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Review article

Effects of particle size reduction, pelleting, and extrusion on the nutritional value of ingredients and diets fed to pigs: A review

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A B S T R A C T

Particle size reduction, pelleting, and extrusion are feed processing technologies used to improve nutrient digestibility and achieve maximum pig growth performance. Particle size reduction may improve the digestibility of energy and nutrients. Digestibility of gross energy may be improved when the particle size is reduced in lupins, corn, soybean meal (SBM), field peas, barley, wheat, and sorghum. Reducing particle size in corn, sorghum, and wheat may also improve growth performance due to increased digestibility of nutrients. Particle size reduction may also reduce the production of short-chain fatty acids and improve dressing percentage. It has, however, been demonstrated that particle size reduction may result in development of ulcers and gastric keratinization. Pelleting is a hydrothermal technique that may improve palatability, reduce feed wastage, and modify structures of starch. Pelleting may improve the digestibility of gross energy in diets containing corn, distillers dried grains with solubles (DDGS), sorghum, barley, wheat, and SBM. Digestibility of amino acids and pig growth performance may also be increased in diets containing corn, SBM, and DDGS. Extrusion may improve the digestibility of nutrients from diets containing peas, SBM, barley, corn, DDGS, sorghum, wheat, wheat bran, and potato starch. Growth performance was improved in weanling and growing-finishing pigs upon extrusion of diets containing chickpeas, wheat, or barley. However, extrusion of ingredients resulted in inconsistent effects on growth performance. Thus, more research is needed to address the impact of feed processing technologies on different diets. Optimum temperature and pressure for pelleting and extrusion of feed ingredients must also be addressed to maximize the beneficial effect of thermal treatments.

1. Introduction

Swine producers aim to achieve maximum pig growth performance while minimizing production costs. Feed cost represents 70 % of the total cost of pork production (Patience et al., 2015), therefore, a number of processing techniques have been developed to maximize utilization of nutrients in feed ingredients and to reduce the impact of increasing feed cost. Particle size reduction, pelleting, and extrusion are some of the feed processing technologies used to modify structures of ingredients and subsequently improve nutritional value of diets fed to pigs (Rojas and Stein, 2017). To reduce the particle size of feed ingredients, grinding is accomplished using roller mills and hammer mills with varying sizes of screens (Wondra et al., 1995a; De Jong et al., 2016a). Particle size reduction

Abbreviations: AID, apparent ileal digestibility; ADFI, average daily feed intake; ADG, average daily gain; ATTD, apparent total tract digestibility; DDGS, distillers dried grains with solubles; GE, gross energy; G:F, gain to feed ratio; SBM, soybean meal

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generally improves feed uniformity, nutrient digestibility, and feed efficiency of pigs (Behnke, 1996; Fastinger and Mahan, 2003; Montoya and Leterme, 2011). Pelleting is a feed processing technology used for many years to compact ground feed ingredients (Hancock and Behnke, 2001). It involves the use of steam, heat, and pressure to subject feed ingredients through die openings for pellet formation (Behnke, 1996; Muramatsu et al., 2015). Pelleting often results in a reduction in feed wastage and improved feed efficiency due to improved digestibility of nutrients (Nemechek et al., 2015; Overholt et al., 2016). This thermomechanical process improves the nutritional value of feedstuffs by mainly increasing the digestibility of nutrients and inactivating the anti-nutritional factors present in animal feed (Traylor et al., 1999; Veum et al., 2017). Extrusion in the United States is commonly used for pet and aqua feed industries which involves the use of single or twin-screw extruders and often results in a change in the physico-chemical characteristics of feed ingredients (Hancock and Behnke, 2001; Rojas et al., 2016b). There is, however, inconsistent information about effects of these processing techniques on physico-chemical characteristics of feed ingredients, energy and nutrient digestibility, and utilization of feedstuffs by pigs. Therefore, the overall objective of this review is to provide an understanding about the impact of particle size reduction, pelleting, and extrusion on the nutritional value of feed ingredients and diets. Effects of these feed processing technologies on nutrient and energy digestibility and on growth performance of pigs are discussed.

