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Review article

# Size reduction in feed technology and methods for determining, expressing and predicting particle size: A review

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ABSTRACT

Particle size of diets or ingredients plays an important role in pig growth and gut health. The way the size of particles is measured and expressed, however, is limited in explaining pig growth performance differences. This review explores new possibilities to determine, express and predict particle size. Different grinding methods, including the use of roller mills, hammer mills, multicracker and multi-stage grinding were reviewed. Roller milling tends to produce a more uniform particle size distribution (PSD) and consumes less energy, whilst hammer mills have a greater grinding capacity and a higher reduction ratio compared to roller mill. The multicracker system, a more recently developed technology, can be considered cost-effective and ensures grinding capacity. Since the effects of different grinding methods vary, multi-stage grinding, combining different grinding methods, might be a solution to obtain a defined PSD. Particle size determination techniques, including dry/wet sieving, laser diffraction, microscopy, and static/dynamic image analysis are described and compared. It is concluded that more characteristics of particles (e.g. shape, volume or surface area) should be investigated. Besides geometric mean diameter (GMD), particle size can also be expressed with parameters such as $D_{50}$, $D_{4,3}$ and span of PSD. Equivalent particle size (EPS) is introduced as a mean of describing the size of particles related to a functional trait of the particles. A meta-analysis was performed by collecting particle size and pig performance data from scientific studies examining the effect of recalculated EPS on pig performance (feed conversion ratio, FCR). Regression/linear modelling shows that recalculated EPS was not better than GMD in explaining pig performance differences due to the high variation among studies. Different expressions of PSD may result in different conclusions. An introduction of describing the breaking behavior of diet ingredients via mathematical models is provided. The development in breakage functions of wheat in roller milling in food preparations indicates that breakage functions are applicable in predicting the output PSD. Functions may also be extended to diet ingredients to be ground in animal feed manufacture. In feed manufacturing diagrams, particle size reduction for downstream processes (e.g. pelleting, extruding, expander processing) should be taken into account when the relationship between pig performance and particle size of diets is investigated. In conclusion, the determination, expression and prediction of particle size can be a new direction for controlling the grinding process in the feed mill to better explain its relationship with pig performance.

*Abbreviations:* ADG, average daily gain; ATTD, apparent total tract digestibility; EPS, Equivalent particle size; FCR, feed conversion ratio; GMD, geometric mean diameter; GSD, geometric standard deviation; PSD, particle size distribution

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## 1. Introduction

In the field of feed manufacturing, grinding is a standard procedure for particle size reduction to make ingredients suitable for animal feeding and digestion. The principle of grinding methods is applying force to the ingredient, so that the bonds between various physical structures in feed materials are broken. For diet ingredients, the energy input and the extent of particle size reduction are important factors in feed manufacturing practices. Reducing particle size of ingredients can bring many benefits for feed processing and animals. According to Goodband et al. (2002), decreasing particle size of raw materials can improve mixing characteristics by reducing segregation with other ingredients in the mixture, and improve the pelleting capacity as well as the pellet quality. In addition, grinding increases the available surface area for the digestive enzymes to interact (Mavromichalis et al., 2000).

The effects of the particle size of ingredients or diets on pig performance and health (stomach and gut functioning) have been widely discussed. Smaller particles of ingredients or diets can improve nutrient digestion in animals (Wondra et al., 1993; Kim et al., 2005) and, therefore, improve pig performance (Huang et al., 2015; Ball et al., 2015; Nemechek et al., 2016). Wondra et al. (1995a) investigated effects of corn with a particle size ranging from 1000 to 400 μm in both mash and pellet form on pig performance. By decreasing the particle size, the average daily feed intake increased and the feed conversion ratio (FCR) improved. These authors also found that the apparent total tract digestibility (ATTD) of dry matter, nitrogen and gross energy was increased by particle size reduction. Ileal digestibility of dry matter, organic matter and energy was improved by lowering the particle size of wheat in pig diets (Lahaye et al., 2008). The results were explained by a better digestion of starch due to fine grinding, so amylase has a better access to the starch (Al-Rabadi et al., 2009). Moreover, reducing particle size of corn improved the apparent ileal digestibility of starch and gross energy (Rojas and Stein, 2015) as well as ATTD of gross energy. Kim et al. (2005) also found that ATTD of starch was significantly increased when particle size of wheat was reduced. In addition to earlier reported influences on digestibility parameters, also crude protein digestibility improved when smaller particles were used (Ball et al., 2015).

However, too finely ground ingredients can increase the risk of gastric ulcer development in pigs (Healy et al., 1994; Wondra et al., 1995a; Grosse Liesner et al., 2009; Ulens et al., 2015), which is considered the main cause of sudden death of pigs on farms, leading to economic losses. Grosse Liesner et al. (2009) showed that if 30% of the particles were smaller than 400 μm, piglets would have a high risk for ulcerations. According to Bao et al. (2016), the number of beneficial bacteria increased and suppressed bacterial pathogens at the same time when particle size of wheat increased from 430 to 470 μm. Mavromichalis et al. (2000) reported that a particle size of 400 μm of wheat increases the development of stomach lesions. Meanwhile, coarsely ground meal had almost no negative effect on the gastric wall of pigs (Nielsen and Ingvartsen, 2000). Similar results were obtained by Millet et al. (2012), indicating that coarse particles may also be essential for animals to maintain gut health.

The relationship between particle size of diet or feed ingredients and pig performance seems obvious: finely ground particles can enhance animal performance and the coarse fraction of particles can aid in maintaining gut health in pigs. So, the optimal particle size distribution (PSD) of animal diets has been of great research interest over the last decades. Although optimal PSD of pig diet is difficult to define, there is a general consensus among researchers that optimal particle sized feed for animals should be evaluated on the basis of animal performance, animal health and processing costs (Stark, 2012). In other words, optimal PSD should maximize the utilization of nutrients, improve animal performance under the precondition of ensuring health (Vukmirović et al., 2017), maintaining pellet quality and a proper grinding efficiency (Amerah et al., 2007). It should be noted that many studies control fine/coarse particles of diet/ingredients by changing the screen size of the grinding machine (Dirkzwager et al., 1998; Ball et al., 2015), or report PSD values based on unstandardized sieve sizes (Grosse Liesner et al., 2009; Millet et al., 2012; Nielsen and Ingvartsen, 2000). In this case, conclusions about how particle size influences pig performance and digestion of nutrients can only be obtained within their own study, and cannot be compared with other studies.

Generally, smaller particles lead to better pig performance, and larger particles are essential for pig health. In some cases, different results were also observed. In the study of Kim et al. (2005), significant effects of particle size of wheat on average daily gain (ADG), feed intake and feed efficiency were not observed. Similarly, ADG was not affected when particle size of sorghum reduced from 724 to 319 μm (Paulk et al., 2015). An increase in growth performance of pigs was observed with course ground corn compared to fine ground corn (Huang et al., 2015), which contradict with the results of Nemecheck et al. (2016). As such, particle size obviously cannot sufficiently explain differences in pig performance and digestion (Paulk et al., 2015).

Particle size of diets and feed ingredients in animal feed manufacturing is usually determined by dry sieving, and reported as PSD or GMD (ASAE, 2008). The difference in results among studies may be because of a poor correlation between the results of dry sieving method and digestive process and pig performance. A further reason is that the dry sieving selects particles based on two dimensions: maximum width and maximum thickness when particles pass the sieves (Allen, 1981). This means the actual shape of particles is not always determining the mass of a particle size class when dry sieving. The challenges then can be found in a more complete characterization of particles (e.g. volume, surface area, hardness, brittleness, hydratability) and different methods of determining and expressing particle size. An additional step is to obtain a better understanding of the breaking behavior of various feed ingredients using mathematical formulas (breakage functions) to describe their breaking behavior. These functions are the result of the interaction between ingredients and mills and can be used to predict PSD.

The objective of this review is to provide new insights into particle reduction technology related to pig feed ingredients based on fundamental theory analysis. Alternative ways to measure particle size are reviewed and the use of breakage functions as an innovative method to predict PSD is discussed.

## 2. Particle size reduction in the grinding process

Particle size reduction is accomplished by grinding for which different types of mills can be used. Currently, the hammer mill and roller mill are the most commonly used mills in the pig feed industry. Thomas et al. (2012; 2018) also investigated the possibility for the use of a multicracker device. Mill choices are usually based on ingredient type, energy consumption, grinding capacity as well as the animal species. Multi-stage grinding, which combines the advantages of different mills, may be a possible solution to obtain an ideal PSD with less cost (Lucht et al., 2011).

### 2.1. Hammer mill

Hammer mills consist of a series of hammers suspended from a central shaft and enclosed within a rigid metal casing. Particle size reduction in a hammer mill occurs as a result of the impaction/attrition between the rapidly moving hammers and relatively slow-moving particles (Koch, 2002; Van der Poel et al., 2018). A screen fitted in the milling chamber allows appropriately sized materials to pass as finished product.

The extent to which the material will be broken down in a mill can be characterized by their reduction ratio. This ratio is calculated by dividing the average input particle size of a whole ingredient by the average output particle size of the ground sample (Thomas et al., 2012). The hammer mill has the highest reduction ratio of 5.95 for coarsely ground corn, followed by the roller mill, whilst the multicracker system (see the description of multicracker in 2.3) has the smallest reduction ratio of 1.60 for coarsely ground wheat. The operational variables, however, may strongly affect the reduction ratio (Thomas et al., 2018). The high grinding capacity, less maintenance cost and ease of operations also makes the hammer mill a preferred grinding method. In addition, in feed manufacturing, the hammer mill is highly suitable for grinding fibrous materials such as hulls (oat, barley, wheat bran) compared to the roller mill and multicracker system.

Compared to the roller mill and multicracker system, the hammer mill requires more energy. For a similar grinding intensity (particle size reduction), the hammer mill consumes more specific mechanical energy (kJ/kg) compared to the roller mill (Wondra et al., 1993; Vukmirović et al., 2016; Thomas et al., 2018). Moreover, a hammer mill tends to produce more fine particles and dust, which can have a negative impact on gut health in pig (Nielsen and Ingvartsen, 2000).

