Importance of feed structure (particle size) and feed form (mash vs. pellets) in pig nutrition – A review

Đuro Vukmirović[a,]*, Radmilo Čolović[a], Slađana Rakita[a], Tea Brlek[a], Olivera Đuragić[a], David Solà-Oriol[b]

[a] *University of Novi Sad, Institute of Food Technology in Novi Sad, Research Center for Feed Technology and Animal Products, Bulevar cara Lazara 1, 21000 Novi Sad, Serbia*

[b] *Animal Nutrition and Welfare Service, Department of Animal and Food Sciences, Universitat Autònoma de Barcelona, Bellaterra, Barcelona 08193, Spain*

*Corresponding author. Tel: +381 21 485 3796; Fax: +381 21 450 730; EM: djuro.vukmirovic@fins.uns.ac.rs, djuro.vukmirovic@gmail.com

Abstract

Pigs are monogastric animals with simple, single-chambered stomach and require easily digestible, high quality feed. One of the most important factors that determine feed utilization by pigs is the particle size distribution. The reduction of particle size of feed improves pigs' performance due to increased specific surface of feed particles allowing better contact with digestive enzymes. In this respect, fine grinding could be recommended in production of pig feed. Additionally, in modern pig production dry feed is predominantly used in pelleted form, which is mainly due to improved (i.e. decreased) feed conversion ratio (FCR) of pigs fed pelleted feed, but also due to other advantages of pelleted over mash feed.

Size of feed particles is strongly reduced during pelleting process. Consequently, digestibility of nutrients in pig feed could be improved. On the other hand, presence of high quantities of fine particles in pig feed (both mash and pelleted) negatively affects the health of gastro-intestinal tract (GIT) leading to higher incidence of stomach ulceration and other negative alterations of gastric mucosa (keratization, erosions). Gastric ulcers are one of the most important causes of sudden death on farm that can result in large economic losses in pig production. Concerning that the animal therapy is expensive, labor-intensive, and mostly non-effective due to late recognition of ulceration, prophylactic recommendations are required. Thus, according to literature data, decreasing the quantity of fine particles in pig feed is strongly recommended.

Particle size distribution of the pigs' feed has a strong influence on presence of pathogen bacteria in GIT of pigs. Feeding pigs with coarse mash feed decreases pH value of stomach content compared to pigs fed finely ground mash feed and compared to pigs fed pelleted feed. This can be explained by slower passage rate, increased dry matter, and more dense consistency of stomach content in pigs fed coarse mash diets. Consequently, feed acidification in stomach is better, number of lactic acid bacteria and concentration of organic acids is higher, and pH of stomach content is lower. These conditions create additional “barrier” against pathogen bacteria.

According to available data, optimal particle size of diets for pigs is in the range between 500 and 1600 μm, while particles smaller than 400 μm are considered as undesirable with high ulcerogenic capacity. Optimal particle size could be designed in the grinding process, and it was shown that the most convenient grinding method is to combine roller mill and hammer mill. Concerning that nowadays pigs are mainly fed pelleted feed, and that pelleting causes strong additional grinding of feed particles, particle size distribution (PSD) obtained within the grinding process would be dramatically changed during pelleting. The possibilities to decrease the intensity of grinding of particles during pelleting, by variation of parameters of pelleting process, are very limited. Modified extrusion process (i.e. processing using expander) followed by shaping element, is suggested in the literature as an alternative for pelleting in order to obtain agglomerated pig feed with preserved PSD, but this process is not extensively studied so far.

Keywords: pig feed, particle size, mash, grinding, pelleting, ulcers, *Salmonella*

Abbreviations: ADG, average daily gain, ADFI, average daily feed intake, FCR, feed conversion ratio, GIT, gastro-intestinal tract, HM, hammer mill, PDI, pellet durability index, PSD, particle size distribution

1. Introduction

Pigs are omnivore animals with simple, single-chambered stomach, where most of digestion is carried out through endogenous enzymes. Consequently, pigs require high quality feed, where nutrients are readily available to the enzymes (Kersten et al., 2005). Besides feed composition, as the most important factor that determines the efficiency of feed utilization by pigs, feed structure (particle size) and feed form (mash, pellets) are also important for the optimal nutrient utilization (Wondra et al., 1995a; Choct et al., 2004; Thorsten, 2011; Ball et al., 2015).

Grinding is inevitable step in feed manufacturing process in which particle size of single feed components is reduced. Optimal particle size distribution (PSD) of the diet, adapted to physiological needs of animal, enables optimal utilization of nutrients and enhances animal performance. Additionally, adequate diminution obtained after grinding process facilitates further processing steps, i.e. mixing, transporting, pelleting, extrusion/expansion (Kersten et al., 2005). According to numerous research results, decreasing the particle size of cereals, as the main diet components, improves pigs' performance (Owsley et al., 1981; Ohh et al., 1983; Hedde et al., 1985; Goodband and Hines, 1988; Healy et al., 1994; Wondra et al., 1995a; Callan et al., 2007; Lahaye et al., 2008; Ball et al., 2015; Rojas and Stein, 2015; Al-Rabadi et al., 2016; Bao et al., 2016). On the other hand, finer particle size of the diet negatively affects health of pig's GIT (Healy et al., 1994; Goodband et al., 2002). For this reason optimal particle size of pig feed is recommended in the literature, and according to available data the share of the finest particles (<400 μm) should be as low as possible due to their negative influence on gut health (Cappai et al., 2013). The quantity of the coarsest fractions (>1600 μm) should also be low due to decreased digestibility of nutrients from coarse particles, and the share of medium-sized particles (approx. 500-1600 µm), which are considered to be optimal for pig's digestive system, should be as high as possible (Healy et al., 1994; Wondra et al, 1995a,b; Lucht, 2011, Cappai et al., 2013). Particle size distribution is directly affected by the grinding process and mill type. Optimal status of hammers in a hammer mill may directly contribute to the optimal PSD of pig feed achieved within the grinding process. In the case of worn hammers, the effects on PSD and the increase of coarse particles have a negative impact on performance (average daily feed intake and average daily gain) in weanling pig fed mash diets (Solà-Oriol et al., 2015). Young piglets are often fed mash feed while using of pelleted feed is much more common for growing pigs. During the pelleting process, tailored PSD of feed is compromised, i.e. coarse particles are intensively crushed and the content of fine particles can be strongly increased (Svihus et al., 2004; Grosse Liesner et al., 2009, Vukmirović, 2015).

