Acta Scientiarum
http://periodicos.uem.br/ojs
ISSN on-line: 1807-8672
Doi: 10.4025/actascianimsci.v44i1.53382

ANIMAL PRODUCTION

Different sieving methods for determining the physical characteristics in ground corn

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ABSTRACT. We evaluated various sieving methods to estimate particle size (PS) and geometric standard deviation (GSD) of ground corn. The corn had been previously divided in six fractions and each one ground in a hammermill (1-, 2-, 3-, 4-, 5- or 12-mm sieves). The stacked sieving method, with prior drying at 105°C without agitators was the reference. We evaluated eight sieving methods, distributed in a factorial design (2 x 2 x 2 x 6), consisting of the following treatments: i) with and without agitators (two 25-mm rubber spheres), ii) with and without previous drying, iii) with a nest of test sieves set in a stacked or reverse, and iv) employing six ground corn degrees, totaling 48 treatments (four replicates). There was a linear increase in PS estimation for methods without drying and stacking and quadratic increases for the others. Reverse, drying, and agitator methodologies gave better sieving of corn, and consequently gave the lowest PS and highest GSD. The results were more pronounced for high-intensity grinding (hammermill sieve with small apertures) in which the differences between the reference method with the drying and reverse methods were up to 210 μm. Reverse sieving combined with agitators allowed the greatest passage of corn particles through the test sieves and promoted better characterization of ground corn.

Keywords: animal nutrition; corn milling; feed processing; geometric particle size; geometric standard deviation.

Received on April 28, 2020.
Accepted on September 11, 2020.

Introduction

Feed processing methods such as extrusion and pelletizing may improve the nutritional benefits of feeds and previous grinding is necessary for subsequent processing or before feeds are mixed. In the corn industry, the most commonly used mills are roller mills and hammermills (Rojas & Stein, 2017).

Corn grinding reduces particle diameter to sizes compatible with the physiology of the target animal, with increased surface area/mass (Rojas & Stein, 2016). Lyu, Wang, Wu, and Huang (2020b) reported linear digestibility increased of energy and protein for growing piglets with the reduction of corn particle size (PS) from 768 to 441 μm; by contrast, a study of growing and finishing pigs in which PS was reduced 865 to 339 μm showed an increase of parakeratosis (Rojas & Stein., 2016); for weaned pigs, Rojas and Stein (2016) showed that reduction of particle size of corn (965-339 μm) improved the average daily gain and feed efficiency. Consequently, it is necessary to determine the optimal particle size of feed ingredients to maximize energy and nutrient digestibility (Rojas & Stein, 2017).

Particle size distribution is influenced by type of cereal, by the grinding process in the hammer mill and by post-mixing treatment as well (Wolf, Rust, & Kamphues, 2010). Another physical parameter that is important for zootechnical performance of ground corn is geometric standard deviation (SD). Reducing PS and increasing the uniformity of ground corn results in improved digestibility and efficient growth in finishing pigs (Wondra, Hancock, Behnke, Hines, & Stark, 1995a).

To optimize the physical characteristics of ground feeds, grinding parameters and rapid methods for determination of grain size are necessary. Particle size determination techniques, including dry/wet sieving, laser diffraction, microscopy, and static/dynamic image analysis (Lyu, Thomasb, Hendriks, & Van Der Poel, 2020a). The most common methodology to evaluate the particle size was proposed by Henderson and Perry (1955) and ASAE (2008). There are many factors affecting the sieving process, including humidity, size and shape of the particles in relation to the sieve apertures, the amount of material at the sieve surface, the density of the material, as well as electrostatic interactions between the particles of the material and between the particles and the sieve (Liu, 2009) crude fat (Groesbeck et al., 2003). An important aspect that deserves mention is the fact that the traditional method was not adapted to consider these factors; therefore, it can overestimate particle size and underestimate particle size distribution (Stark & Chewning, 2012).