2. Particle size

Reduction of particle size is usually accomplished to increase feed uniformity, enhance nutrient digestibility, and improve feed efficiency of pigs (Kim et al., 2016). The most common grinders used for particle size reduction are roller mills and hammer mills (Rojas and Stein, 2015). In feed mills, 2 or 3 roller mills may also be placed in sequence, which makes it possible to reduce the particle size of grains ground through roller mills (Rojas and Stein, 2017). Preferences for use of grinders are often based on the particle size required, grinding capacity, electric efficiency, and type of feed ingredient used (Hancock and Behnke, 2001). In corn, the grain is usually milled to an average particle size of 640–650 µm (Wondra et al., 1995b; Kim et al., 2002), but results of recent research demonstrated that improved energy digestibility may be obtained by reducing particle size to around 400–500 µm (Rojas and Stein, 2015).

2.1. Effect of particle size on digestibility of energy and nutrients

Particle size reduction in cereal grains often results in an improved digestibility of starch due to increased surface area of grain, which subsequently increases interaction with digestive enzymes (Huang et al., 2015; Rojas and Stein, 2015; Rojas et al., 2016a). Consequently, the apparent ileal digestibility (AID) of starch and gross energy (GE) increases as particle size is reduced from 865 to 339 µm (Rojas and Stein, 2015). The increase in AID of starch and GE upon particle size reduction has been demonstrated in lupins (Kim et al., 2009), corn (Rojas and Stein, 2015), and sorghum. Improvement in the apparent total tract digestibility (ATTD) of GE upon particle size reduction has also been demonstrated in corn (Healy et al., 1994; Kim et al., 2002; Huang et al., 2015), field peas (Montoya and Leterme, 2011), soybean meal (SBM; Fastinger and Mahan, 2003), barley (Oryschak et al., 2002), wheat (l'Anson et al., 2012; De Jong et al., 2016a), and sorghum (Owsley et al., 1981) when fed to weanling and growing-finishing pigs (Fig. 1). Particle size reduction may also improve digestibility of GE in diets containing high concentration of fiber by disrupting the fiber matrix that may encapsulate energy-containing nutrients. Concentrations of digestible energy and metabolizable energy of distillers dried grains

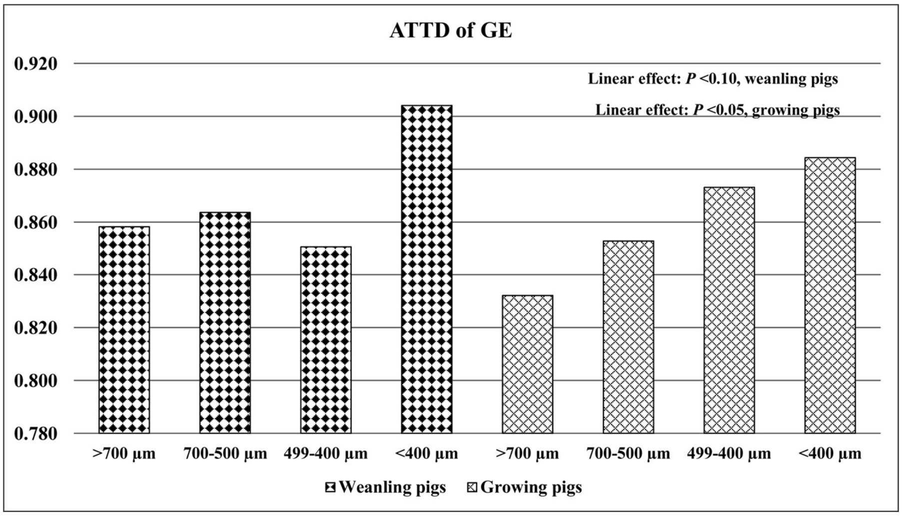

Fig. 1. Effect of particle size reduction of feed ingredients on the apparent total tract digestibility (ATTD) of gross energy (GE) by weanling and growing pigs[1].

[1]Adapted from Owsley et al. (1981), Healey et al. (1994), Wondra et al. (1995), Kim et al. (2002), 2009; Montoya and Leterme (2011); l'Anson et al. (2012); Bao et al. (2016); Huang et al. (2015); Rojas and Stein (2015), and Fan et al. (2017).

Table 1
Effect of reducing the particle size of feed ingredients on growth performance of weanling and growing pigs[a].