The aim of the present article is to give an overview of available literature data about the importance of particle size distribution of pig feed related to the efficiency of feed utilization in pig's digestive system, influence on further processing steps, and influence on health of GIT. Furthermore, the possibilities of achieving desired PSD in grinding process, as well as the influence of downstream processing on PSD of pig feed are reviewed.

2. Importance of particle size and feed form in pig nutrition

2.1. Mash pig feed

Compound feeds are multi-component mixtures comprised of up to 40 macro and micro-ingredients that have to be mixed homogenously to provide quality and safe feed for animals (Kirchner et al., 2013). Cereal grains are primary energy sources in pig diet and need to be processed before or after mixing with other diet components. Processing always includes grinding step which facilitates further processing (mixing, pelleting, extrusion, expansion), and improves nutritional value of feed (Table 1) by increasing the surface area allowing better contact with digestive enzymes (Behnke, 1996; Goodband et al., 2002; Blasel et al., 2006). This leads to increased dry matter digestibility and improved feed conversion efficiency (Ohh et al., 1983; Healy et al., 1994; Oryschak and Zijlstra, 2002; Millet et al., 2012; Ball et al., 2015; Liermann et al., 2015; Rojas and Stein, 2015). Owsley et al. (1981) determined improvement of ileal digestibility of dry matter, starch, gross energy and nitrogen in growing pigs when geometric mean diameter of sorghum was decreased from 1262 to 471 µm. Hedde et al. (1985) observed an increase in daily gains of finishing pigs by 8% when they were fed with fine diet, with >80% of particles smaller than 1200 µm, compared to coarse diet with <20% of particles smaller than 1200 µm. Reducing particle size of barley from 789 to 676 µm improved average daily gain (ADG) of starter pigs by 5% (Goodband and Hines, 1988). Giesemann et al. (1990) determined increase of total tract digestibility of nitrogen, gross energy and dry matter by reducing the particle size of corn-based diets for finishing pigs from 1500 to 641 µm. Furthermore, in the research of Healy et al. (1994) energy digestibility was increased in the experiment with nursery pigs when geometric mean diameter of corn and sorghum was decreased from 900 to 300 µm and it was concluded that optimal particle size increases with rising age of pigs. Wondra et al. (1995a) observed decrease of FCR by 8% ($P<0.001$), increase of gross energy digestibility by 7% ($P<0.03$), 26% decrease of dry matter daily excretion and 27% decrease of nitrogen daily excretion in the feces, when particle size of corn in diets for finishing pigs was reduced from 1000 to 400 µm. They concluded that decreasing corn particle size by 100 µm, increases feed conversion by 1.3%. Oryschak et al. (2002) observed improvements in energy digestibility and improved apparent total-tract N digestibility when mean particle size of barley and field peas (that represented approximately 80% of the diet) was reduced from 900 to

600 μm. Callan et al. (2007) found that fine grinding (3 mm compared to 6 mm screen size of hammer mill) improved feed efficiency by 8%, 5% and 7% respectively, during the grower, finisher and combined grower–finisher period. Decreasing mean particle size from 1000 to 500 μm improved ileal digestibility of dietary energy, organic matter and dry matter digestibility in the research of Lahaye et al. (2008). Regrinding the coarse particles of sorghum-based or barley-based diets in the experiment with grower pigs performed by Al-Rabadi et al. (2016), improved feed efficiency concerning that FCR was reduced by 10% and 7.8%, respectively. Bao et al. (2016) determined approximately linear increase of *in vitro* dry matter (from 17% to 26%) and crude protein digestibility (from 55% to 66%) with decrease of wheat particle size. In this research mean diameters of ground wheat were 330, 430, 450, 470, 580, and 670 μm, while diets contained 70.85% of wheat.

Digestion of starch in pigs is affected by many factors with particle size of cereal-component of the diet being one of them. This was related to specific surface area of particles that is available for the alpha-amylase enzymatic action. Blasel et al. (2006) determined that each decrease of cereal particle size for 100 μm increased starch access by alpha-amylase by 26.8 g per 1 kg of starch. In the research of Owsley et al. (1981) starch digestibility increased by 19% when sorghum grain was ground on hammer mill with 3.2 mm screen, compared to coarse milling with roller mill. According to Al-Rabadi et al. (2009), in vitro starch digestion decreased four times with doubling of mean particle size of barley and sorghum. In a study of Amaral et al. (2014), an increase of starch digestion rate in small intestine was observed when mean particle size was decreased from 850 to 550 μm. In an experiment conducted by Rojas Martinez (2015), reducing of mean corn particle size from 865 to 339 linearly increased starch and gross energy digestibility and increased concentration of metabolisable energy which enabled reduction of fat added to pig diet without affecting growth performance and carcass composition. It was concluded that if corn is ground to a smaller particle size, it will be less expensive to formulate a pig diet; however, finer grinding increases mill energy consumption, which also has to be considered. Strong decrease ($P<0.001$) of the FCR in the experiment with grower pigs performed by Al-Rabadi et al. (2016), was related to more dietary energy being available due to increased starch digestion in small intestine with decreased particle size of barley and sorghum. Rojas and Stein (2015) observed linear increase of starch digestibility when corn particle size was reduced from 865 to 339 μm, but there was no effect on digestibility of amino acids and crude protein. On the other hand, Fastinger and Mahan (2003) determined a small increase of amino acids digestibility with decreasing the particle size of soybean meal. Likewise, Lahaye et al. (2008) concluded that decreasing the particle size of wheat to 500 μm increases nitrogen digestibility but further decrease of particle size did not result in significant improvements. Similarly to starch, increased digestibility of protein with decreasing diet particle size can be attributed to higher exposure of protein to digestive enzymes due to increased specific surface of feed particles (Wondra et al. 1995a; Behnke, 1996; Goodband et al., 2002; Barneveld and Hewitt, 2003). High grinding intensity improves feeding value of high-fibre cereals, e.g. barley and oats, which is ascribed to better digestion of fibers in diet with finer particle size (Ziggers, 2009).

On the other hand, it was determined that too fine particle size decreases average daily feed intake (ADFI) of pigs due to decreased palatability of the mash diets containing finer particles. This was observed in the research of Wondra et al. (1995a) when corn particle size was decreased from 800 to 400 μm. Similarly, the decrease in ADFI was noticed in the study of De Jong et al. (2013) when diet's particle size was reduced from 596 to 360 μm, and in the research of Nemechek et al. (2016) when particle size was reduced from 650 to 350 μm. Additionally, increasing of grinding intensity (finer grinding) increases the energy consumption and decreases capacity of grinding equipment and flowability, increases dust problems, and most importantly, too fine structure of pig feed negatively affects the health of GIT (Healy et al., 1994; Goodband et al., 2002).