Many factors influence the milling output of hammer mills. For a similar percentage of screen openings, large screen openings result in less screen area leading to less collisions of particles in the hammer mill, therefore, the yield of coarse particles increased (Islam and Matzen, 1988); larger openings reduce the residence time in the grinding chamber (Martin, 1981). The impact of particles on the screen area is of great importance for the breakage of cereals, in addition to the impact of the hammers. A large screen area generates additional heat, which can reduce the efficiency of the hammer mill (Guo et al., 2016). Applying air flow through the hammer mill aids to improve the capacity of the mill and to achieve a more uniform PSD. Moisture content of feed ingredients influences breaking behavior (Jindal and Austin, 1976; Adapa et al., 2011), as it affects the minimum cutting blade speed to ensure breakage of the material. When moisture content is low, material becomes harder and more brittle (Jindal and Austin, 1976). They also found that both less loading or overloading results in a different absolute rate of breakage, being also the case when using laboratory mills. This can be explained since a higher loading can result in a decrease in speed of the particles compared to one another and, therefore, leads to a lower breakage rate and higher energy consumption. Both the shape and the material of the hammer is of influence. Bochat et al. (2015) used a new rotor design with hammers in the shape of a circle section with an angle 45° and concluded that the grinding efficiency of cereals is improved by primarily reducing the time needed for grinding. The material of hammers was shown to have different wear mechanism during grinding process (Bao et al., 2011). Finally, the tip speed of hammers is found a factor of influence: Islam and Matzen (1988) found that when the tip speed is decreased, the percentage of coarse particles will increase under identical operating conditions. In the study of Dey et al. (2013), the reduction ratio as well as the energy consumption increases when the rotor speed increases from 1000 to 1400 rpm. Today's hammer mills have been developed to control PSD by adjusting tip speed and screen openings.

### 2.2. Roller mill

Particle size reduction in a roller mill is achieved by compression (same roll rotating speed) or shear (different roll rotating speed) forces and the roll design features (grooves and corrugations) (Koch, 2002; Vukmirović et al., 2017). This has made the roller mill suitable for very accurate controlled milling of the product, although it has difficulty in milling fibrous materials or hulls. Roller mills have better energy efficiency compared to hammer mill and multicracker devices (Wondra et al., 1993; Vukmirović et al., 2016; Thomas et al., 2018). Grain type can also be a factor affecting energy consumption. Healy et al. (1994) indicated that grinding sorghum took less energy than grinding corn when roller milling was applied. Coarse grinding of full fat soybeans requires more effective specific mechanical energy, followed by wheat and maize (Thomas et al., 2018).

Thacker (2006) suggests that pig producers consider the use of a roller mill rather than a hammer mill for grinding ingredients because pig performance and carcass traits were not affected by the grinding method; a roller mill however requires less energy, has lower maintenance costs, is a quieter operation and has a more exact control of particle size. Particles processed by roller milling had a better uniformity, and rolled feed contained less fine and more coarse particles than hammer-milled feed (Nielsen and Ingvartsen, 2000; Svihus et al., 2004). In the study of Wondra et al. (1993) such results were also observed when corn was ground to 800 µm. These results correspond well with the research of Vukmirović et al. (2016) who found that coarsely rolled corn was more uniform than hammer milled corn. On the other hand, roller mills tend to produce more irregular particles (Vukmirović et al., 2017) due to

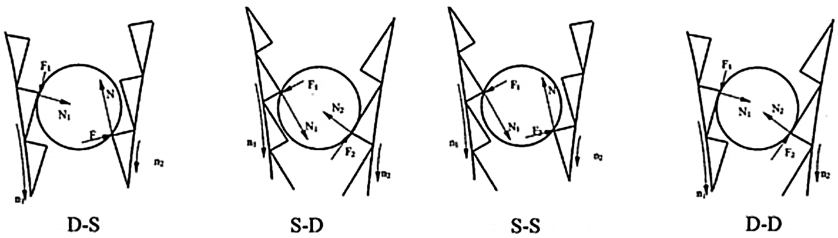


**Fig. 1.** The four possible break roll dispositions: dull-to-sharp (D-S), sharp-to-dull (S-D), sharp-to-sharp (S-S) and dull-to-dull (D-D) and its forces acting on the particle. (Fang and Campbell, 2002).

the difference in packing of same sized material (Koch, 2002). For a unit mass of particles, irregular particles usually indicate a larger surface area and this may aid enzyme accessibility in the gastrointestinal tract of pigs.

For the development of breakage equations with roller mill, many factors have been identified that influence the breakage process of diet ingredients. From roller mill studies, it became evident that kernel size, milling ratio (the ratio of the roller gap to the input particle size) and the hardness of wheat for example have their influence on the quantity of larger and smaller particles in the output of the PSD. It has been shown that the number of large particles increased when kernel size decreased (Fistes and Tanovic, 2006), the milling ratio increased (Campbell et al., 2001) or softer wheat seeds were milled (Campbell et al., 2007, 2012). Furthermore, roll disposition influences the uniformity of the PSD. The disposition of the rollers, resulting from used grooves and corrugations, determines the kind of force affecting the particle: a sharp-sharp (S-S) disposition makes use of shearing or cutting force, while a dull-dull (D-D) disposition makes more use of compression (see Fig. 1). Using a S-S position will result in a less uniform PSD than using a D-D disposition (Fang and Campbell, 2002). Also, moisture content is of influence (Fang and Campbell, 2003b). Moisture contents lower than 10% show a more uniform distribution in comparison to wheat kernels with a moisture content of 20%. On the other hand, lower moisture kernels are easier to grind and require less energy for breakage (Dziki, 2007).

### *2.3. Multicracker system*

The multicracker was introduced in 2005 as an alternative method to the conventional particle size reduction systems, such as hammer and roller mills. This technology comminutes ingredients by a method of cracking/cutting-edge crushing by two rows of special discs. Thomas et al. (2012) showed a schematic diagram of a multicracker system (see Fig. 2), with discs forming two contra-revolving rows. This system is relatively energy efficient and ensures grinding capacity at the same time. In the study of Thomas et al. (2018), compared to the hammer mill, the multicracker consumed less total specific mechanical energy to realize a similar mean particle size for coarsely ground maize, soybeans and wheat. In this comparative study between comminution devices, the roller mill used the lowest quantity of energy although it was not significantly different from the multicracker. Thomas et al. (2012) also investigated two factors affecting the grinding performance of different feed ingredients in a multicracker system. Disc type was considered to be an essential variable that significantly affects particle characteristics, as well as the use of specific mechanism energy. Compared to ceramic discs, steel discs had lower energy consumption and a lower reduction ratio. The gap between the discs also affected the mean particle size: a smaller opening between the discs led to a more uniformity PSD. In addition, a narrower width of PSD was observed and the smallest particles were generated when a higher disc speed was applied.

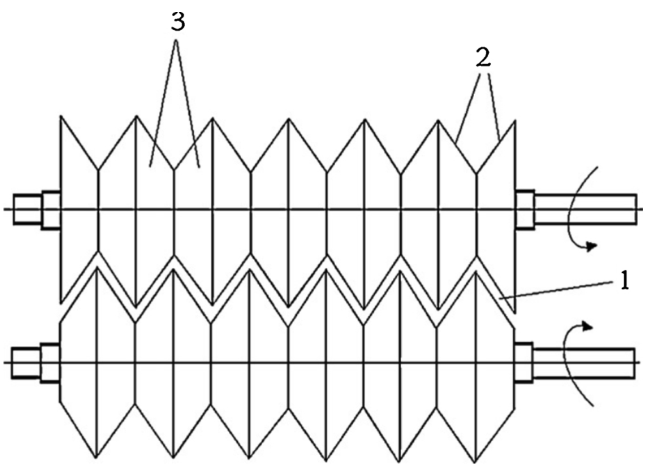


**Fig. 2.** Schematic diagram of twin parallel shafts in the multicracker grinding system: view from above. 1. Adjustable gap, 2. disc surface, 3. discs; → , shaft rotation direction (Thomas et al., 2012).

### 2.4. Multi-stage grinding

A desired pig feed structure is considered to contain the highest possible amount of medium- sized particles, with a low fraction of fine particles as well as coarse or very coarse particles (Healy et al., 1994; Wondra et al., 1995a;b; Lucht et al., 2011; Cappai et al., 2013). A roller mill produces a lower content of fines and is more efficient in energy consumption, while a hammer mill is more suitable for grinding husks. As such, different milling techniques can be combined to achieve a better grind and this multi-stage grinding is often applied (Rojas and Stein, 2015). Multi-stage grinding combines a hammer mill with a roller mill to maximize grinding efficiency and minimizing PSD variation. Multi-stage grinding often involves a sieving step after first grinding to sieve all particles of undesired size. Al-Rabadi et al. (2017) reported that regrinding the coarse fraction of grains (barley and sorghum) in a two-stage hammer mill system significantly improved the FCR in pigs by 6.6%. They suggested that regrinding coarse particles may be an alternative method to the pelleting process, due to the similar feed efficiency in pig growth performance. Similar results were reported by Black and Gidley (2017) in regrinding large particles of ground cereals. Lucht et al. (2011) compared four combined grinding methods to determine which combination can produce a well-structured pig diet in which 30% barley was included with the objective to have a low fine fraction (max. 25% < 0.5 mm), and where husks were ground efficiently. The four variants used by Lucht et al. (2011) were: 1. a two-stage crushing roller mill without intermediate sieving, 2. two hammer mills with pre-mill/ post-mill and intermediate sieving, 3. a hammer mill + one stage crushing roller mill with intermediate sieving and 4. a hammer mill + laboratory grinder with intermediate sieving. The most uniform feed structure was achieved by the combined hammer mill and roller mill, which resulted in the largest quantity of medium-sized (0.5–1.6 mm) particles (60%), and the lowest quantity (lower than 25%) of fine (< 0.5 mm) particles as intended set-point values. Energy consumption was 30% lower compared to the use of two hammer mills.