Item	Particle size, μm				SEM	*P*-value	
	> 700	700 − 500	499 − 400	< 400		Linear	Quadratic
Weanling pigs							
ADG[b], kg	0.416	0.417	0.414	0.410	0.0133	0.723	0.746
ADFI[b], kg	0.608	0.595	0.572	0.577	0.0252	0.005	0.258
G:F[b]	0.690	0.710	0.727	0.713	0.0255	0.006	0.032
Growing pigs							
ADG, kg	0.976	0.978	0.980	0.974	0.0246	0.794	0.523
ADFI, kg	3.686	2.898	2.971	2.716	0.5397	0.207	0.540
G:F	0.330	0.333	0.342	0.336	0.0112	0.001	0.074

[a] Adapted from Healey et al. (1994), Wondra et al. (1995b); Mavromichalis et al. (2000); Kim et al. (2002); Huang et al. (2015); Liermann et al. (2015); Paulk et al. (2015); Ulens et al. (2015); De Jong et al. (2016a), and Rojas et al. (2016a).
[b] ADG, average daily gain; ADFI, average daily feed intake; G:F, gain to feed ratio.

with solubles (DDGS) with fine particle size were greater than in DDGS ground to a coarser particle size (Liu et al., 2012).

In contrast to the well-demonstrated improvement in the AID of starch and GE, the effects of particle size reduction on the digestibility of nitrogen and amino acids in feed ingredients have been inconsistent. The AID of most amino acids by weanling or growing pigs did not improve upon reduction of particle size in corn and barley (Medel et al., 2000; Huang et al., 2015). Likewise, particle size reduction did not affect the standardized ileal digestibility of most amino acids in corn and SBM (Fastinger and Mahan, 2003; Rojas and Stein, 2015). However, it was demonstrated that the standardized ileal digestibility of amino acids in lupins is improved by reducing the particle size from 1,304–567 μm (Kim et al., 2009). The ATTD of nitrogen is also improved in corn and wheat when particle size is reduced from 1,200–400 μm and from 1,300–600 μm, respectively (Wondra et al., 1995c; Mavromichalis et al., 2000). Therefore, it appears that the effect of particle size reduction on digestibility of nitrogen and amino acids varies and may depend on a particular ingredient (Rojas and Stein, 2017). In contrast, the apparent total tract digestibility of phosphorus in corn and DDGS is not affected by particle size reduction (Liu et al., 2012; Rojas and Stein, 2015).

2.2. Effect of particle size on growth performance

Particle size reduction increases surface area of feed particles, and thus allows for greater interaction with endogenous enzymes (Kim et al., 2002). Therefore, particle size increases nutrient availability, and may subsequently improve overall growth performance of pigs which has been demonstrated in multiple experiments (Table 1). Pigs fed finely ground corn had a greater gain to feed ratio (G:F) compared with pigs fed coarsely ground corn (Huang et al., 2015; Rojas et al., 2016a), but the response to particle size reduction of corn is greater than of sorghum (Healy et al., 1994). However, the beneficial effects of particle size reduction are not demonstrated for particle sizes less than 400 μm where no improvement in average daily gain (ADG) nor G:F is observed (Healy et al., 1994). The beneficial effect of particle size reduction also appears to be more consistent on G:F compared with its effect on ADG and feed intake (Wondra et al., 1995c; Rojas et al., 2016a). Similar effect has been demonstrated for sorghum where pigs had reduced feed intake and increased G:F upon reduction of particle size from 724 to 319 μm (Paulk et al., 2015). For wheat, improved ADG and G:F in weanling pigs is observed upon reduction of particle size from 1,000–600 μm, but reduction of particle size to less than 600 μm did not result in further improvement in growth performance (Mavromichalis et al., 2000; l'Anson et al., 2012). It also appears that the improvement in G:F upon reduction of particle size is more evident in corn than in wheat (Mavromichalis et al., 2000; De Jong et al., 2016a). In contrast, reducing the particle size of SBM to 639 μm or 444 μm did not affect growth performance of pigs (Lawrence et al., 2003). This indicates that reduction of particle size of ingredients with low inclusion rate may not be as beneficial as effects of reduction of particle size of cereal grains.