2.2. Pelleted pig feed

In modern pig farming, diets are rarely used in mash (powder, meal) form. There is a common practice that after mixing of all the components, diets are pelleted (Fahrenholz, 2012). During pelleting process heat, moisture, and pressure are applied to the feed and small feed particles are agglomerated (Skoch et al., 1981; Skoch et al., 1983). Literature generally suggests that pelleting of pig's diets improves pig performance compared to mash feeding. Skoch et al. (1983) observed that when pigs were offered a free choice between corn-based pelleted and mash diets, pigs preferred pelleted diets (85.5 vs. 14.5%, respectively). This was in agreement with results of Solà-Oriol et al. (2009a) who determined greater preference for pelleted over mash feed when pigs were fed barley or oat based diets. In the research of Jensen and Becker (1965), ADG of young pigs was unaffected by switching to pelleted diets, but FCR was significantly improved, i.e. decreased ($P<0.05$). Besides significant improvements of FCR ($P<0.05$), Hanke et al. (1972) determined significant increase of ADG ($P<0.01$) of pigs fed pelleted feed compared to pigs fed mash feed. In the research of Skoch et al. (1983), differences of ADG, FCR, and ADFI were not determined for weanling pigs, but for the grow-finishing pigs, significant improvement of FCR ($P<0.05$) was reported when diets in pelleted form were used. According to summary of 16 trials, Ohh (1991) observed that growth performance and FCR were improved by 3-4% when pelleted feed was used. Stark (1994) observed improved FCR by 12% when pelleted feed was used, compared to using mash feed for finishing pigs. Wondra et al. (1995a) found that pelleting increased ADG by 5% (P<0.01), decreased FCR by 7% (P<0.001), and increased apparent digestibility of dry matter and nitrogen (P<0.001). Similarly, Traylor (1997) reported that pelleting improved dry matter and nitrogen digestibility (P<0.001), FCR of nursery pigs (P<0.04), as well as FCR (P<0.08) and ADFI (P<0.02) of finishing pigs. According to the research of Chae et al. (1997), average daily gain and FCR of pigs (20-90 kg of body weight) fed pelleted diet were significantly better compared to pigs fed mash or extruded diets. Improved FCR related to feeding pelleted diets was also determined in the research of Lawrence (1982), Nahm (2002), I'Anson et al. (2012, 2013) and Ball et al. (2015). Nitrogen excretion is lower when pigs are fed pelleted compared to mash feed (Wondra et al., 1995a; Ball et al., 2015) which has positive nutritional and environmental effects.

Numerous mechanisms of positive influence of pelleted pig feed on pig performance are proposed in literature. Graham et al. (1989) and O'Doherty et al. (2000), attributed improvement of nutrient digestibility to disruption of endosperm cell wall during the pelleting process which increases the accessibility of digestive enzymes. Additional reasons for enhanced pig performance could be improved nutrient digestibility and hygienic quality of pelleted feed, improved starch digestibility due to partial gelatinization of starch, reduced segregation of diet components, reduced wastage during consumption of pelleted feed, preventing the animal from sorting out palatable ingredients, elimination of antinutritional substances, and increased passage rate of material through digestive system (Vanschoubroeck et al., 1971; Hanke, et al. 1972; Owsley et al., 1981; Lawrence, 1982; Skoch et al., 1983; Giesemann et al., 1990; Morrow, 1992; Healy et al., 1994; Wondra et al., 1995a,b; Traylor, 1997; Chae and Han, 1998; Eisemann and Argenzio, 1999; Goelema et al., 1999; Jørgensen et al., 1999; Kim et al., 2000; Nahm, 2002;

Medel et al., 2004; Mikkelsen et al., 2004; Hedemann et al., 2005; Kamphues et al., 2007; Lundblad et al., 2011; Fahrenholz, 2012; I'Anson et al., 2012, 2013; Ball et al., 2015).

In a very interesting research of Laitat et al. (1999), pigs were fed either with mash or pelleted feed, and three trials were performed with different number of pigs (30 – trial 1; 40 – trial 2; 50 – trial 3). The pigs were housed in the two same rooms, and the only difference was the form of feed provided, with mash feed in one room, and pelleted feed in the other. The same number of feeders (providing both feed and water) were used in all three trials.

It was observed that ADG was significantly reduced by increasing the number of pigs both for mash and pelleted feed ($P<0.01$). ADG of pigs fed pelleted diets was higher compared to pigs fed mash feed in trial 2 and 3, but this was not observed in the trial with 30 pigs per pen. It was concluded that the number of animals using the feeder must be considered when comparing mash and pelleted diets. On the other hand, the additional costs due to pelleting process (costs of additional equipment, storage bins and energy costs) must be compared with the effect of improved performance of pigs fed pelleted diets. The conclusion of Laitat et al. (1999) was that the pellets were probably preferable to meal when animals were kept in large groups concerning that in trial 1 performance was not different according to the diet, while in crowded conditions, especially in trial 3, performance was better with pellets.

With increasing the number of pigs per pen, daily water intake of pigs decreased when pigs were fed mash diet, but the difference was statistically significant only when extreme situations of 30 and 50 pigs per pen were compared ($P<0.01$). When pigs were fed pelleted diet, there was a trend of decreased water intake with increasing the number of pigs, but differences were insignificant. It was concluded that water consumption of pigs was influenced by number of pigs per pen, but this effect was more pronounced when pigs were fed mash feed compared to pigs fed pellets. When comparing pigs fed mash and pelleted diets, water consumption of mash fed pigs was higher but the difference was significant only when comparing groups with 30 pigs. With increasing the number of pigs per pen, the difference between daily water intakes of pigs fed mash and pelleted feed decreased. This was related to easier access to feeders when pigs were fed pelleted diets due to shorter occupation time of feeders when pigs were fed pellets. It was also concluded that it would be important to test this hypothesis in the trial where watering device is separated from the feeders (Laitat et al., 1999).

