increased incidence of gastric ulcer by reduced particle size was reported by previous researches (Mahan et al., 1966; Reimann et al., 1968; Pickett et al., 1969; Maxwell et al., 1970). However, those responses could be differed by other factors, such as management methods and type of housing (Kowalczyk et al., 1969; Ramis et al., 2004). In this trial, there was no pig which have gastric ulcer problem, because of good environment. However, there was a tendency for increased keratinization score as particle size increased (P=0.07).

CONCLUSION

During the whole experimental period, feed efficiency of pigs was improved with pellet diet (P<0.01) and reduced particle size (P<0.01). Pelleting had no effects on DM and crude protein digestibilities, but resulted in improved crude fat digestibility relative to mash diet (P<0.01). There was no considerable change of carcass characteristics by dietary treatments, but increased incidence of keratinization in the esophageal region was observed as particle size decreased (P=0.07).

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1	2
	
3	4
	

Figure 1. Keratinization incidence scoring standard

Table 1. The formulas and chemical composition of growing and finishing diet

Ingredients	Growing diet, %	Finishing diet, %
Corn	40.57	45.81
Wheat	35.00	35.00
Soybean meal	16.70	13.66
Mixed animal fat	3.84	2.30
MDCP	1.24	0.82
Limestone	0.76	0.68
Salt	0.40	0.40
L-Lysine HCl (78%)	0.57	0.55
DL-Methionine (99%)	0.20	0.18
L-Tryptophan (99%)	0.05	0.05
L-Threonine (99%)	0.23	0.22
Vitamin Mix[1]	0.05	0.05
Mineral Mix[2]	0.34	0.23
Choline Cl (50%)	0.05	0.05
Total	100.00	100.00
Chemical composition[3]		
ME, kcal/kg	3,300.00	3,275.00
CP, %	15.00	14.00
Lys, %	1.11	1.01
Met, %	0.43	0.39
Ca, %	0.66	0.52
Total P, %	0.56	0.47

[1]Provided per kg of diet: vitamin A, 12,000 IU; vitamin D_3, 2,400 IU; vitamin E, 10 IU; vitamin K, 5.6 mg; vitamin B_2, 4 mg; vitamin B_6, 2 mg; vitamin B_{12}, 40 µg; pantothenic acid, 16 mg; biotin, 100 µg; niacin, 20 mg; folic acid 1 mg

[2]Provided per kg of diet: Fe, 65 mg; Mn, 30 mg; Zn, 30 mg; Cu, 50 mg; Se, 500 µg; I, 1.24 mg.

[3]Calculated values.

Table 2. Proximate composition[1] of growing and finishing diet

Feed form	Mash			Pellet		
Particle size, μm	600	750	900	600	750	900
Growing diet						
Moisture, %	11.45	11.51	11.53	11.15	11.77	12.25
Crude protein, %	15.03	14.81	14.52	14.49	14.67	14.83
Crude fat, %	5.50	6.18	5.76	6.36	6.07	5.87
Crude fiber	2.61	2.43	2.38	2.62	2.88	2.50
Crude ash, %	4.15	4.12	4.13	4.14	4.31	4.18
Ca, %	0.66	0.66	0.64	0.64	0.66	0.62
Total P, %	0.57	0.56	0.55	0.59	0.58	0.57
Starch, %	48.72	48.00	48.82	49.13	47.96	47.31
Gelatinization,%	23.21	24.04	24.95	24.45	24.75	24.67
Finishing diet						
Moisture, %	11.44	11.56	11.95	12.12	13.48	12.12
Crude protein, %	13.81	13.98	14.10	13.56	14.05	13.56
Crude fat, %	4.38	4.49	4.45	4.95	4.75	4.95
Crude fiber	2.41	2.56	2.79	2.33	1.91	2.33
Crude ash, %	3.73	3.80	3.65	3.56	3.67	3.56
Ca, %	0.52	0.53	0.52	0.53	0.55	0.53
Total P, %	0.49	0.46	0.45	0.45	0.43	0.45
Starch, %	51.47	51.39	51.66	51.62	49.17	51.62
Gelatinization,%	21.92	21.68	23.91	29.63	29.16	29.63

[1]Analized values.