## 3. Particle size determination

Methods of measuring and expressing particle size are different; in order to describe particle size or PSD, we therefore have to make a choice among available methods. Particles used in pig feed are normally larger than 100 μm, meaning that methods like sedimentation, electro zone sensing and dynamic light scattering systems are not routinely included in pig feed particle size research, since they are mainly used for very small particles (< 100 μm). An overview of techniques that can be used for pig feeds is provided below including dry sieving, wet sieving, microscopy, laser diffraction, static and dynamic image analysis is presented in Table 1.

### 3.1. Dry sieving

At present, dry sieving which discriminates particles into size classes and converts these to mass, is the most commonly used method to investigate particle size in animal nutrition. According to the recommended procedure of ASAE (2008), the feed ingredient mash was sieved into different size classes, and PSD can be presented with mass percentage in each class. Then the particle size can be calculated and expressed with geometric mean diameter (GMD) and geometric standard deviation (GSD). This standard procedure has made it possible to compare particle size of ingredients or diets between studies. Dry sieving is widely employed because it is a low-cost method that requires little training. However, this method has a number of drawbacks. For example, very small particles may stick to the sieves because of electrostatic forces. In addition, ingredients with a high fat content (like ground soybeans) tend to clog the sieves and make it difficult to obtain accurate data although using a dispersing agent can help prevent clogging while sieving (ASAE, 2008). In the study of Stark and Chewning (2012), it was shown that GMD decreased when a dispersing agent was added.

### 3.2. Wet sieving

Wet sieving is commonly applied in soil science, but can also be employed in the pig feed industry. Wet sieving is often used to determine the PSD of feed pellets. The pellet sample (50 g) is soaked in 1000 ml water for 1 h, and the feed-water-suspension is then poured onto a sieve tower (Wolf et al., 2010; Millet et al., 2012). Unlike dry sieving, flow of water should be provided from the top to the bottom when sieving to separate samples into different grades. After the sample is washed, the material that is left on the sieve is recovered, dried and weighed. Then particle size can be calculated and the characteristics of PSD (median, span etc.) can be reported.

Dirkzwager et al. (1998) measured the PSD of medium diets (composed by mixing 50% of a fine and 50% of a coarse diet) before and after pelleting with the dry and wet sieving method (see Fig. 3). A significant increase in the percentage of small particles (< 0.1 mm) can be observed after the meal was wet sieved. This might be due to the moving water bringing small particles to the lower sieves. Using water in a sieving procedure is considered to be more accurate because it prevents the clogging of particles; it should be noted that, however, wet sieving is more complicated and takes much more time than dry sieving.

Wet sieving makes it possible to examine PSD in pellets and to investigate the influence of pelleting and expander treatment on PSD (Nielsen and Ingvartsen, 2000). Wolf et al. (2010) also indicated that measuring particle sizes in pellets with wet sieving made it possible to compare results from different studies. Wet sieving resembles the process of moisturizing in the gut, which could be a more specific and digestion-related representation of PSD than dry sieving (Engberg et al., 2002).

### 3.3. Other measurements

Optical microscopy can also be used to determine particle size and provide information on the shape of particles. Despite that, the

**Table 1**
Comparison of different particle size measurements.

| Items | Principle | Range | Situation | Pros | Cons | Property measured |
|---|---|---|---|---|---|---|
| Dry sieving | -Mass | -Depends on sieve size | -Standard in feed industry | -Easy operation and low cost<br>-Widely used | -Electrostatic forces make small particles stick to the sieves<br>-Clogging of sieves<br>-Not accurate enough | -Length |
| Wet sieving | -Mass | -Depends on sieve size | -Pellets<br>-Mash | -Fines may be removed<br>-Prevent blockage<br>-More representative PSD than dry sieving with respect to animal performance | -Take long time<br>-Not practical<br>-Not suitable for soluble samples | -Length |
| Laser diffraction | -Volume | 0.1-1000 μm | -Wet and dry samples | - Time saving<br>-Small particle<br>-Accurate<br>-Easy operation | -Expensive<br>-Geometry of particles is not considered<br>-Lost small amounts of oversize and undersize particles | -Volume |
| Static image analysis | -Number | -Depends on the equipment | -Pastes<br>-Sticky particles<br>-Suspensions<br>-When shape information is needed | -Distinguish individual particle<br>-Predict the distribution of mixture | -Images can be affected by light and focus<br>-Unrepresentative sample may be chosen<br>-Limited mages/particles | -Shape<br>-projected Area<br>-Length<br>-Width |
| Dynamic image analysis | -Volume<br>-Number | 20 μm ~ 30 mm | -Powders<br>-Granulates<br>-Pellets<br>-Extrudates<br>-Glass beads | -Time saving<br>-Accurate<br>-Highly automated<br>-Closely match sieve results<br>-Collect shape information<br>-Broad size distribution | -Expensive | -Shape<br>-projected Area<br>-Length<br>-Width |
| Microscopy | -Number | -Depends on the equipment | -Simple analysis<br>-When shape information is needed | -Measure size and shape of particles<br>- Easy operation | -Time consuming<br>-Not accurate enough<br>-Cannot examine individually | -Shape<br>-projected Area |

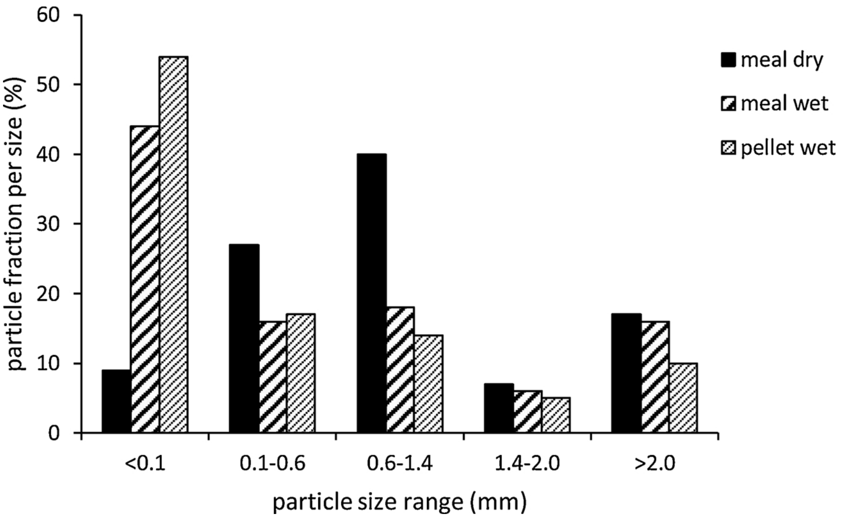


**Fig. 3.** Particle size distribution of medium ground meal diet and pellet diet for starter pigs using dry sieving and wet sieving (Dirkzwager et al., 1998).

use of microscopy in particle size determination can be influenced by the limited freedom in the orientation of the particles during measurement (Foqué et al., 2017). The drawback of using microscopy to measure PSD is that it is time-consuming and is a tedious measurement for analyzing a large number of particles: it is impractical to obtain a large enough set of measurements to obtain meaningful summarizing parameters such as mean, median and span (Ulusoy and Yekeler, 2014).

Laser diffraction measures angular variation in intensity of light scattered as a laser beam passes through a dispersed particulate sample to evaluate PSD. When the laser hits the flowing particles, it will provide a geometric size of the particles by measuring scatter light angle size and intensity (Dodds et al., 2013). Laser diffraction enables to determine particle size of samples within a large range, from 0.1 to 3000 μm. Additionally, the software used in conjunction with the laser diffraction techniques makes already an instant calculation of particle size from volume cumulative PSD, referred to as $D_{v10}$, $D_{v50}$, $D_{v90}$, particle uniformity and equivalent volume diameter like $D_{4,3}$, $D_{3,2}$ (see 4.1 for explanation). In addition, dry and wet samples are able to be measured by the laser diffraction technique. The high accuracy of measuring a large number of samples with low costs make laser diffraction a widely used technology (Fedotov et al., 2007).

Besides the size of particles, particle shape is considered another important characteristic. Particles sharing the same size in cross section but with different shapes may have different properties and behaviors (e.g. the flow ability of materials). Sedwell et al. (2017) indicated that pellets with low sphericity surfaces had a higher drug dissolve percentage compared to more spherical pellets (see Figs. 4 and 5). As such, the shape of particles may also influence the nutrient release of feed in the gut of the pig.

Compared to traditional manual particle measuring methods, image analysis combined with computer programs has been widely employed due to the quicker and more objective measurement (Rodriguez et al., 2013). Static image analysis combines microscopy and a digital camera with computer software providing a full morphology of particles (2 dimensional) in a projected area. Extended subsequent statistical analysis is needed when using static image analysis. In addition, a good preparation of samples is required, so that computer can distinguish between the individual particle instead of analyzing agglomerates as one particle.