Another important factor that needs to be considered when comparing mash and pelleted feed is the influence of pelleting process on particle size of ingredients in pelleted feed. Numerous research results showed that pelleting process results in a strong reduction of particle size of feed components (Wondra et al., 1995a; Dirkzwager et al., 1998; Engberg et al., 2002; Svihus et al., 2004; Amerah et al., 2007; Abdollahi et al., 2011; Klausing, 2011; Vukmirović, 2015; Vukmirović et al., 2016a). Grinding of feed particles during pelleting (secondary grinding) occurs due to narrow distance between pellet rollers and pellet die (Svihus et al., 2004; Vukmirović et al., 2016a), and due to frictional force in the die holes of the pellet press (Abdollahi et al., 2011). It was already explained that the reduction of particle size of diet components improves dry matter digestibility and feed conversion efficiency. Secondary grinding during pelleting process will additionally reduce particle size and consequently it can be expected that nutrient digestibility will be additionally enhanced. In the research of Al-Rabadi et al. (2016) barley and sorghum were ground and included in pig feed with or without regrinding of coarse particle fraction, and used as mash or as pellets. Regrinding of coarse particles improved FCR in pigs fed mash diets, and it was similar in pigs fed pelleted feed with non-reground coarse particles. It was suggested that the reduction of particle size during feed pelleting was the major factor for improvement of nutritive value of pelleted diets. On the other hand, an increased quantity of fine particles due to secondary grinding induces problems related to health status of pig's GIT which will be discussed later.

2.2.1. Importance of pellet quality

As it was already pointed out, pelleting of diets for pigs improves their growth performance. On the other hand, it was also determined that if pellets have low quality, with high quantity of fines, the wastage of feed will be higher, palatability would be reduced, and feed intake decreased. The study of Stark et al. (1993) examined the influence of pellet quality in pig feeding and it was found that performance and FCR were poorer if more fine particles were present in pellets due to intensive attrition of pellets as a consequence of poor quality. Many factors influence the quality of produced pellets, such as formulation, particle size, conditioning, die specification (die thickness, diameter of die openings), cooling/drying, etc. Literature data generally suggest that finer grinding results in better quality of pellets. This is usually attributed to higher specific surface of fine particles that positively affects their binding during pelleting (Franke and Rey, 2006). Additionally, fine particle structure leads to better hydration during steam conditioning, resulting in better compression and binding of particles (Fahrenholz, 2012).

Angulo et al. (1996) determined strong decrease of pellet quality, expressed as pellet durability index (PDI), when screen size of hammer mill was increased from 3 to 6 mm. This was in agreement with the results of Svihus et al. (2004) and Čolović et al. (2015). On the other hand, differences in PDI were not significant when comparing pellets made of coarse and fine material (screen size of hammer mill 7 mm vs. 3 mm) in the research of Amerah et al. (2007). Some researchers even suggest that the effect of particle size on pellet quality is insignificant (Stevens, 1987; Stark, 1994; Fahrenholz, 2012). Paulk et al. (2015) found no differences in pellet quality when mean particle size of sorghum, which comprised more than 75% of the diet, was decreased from 800 to 400 μm. Possible reasons for these confounding results could be the differences in pellet press settings and differences in diets formulation within different studies. In this respect, Vukmirovic et al. (2016a) specifically investigated the effects of distance between rollers and the die of pellet press (roller-die gap). They observed that pellet quality was strongly deteriorated with coarser grinding of corn on hammer mill only when the smallest roller-die gap (0.30 mm) was applied during pelleting of ground corn (Figure 1). Increasing the roller-die gap to 1.15 mm and to 2.00 mm increased PDI and decreased or even nullified differences in PDI of pellets produced from corn ground to different particle size. The improvement of pellet quality by increasing the roller-die gap can be attributed to elevated pressure in the pelleted material and prolonged pre-compaction (Thomas et al., 1997) which enhances binding between particles. Additionally, the intensity of secondary grinding was increased which evened out particle size distribution in pellets produced from corn ground to different particle size, thus equalizing the quality of pellets in the research of Vukmirovic et al. (2016a). Increasing the roller-die gap is limited, because when roller-die gap is increased above certain value (that is depended upon characteristics of pellet press and characteristics of pelleted material) stability of the layer of pelleted material on the die surface is compromised, resulting in sideways “leaking” of the material (Thomas et al., 1997) and clogging of the pellet press (Miladinovic and Svihus, 2005). According to the results of Vukmirovic (2015), increasing the thickness of the die also increases the intensity of secondary grinding and positively affects pellet quality. In the research of Miladinovic and Svihus (2005), pellet quality was positively affected by increasing the roller-die gap and also by decreasing the throughput of pellet press. However, increasing the roller-die gap, and die thickness, and decreasing the throughput, increase specific energy consumption of the pellet press which could be commercially non-justified.

It can be concluded that if cereals are coarsely ground in order to reduce the content of fine particles after pelleting (for the benefit of GIT health), the quality of pellets could be negatively affected. This can be mitigated by increasing the roller-die gap, increasing the die thickness, and by decreasing the feeding rate of the pellet press. As already pointed out, these interventions have limitations regarding specific energy consumption of pellet press and due to increased intensity of secondary grinding. Consequently, the optimum balance needs to be determined in each specific case.

In the research of Vukmirović (2015), PDI was decreased with coarser grinding of corn on hammer mill, but this was not observed when corn was ground to different particle size using roller mill (Figure 2). Generally, pellet quality was better when the roller mill was used in grinding stage compared to the hammer mill. This was related to better resistance of more spherically shaped particles obtained at the hammer mill which resulted in higher percentage of coarse particles incorporated in the pellets. Coarse particles create "weak points" in the structure of pellets, i.e. points where coarse particles are surrounded with finer particles and where a pellet is more sensitive to breakage (Thomas and van der Poel, 1996). Consequently, PDI of such pellets is decreased. On the other hand, in Figure 1 it was already shown that the problem of low pellet quality when coarsely hammer milled corn is pelleted, could be solved by increasing the roller-die gap but then increased intensity of secondary grinding and increased specific energy consumption of pellet press could be expected (Vukmirović et al., 2016a). Thus, optimization of the process regarding particle size after pelleting, specific energy consumption of pellet press, and pellet quality, is necessary.

3. Influence of particle size and feed form on gastro-intestinal health of pigs

Gastric lesions and ulcerations are very common in pig production, and present a worldwide problem in modern, intensive pig farming (Grosse Liesner et al., 2009; Cappai et al., 2013) resulting in high financial loses (Friendship, 2003). Usually non-glandular gastric mucosa (*pars esophagea*) is affected, and between 1 and 2% of farmed pigs die from bleeding gastric ulcers, mainly three to six months old pigs (Cappai et al., 2013).