Table 3. The effect of feed form and particle size on growth performance of growing and finishing pigs

Items	Feed form		Particle size, µm			SEM[1]	P-value[2]		
	Mash	Pellet	600	750	900		F	PS	F*PS
Body weight, kg									
Initial	22.64	22.64	22.63	22.64	22.65	0.580	0.67	0.99	0.84
3 week	37.70	38.69	38.62	38.35	37.62	1.072	0.97	0.94	0.97
6 week	57.56	58.22	58.33	57.96	57.38	1.187	0.81	0.97	0.80
10 week	85.58	86.37	87.62	86.30	84.01	1.356	0.91	0.62	0.82
12 week	100.09	100.99	101.71	101.14	98.79	1.411	0.98	0.73	0.93
ADG, g									
0-3 week	717	765	762	749	713	25.2	0.59	0.70	0.86
4-6 week	946	930	939	934	941	14.0	0.24	0.93	0.17
0-6 week	831	847	850	841	827	18.7	0.63	0.58	0.36
7-10 week	1,001	999	1,039	1,013	952	13.0	0.86	0.03	0.93
11-12 week	1,037	1,044	1,007	1,060	1,056	19.9	0.66	0.53	0.40
7-12 week	1,013	1,015	1,027	1,029	986	10.0	0.66	0.17	0.75
0-12 week	922	933	942	934	907	10.8	0.81	0.42	0.95
ADFI, g									
0-3 week	1,345	1,319	1,344	1,338	1,314	43.6	0.52	0.97	0.90
4-6 week	1,936	1,830	1,893	1,854	1,903	42.8	0.10	0.84	0.53
0-6 week	1,640	1,574	1,618	1,596	1,608	41.8	0.25	0.98	0.74
7-10 week	2,625	2,491	2,523	2,552	2,600	33.0	0.04	0.48	0.19
11-12 week	2,576	2,444	2,480	2,576	2,475	36.3	0.04	0.74	0.51
7-12 week	2,609	2,469	2,508	2,550	2,559	31.5	0.03	0.67	0.52
0-12 week	2,125	2,022	2,064	2,073	2,084	34.3	0.09	0.93	0.66
G:F ratio									
0-3 week	0.533	0.581	0.568	0.561	0.542	0.071	<0.01	0.11	0.90
4-6 week	0.493	0.517	0.508	0.510	0.499	0.080	0.13	0.83	0.53
0-6 week	0.510	0.544	0.533	0.532	0.517	0.058	<0.01	0.30	0.68
7-10 week	0.383	0.403	0.413	0.398	0.368	0.063	0.04	<0.01	0.28
11-12 week	0.402	0.431	0.407	0.414	0.429	0.082	0.03	0.66	0.30
7-12 week	0.389	0.412	0.411	0.405	0.387	0.050	<0.01	0.04	0.16
0-12 week	0.435	0.463	0.459	0.453	0.437	0.043	<0.01	0.01	0.28

[1] Standard error of mean.
[2] F: feed form; PS: particle size.

Table 4. The effect of feed form and particle size on blood urea nitrogen of growing and finishing pigs

Items	Feed form		Particle size, µm			SEM[1]	P-value[2]		
	Mash	Pellet	600	750	900		F	PS	F*PS
BUN, mg/dL									
Initial			6.6			-	-	-	-
3 week	7.9	6.5	7.2	7.0	7.5	0.421	0.27	0.84	0.46
6 week	11.3	9.5	10.5	11.0	9.7	0.614	0.11	0.72	0.21
10 week	11.3	10.8	11.9	10.7	10.6	0.400	0.33	0.42	0.37
12 week	12.1	11.3	11.5	11.4	12.1	0.438	0.64	0.87	0.36

[1] Standard error of mean.

[2] F: feed form; PS: particle size.