2.3. Effect of particle size on short-chain fatty acids and pH

Most starch is digested in the small intestine, but starch that is not digested in the small intestine is fermented in the large intestine, which results in synthesis of short-chain fatty acids (Bach Knudsen, 2011). Digestibility of starch in finely ground corn is greater compared with coarsely ground corn due to increased surface area of grain which increases access of α-amylase to starch granules (Huang et al., 2015). However, feeding pigs with diets containing finely ground feed ingredients may result in reduced synthesis of short-chain fatty acids and increased pH in the large intestine. Rojas et al. (2016a) demonstrated a reduction in the concentration of short-chain fatty acids in cecal contents when the particle size of corn is reduced from 865 μm to 339 μm. However, this is in contrast with data indicating that particle size reduction in lupins resulted in an increased proportion of branched-chain fatty acids in the large intestine, which is probably due to increased surface area for interaction of microbes with the globoid and the proteinaceous matrix in legumes (Kim et al., 2009).

2.4. Effect of particle size on carcass characteristics

Dressing percentage, commonly referred to as carcass yield, reflects the carcass weight as a percentage of the live weight of the animal (Coyne et al., 2019). Producers aim a high dressing percentage as this implies greater saleable yield. Improvement in dressing percentage upon reduction of particle size has been demonstrated in pigs fed diets based on corn (Wondra et al., 1995a), wheat (Mavromichalis et al., 2000; De Jong et al., 2016a), sorghum (Paulk et al., 2015), and a mixture of wheat, rye, barley, and triticale (Liermann et al., 2015). Reduction of particle size in corn-based diets also improved the dressing percentage by approximately 1 percentage unit (Wondra et al., 1995a; Rojas et al., 2016a). However, backfat thickness, loin depth, or fat-free lean percentage are not affected by particle size reduction (Mavromichalis et al., 2000; Paulk et al., 2015; Rojas et al., 2016a). The reason for the improved dressing percentage in pigs fed diets with finer particle size is most likely due to a reduced microbial fermentation in these pigs, which resulted in a reduced weight of intestinal tract (Rojas et al., 2016b).

2.5. Effect of particle size on ulcer development

Ulcer development is one of the most common problem in the swine industry, and one of the main causes for ulcer development is fine grinding (Mahan et al., 1966; Maxwell et al., 1970; Hedde et al., 1985). Feeding diets with high concentration of finely ground cereal grains results in increased acidity and pepsin activity due to a lack of protective mucus in the esophageal region of the stomach (Mahan et al., 1966; Hedde et al., 1985; Varum et al., 2010). Pigs fed diets containing corn ground to 400 μm have greater incidence of ulcers and parakeratosis compared with pigs fed diets containing corn ground to 1200 μm (Wondra et al., 1995a). This result also concurs with data in sows indicating that ulcer incidence and parakeratosis increase as particle size decreases (Wondra et al., 1995d).

Ulcer development, however, may not affect growth performance of growing-finishing pigs. Reducing the particle size of wheat to 600 μm increased the incidence of ulcer and tissue keratinization of pigs, but did not affect G:F of pigs (Mavromichalis et al., 2000). Similar observation was reported for pigs fed diets containing corn ground to 339 μm (Rojas et al., 2016a). Therefore, it appears that parakeratosis, which occurs before pigs develop ulcers, is not detrimental to growth performance of pigs. However, it is not known, which factors need to be addressed for parakeratosis to trigger ulcer development.

3. Pelleting

Pelleting is a hydrothermal process, which involves the use of steam, heat, and pressure. The steamed ingredients are subsequently pressed through die openings for pellet formation (Lahaye et al., 2008; Muramatsu et al., 2015). Pelleting is usually accomplished to reduce segregation, increase bulk density, improve palatability, reduce dust, reduce feed wastage, improve handling and transportation, and modify structures of starch and protein (Chae and Han, 1998; De Jong et al., 2016b). Pellet quality is important to maximize the beneficial effects of this processing technology. Pigs fed pelleted diets processed at excessively high temperature had decreased growth performance compared with pigs fed pelleted diets at lower temperature (Jongbloed and Kemme, 1990; Johnston et al., 1999a; Steidinger et al., 2000). During the pelleting process, temperatures may reach beyond 85 °C, and this may reduce enzyme activity and absorption of nutrients (Jongbloed and Kemme, 1990). Factors affecting pellet quality also include formulation, particle size, conditioning, die specification, and method of cooling and drying (Chae and Han, 1998).

3.1. Effect of pelleting on digestibility of energy and nutrients

Pelleting may result in improved digestibility of GE, which is primarily due to increased gelatinization of starch that occurs when

Table 2
Effect of pelleting on apparent total tract digestibility (ATTD) of gross energy (GE) and growth performance of weanling and growing pigs[a].