Dynamic image analysis allows materials to flow free over one or more cameras allowing a large number of particles to be projected in a random orientation (3D) during the measuring procedure. Consequently, a large number of images (several $10^3$) can be obtained and both particle size and shape can be analyzed (Shang et al., 2017). This approach has the advantage over static image analysis, which can only do analysis on a limited number of images resulting in a small quantity of particles analyzed. Being sensitive

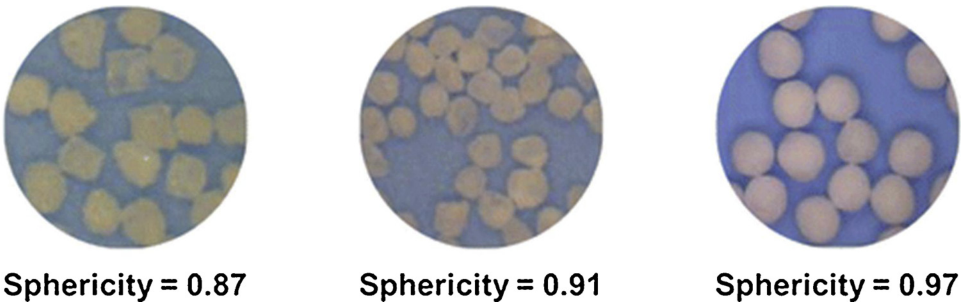


**Fig. 4.** Images of sugar spheres with different sphericity values (Sedwell et al., 2017).

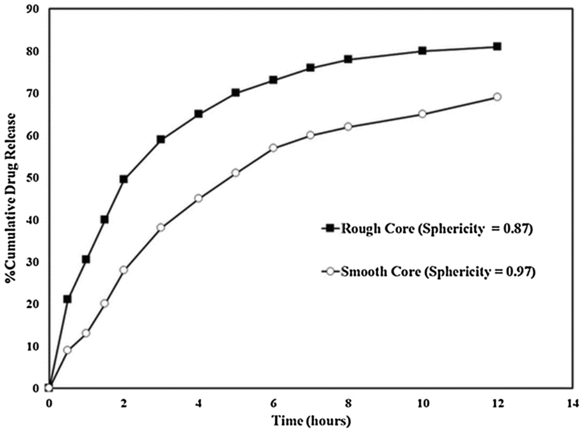


**Fig. 5.** Effect of particle shape as measured by sphericity of starting sugar spheres on release profile of chlorpheniramine maleate drug loaded on sugar spheres (Sedwell et al., 2017).

to the different particle size and shape characteristics, dynamic image analysis provides more accurate results compared with sieving especially in determining particles of 38 μm and below (Ulusoy and Igathinathane, 2015). Technologies like sieving merely determine the equivalent spherical diameter (see 4.2 for explanation), while image analysis is able to detect various dimensions of irregularly shaped particles, such as length, width and area (Ulusoy and Yekeler, 2014).

The techniques mentioned above define a particle size in different ways. As such, the analytical facilities used to determine the particle size can yield different summarizing statistics of identical samples. In fact, no analysis method provides the true particle size except for spherical particles (Iacocca et al., 2010; Foqué et al., 2017) or other well-defined geometric shapes.

## 4. Particle size expression

Curves or plots are a very common tool to visualize the analysis of PSD measurements, which are very suitable for quality control. However, PSD are not always easily viewed using graphs, especially when a large quantity of PSD measurements needs to be compared or different size classes were used. Using numerical values to describe PSD makes a rapid comparison possible among different ingredients and analysis methods. In addition to calculated mean particle size and parameters derived from PSD, an equivalent particle size (EPS) can be determined. This EPS provides the possibility to describe irregular-shaped particles with one single parameter, and may be an alternative way to express particle size by using other properties of particles, like volume, surface area or ratio of surface area to volume.

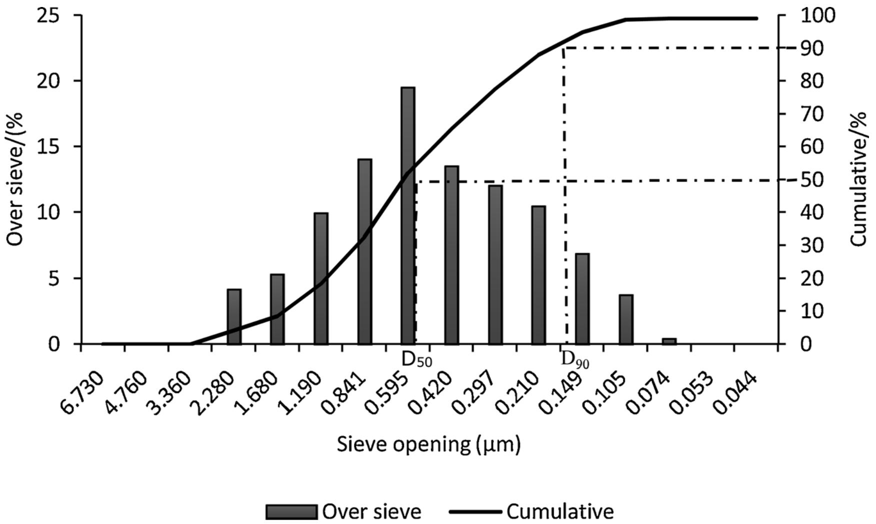


**Fig. 6.** Expression of fractional distribution (bars) and the undersize cumulative distribution (line) of particle size, based on mass (ASAE, 2008).

### 4.1. Description of particle size

According to the ASAE standard (2008), after sieving and weighing, both fractional and cumulative PSD can be obtained (see Fig. 6), which represents a visual mean of the distribution of particles in a range of particle size classes. In addition, the particle size can be calculated using a logarithmic approximation calculation, and reporting values as GMD and GSD, referring to the mean diameter of individual particles of a feed or simply the fineness of ground feeds (Eq. 1) and the width of distribution (Eqs. 2 and 3), respectively.

$$d_{gw} = log^{-1}\left[\frac{\sum_{i=1}^{n}(W_i \times \log(d_i \times d_{i+1})^{1/2}\_)}{\sum_{i=1}^{n} W_i}\right] \tag{1}$$

$$S_{log} = \left[\frac{\sum_{i=1}^{n} W_i(\log(d_i \times d_{i+1})^{1/2}\_ - \log d_{gw})^2}{\sum_{i=1}^{n} W_i}\right]^{1/2} \tag{2}$$

$$S_{gw} \approx \frac{1}{2} d_{gw}\left[log^{-1}S_{log} - (log^{-1}S_{log})^{-1}\right] \tag{3}$$

where:

$d_{gw}$ = geometric mean diameter or median size of particles by mass, mm

$d_i$ = nominal sieve aperture size of the $i^{th}$ sieve, mm

$d_{i+1}$ = nominal sieve aperture size in next larger than $i^{th}$ sieve (just above in a set), mm

$W_i$ = mass on $i^{th}$ sieve, g

n = number of sieves +1 (pan)

$S_{gw}$ = geometric standard deviation of log-normal distribution by mass, dimensionless

Slog = geometric standard deviation of log-normal distribution by mass in ten-based logarithm, dimensionless

*gw* = geometric weight

Mean, median and mode are parameters that can be derived from absolute PSD values. The median is obtained by sorting all the sizes, which is not affected by the maximum and minimum extreme values and choosing the value where half of the data falls below and half above this number. The influence of extreme data values has no effect on the median. The mean is calculated based on all sizes of particles in the sample, so it is sensitive to each data change. The mode is the most frequently occurring particle size class in the sample, reflecting the concentration of a set of particles in the sample.

The cumulative distribution curve (see Fig. 6) is another commonly used way to provide a visualized description of the PSD which makes it possible to have a quick view of PSD. In addition, the particle size can also be described by parameters derived from the cumulative mass based PSD referred to as $D_{50}$ (known as median), $D_{10}$ and $D_{90}$, which indicate the 10%, 50% and 90% of the population below the respective size. This also enables the comparison of particle sizes among different samples.

Besides GMD, GSD, mean, median and mode, the 'Sauter mean' diameter (surface weighted mean diameter) can also be used to estimate the mean particle size of a given particle distribution (see Eq. 4). It is defined as the diameter of a sphere that has the same volume-surface area ratio as the particle of interest (Filippa et al., 2012). Decreasing particle size will increase the surface area, thus increasing the surface-volume ratio. Sauter mean diameter is used in applications where specific area is important as in dissolution of material or reactivity of components (Merkus, 2009). For example, it would be a reasonable parameter to reflect the digestive processes where enzymes attack the surface of particles.

$$D_{3,2} = \frac{\sum_{i=1}^{n} n_i D_i^3}{\sum_{i=1}^{n} n_i D_i^2} \tag{4}$$

Where:

$n_i$ = the (number-based) frequency of occurrence of particles in size class *i*;

$D_i$ = the mean diameter of size class *i* (for linearly spaced size classes, the arithmetic mean size of the classes is taken, for logarithmically spaced classes, $D_i$ can be taken as the geometric mean size).

Another weighted mean diameter is 'de Brouckere mean' diameter (volume weighted mean diameter). It can be applied where coarse particles that make up the bulk of volume is the determining factor. The number of particles is not required in this formula, and the laser diffraction detects the volume of the particles, not the quantity, so the results of the laser diffraction are presented with ($D_{4,3}$) (Anonymous, 2016).

$$D_{4,3} = \frac{\sum_{i=1}^{n} n_i D_i^4}{\sum_{i=1}^{n} n_i D_i^3} \tag{5}$$

Where:

$n_i$ = the (number-based) frequency of occurrence of particles in size class *i*;

$D_i$= the mean diameter of size class *i*

The span of PSD is an additional parameter to the average particle size, which provides the user with additional information on the PSD (Anonymous, 2016). Span indicates the size range of the population of particles, and can be calculated from $D_{10}$, $D_{50}$ and $D_{90}$ values (see Eq. 6).