Reasons for occurrence of these gastric epithelial alterations are not clear enough, but one of the risk factors is structure of diet, i.e. particle size of cereals and other feed components (Mahan et al., 1966; Riker et al. 1967; Reimann et al., 1968; Baustad and Nafstad, 1969; Flatlandsmo and Slagsvold, 1971; Lawrence et al. 1980; Hedde et al., 1985; Wondra et al., 1995a; Ayles et al., 1996; Friendship, 2006). Regarding PSD of pig feed, strong grinding intensity during pelleting process must be considered. In the research of Mikkelsen et al. (2004), Canibe et al. (2005), Cappai et al. (2013), Mößeler et al. (2014), and Liermann et al. (2015), hyperkeratosis, mucosal erosions, and bleeding ulcers were more frequently determined when pigs were fed pelleted diet compared to feeding mash diet.

Wondra et al. (1995a) fed pigs with corn based diets where corn was ground to mean particle size of 1000, 800, 600, and 400 µm. Diets were provided to pigs in mash and pelleted form. Lesions and keratinization of *pars esophagea* increased with particle size reduction ($P<0.003$) and with pelleting ($P<0.02$) of feed for finishing pigs, but the growth performance was significantly increased, as well. The conclusion of this research was that mean diameter of diet particles of 600 µm was optimal regarding growth performance, mill energy consumption, stomach morphology, nutrient digestibility, and nutrient excretion. Stomach morphology was negatively affected in the study of Cabrera et al. (1993) when mean particle size of grains (corn and sorghum) was decreased below 600 µm. On the other hand, they observed improved performance and significant decrease of daily dry matter and nitrogen excretion with decreasing grain particle size. They concluded that an acceptable compromise was necessary. Morel and Cotam (2007) found no effect on pig performance when average particle size of barley was changed between 400 and 1100 µm, but integrity of the stomach mucosa and structure of small intestine (morphological damage of the villi) were negatively affected by fine grinding, thus compromising overall gut health. Mavromichalis et al. (2000) observed more ulcers and keratinization when pigs were fed diet containing wheat ground to 600 µm, in comparison to diet containing wheat ground to 1200 µm. In the research of Grosse Liesner et al. (2009), particles smaller than 400 µm were considered as fine, and for the share of fine particles lower than 20% no mucosal damages were observed, while the increase in the share of fine particles to 36% was detrimental to mucosa membrane. On the basis of the results of Grosse Liesner et al. (2009), Cappai et al. (2013) defined three classes of ulcerogenic risk of the diets:

- Class 1, high risk (>36% particles smaller than 400 µm);
- Class 2, moderate risk (29 - 36% of particles smaller than 400 µm);
- Class 3, low risk (<29% of particles smaller than 400 µm).

One of the main aspects of a healthy GIT is a low level of enterobacteria (i.e. *Salmonella* and coliform bacteria) in GIT of pigs (Canibe et al., 2005) with *Salmonella* infections being of a major concern regarding the pigs health as well as the human health (Hedemann et al., 2005). Physical characteristics of feed have a strong influence on susceptibility of pigs to infections with *Salmonella* spp. Coarse grinding reduces the incidence of *Salmonella* in pigs fed mash diet compared to fine grinding (Wingstrand et al., 1997; Jørgensen et al., 2002; Mikkelsen et al., 2004; Klausing, 2011). Additionally, Jørgensen et al. (1999) observed that feeding pelleted feed increased the risk of *Salmonella* infections compared to feeding mash feed. In the research of Mikkelsen et al. (2004), significantly higher total anaerobic bacteria counts, increased concentration of different organic acids, and lower pH in the stomach, were determined when pigs were fed coarsely ground mash diet, in comparison to finely ground mash diet, coarsely ground pelleted diet, and finely ground pelleted diet. Similar results were obtained by Canibe et al. (2005). Maxwell et al. (1970) and Regina et al. (1999) concluded that if diet particles are coarser, the passage rate in the pig's stomach is slower and dry matter of the stomach content increases. They also determined that the consistency of the material in the stomach of pigs fed coarse diet was more firm, compared to the stomach content of pigs fed fine diet where solid and liquid phase separated rapidly after sampling. This promoted microbial activity, i.e. growth of lactic acid bacteria, due to increased time for microorganisms to proliferate in the stomach. Increased concentration of lactic and other organic acids lower the pH and create additional barrier against *Salmonella* and other gram-negative bacteria (Mikkelsen et al., 2004; Canibe et al., 2005; Klausing, 2010).

If pigs are fed a coarse diet, a higher portion of starch will not be digested in duodenum and will reach the ceacum. The present microflora in the ceacum will degrade starch to short chain fatty acids that will limit the growth of coliform bacteria and *Salmonella* (Maxwell et al., 1970; Regina et al., 1999; Visscher et al., 2009; Klausing, 2011). On the other hand, reduced prececal digestion of starch negatively affects energetic value of the diet, decreases feed efficiency, and results in economic losses to pig producers (Callan et al., 2007), but as concluded by Kamphues et al. (2007), this should be tolerated regarding the reduction of *Salmonella* prevalence in pig production.

4. Possibilities for obtaining optimal particle size of pig feed in grinding process

4.1. Optimal particle size

Desired PSD of pig feed can be achieved during grinding of diet components, mainly cereals. According to existing research data, optimal particle size of diets for pigs is in the region of medium particle sizes, i.e. between 500 and 1600 µm, while particles smaller than 400 µm are considered as undesirable due to negative influences on gut health (Lucht, 2011; Cappai et al., 2013; Ball et al., 2015). However, optimal particle size of the diet is affected by diet complexity, type of grain, and the age of the animal (Chae and Han, 1998). By changing the ingredient composition of the feeds their particle size characteristics are modified. Solà-Oriol et al. (2009b) reported that the relative impact of common cereals and fiber sources for pig diets was less important than the relative impact of protein and lipid sources. For cereals, the changes in mean particle size per percentage unit of ingredient ranged between 1.8 and 2.2 µm, and for fiber sources these ranged between 0 and 5.2 µm, whereas they ranged between 2.3 and 21.6 µm for protein sources and between 15 and 16 µm for lipid sources. According to Healy et al. (1994), optimal particle size of corn and sorghum in nursery phase, which took into account FCR and integrity of pig's gastric mucosa, is about 500 µm. The optimal mean particle size for wheat-based diets of 600 µm was determined by Mavromichailis et al. (2000). Similarly, Behnke (1994) suggested particle size between 500-700 µm as the optimal range for growing-finishing pigs. For the lactation diets, according to Wondra et al. (1995a, b), slightly finer particle size is required with optimum particle size of about 400 µm in primiparous and 400-600 µm in second-parity sows. After literature review, Barneveld and Hewitt (2003) concluded that grinding of wheat, corn, barley, and sorghum to particle size bellow 700 µm will improve nitrogen and energy digestibility, and that there is a minor difference in nutritional value when particle size of milled cereal grains is between 700 and 1500 µm. They suggested that roller milling of cereals to particle sizes 600 to 700 µm is optimal regarding nutrient yield, milling efficiency, and gut health. High-fibre cereals (barley, oats) need to be ground more finely to improve their feeding value. Grinding to approx. 700 µm could be optimal to make these ingredients more attractive as a substitute for corn. Wheat should be ground more coarsely (between 800-900 µm) than corn and sorghum when used in pig feed due to its propensity to become floury (Ziggers, 2009). Albar et al. (2000) concluded that optimal particle size of cereals in piglet diets is between 500 and 600 µm. Wondra et al. (1995a) compared a diet with more uniform particle size distribution to a diet with higher variation of particle size and concluded that uniformity of particle size also affects nutritional value of pig feed. More uniform particle size resulted in greater nutrient digestibility in an experiment with finishing pigs, compared to diet with higher variation of particle size, despite a similar mean diet particle size (850 µm).