Table 5. The effect of feed form and particle size on total collection digestibility of growing pigs[1]

Items	Feed form		Particle size, µm			SEM[2]	P-value[3]		
	Mash	Pellet	600	750	900		F	PS	F*PS
Nutrient digestibility, %									
Dry matter	95.00	95.14	94.91	95.26	95.04	0.09	0.42	0.25	0.21
Crude protein	94.52	94.16	94.21	94.56	94.26	0.14	0.19	0.53	0.32
Crude fat	91.57	93.70	92.55	92.99	92.37	0.31	<0.01	0.38	0.29
Nitrogen retention, g/d									
N intake	29.15	29.15	29.15	29.15	29.15	-	-	-	-
Fecal N	1.61	1.69	1.66	1.57	1.71	0.04	0.28	0.37	0.16
Urinary N	1.22	1.17	1.20	1.23	1.14	0.19	0.16	0.14	0.63
N retention[4]	26.32	26.29	26.28	26.34	26.29	0.04	0.68	0.81	0.26

[1] A total 24 growing pigs was fed from average initial body 33.65 ± 1.78 kg.
[2] Standard error of mean
[3] F: feed form; PS: particle size.
[4] N retention = N intake - Fecal N - Urinary N.

Table 6. The effect of feed form and particle size on carcass characteristics of finishing pigs

Item	Feed form		Particle size, µm			SEM[1]	P-value[2]		
	Mash	Pellet	600	750	900		F	PS	F*PS
Live weight, kg	111.2	112.0	111.8	111.4	111.4	1.30	0.77	0.96	0.67
Carcass yield, %	77.0	76.8	77.0	76.8	76.9	0.05	0.22	0.69	0.68
Back fat P_2, mm	23.5	24.3	23.5	24.2	23.8	0.94	0.64	0.98	0.38

[1] Standard error of mean.

[2] F: feed form; PS: particle size.

Table 7. The effect of feed form and particle size on ulceration and keratinization of finishing pigs

Items	Feed form		Particle size, μm			SEM[1]	P-value[2]		
	Mash	Pellet	600	750	900		F	PS	F*PS
Keratinizaition[3]	1.83	1.72	2.25	1.75	1.34	0.170	0.66	0.07	0.23
Ulceration[4]	0.0	0.0	0.0	0.0	0.0	-	-	-	-

[1] Standard error of mean.

[2] F: feed form; PS: particle size.

[3] 1 being normal or no keratinization of the esophageal region; 2 being keratin covering <25% of the esophageal region; 3 being keratin covering 25 to 75%of the esophageal region; and 4 being keratin covering >75% of the esophageal region.

[4] Ulcer scores were also assigned on a scale from 1 to 4 with 1 being no ulcers present; 2 being ulceration affecting <25% of the esophageal region; 3 ulceration affecting 25 to 75% of the esophageal region; and 4 being ulceration affecting >75% of the esophageal region.

Chapter VI. Overall Conclusion

Optimizing feed form and particle size of ingredients is the most important projection to improve plant productivity and animal performance, but limited information is available and the consequences are inconsistent in different environment and facilities. Therefore, 3 experiments were conducted to investigate 1) the effects of particle size on plant productivity and pellet quality of diets for growing and finishing pigs, 2) the effects of different particle size on ileal amino acid digestibilities of growing pigs, and 3) the effects of feed form and particle size on growth performance, nutrient digestibility, carcass characteristics, and gastric health.

In the first study, standard deviation of geometric weight (SGW) was reduced as particle size decreasing in both growing and finishing diets. Pellet durability was decreased significantly when the pigs fed diet for 750 μm particle size ($P<0.01$), and there was no significant difference in pellet hardness. In case of finishing diet, pellet durability was the highest at diet for small particle size (600 μm) compared with other diets ($P<0.01$), and pellet hardness was improved significantly as particle size decreasing ($P<0.01$, linear and quadratic responses). The grinding energy for low particle size diets was higher than those for large particle size diet, but different particle size had no effects on pelleting energy. Grinding production rate was the highest when diet was grinded to 900 μm, and it was reduced as particle size decreased. Production rate for pelleting was not changed by different particle size.

In the second study, experimental diets were fed to pigs with 2.0 times of the maintenance requirement for ME (NRC, 2012), and there was no significant difference on AID and SID of amino acids. Although there was no considerable change, the pigs fed diet of 750 μm particle size showed numerically lower AID and SID of amino acids than those fed other diets. In case of diets for 600 and 900 μm particle size, there was no difference on amino acid digestibility.