	Diet form			
Item	Meal	Pelleted	SEM	*P*-value
ATTD of GE	0.868	0.896	0.0928	0.001
Weanling pigs				
ADG[b], kg	0.415	0.423	0.0296	0.394
ADFI[b], kg	0.650	0.615	0.0566	0.013
G:F[b]	0.652	0.716	0.0269	0.001
Growing pigs				
ADG, kg	0.940	0.959	0.0269	0.052
ADFI, kg	2.626	2.532	0.1053	0.002
G:F	0.362	0.383	0.0108	< 0.001

[a] Adapted from Skoch et al. (1983); Walker (1989); Patterson (1991); Wondra et al. (1995a); vande Ginste and de Schrijver (1998); Johnston et al. (1999a), b; Steidinger et al. (2000); Ohh et al. (2002); Park et al. (2003); Medel et al. (2004); Xing et al. (2004); Stein and Bohlke (2007); Le Gall et al. (2009); Berrocoso et al. (2013); l'Anson et al. (2012); Lewis et al. (2015); Liermann et al. (2015); Ulens et al. (2015); De Jong et al. (2016b); Rojas et al. (2016b); Paulk and Hancock (2016); Overholt et al. (2016), and Rodriguez et al. (2018).
[b] ADG, average daily gain; ADFI, average daily feed intake; G:F, gain to feed ratio.

cereal grains are processed in the presence of heat (Table 2; Jensen and Becker, 1965; Rojas and Stein, 2017). The heat generated in the pelleting process may also remove some moisture in the diets, which may result in increased concentrations of energy and nutrients (Rojas et al., 2016b). Improvement in the digestibility of GE and starch due to pelleting has been demonstrated in diets containing corn, DDGS, sorghum, barley, wheat, or SBM (Skoch et al., 1983; Wondra et al., 1995a; Johnston et al., 1999a,b; Medel et al., 2004; Le Gall et al., 2009; Rojas et al., 2016b). In pigs fed pelleted diets containing field peas, pelleting did not affect the AID of GE, however, an improvement in ATTD of energy was observed (Stein and Bohlke, 2007).

Pelleting may also improve the digestibility of protein and amino acids due to increased protein denaturation that occurs when feed ingredients are processed. This allows for the inactivation of anti-nutritional factors and subsequently improve nutritional value of feed ingredients (Svihus and Zimonja, 2011). High temperatures during the pelleting process may also result in a reduction in the concentration of secreted endogenous proteins, and therefore, may lead to an increased absorption of amino acids and peptides (Lahaye et al., 2008). The digestibility of crude protein and amino acids is improved in pelleted diets containing corn, SBM, and DDGS (Rojas et al., 2016b). Lahaye et al. (2008) also reported an improvement in the digestibility of amino acids in pelleted diets based on wheat. However, high temperatures during the pelleting process may result in heat damage of protein (González-Vega et al., 2011). Maillard reaction may occur if an amino group of an amino acid reacts with the carbonyl group of reducing sugars (Erbersdobler and Hupe, 1991), and this makes amino acids unavailable for protein synthesis. Pelleting diets containing field peas did not affect the standardized ileal digestibility of amino acids (Stein and Bohlke, 2007).

3.2. Effect of pelleting on growth performance

Average daily feed intake is often reduced in weanling and growing-finishing pigs fed pelleted diets compared with pigs fed diets in meal form (Table 2) and this is likely a result of a reduction in feed wastage and increased digestibility of nutrients (Wondra et al., 1995a; Rojas et al., 2016b). Increased ADG is often observed when growing-finishing pigs are fed pelleted diets compared with growing-finishing pigs fed diets in a meal form (Skoch et al., 1983; Walker, 1989; Patterson, 1991; Wondra et al., 1995a; Liermann et al., 2015; Overholt et al., 2016). Feed efficiency is also improved by pelleting diets fed to growing-finishing pigs due to reduction in feed wastage and increased ADG (Skoch et al., 1983; Walker, 1989; Patterson, 1991; Johnston et al., 1999a; Liermann et al., 2015; De Jong et al., 2016b; Paulk and Hancock, 2016). Similar results have been observed in weanling pigs where ADFI was reduced and G:F was greater in pigs fed pelleted diets compared with pigs fed diets in meal form (Skoch et al., 1983; Laitat et al., 1999; Xing et al., 2004; Lewis et al., 2015; Ulens et al., 2015). Pelleting diets containing spray-dried animal plasma at temperatures below 77 °C also improved ADG and G:F of weanling pigs during the first 7 days of post-weaning (Steidinger et al., 2000).