4.2. Optimal grinding procedure

Grinding in production of pig feed is usually accomplished using hammer mills, roller mills, or their combination. There are advantages and disadvantages to be considered when choosing the optimal mill. Hammer mills have greater capacity of grinding and it is easier to switch from one grain to another by changing the sieve. However, hammer mills will produce higher quantity of fine particles and dust, and will require more energy per ton of material compared to roller mills (Ziggers, 2001). Hammer status in the hammer mill may seriously affect PSD and the homogeneity of the PSD as function of time use, wear and quality of raw ingredients milled. Therefore, PSD could be a good indicator of need for replacement of hammers before affecting pig performance (Solà-Oriol et al., 2015).The advantage of roller mills is in creating a more uniform particle size distribution than hammer mills, and creating much lower quantity of fine particles and dust, which is very important in pig nutrition concerning the negative influence of fine particles on health status of pig's GIT. Furthermore, roller mills' specific energy consumption is lower. Thacker (2006) found no effect of mill type (hammer vs roller mill) on performance of pigs but roller mill had lower energy consumption, more accurate control of particle size, and quieter operation. Vukmirović et al. (2016b) determined that specific energy consumption of roller mill was significantly lower ($P<0.001$) compared to hammer mill for similar geometric mean diameter of particles.

On the other hand, the investment and maintenance costs are higher for roller mills (Barneveld and Hewitt, 2003). Additionally, if roller mills are used in pig feed production, it is important to consider the type of cereals that will be used since if barley, oats, or wheat middling's (wheat bran) are used, problems regarding grinding the hulls can be expected. For this reason, combined use of both types of mills could be optimal, especially if high fiber cereals like barley and oats are used as a cereal component of the diet. In this approach grinding with low content of fines by means of roller mill is combined with hammer mill suitable for grinding of hulls. In the research presented by Lucht (2011), three arrangements of grinding machines were tested during preparation of barley-based pig diet:

1. Roller mill treatment, where a roller mill with two pairs of corrugated rollers was used without intermediate sieving.
2. Stage grinding with two hammer mills and with pre-, intermediate- , and post-sieving.
3. Combination of hammer mill and roller mill (one pair of rollers) with pre-, and intermediate-sieving.

The following particle size ranges were observed: fine (<0.5 mm), medium (0.5-1.6 mm), coarse (1.6-2.0 mm), and very coarse (>2.0 mm). The aim was to obtain the highest possible quantity of medium-sized particles, and to have the lowest possible quantity of fine particles that should not exceed 25%. Additionally, coarse and very coarse fractions were undesirable due to their low digestibility rates in GIT of pigs. The best structure resulted from the combination of the hammer mill and the roller mill, with the quantity of medium size particles of 60%, low quantity of fine particles (22.5%), and also low quantities of both coarse fractions. The energy consumption was 50% lower when roller mill treatment was compared to stage grinding with two hammer mills, while combination of the roller mill and the hammer mill had 30% lower energy consumption compared to the stage grinding with two hammer mills. It can be concluded that installation of a roller mill in existing feed plants, and combining it with existing hammer mills, can improve the structure of pig feed and will result in significant decrease of energy consumption of the grinding equipment.

When addressing the particle size of pig feed, the effects of mean particle size are usually discussed. On the other hand, it is well known that hammer mills and roller mills result in different variation of particle size within the mean value, i.e. roller mills produce more uniform particle size (Lawrence, 1970; Wu and Fuller, 1974; Vukmirovic, 2015; Vukmirovic et al., 2016b). Wondra et al. (1995b) investigated the effect of different uniformity of particle size, resulting from the use of different mill types, on growth performance, apparent nutrient digestibility, and stomach morphology in finishing pigs. In this research, corn was ground to mean particle size of 850 µm both on hammer mill and roller mill. Grinding with different mills resulted in differences in uniformity of the particle size, with more uniform particle size obtained at the roller mill. Average daily gain and average daily feed intake were not affected by uniformity of particle size. On the other hand, increased particle size uniformity by using roller mill improved apparent nutrient digestibility and reduced undesirable changes in stomach morphology.

Different mechanism of particle size reduction in hammer mills and roller mills also results in different shape and morphology of particles after grinding. In roller mills, particles are pressed between the rolls, and at the same time cutting and shearing of particles occur as a result of corrugations and roller speed difference. This results in irregular shape of particles with many edges and corners. Particles obtained at hammer mill are more spherical and polished. Consequently, particles produced in a roller mill have more surface area for the action of digestive enzymes in GIT of pigs, and could possibly improve feed efficiency (Ziggers, 2001).

5. Influence of downstream processing on particle size of pig feed

As it was already shown, diet particle size can be optimized in the grinding process, but if pig feed production involves downstream processing steps, like pelleting, extrusion or expansion, particle size could be dramatically changed. While pelleting binds particles in larger agglomerates, it simultaneously reduces size of particles (Svihus et al., 2004; Grosse Liesner et al., 2009). In the research of Vukmirović (2015) corn was ground to different particle sizes using a hammer mill and roller mill, and pelleted afterwards. It was observed that the intensity of secondary grinding of coarse particles produced using the roller mill was higher compared to coarse particles produced with the hammer mill. This was attributed to the shape of particles which are more spherical after grinding on a hammer mill (Ziggers, 2001) and consequently less prone to secondary grinding. The share of the finest fraction in the same research of Vukmirović (2015) was strongly increased during pelleting. It was between 10% and 20% before pelleting, depending of coarseness of grinding and the type of mill, while after pelleting, the share of the finest particles was between 44 and 47%.