Sieving has been studied for food products (Liu, 2009) and for products that are employed in animal nutrition such as corn, wheat, and sorghum (Stark & Chewning, 2012). Nevertheless, in the specialized literature, there are no studies that evaluate sieving methods for corn based on the method proposed by Henderson and Perry (1955) with corn ground to varying extents.

Therefore, in the present study, we evaluated various screening techniques aiming to improve the accuracy for determination of the physical characteristics of corn using different grinding intensities.

Material and methods

Sieving was carried out at 26.5 ± 1.1°C and relative humidity 52.5 ± 8.9%. The corn contained 89.2% of dry matter, 3.99 Mcal kg^{-1} of gross energy, 10.97% of neutral detergent fiber, 4.37% of acid detergent fiber, 3.37% of crude fat, 8.5% of crude protein according Silva and Queiroz (2002) and 0.81 g cm^{-3} of density and 0.271 g corn $seed^{-1}$. The corn nutrient content values were near described by Rostagno et al. (2017).

The corn grain was previously sieved with 4-mm aperture screen sieves to remove broken corn and foreign material. Subsequently the corn was divided into six fractions and each fraction was ground in a hammermill (M609/Maqtron) at 3,505 rpm using six different hammermill screen sieves (Table 1).

Table 1. Features of the sieves and corn particles after grinding.

	Features of the hammermill sieves (FS)					
Sieves aperture diameter, mm	1	2	3	4	5	12
Area of the sieve apertures, mm^2	0.79	3.14	7.07	12.57	19.63	113.09
Sieve aperture area, %	34.5	28.3	30.7	37.7	44.2	31.1
Solid sieve area, %	65.5	71.7	69.3	62.3	55.8	68.9
	Features of the corn particles after ground*					
Angle of repose, °	21.84	20.72	19.52	18.39	17.16	16.50
Density, kg m^{-3}	644.1	678.1	687.3	709.8	709.9	755.3

*Angle of repose = 23.700 - 1.776FS + $0.105FS^2$ (R^2 = 0.99; $p < 0.05$); Density = 627.800 + 23.302FS-$1.064FS^2$ (R^2 = 0.97; $p < 0.05$).

After grinding, the angle of repose was measured, a total of 400 grams of grounded grains were placed on a cellulose surface by allowing them to fall from a height of 30 cm, according to Syamsu, Yusuf, and Abdullah (2015).

A set of wire-cloth test sieves having frame diameters of 4, 2, 1.2, 0.6, 0.3, or 0.15 mm and pan were used to determine particle size distributions according to Henderson and Perry (1955), with a nest of test sieves set stacked and previously dried at 105°C for 24 hours. We considered this methodology to be the reference treatment (M.1).

In addition to the usual treatments, we adapted a reverse sieving methodology (Liu, 2009), adding two agitators (rubber spheres 25 mm diameter and 11 g) for each test sieve as agitators (Brasil, 1991; Stark & Chewning, 2012) and without previous drying.

We used a factorial design (2 x 2 x 2 x 6), consisting of stacked and reverse sieving, with and without agitators and with and without drying at 105°C with six different grinding intensities (six different apertures of screen sieves set for the hammermill) and four replicates for each measurement, resulting in a total of 192 experimental units.

The time of the sieving process was fixed at 10 minutes for both stacked and reverse sieving. For the reverse methodology, the time expended at each sieve was 6, 24, 50, 125, 170, and 225 seconds for the screen sieves of 4, 2, 1.2, 0.6, 0.3, and 0.15 mm, respectively. The proportion time used for each sieve in the reverse method was proportional that used by Liu (2009).

The particle size and geometric standard deviation of particle diameter was calculated using equations provided in the standard methods (ANSI/ASAE S319.3) (ASAE, 2008).

Data were analyzed based on a factorial design (2 x 2 x 2 x 6) with four replicates. In cases of significant interaction, the Scott and Knott (1974) test was applied, and significant differences were defined as $p < 0.05$.

Subsequently, in cases of significant interaction, a polynomial equation was elaborated for each screening methodology. Linear regression models were tested to select the predictive model to find best fit for the average values. The least squares method was used to calculate the regression coefficients and of each coefficient was tested using the t-test ($p < 0.05$).