In the third study, there was no significant difference in the results of BW and ADG. But, the pigs fed diet for 600 μm particle size had numerically higher ADG than those fed other diets. Feed intake of growing pigs was not affected by dietary treatment, but ADFI of finishing pigs was increased with mash diet ($P<0.05$). Also, for overall period, there was a tendency for improved feed intake when the pigs fed mash diet ($P=0.09$), and different particle size had no significant effects on ADFI. Feed efficiency of pigs was improved with pellet diet ($P<0.01$) and reduced particle size ($P<0.01$), and there was no considerable interaction between two factors (particle size and feed form) for all parameters of growth trial. Pelleting had no effects on DM and crude protein digestibilities, but resulted in improved crude fat digestibility relative to mash diet ($P<0.01$). In the results of carcass characteristics, there was no considerable change by dietary treatments, but the pigs fed pellet diet showed numerically higher backfat thickness compared with those fed mash diet. In the results of parameters for evaluating gut health, tendency for increased incidence of keratinization in the esophageal region was observed as particle size decreased ($P=0.07$).

Consequently, pellet diet improved feed efficiency and fat digestibility and reduced particle size could induce increased feed efficiency and incidence of keratinization in the esophageal region. However, high level of grinding energy was needed for fine grinded diet with low grinding production rate.

Chapter VII. Summary in Korean

본 실험은 사료의 입자도가 공장 생산성 및 가공 사료 품질에 미치는 영향과 사료형태 및 사료의 입자도가 육성돈의 성장성적, 영양소소화율 및 도체성적에 미치는 영향을 평가하기 위해 수행되었다.

실험 1. 양돈 사료의 입자도가 공장 생산성 및 펠렛 품질에 미치는 영향

본 실험은 사료의 입자도가 공장 생산성 및 가공 사료 품질에 미치는 영향을 검증하기 위해 수행되었다. 실험사료는 해머밀에 의해 총 3종류의 입자도로 (600, 750 및 900 µm) 분쇄되었으며 (ANDRITZ Feed & Biofuel, Denmark), 스크린 사이즈는 각각 1.6, 2.6 및 3.6 mm였다. 주요 원료는 옥수수, 밀 및 대두박이었으며, 육성돈 사료는 3,300 kcal/kg ME, 15.00% 조단백, 1.11% 총라이신, 0.66% 칼슘 및 0.56% 총인을 함유하도록 설계되었다. 비육돈 사료의 경우 3,275 kcal/kg ME, 14.00% 조단백, 1.01% 총라이신, 0.52% 칼슘 및 0.47% 총인을 함유하도록 설계되었으며, 다른 영양소의 경우 NRC (2012) 요구량을 충족하였다. 시험 사료 분석 결과, 입자도 편차(SGW, standard deviation of geometric weight)는 육성돈 및 비육돈 사료 모두에서 평균입자도가 낮아질수록 함께 낮아지는 경향을 보였다. 육성돈 사료의 경우, 750 µm 평균입자도를 가진 사료의 PDI가 유의적으로 낮았으며 ($P<0.01$), 펠렛 경도에는 차이가 없었다. 비육돈 사료의 경우 입자도가 낮을수록 PDI 및 펠렛 경도가 상승되는 경향을 나타냈다 ($P<0.01$, linear−quadratic responses). 입자도가 낮을수록 분쇄 에너지가 증가되었으며, 펠렛 가공을 위한 에너지의 경우 입자도에 따른 영향이 없는 것으로 나타났다. 분쇄 생산성은 입자도가 높을수록 좋은 것으로 나타났으며, 가공사료 생산성에는 차이가 없었다. 결론적으로 입자도가 감소할수록 PDI 및 펠렛 경도는 개선되었으나, 분쇄 에너지 및 생산성에는 악영향을 미치는 것으로 나타났다.