Svihus et al. (2004) measured PSD of broiler feed before and after pelleting and determined strong reduction of coarse particles, while the content of fine particles (<200 μm) was increased from 40-50% before pelleting to 50-60% after pelleting. Similarly, Amerah et al. (2007) and Abdollahi et al. (2011) determined decrease of coarse particles (>1000 μm and >2000 μm, respectively), and an increase of fine particles (<75 μm) as a consequence of pelleting. Engberg et al. (2002) concluded that pelleting evened out PSD of coarse and fine diets. Pelleting of the coarse mixture decreased the share of coarse particles (> 1000 μm) from 26.2% to 14.9%, while pelleting of the fine mixture decreased the coarse particles share from 20.9% to 13.5%. Vukmirović et al. (2016a) used the quantity of the finest fraction of particles (<125 μm) as an indicator of secondary grinding during pelleting of corn. Different pelleting conditions were applied (particle size before pelleting, roller-die gap and moisture content of pelleted material) but all resulted in strong increase of fine particles with the most significant influence of the roller-die gap. The lowest extent of secondary grinding was achieved with the smallest roller-die gap (0.30 mm), while increasing the gap resulted in strong increase of secondary grinding, which was also followed by an increase of specific energy consumption of the pellet press, and significantly better pellet quality. Nemechek et al. (2016) observed increased feed efficiency of pigs fed mash diet when particle size of corn was reduced (from 650 to 350 μm), but grinding of corn finer than 650 μm provided no beneficial effect on FCR when pigs were fed pelleted diets. This was attributed to additional particle size reduction that occurs during pelleting. According to Nemechek et al. (2016), there is no need for too fine grinding of cereals if pelleted pig feed will be used due to intensive grinding of particles during pelleting process.

Besides pelleting, processes of extrusion and expansion are also sometimes used for downstream processing of pig feed. Extrusion is an important operation unit for processing of single feedstuffs and compound feed aiming at increasing energy and nutrient digestibility, and consequently improving FCR and growth performance of pigs (Hancock and Behnke, 2001). Extruders and expanders are similar machines differing mainly in the amount of energy that the machine “puts” in the product. Although there is no clear-cut dividing line between the expander and single shaft extruder; expanders work at higher capacities, for the similar barrel diameter, with lower energy inputs. Furthermore, expansion is mainly used as a pretreatment before pelleting, so there is no need for shaping the product, in contrast to extruders where the product has the shape that results from the shape of die opening. In production of pig feed, expansion process is used more frequently than extrusion, as so called “mechanical conditioning” treatment that precedes the pelleting process. In both cases, extrusion and expansion treatment results in increased digestibility of ingredients, improved flexibility in the use of raw ingredients, and better pellet quality (Coelho, 1994; Chae and Han, 1998; Ginste and Schrijver, 1998; Lucht, 2002; Lucht, 2007; Riaz, 2007).

It is well known that the extruders/expanders can act as grinders due to high friction and shear forces along the barrel, and thus can even be fed with the whole grains. In these processes material gets plasticized to a certain extent due to high temperature and pressure in the barrel. This results in agglomeration of material that is specifically shaped at the outlet of the barrel with the die or annular gap outlet (Riaz, 2007). Lower cooking degree compared to extrusion process enables that particle size of expanded material can be optimally adapted to GIT of pigs due to its preservation in the process, but the form of the expanded material is not suitable for further usage. Therefore, after expansion, grinders and crushers are used, where grinding or crushing of the expanded material results in the meal with very little or even no dust, while grinding intensity depends on specific physiological requirements of the animals. Even when pelleting process is used after the expansion process, thus exposing the material to secondary grinding (as explained previously), intensity of the pelleting process is lower, because usually the die thickness can be 50% lower if material is processed at the expander before pelleting (Lucht, 2007). Therefore, it is to be expected that the grinding intensity of the pelleting process which includes expansion process is lower when compared to the conventional pelleting process, although to the best of authors' knowledge, there is no data describing it. Recently an expander with crown-shaped die and cutting device is utilized in order to completely avoid secondary grinding. This machine produces regularly shaped pellets with preserved coarse particles and agglomerated fine particles, i.e. coarse particles are embedded in the matrix of fine particles (von Reichenbach, 2011). Despite the advantages of using extruders or expanders in the processing line, their utilization increases the investment and operational costs, which also has to be considered.

6. Conclusions

Research results generally suggest that reduction of feed particle size improves pigs' performance, and that fine grinding could be recommended in production of pig feed. Moreover, it was observed that pelleting has similar effect as fine grinding due to intensive particle size reduction in the pellet press. On the other hand, fine particle size of the diet (both mash and pelleted) negatively affects health of GIT by increasing the incidence of pre-ulcerous lesions and ulcerations. Generally, share of particles smaller than 400 μm should be as low as possible due to their negative effect on the health of GIT. Additionally, feeding pigs with coarsely ground mash feed reduces the incidence of *Salmonella* and other pathogen bacteria compared to pigs fed finely ground mash feed or pigs fed pelleted feed. This is a consequence of lower pH in the stomach and small intestine content of pigs fed coarse mash diets.

Optimal particle size of pig feed could be obtained in the grinding process, and it was shown that the combination of a hammer mill and roller mill enables the easiest tailoring of targeted PSD. According to available data, optimal particle size of pig feed should be in the range between 500-1600 µm, while high share of particles coarser than 1600 µm should be avoided due to reduced feed intake and decreased availability of nutrients from coarse particles in GIT of pigs. Pig feed with less than 29% of particles smaller than 400 µm is considered as a low risk diet regarding ulcer occurrence.

In modern pig farming, animals are mainly fed pelleted feed due to numerous advantages of pelleted over mash feed. When pig feed is pelleted, PSD of the diet is substantially changed, with intensive grinding of particles followed by multiple increase of the share of fine particles. This could positively affect digestibility of nutrients but, on the other hand, this will have a negative impact on gut health. Some efforts have been made to optimize particle size distribution in pellets by manipulating the parameters of the pelleting process but only minor improvements were achieved.