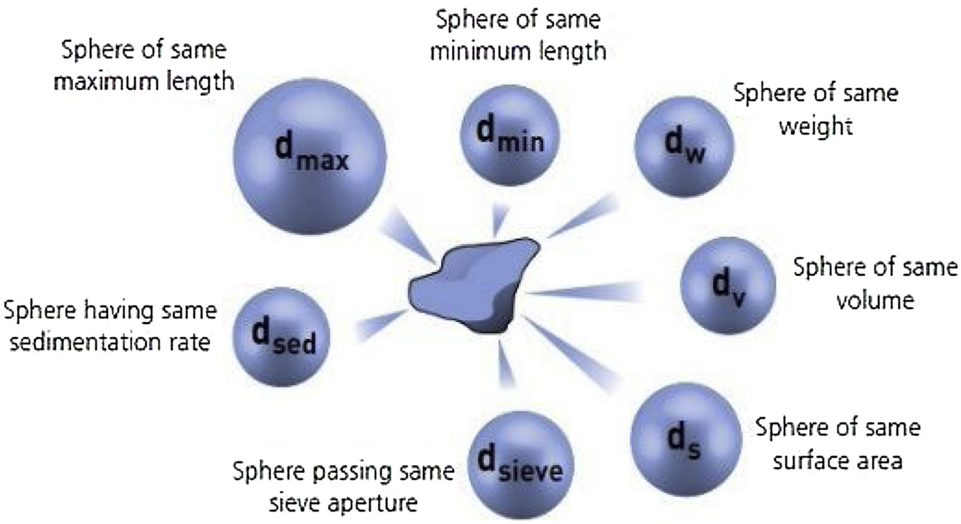


**Fig. 7.** Virtual diameters of sphere representing an irregular shaped particle (Rawle, 2003).

$$Span = \frac{D_{90} - D_{10}}{D_{50}} \tag{6}$$

The type of parameter that should be used depends on the objective for which it may be used. For example, $D_{10}$, $D_{50}$ and $D_{90}$ are usually applied in comparative tests of quality among laboratories. When surface area is the factor of interest, the Sauter mean diameter - that relates to both particle quantity (volume) and weighting (by area) - is applicable (Merkus, 2009). Therefore, parameters to describe particle size should be chosen wisely, since different expression methods may produce quite different results for the same ground material.

### 4.2. Equivalent particle size

The main idea of expressing the particle size of a ground material is to obtain one descriptive parameter to allow comparison of values between ground materials and for quality control. However, it is difficult to describe a three dimensional (3D) and irregular-shaped particle with only one parameter. Spheres can be described by only one parameter (diameter); this directs us to describe these irregular shaped particles also with one parameter by equalling them to a sphere but on a different basis (see Fig. 7).

Equivalent particle size is a virtual diameter of a sphere to represent the size of a given irregular particle, calculated based on the same volume, surface or weight etc. So, an equivalent sphere has the same characteristics as the observed particle in relation to a given measurement principle, whether volume, projected perimeter, surface area, etc. This means that a given irregular particle can be represented with several equivalent spheres depending on the property considered. For example, consider a cube with a side length of 1 cm, then the volume of this cube is 1.0 $cm^3$. Then many equivalent sphere diameters can be obtained: an equivalent volume diameter of 1.24 cm, an equivalent area diameter of 1.38 cm and an equivalent projected perimeter of 1.27 cm. In practice, different instruments will give different EPS, for instance, laser diffraction gives results regarding the particle volume.

Estimates of certain EPS's can be derived when GMD and GSD are known (Lachman et al., 1987). The formulas were first described by Hatch and Choate (1929) and are used e.g. to describe pharmaceuticals. These formulas, Eqs. (7) – (10), can calculate the EPS for arithmetic, surface, volume and volume-surface which provide more information on the particle size with respect to its intended use. Especially these calculations assumed that the PSD is log-normally distributed, which is the same as the ASAE standard being used to calculate the GMD. This makes it very suitable for recalculating the PSDs of animal feeds.

$$\log d_{ave} = \log d_{gw} - 5.7560 \times \log^2 S_{gw} \tag{7}$$

$$\log d_s = \log d_{gw} - 4.6052 \times \log^2 S_{gw} \tag{8}$$

$$\log d_v = \log d_{gw} - 3.4539 \times \log^2 S_{gw} \tag{9}$$

$$\log dvs = \log d_{gw} - 1.1513 \times \log^2 S_{gw} \tag{10}$$

where:

$d_{ave}$ = arithmetic mean
$d_s$ = Surface mean
$d_v$ = Volume mean
$dvs$ = Volume-to-surface mean (or Sauter mean)
$d_{gw}$ = geometric mean diameter

**Table 2**
Effect of grain/complete diet particle size and recalculated equivalent particle size on pig performance (data collected from different studies a–e).

| Main dietary grain | Feed form | Weight class | GMD/ µm | GSD/ µm | AM/ µm | MSD/ µm | MVD/ µm | MVSD/ µm | ADG/ kg | ADFI/ kg | FCR | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Barley | Meal | Fattening | 1030 | 2.08 | 269.5 | 352.3 | 460.7 | 787.7 | 0.80 | 1.62 | 2.04 | Al-Rabadi et al., 2017 |
| Barley | Meal | Fattening | 700 | 1.88 | 258.5 | 315.5 | 385.0 | 573.5 | 0.86 | 1.60 | 1.88 | |
| Sorghum | Meal | Fattening | 830 | 2.38 | 126.7 | 184.5 | 268.7 | 569.9 | 0.85 | 1.84 | 2.20 | |
| Sorghum | Meal | Fattening | 540 | 1.90 | 192.8 | 236.9 | 291.1 | 439.5 | 0.87 | 1.72 | 1.98 | |
| Barley | Pellet | Fattening | 1030 | 2.08 | 269.5 | 352.3 | 460.7 | 787.7 | 0.41 | 1.66 | 1.96 | |
| Barley | Pellet | Fattening | 700 | 1.88 | 258.5 | 315.5 | 385.0 | 573.5 | 0.85 | 1.62 | 1.90 | |
| Sorghum | Pellet | Fattening | 830 | 2.38 | 126.7 | 184.5 | 268.7 | 569.9 | 0.80 | 1.60 | 2.02 | |
| Sorghum | Pellet | Fattening | 540 | 1.90 | 192.8 | 236.9 | 291.1 | 439.5 | 0.81 | 1.59 | 1.92 | |
| Corn | Pellet | Finishing | 555 | 3.14 | 21.0 | 40.5 | 77.9 | 288.4 | 1.08 | 2.90 | 2.69 | Paulk et al., 2015 |
| Sorghum | Pellet | Finishing | 724 | 2.46 | 95.5 | 143.2 | 214.7 | 482.8 | 1.13 | 3.10 | 2.75 | |
| Sorghum | Pellet | Finishing | 573 | 2.31 | 99.3 | 141.0 | 200.2 | 403.6 | 1.10 | 2.99 | 2.71 | |
| Sorghum | Pellet | Finishing | 319 | 2.52 | 37.7 | 57.8 | 88.6 | 208.1 | 1.10 | 2.91 | 2.65 | |
| Barley | Meal | Grower | 390 | 2.20 | 82.4 | 112.5 | 153.5 | 285.8 | 0.79 | 1.74 | 2.19 | Morel and Cottam, 2007 |
| Barley | Meal | Grower | 716 | 2.30 | 126.4 | 178.8 | 252.9 | 506.1 | 0.88 | 1.76 | 2.00 | |
| Barley | Meal | Grower | 1026 | 2.30 | 181.1 | 256.2 | 362.4 | 725.3 | 0.80 | 1.66 | 2.07 | |
| Barley | Meal | Grower | 880 | 2.60 | 89.8 | 141.7 | 223.7 | 557.5 | 0.92 | 1.83 | 1.99 | |
| Barley | Meal | Finisher | 479 | 1.70 | 236.9 | 272.8 | 314.0 | 416.1 | 1.15 | 2.81 | 2.46 | |
| Barley | Meal | Finisher | 854 | 2.10 | 215.7 | 284.0 | 374.0 | 648.5 | 1.09 | 2.62 | 2.44 | |
| Barley | Meal | Finisher | 1175 | 2.10 | 296.8 | 390.8 | 514.6 | 892.3 | 1.10 | 2.67 | 2.45 | |
| Barley | Meal | Finisher | 698 | 2.30 | 123.2 | 174.3 | 246.6 | 493.4 | 1.11 | 2.76 | 2.53 | |
| Corn | Meal | – | 610 | 2.17 | 136.1 | 183.7 | 247.9 | 451.9 | 0.90 | 2.41 | 2.68 | Nemechek et al., 2016 |
| Corn | Pellet | – | 610 | 2.17 | 136.1 | 183.7 | 247.9 | 451.9 | 0.94 | 2.35 | 2.50 | |
| Corn | Meal | – | 464 | 2.33 | 77.6 | 110.9 | 158.6 | 324.5 | 0.86 | 2.26 | 2.63 | |
| Corn | Pellet | – | 464 | 2.33 | 77.6 | 110.9 | 158.6 | 324.5 | 0.92 | 2.35 | 2.55 | |
| Corn | Meal | – | 502 | 2.25 | 97.0 | 134.7 | 187.2 | 361.3 | 0.89 | 2.37 | 2.66 | |
| Corn | Pellet | – | 502 | 2.25 | 97.0 | 134.7 | 187.2 | 361.3 | 0.93 | 2.37 | 2.55 | |
| Corn | – | Fattening | 624 | 2.26 | 118.4 | 165.1 | 230.2 | 447.5 | 0.46 | 0.78 | 1.70 | Ohh et al., 1983 |
| Corn | – | Fattening | 877 | 2.25 | 169.5 | 235.4 | 327.0 | 631.2 | 0.45 | 0.80 | 1.78 | |
| Corn | – | Fattening | 822 | 2.04 | 230.7 | 297.4 | 383.5 | 637.5 | 0.46 | 0.84 | 1.81 | |
| Corn | – | Fattening | 1147 | 1.99 | 351.1 | 444.9 | 563.7 | 905.2 | 0.47 | 0.91 | 1.92 | |
| Sorghum | – | Fattening | 539 | 2.10 | 136.1 | 179.2 | 236.0 | 409.3 | 0.44 | 0.78 | 1.78 | |
| Sorghum | – | Fattening | 722 | 2.07 | 192.3 | 250.5 | 326.4 | 554.1 | 0.45 | 0.81 | 1.79 | |
| Sorghum | – | Fattening | 885 | 1.81 | 367.1 | 437.7 | 521.9 | 742.2 | 0.45 | 0.87 | 1.92 | |
| Sorghum | – | Fattening | 1217 | 1.74 | 565.2 | 658.9 | 768.1 | 1043.9 | 0.43 | 0.83 | 1.94 | |

dgw: geometric mean diameter; sgw: geometric standard deviation of particle diameter by mass; AM: Arithmetic mean; MSD: Mean surface diameter; MVD: Mean volume diameter; MVSD: Mean volume-surface diameter; ADFI: average daily feed intake; FCR: feed conversion ratio, = feed (g) / gain (g).