실험 2. 사료의 입자도가 육성돈의 회장 아미노산 소화율에 미치는 영향

본 실험은 사료의 입자도가 육성돈의 회장소화율에 미치는 영향을 평가하기 위하여 수행되었다. 평균 개시체중 23.66 ± 0.75 kg의 육성돈 ([Yorkshire × Landrace] × Duroc) 12두를 3개의 처리구 및 무질소사료 급이구에 완전임의배치법 (CRD)으로 배치하였다. 회장소화물을 수거하기 위해 Stein 등 (2007)의 방법에 따라 T-cannula를 설치하였으며 시험 처리구는 3종류의 사료입자도 (600, 750 및 900 μm)였다. 육성돈 사료의 경우 3,300 kcal/kg ME, 15.00% 조단백, 1.11% 총라이신, 0.66% 칼슘 및 0.56% 총인을 함유하도록 설계되었으며, 다른 영양소의 경우 NRC (2012) 요구량을 충족하였다. 내생질소를 구하기 위해 무질소사료 급이구가 활용되었으며, 주요 원료는 타피오카전분, 포도당, 설탕 및 대두유였다. 모든 사료에는 0.5%의 산화구리가 지시제로서 첨가되었으며, 개시체중을 기준으로 유지에너지의 2배를 개체별로 산정하여 급이하였다 (NRC, 2012). 시험 결과, 아미노산의 AID 및 SID에 대한 평균 입자도의 유의적인 영향은 없는 것으로 나타났다. 600 및 900 μm 평균

입자도를 가진 사료를 급이한 경우 750 µm 평균입자도를 가진 사료를 급이한 경우에 비해 수치적으로 육성돈의 AID 및 SID가 높았으나, 유의적인 차이는 없었다. 결론적으로 600-900 µm 범위의 평균 입자도 변화는 육성돈의 AID 및 SID에 영향을 미치지 않는 것으로 나타났다.

실험 3. 사료의 형태와 입자도가 육성비육돈의 성장성적, 영양소 소화율, 도체성적 및 위 건강에 미치는 영향

본 실험은 사료형태 및 입자도가 육성비육돈의 성장성적, 영양소 소화율, 도체특성 및 위건강에 미치는 영향을 규명하기 위하여 수행되었다. 평균 개시체중 22.64 ± 0.014kg의 육성돈 ([Yorkshire × Landrace] × Duroc) 360두를 체중을 고려하여 2 x 3 요인설계 방법에 따라 배치하였다. 요인은 가공여부 (가루 및 펠렛) 및 사료의 입자도 (600, 750 및 900 µm)였으며, 총 12주의 시험 기간 동안 3주 단위로 ADG, ADFI, 및 G:F ratio를 측정하였다.육성돈 사료는 3,300 kcal/kg ME, 15.00% 조단백, 1.11% 총라이신, 0.66% 칼슘 및 0.56% 총인을 함유하도록 설계되었으며, 비육돈 사료의 경우 3,275 kcal/kg ME, 14.00% 조단백, 1.01% 총라이신, 0.52% 칼슘 및 0.47% 총인을 함유하도록 설계되었다. 다른 영양소의 경우 NRC (2012) 요구량을 충족하였다. 성장성적 측정 결과, 처리구에 의한 유의적인 변화는 없었으나, 600 µm의 입자도를 가진 사료를 급이한 경우 수치적으로 높은 ADG를 나타냈다. 비육돈을 대상으로 가루사료를 급이한 경우 섭취량이 개선되었으며 ($P<0.05$), 이러한 경향은 전구간 사료섭취량에서도 동일하게 나타났다 ($P=0.09$). 반면에 사료 입

자도에 따른 섭취량 차이는 없었으며, FCR의 경우 펠렛사료를 급이하거나 (P<0.01), 입자도가 작아질수록 (P<0.01) 개선되는 것으로 나타났다. 영양소 소화율 측정 결과, 펠렛 사료를 급이한 경우 조지방 소화율이 개선되는 것으로 나타났으며 (P<0.01), 건물 및 조단백 소화율에는 처리구에 따른 유의적 차이가 나타나지 않았다. 도체특성 분석 결과, 유의적인 차이는 없었으나, 펠렛 사료를 급이한 돼지의 등지방이 수치적으로 높았으며, 위궤양 발생률에 차이는 없었으나, 입자도가 작아질수록 식도구 주변의 각질 발생률이 높아지는 경향이 나타났다 (P=0.07). 결론적으로 펠렛 사료를 급이한 경우 사료효율 및 조지방 소화율이 개선되었으며, 사료입자도가 작아질수록 사료효율 및 식도구 주변의 각질 발생률이 높아지는 것으로 나타났다.