It can be concluded that if pig feed is used in mash form, the most convenient method for particle size reduction, considering targeted particle size and specific energy consumption of the grinding process, is to combine a hammer mill and roller mill. However, if pig feed is used in pelleted form, the best option is to apply coarse grinding on roller mill before pelleting. In that manner, specific energy consumption of the grinding process will be lower, the share of coarse (>1600 µm) and fine particles (<400 µm) in the pellets will be lower, and also the quality of pellets will be better, compared to processes using a hammer mill in the grinding stage. Additionally, processing of pig feed by expander equipped with shaping element can be an alternative to pelleting in providing better preservation of feed structure but this process needs to be studied more deeply.

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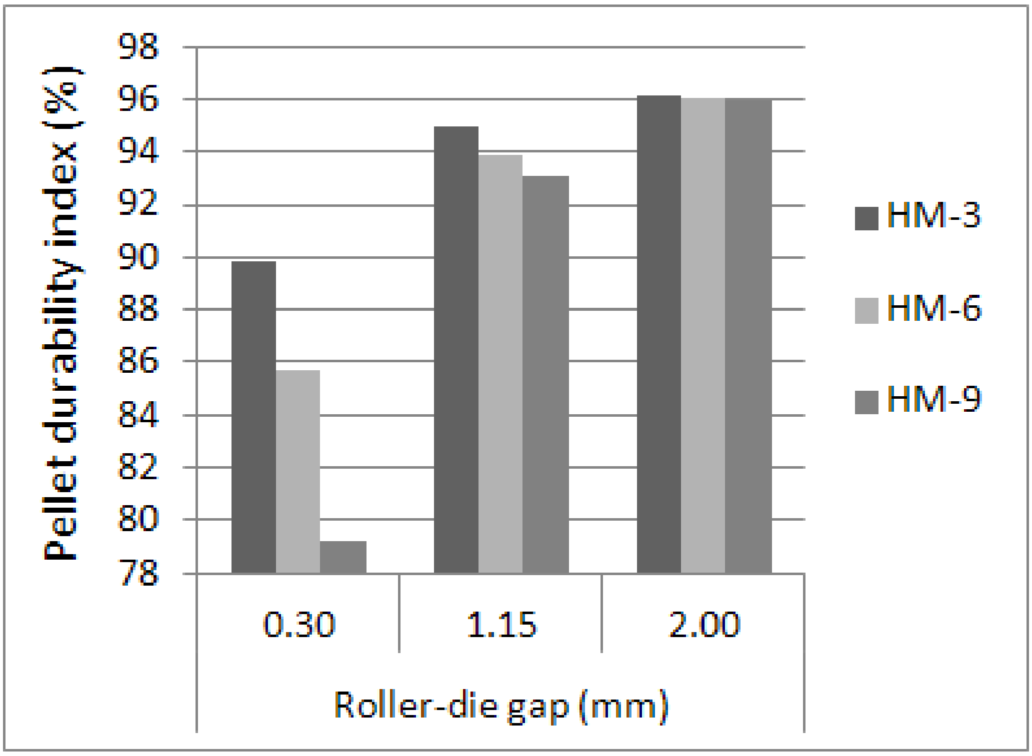
Table 1
The effects of decreasing the particle size of mash pig feed

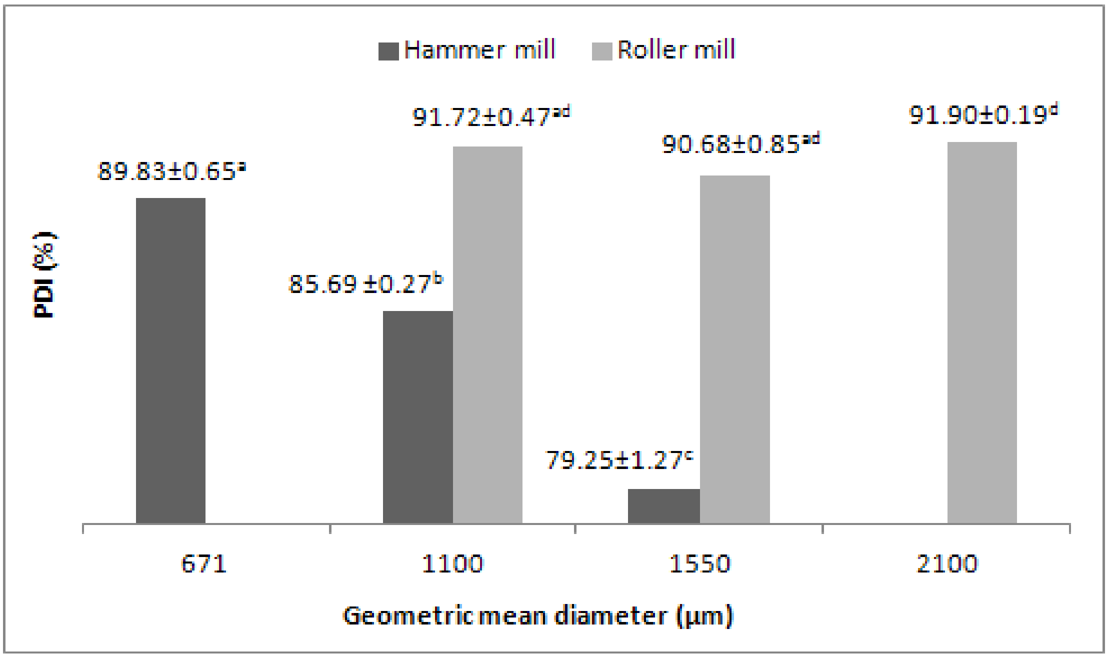
Reference	Digestibility of dry matter	Feed conversion ratio (gain/feed)	Protein digestibility	Starch digestibility	Energy digestibility
Owsley et al. (1981)	+		+	+	+
Ohh et al. (1983)	+	+	+		+
Hedde et al. (1985)					
Healy et al. (1994)	+	+			+
Carbera (1994)	+	+			
Goodband and Hines (1988)		+			
Giesemann et al. (1990)	+	+	+		+
Wondra et al. (1995a)	+	+	+		+
Blasel et al. (2006)				+	
Callan et al. (2007)		+			
Lahaye et al. (2008)	+		+		+
Al-Rabadi et al. (2009)				+	
Amaral et al. (2014)				+	
Rojas Martinez (2015)				+	+
Rojas and Stein (2015)				+	
Al-Rabadi et al. (2016)		+		+	

Figure 1. Influence of pelleting variables on pellet durability index



HM – hammer mill; 3, 6 and 9 – diameter of sieve openings used in hammer mill (Vukmirovic et al., 2016a)

Figure 2. Influence of mill type and grinding intensity on pellet durability index (PDI)



Values with different letters are significantly different at level $P<0.05$ (Vukmirovic et al., 2015)