Results

The density increased and angle of repose of grinded corn decreased ($p < 0.05$) with increased aperture size of hammermill sieves (Table 1).

There was a significant interaction between methods of sieving and grinding intensity for PS and GSD ($p < 0.05$) with varying flows of ground corn through the sieves depending on grinding intensity and methodology (Tables 2 and 3).

At higher corn grinding intensity (hammermill set with 1-mm sieve aperture), reverse and dry sieving methodologies (M.5 and M.6) gave lower PS and higher SD ($p < 0.05$) than the reference method (M.1.) (Figure 1) and the use of the agitator and previous drying gave lower PS and higher SD ($p < 0.05$) than the reference method (Tables 2 and 3).

Table 2. Particle size (μm) of corn particles obtained under different sieving methods[1].

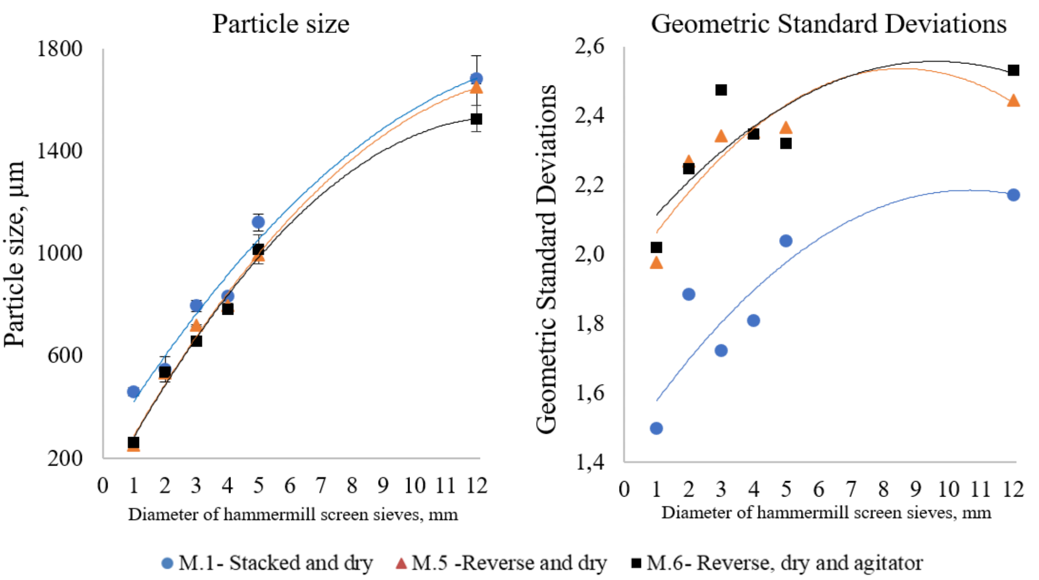
	Sieving Methodologies							
	M.1	M.2	M.3	M.4	M.5	M.6	M.7	M.8
Method	Stacked	Stacked	Stacked	Stacked	Reverse	Reverse	Reverse	Reverse
Drying	Yes	Yes	No	No	Yes	Yes	No	No
Agitators	No	Yes	No	Yes	No	Yes	No	Yes
1 mm	460J	294L	527J	545J	250L	261L	407K	347K
2 mm	548J	559J	670I	689I	535J	537J	594J	588J
3 mm	796H	788H	862G	841G	719H	658I	759H	724H
4 mm	833G	808H	907G	895G	796H	784H	827G	862G
5 mm	1122E	1009F	1166E	1075E	995F	1017F	1084E	1005F
12 mm	1682C	1504D	2015A	1785B	1650C	1527D	1780B	1760B
	Probability							
Linear	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Quadratic	<0.01	<0.01	0.19	0.14	<0.01	<0.01	<0.01	<0.01
CV	6.78	13.18	7.33	7.03	7.52	5.98	7.29	3.62
	Regression coefficients							
A	234.56	117.22	419.12	471.86	72.69	62.57	228.26	189.28
B.X	194.72	225.16	134.53	110.81	223.49	228.80	185.60	190.21
$C.X^2$	-6.15	-9.15	-	-	-7.69	-8.89	-4.68	-4.95
R^2	0.98	0.93	0.98	0.97	0.98	0.99	0.98	0.99

[1]Means followed by different letters differ ($p < 0.05$) by the Scott-Knott test ($p < 0.05$).