4. Extrusion

Extrusion consists of continuous cooking under pressure, moisture, and elevated temperature (Riaz, 2020), which involves the use of shear force, and may be applied to feed ingredients to increase absorption and utilization of nutrients (Li et al., 2010). Use of optimum temperature, pressure, and conditioning during extrusion may also enhance utilization of nutrients due to physicochemical characteristics in the structure of the grain particle (NRC, 2012). This process was also developed to improve storability, prevent segregation, and inactivate anti-nutritional factors that may be present in feed ingredients (Traylor et al., 1999). Because of the use of moisture, pressure, friction, and heat in extrusion, particle size, and composition of particles in feed ingredients is changed during the process (Ruiz et al., 2018). Starch is the primary component in cereal grains, and extrusion may gelatinize starch due to the heat and moisture that is applied (Zhu et al., 2016). When extrusion temperature is greater than 80 °C, gelatinization of wheat flour increases. Gelatinization begins in amorphous intermicellar areas where the hydrogen bonds are weak (Bhattacharya and Hanna, 1987). These changes in the physicochemical characteristics in extruded feed are believed to improve palatability, digestibility of nutrients, and animal growth performance (Amornthewaphat et al., 2005; Amornthewaphat and Attamangkune, 2008). Extrusion of wheat may also reduce the incidence and severity of swine dysentery by reducing the concentration of resistant starch in the diet and thereby reducing hindgut fermentation (Durmic et al., 2000).

4.1. Effect of extrusion on digestibility of energy and nutrients

Improvement in the AID of starch in extruded peas has been observed (Fig. 2; Sun et al., 2006; Stein and Bohlke, 2007). However, extrusion temperature may influence the digestibility of nutrients because the optimum temperature for extrusion is between 75 and 115 °C, with no further improvement of extrusion at 155 °C (Stein and Bohlke, 2007). Dry extruded-expelled SBM without or with hulls also had greater concentrations of digestible energy and metabolizable energy compared with dehulled solvent-extracted SBM indicating that extrusion may increase fermentability of fiber (Woodworth et al., 2001). Extrusion of corn and sorghum, but not wheat, also increased the apparent total tract digestibility of energy and the metabolizable energy in the grain (Rodriguez et al., 2020). Extrusion also increased the ileal digestibility of starch and energy in barley (Fadel et al., 1988) due to increased access of α-amylase to starch granules. Likewise, the ileal digestibility of starch in corn, wheat, and sorghum increased starch gelatinization, which subsequently resulted in increased ileal digestibility of starch in all grains (Rodriguez et al., 2020). In diets containing potato starch and wheat bran, extrusion improved the AID of starch due to the mechanical rupture of the plant cell wall matrix, and therefore, may have enhanced the interaction between digestive enzymes and the substrates (Holm et al., 1988; Sun et al., 2006). Improvement in the digestibility of GE and starch due to extrusion is also observed in corn, wheat, and distiller dried grains with solubles (Herkelman et al., 1990; Hongtrakul et al., 1998; Cho et al., 2001; Li et al., 2010; Lundblad et al., 2011; Rojas et al., 2016b).