$S_{gw}$ = geometric standard deviation of particle diameter by mass.

These four EPS's are used in very different ways for measurements, in pharmaceuticals, food or mining. According to Lachman et al. (1987), the arithmetic mean can be used for measurements of the evaporation of liquids; surface mean can be used in processes such as dissolution and absorption; as for volume mean, it can be used for the packing or flow of powders or granulation; and the volume-surface mean can be used for efficiency or chemical reactions (e.g. catalysis or combustion).

### *4.3. Equivalent particle size relating to pig performance*

We use Eqs. (7) – (10) to transform GMD and GSD to EPS. To explore the relationships between EPS and pig performance, studies in the scientific literature were collected which reported both GMD and indicators for pig performance, then EPS was calculated (Table 2). Data from Ohh et al. (1983; see Fig. 8) and Al-Rabadi et al. (2017; see Fig. 9) were used as an example of analysis, and FCR was taken as the indicator of pig performance. We observed that FCR increased ($P < 0.01$) when particle size of corn or sorghum increased with all manners of expressing particle size (see Fig. 8). All EPS expressions showed a better fit to FCR in a linear model than GMD, with $r^2$ values from 0.80 to 0.85 against 0.70 for GMD. This indicates that the mean volume diameter and arithmetic mean diameter are a better predictor of pig performance when it comes to particle size.

However, similar results for EPS were not obtained from the data of Al-Rabadi et al. (2017). When data of Al-Rabadi et al. (2017) and data of Ohh et al. (1983) are compared, relevance between particle size and FCR cannot be observed with the expression of GMD or arithmetic mean, mean volume diameter and mean volume surface diameter ($P > 0.05$). However, when particle size was

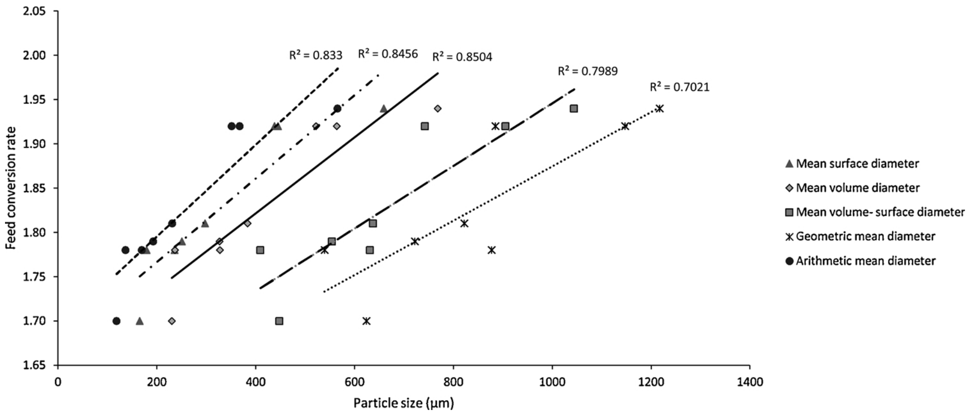


**Fig. 8.** Effect of differently expressed feed particle size on the feed conversion ratio of weaned pigs and fitted linear equations (data from Ohh et al., 1983).

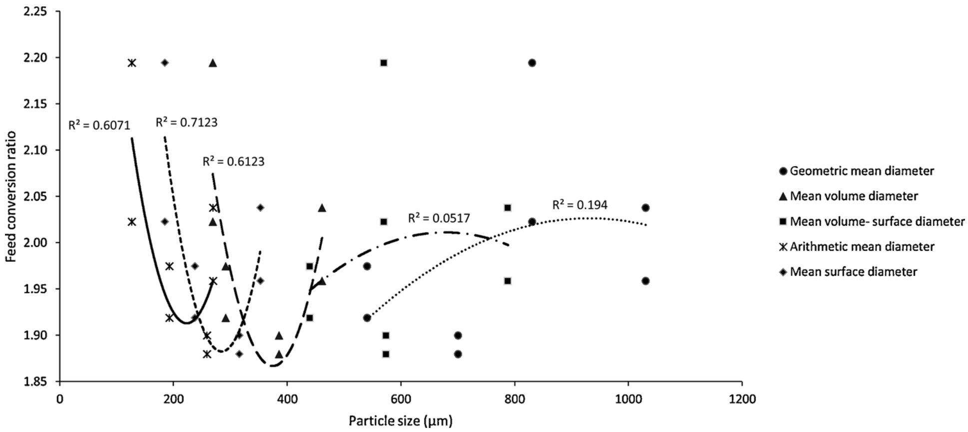


**Fig. 9.** Effect of differently expressed feed particle sizes on the feed conversion ratio of fattening pigs and fitted polynomial regression equations (data from Al-Rabadi et al., 2017).

expressed as mean surface diameter, particle size had a significant influence on FCR ($P < 0.05$). Expressions of particle size with arithmetic mean, mean surface diameter and mean volume diameter fit the FCR better than GMD in a 2nd degree polynomial regression model with the $r^2$ values ranging from 0.61 to 0.71. The trend of the fitted lines is different: when particle size was expressed with arithmetic mean, mean surface diameter and mean volume diameter, FCR decreased and then increased with increasing particle size. However, when particle size was expressed with GMD and mean volume-surface diameter, FCR increased to a plateau with increasing particle size. This indicates that different methods of expressing particle size may lead to different conclusions.

These two examples indicate that some of these EPS expressions might be superior in explaining pig performance to GMD, but not in all cases. The variation of different study results should be accounted for in studies relating pig performance to particle size. The variation of results, based on the different plots led to the unsuccessful construction of a mathematical model. It becomes clear that different expressions of particle size differ when related to pig performance, and directly measured EPS data contrary to recalculated data have a preference in further research.

## 5. Prediction of output PSD in milling

Grinding theory is supposed to provide design concepts and equations that can help engineers to improve milling systems, so that the required PSD can be obtained efficiently (Anustin, 1971). A better understanding of breaking behavior of ingredients in different milling systems is quite important in developing grinding theories. Breakage functions are mathematical formulas that describe the breakage of material and can be included in particle size prediction models. As a result, suggestions on milling operations can be given, which may further optimize the grinding process leading to a lower energy consumption and higher yield of particles in the desired size class.

**Table 3**
Forms of breakage functions and prediction models under different grinding conditions.

| Conditions and forms | Property | Formulas | Parameters | References |
|---|---|---|---|---|
| Cumulative form. Assume that particles of every size break in the same way in every process. | Breakage function | $B_{x,y} = \frac{1-e^{-\frac{x}{y}}}{1-e^{-1}}$ | $\frac{x}{y}$ = the reduction ratio. | a,b,c |
| Fitting breakage function. Material characteristics were included, like hardness, moisture level, kernel shape and kernel size. | Breakage function | $B\left(x, \frac{G}{D}\right) = a_0 + b_0x + c_0x^2 + d_0x^3 + (a_1 + b_1x + c_1x^2 + d_1x^3)\left(\frac{D}{G}\right) + (a_2 + b_2 + c_2x^2 + d_2x^3)\left(\frac{D}{G}\right)^2$ | $a_i$, $b_i$, $c_i$ and $d_i$ = fitted coefficients, such as hardness, moisture level, kernel shape and kernel size; $\frac{D}{G}$ = milling ratio; $G$ = roll gap; $D$ = size of wheat kernel; $x$ = particle size. | d |
| Cumulative form. Feed and product PSD change with time. For steady state continuous grinding in retention mills. | Prediction model | $\frac{\partial P(x,t)}{\partial t} = \int_{y=x}^{x_{max}} S(y)B(x, y)\rho_M(y, t)dy$ | y = Input particle size; $x$ = output particle size; $S(y)$ = selection function; $B(x, y)$ = breakage function; $\rho_M(y, t)$ = PSD in the mill at time $t$. | e |
| Cumulative form. Feed and product PSD do not change with time. For steady state continuous grinding in retention mills. | Prediction model | $P(x) = F(x) + \tau\int_{y=x}^{x_{max}} S(y)B(x, y)\rho_M(y)dy$ | $F(x)$= fraction of feed material of size less than x; $\tau$ = the average residence time in the mill; $\rho_M(y)$ = PSD in the mill. | e |
| Cumulative form. For once-through grinder with no retention. | Prediction model | $P(x) = F(x) + \int_{y=x}^{x_{max}} s(y)B(x, y)\rho_1(y)dy$ | $P(x)$ = the amount smaller than $x$ in the feed before grinding; $\rho_1(y)$ = input PSD. | e |
| Matrix form. Discrete time and size interval. | Prediction model | $P = M \times F$<br>Where: $M = BS + I - S$ | $P$ = product vector; $F$ = feed vector; $B$ = breakage matrix; $S$ = selection matrix; $I$ = unit matrix; M = milling matrix. | e |
| Matrix form. Recycle is included by means of classifier. | Prediction model | $P2 = [M \times I - (I - C)]^{-1} \times F \times C$ | P2 = product vector;<br>C = classification matrix. | f |

a, b,c,: Broadbent and Callcott, 1956a, 1956b, 1957; d: Fang and Campbell, 2003a; e: Anustin, 1971; f: Holdich, 2002.