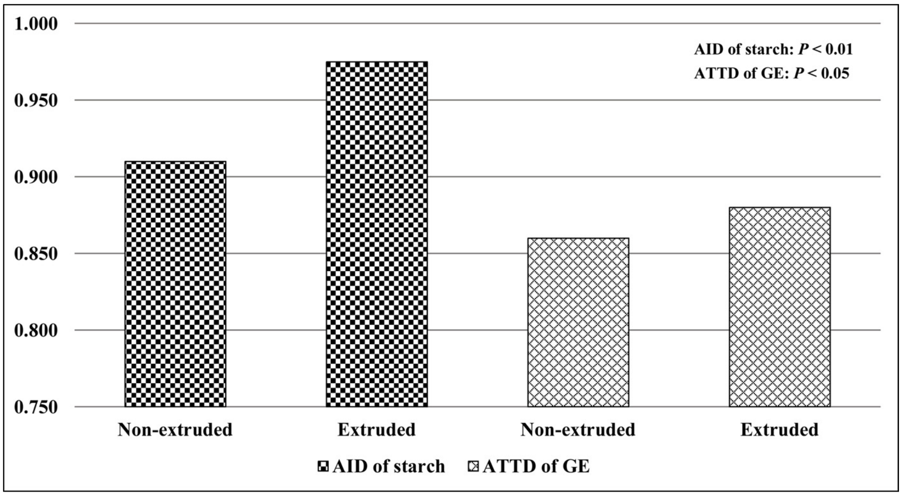

Fig. 2. Apparent ileal digestibility (AID) of starch and apparent total tract digestibility (ATTD) of gross energy (GE) in non-extruded and extruded diets[1].
[1]Adapted from Fadel et al. (1988); Herkelman et al. (1990); Hongtrakul et al. (1998); Cho et al. (2001); Sun et al. (2006); Stein and Bohlke (2007); Lundblad et al. (2011); Rojas et al. (2016b), and Rodriguez et al. (2020).

Extrusion also improved the digestibility of amino acids in extruded diets containing corn and SBM (Li et al., 2010; Lundblad et al., 2011; Rojas et al., 2016b). Likewise, extrusion improved the standardized ileal digestibility of all amino acids in field peas (Stein and Bohlke, 2007) and of all amino acids except lysine and proline in corn, but not in wheat and sorghum (Rodriguez et al., 2020). However, no improvement in lysine digestibility was observed by extruding corn (Muley et al., 2007).

4.2. Effect of extrusion on growth performance

Pigs fed extruded diets had greater ADG and G:F compared with pigs fed diets non-extruded diets (Lundblad et al., 2011) and as an average of published experiments, the G:F of growing-finishing pigs was increased if pigs were fed extruded diets compared with non-extruded diets (Table 3). However, for weanling pigs, there were no significant improvements in growth performance when data from all published experiments were summarized, although there are individual experiments in which improvements have been reported. Growing-finishing pigs fed extruded diets containing field peas have improved ADG, feed intake, and G:F compared with pigs fed non-extruded diets due to inactivation of anti-nutritional factors (O'Doherty and Keady, 2001). Extrusion of diets containing wheat and barley also improved growth performance of growing-finishing pigs (O'Doherty and Keady, 2001; Millet et al., 2012). Similar results have been observed in weanling pigs where ADG and G:F were greater in pigs fed extruded diets compared with pigs fed diets without thermal treatment (Hongtrakul et al., 1998; Cho et al., 2001; Veum et al., 2017). However, improvements in nutrient digestibility may not always result in improved growth performance (Rodrigues et al., 2016). Amornthewaphat and Attamangkune (2008) reported that extruding corn did not affect feed intake or ADG of weanling pigs.

Table 3
Effect of extrusion on growth performance of weanling and growing pigs[a].

	Diet type			
Item	Non-extruded	Extruded	SEM	*P*-value
Weanling pigs				
ADG[b], kg	0.333	0.341	0.0274	0.106
ADFI[b], kg	0.492	0.489	0.0331	0.819
G:F[b]	0.671	0.701	0.0481	0.167
Growing pigs				
ADG, kg	0.826	0.851	0.0457	0.445
ADFI, kg	2.148	2.080	0.1961	0.239
G:F	0.395	0.439	0.0278	0.004

[a] Adapted from Richert et al. (1992); Chu et al. (1998); Hongtrakul et al. (1998); Piao et al. (1999); Cho et al. (2001); O'Doherty and Keady (2001); Ohh et al. (2002); Sun et al. (2006); Amornthewaphat and Attamangkune (2008); Lundblad et al. (2011); Millet et al. (2012), and Veum et al. (2017).
[b] ADG, average daily gain; ADFI, average daily feed intake; G:F, gain to feed ratio.

5. Conclusion

Particle size reduction, pelleting, and extrusion are processing technologies used to improve the nutritional value of feed ingredients fed to pigs. These technologies are used to overcome dust issues, improve palatability, reduce feed wastage, inactivate anti-nutritional factors, improve nutrient digestibility, and increase feed efficiency. Optimum temperature and pressure for pelleting and extrusion of different feed ingredients must also be addressed to maximize the beneficial effect of thermal treatments. Further research is also needed to determine interactions among the use of enzymes and/or vitamins and feed processing technologies.

Declaration of Competing Interest

The authors have no conflicts of interest.

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