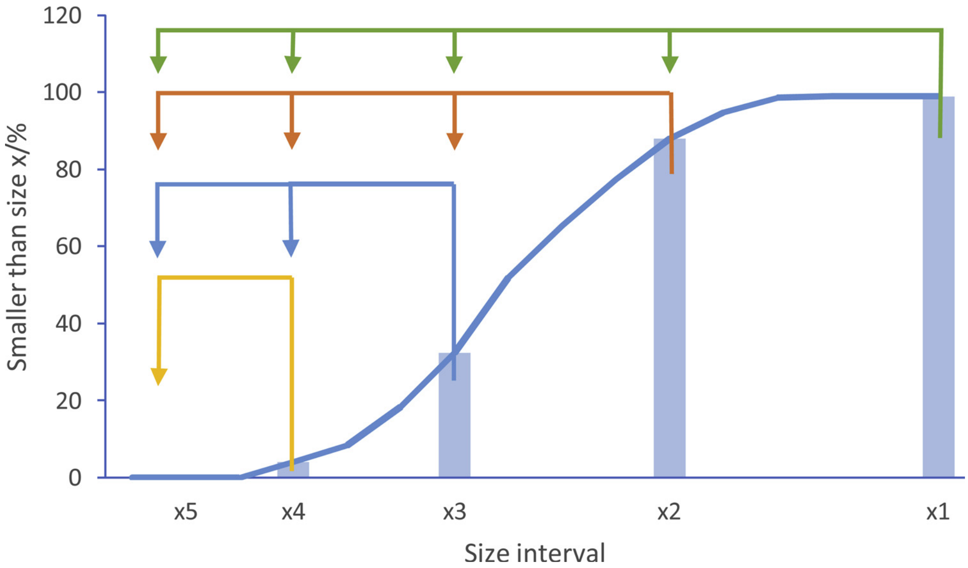


**Fig. 10.** Schematic diagram of illustrating the first-class breakage process.

### *5.1. Principle calculation of breakage functions*

Breakage functions are mathematical functions for describing particles breakage behavior during the comminution process, which can provide information on milling system design and grinding efficiency (Singh et al., 2016). Breakage functions can be defined as B (*y*, *x*), which is the mass fraction of breakage products from size *x* that fall below size *y* after grinding during a certain time ($x \geq y$). There have been many different forms of breakage equations developed at different milling conditions as shown in Table 3. Although different symbolism and mathematical techniques were used, the basic concept is generally the same: during the comminution process, the mass formula may be written as:

'Retained mass in a size interval = [original mass] – [mass broken into down size interval] + [mass created from size interval above]'.

For example, consider a batch of material to be ground, which can be divided into 5 classes, named $x_1$, $x_2$, $x_3$, $x_4$ and $x_5$, then the cumulative PSD of the material can be illustrated as shown in Fig. 10. Each class has input of material coming from the class of larger sized particles and output of material into smaller sized classes during the grinding process (except the largest particle size class without input and final smallest size class without output). After grinding for some time, some material in class $x_1$ is selected and ground into $x_2$, $x_3$, $x_4$ and $x_5$. At the same time, a fraction of particles in class $x_2$ is also broken into class $x_3$, $x_4$ and $x_5$, along with some material is added into class $x_2$. The same logic can be applied to the materials of size $x_{3,}$ $x_4$ and $x_5$.

In grinding, a certain rate of the material is selected and engaged in breakage, which can be described by a (mathematical) selection function. Particles selected for grinding from a certain size class depend on raw material characteristics, grinding time, as well as properties and geometry of the mill. In the batch processing, the material is kept in the mill until everything is ground; for continuous grinding process, the material flows continuously, and therefore, grinding time and properties are related to the selected particles. This means for instance there is a difference between batch processing and continuous grinding. However, it is difficult to determine the selection functions in practical feed manufacturing. Usually in practice the selection function is assumed to be equal to one, and is combined with the breakage functions.

When the ground material can be distributed into *n* grades, and when we take $b_{\text{ij}}$ as mass fraction of material entering into grade *j* from grade *i* ($i > j$), then the mass fraction retained on all grades originating from size $x_i$ can be expressed as:

$$b_{ij} = B_{(x_i,x_j)} - B_{(x_{i+1},x_j)} \tag{11}$$

It should be noticed that:

$$\sum_{i=j}^{n} b_{ij} = 1 \tag{12}$$

If the ground product is taken as *p*, and mill feed (material to be ground) as *f*, then the mass flows entering all the other sized fraction into grade *j* will be:

$$p_i = b_{ij} f_i \tag{13}$$

Then it is possible to present these equations in matrix form (take 5 classes as example):

$$\begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \end{bmatrix} = \begin{bmatrix} b_{11} & 0 & 0 & 0 & 0 \\ b_{21} & b_{22} & 0 & 0 & 0 \\ b_{31} & b_{32} & b_{33} & 0 & 0 \\ b_{41} & b_{42} & b_{43} & b_{44} & 0 \\ b_{51} & b_{52} & b_{53} & b_{45} & b_{55} \end{bmatrix} \times \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \end{bmatrix} \tag{14}$$

The matrix (14) can be expressed in short as:

$$P = B \times F \tag{15}$$

where:

$P$ = product vector;
$B$ = breakage matrix;
$F$ = feed vector.

This matrix is referred to as the basic breakage matrix, which is considered sufficient for milling application (Campbell and Webb, 2001). It was built based on assumption that the selection function equals one, which means all the material is considered involving into comminution process. However, when the selection function is taken into account, the ground product vector may be illustrated with following formula:

'Product = [selected breakage material] + [non selected breakage material]'

Where the ground product vector ($P$) can be written as:

$$P = [B \times S \times F] + [(I - S) \times F] \tag{16}$$

In which:
$S$ = selection matrix;
$I$ = unit matrix.

Selection matrix (Eq. 17) is shown below: it's units depend on the layout of the process and can be expressed in (fractional) rate of degradation per second ($s^{-1}$) or as a function of some machine parameter (e.g. the number of revolutions of a mill).

$$\begin{bmatrix} s_{11} & 0 & 0 & 0 & 0 \\ 0 & s_{22} & 0 & 0 & 0 \\ 0 & 0 & s_{33} & 0 & 0 \\ 0 & 0 & 0 & s_{44} & 0 \\ 0 & 0 & 0 & 0 & s_{55} \end{bmatrix} \tag{17}$$

The basic breakage matrix (Eqs. 14 and 15) is describing a once-through grinding process ('open circuit') without classification, like roller milling or hammer milling in the feed milling operation. While in practice, feed materials are hardly broken into the desired sizes within a single pass which, therefore means a classifier is needed to bring the oversized material back to the mill, and remove undersized material. This process ('closed circuit grinding') is illustrated in Fig. 11 (Holdich, 2002): fresh feed material ($F$) is milled into product $P1$, after classification, the desired sized product $P2$ comes out, while the oversized particles ($P1$-$P2$) are recycled into feeder, and together with the fresh feed material (which is $k$) are ground again, until desired products are obtained.

The classifier matrix is shown below:

$$C = \begin{bmatrix} c_{11} & 0 & 0 & 0 & 0 \\ 0 & c_{22} & 0 & 0 & 0 \\ 0 & 0 & c_{33} & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & c_{55} \end{bmatrix} \tag{18}$$

From Fig. 11 referred to the various flows, we know that the output product $P2$ is:

$$P2 = P1 \times C \tag{19}$$

The milling product $P1$ is:

$$P1 = M \times k \tag{20}$$

And the material to recycled is:

$$P1 - P2 = (I - C) \times P1 \tag{21}$$

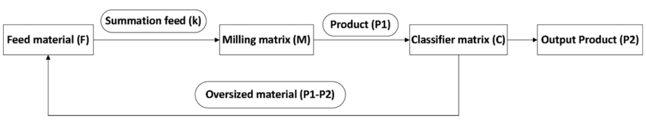


**Fig. 11.** Flow chart of the grinding process including classifier and recycled streams.

Then the mass ($k$) flows into the mill which is the summation of feed material and recycled material:

$$k = F + (I - C) \times P1 = F + (I - C) \times M \times k \tag{22}$$

Therefore, $k$ can be presented as:

$$k = [I - (I - C) \times M]^{-1} \times F \tag{23}$$

Then combine Eqs. (19) – (23), it is possible to provide the recycled product:

$$P2 = [I - (I - C) \times M]^{-1} \times F \times C \tag{24}$$

The above equations can be used for all grinding processes, however, its accuracy will differ between the type of machines, since materials will show a different breaking behaviour in different machines. For example, in the roller mill, particles are ground independently, while in the hammer mill, there are interactions among particles during grinding. Therefore, selection of particles for grinding within the mill as well as the total grinding time must be considered in order to optimize the grinding efficacy of the milling operation. Developing the breakage equations and turning them into breakage matrices greatly improves understanding of certain milling systems and the raw materials that are comminuted by those systems. However, having determined the breakage matrix of a product and machine, this matrix can only be used for these products/machine combination specifically. This makes this method very inflexible. A breakage matrix determined for one set of grinding conditions cannot be instantly used for another set of conditions. Since diet ingredients in animal feeds may differ in their nutrient levels, size, moisture content, hardness etc., this is not desirable. Breakage functions have been widely discussed in the mining and coal industry comminution process. However, in feed manufacturing practices, to the best knowledge of authors, the breakage function was only developed for the combination wheat/roller mill by the research group of Campbell (Campbell and Webb, 2001; Campbell et al., 2001, 2007; 2012; Fang and Campbell, 2003a, 2003b; Mateos-Salvador et al., 2011) and Fistes and Tanovic (2006).

### 5.2. Development of breakage functions in milling wheat

Campbell and Webb (2001) investigated the discretized form of breakage equation in the roller mill with wheat and applied the equations to predict the output PSD that covered different size ranges. The results showed a high agreement between predicted and experimental data. In addition, the research group of Campbell also explored the factors that may influence the breakage pattern of individual particles. They showed that the breakage pattern for wheat depends heavily on chemical, structural and physical characteristics of the grain, such as moisture level (Fang and Campbell, 2003b), endosperm hardness and shape (Campbell et al., 2007) and density (Galindez Najera, 2014). Fistes and Tanovic (2006) found that breakage equation can be used not only to predict output PSD, but also to predict the ash and protein content of wheat over various particle sizes. Furthermore, technical mill parameters affect the breakage pattern, thus the effects of roll gap (Campbell et al., 2001), roll disposition (Fang and Campbell, 2003a), roll velocity, roll surface, and ratio of roll gap to kernel size were investigated (Campbell et al., 2001).

As Campbell and Webb described in their study, a single setting cannot be used all year round to mill a certain product. Therefore, it is needed to develop a breakage function which considers the characteristics of the whole and milled product and the traits of the milling machine. Consequently, some conditions in the breakage equation were considered, which include the concept of normalization, selection and first-order law of breakage (Anustin, 1971; Campbell and Webb, 2001). This led to the involvement of the cumulative breakage function in the breakage equation, ensuring that the different circumstances of input material and machine are covered.

### 5.3. Development of cumulative breakage function in milling wheat

Cumulative breakage functions are currently investigated to be employed in the breakage equations of wheat (Galindez-Najera et al., 2016). Fang and Campbell et al. (2003a) fitted many different characteristics of wheat (e.g. hardness, moisture level, kernel shape and kernel size) into cumulative breakage function (see Table 3). The incorporation of wheat kernel characteristics and milling process parameters in the breakage function made it flexible in predicting output PSD, but this function required inordinate experimental data. This major drawback led to the development of the Normalised Kumaraswamy Breakage Function (NKBF), which is a more practical function (Mateo-Salvador et al., 2011). This method involves less factors to be determined, however, less accurate results were obtained, but such decrease in accuracy was considered to be acceptable (Campbell et al., 2012). Therefore, NKBF is thought to be a quicker method in predicting PSD output (Mateos-Salvador et al., 2011). Further development led to the Double Normalised Kumaraswamy Breakage Function (DNKBF), which describes two types of breaking behavior). Type 1 describes a narrow range of medium sized particles, whilst the type 2 describes more the extremes of the PSD: the larger and smaller particles in the distribution (Campbell et al., 2012). Eventually the DNKBF is used to give the composition of the broken particles into four major wheat components: pericarp, aleurone, endosperm and germ (Galindez-Najera, 2014) and the predictive power for wheat is good (Galindez-Najera et al., 2016). Both types of breakage equations - compositional breakage equations - make it possible to mill anatomical parts of cereals to a desired size, which is helpful in exploring the relations between particle size and nutrient composition of a feed ingredient. A complementary benefit from developing the two breakage equations is that it gives insight in the variation between milling conditions and product.

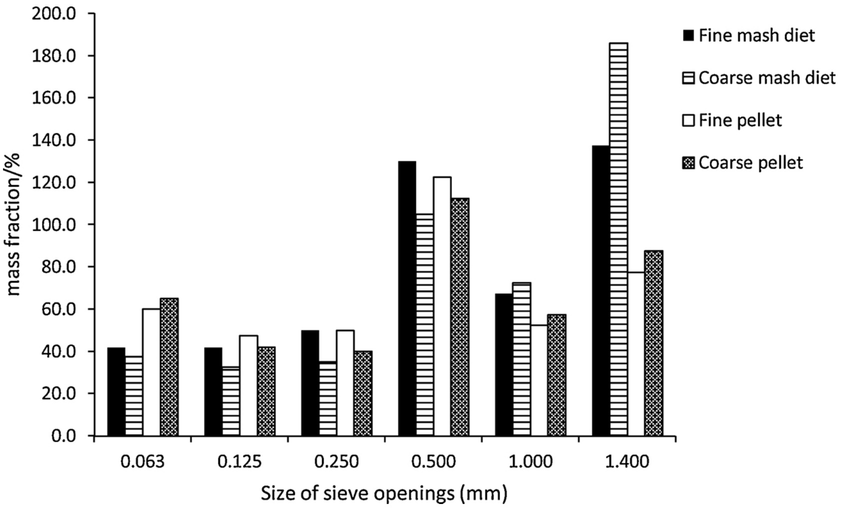


**Fig. 12.** Particle size distribution of mash diet and pellet diet with fine and coarse grinding (Engberg et al., 2002).

### 5.4. Breakage functions for other raw materials and mills

As illustrated above, many researches were done with respect to the breakage of wheat using a roller mill. Jindal and Austin (1976) also investigated breakage functions for hammer mills. This research was executed by using an experimental mill, which differed from a commercial hammer mill, but this kind of experimental trials may help to identify factors that are of influence on the kinetics of hammer milling. Specific development of breakage functions, such as done for wheat with roller milling, should be done for other feed materials in both roller mills, hammers mills or a multicracker system, with many characteristics (e.g. moisture contents, hardness, shape) of different ingredients being considered.

## 6. Particle size reduction in downstream processing

As shown above, reducing particle size of diet ingredients can bring many benefits. In order to further increase the availability and digestibility of nutrients, thermal treatments (pelleting, extrusion or expander treatment) are often involved as feed processing technologies. Therefore, the effects of particle size reduction in the downstream feed manufacturing processes should also be considered.

There are some researches indicating that the pelleting process can even out the PSD of feed diets (Amerah et al., 2007; Abdollahi et al., 2011). In Fig. 12, particle size of fine and coarse diet were determined before and after pelleting (Engberg et al., 2002). It can be observed that in the fine diet, the percentage of small particles (< 0.5 mm) increased, and the fraction of large particles (> 0.5 mm) decreased after pelleting. In the coarse diet, a similar trend was observed. The gap between rolls and die in a pellet press was considered to lead to further comminution of feed particles (Svihus et al., 2004), and the reduction of particle size was stronger when the diet was conditioned at a lower temperature (Abdollahi et al., 2011). This might be because a high temperature brings more moisture from steam which can decrease the frictional force in the die. In addition, the combination of more moisture and a higher temperature moves the amorphic polymeric materials through the glass-transition, turning the physical characteristics of the materials from brittle and hard into rubber and leathery (Roos and Karel, 1991). Dirkzwager et al. (1998) determined the PSD of mash feed and pelleted feed by wet sieving and observed that the fraction of fine particles (< 0.6 mm) increased while the fraction of coarse particles (> 0.6 mm) was reduced. Grosse Liesner et al. (2009) also found that PSD changed after pelleting especially the fraction of particles smaller than 0.4 mm, which increased by 27% and 37% for finely and coarsely ground diet, respectively. This was in line with the research of Vukmirović et al. (2016), who found that the fraction of small particles (< 0.125 mm) was increased significantly after pelleting, while the number of large particles (> 2.5 mm) was decreased.

Particle size reduction during pelleting also gave some reasonable explanation about differences in animal performance. According to the research results of Engberg et al. (2002), the influence of feed form on broilers growth performance was larger than that of grinding the feed, which may have been due to the particle size reduction as a result of pelleting. Nemechek et al. (2016) found that feed efficiency for finishing pig was increased as particle size of corn was decreased in mash diet, while this trend was not observed in feeding pigs a pelleted diet form. The authors concluded that this was because particle size reduction occurred during the pelleting process due to the force and pressure from the pellet mill die.

Extrusion and expander technology can also be involved in the feed processing for pigs starter diets to increase the palatability and nutrient availability. High temperature steam is then added in this process to reach a higher moisture content (20 ~ 30%) and temperature (up to 130°C) of diets which cannot be realized in pelleting (van der Poel et al., 2018). High friction and shear forces, heat and water in the expander contribute to a more rapid gelatinisation of starch from the combination of shear between screw and barrel, which can be considered as a secondary grinding; as a result this leads to particle size reduction. If a pellet form is required, then the grinding intensity can be lower (Vukmirovic et al., 2017). That is also why a pellet mill die usually can be 50% thinner if the material is conditioned in an expander prior to pelleting (Lucht, 2007).

## 7. Conclusions and perspectives

Reducing the energy consumption during grinding, whilst obtaining an optimal PSD for pigs is one of the key objectives in a feed milling operation. Roller mill, a hammer mill and the multicracker all have different advantages and drawbacks and have been reviewed in this article. In addition, new configurations and systems can be used, like multi-stage grinding. However, only limited research data is available for these two technologies, and further research in comparing these configurations and systems in terms of PSD and energy utilization should be carried out.

Dry sieving is the most used method in pig feed research regarding particle size determination. Wet sieving, laser diffraction, microscopy or statistic/dynamic image analysis are further methods for determining particle size to explore additional characteristics of particles like volume, surface area. As a result, better suggestions about the efficacy of milling operations may be provided. However, no research has been done to address such possibilities. For example, the use of EPS along with span of PSD, $D_{v50}$, and Sauter mean may be alternative ways to indicate size characteristics. Yet, it is not clear how these expressions relate to pig performance, neither it is conclusive if the equivalent expressions are a better predictor of technical performance in comparison to the GMD. For further investigation, it is suggested to obtain original data and relate these data to young animals, because more significant effects of particle size on young pig growth performance are expected compared to those of adult livestock. As reported by some papers, surface area can be an interesting parameter to be considered in further research.

Breakage functions are applicable in predicting the output PSD. The development of breakage equations for the first milling of wheat with a roller mill has been done, and many factors of milling operation and material characteristics then can be considered. This type of research can be extended to predict the output PSD using hammer mill to grind ingredients for pig diets. Factors that may affect the milling of feed ingredients such as grinding time, feeder capacity and material characteristics will lead to a better understanding of breaking behavior of specific feed ingredients in the hammer mill. Therefore, a better-defined PSD of feed can be realized with a higher accuracy: the development of breakage functions is necessary to increase the accuracy of prediction and to predict output PSD of different feed materials under several different grinding conditions in different types of mills. Whether the breakage function can be used to predict defined PSD for animal performance is a further issue that can be examined in the future. To ensure a certain PSD in animal feeds, the use of breakage functions shows a promising application.

After grinding and mixing, material is processed by pelleting, expander treatment or extrusion. Particle size reduction also takes place in these downstream processes, which is considered a possible reason for pigs performance differences in this kind of studies. Pelleting can decrease the large particle size fraction, so in order to achieve a defined PSD for pigs, particle size changes as a result of the pelleting process should not be ignored. However, there are few researches being done which show how expander treatment and extrusion affect the PSD of diets. This can be a direction for further research into the particle size distribution in animal feed processing technology.

## Declaration of Competing Interest

The authors declare that none of them have a conflict of interest regarding this manuscript.

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