Table 3. Geometric standard deviations of ground corn under different sieving methods[1].

	Sieving Methodologies							
	M.1	M.2	M.3	M.4	M.5	M.6	M.7	M.8
Method	Stacked	Stacked	Stacked	Stacked	Reverse	Reverse	Reverse	Reverse
Drying	Yes	Yes	No	No	Yes	Yes	No	No
Agitators	No	Yes	No	Yes	No	Yes	No	Yes
1 mm	1.50F	1.80D	1.51F	1.51F	1.98C	2.02C	1.77E	1.82D
2 mm	1.89D	1.96C	1.54F	1.58F	2.27B	2.25B	2.06C	1.90D
3 mm	1.72E	1.77E	1.65E	1.69E	2.34B	2.48A	2.24B	2.36B
4 mm	1.81D	1.98C	1.72E	1.83D	2.35B	2.35B	2.29B	2.36B
5 mm	2.04C	1.86D	1.89D	1.99C	2.37B	2.32B	2.32B	2.36B
12 mm	2.17B	2.51A	2.01C	2.25B	2.45A	2.53A	2.39B	2.46A
	Probability							
Linear	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Quadratic	<0.01	ns	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CV	6.95	11.42	3.07	2.67	3.36	4.60	3.31	9.81
	Regression coefficients							
A	1.44	1.69	1.34	1.32	1.93	2.01	1.63	1.58
B.X	0.14	0.06	0.13	0.16	0.14	0.11	0.22	0.25
$C.X^2$	-0.01	ns	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
R^2	0.72	0.53	0.93	0.97	0.78	0.65	0.90	0.57

[1]Means followed by different letters differ ($p < 0.05$) by the Scott-Knott test ($p < 0.05$).



$$PS\ (M.1) = 234.56 + 194.72X - 6.15X^2\ (R2 = 0.98)$$
$$PS\ (M.5) = 72.69 + 223.49X - 7.69X^2\ (R2 = 0.98)$$
$$PS\ (M.6) = 62.57 + 228.8X - 8.89X^2\ (R2 = 0.99)$$
$$GSD\ (M.1) = 1.44 + 0.14X - 0.01X^2\ (R2 = 0.72)$$
$$GSD\ (M.5) = 1.93 + 0.14X - 0.01X^2\ (R2 = 0.78)$$
$$GSD\ (M.6) = 2.01 + 0.11X - 0.01X^2\ (R2 = 0.65)$$

Figure 1. Particle size and geometric standard deviations of corn ground by different features of the hammermill screen sieves (FS) analyzed under different sieving methodologies.

In regression analysis, the treatments with stacked set test sieves and no prior dried corn (M.3 and M.4) showed linear increases for PS with increasing hammermill sieve apertures ($p < 0.05$). When the other combinations were used, we observed a quadratic effect for increases in the hammermill sieve aperture. In both cases, the values of PS obtained for the determination coefficient, R2, were close to 1, indicating a good fit.

In intermediate grinding (3-, 4-, and 5-mm hammermill aperture sieves), the most common intensity of corn milling for poultry and pig feed, the methods using reverse screening and agitators gave lower PS and higher SD ($p < 0.05$) than the reference method.

At low milling intensity (12-mm hammermill sieve apertures), similar to those observed at the high intensity, reverse sieving gave lower PS, and the agitators gave lower PS when combined with previous drying.

GSD showed linear increases in M.2 with increased aperture of hammermill sieve ($p < 0.05$). Other treatments showed quadratic effects with increased hammermill sieve aperture ($p < 0.05$).

Discussion

Similar results for increased density and decreased angle of repose in ground corn were reported by Rojas, Liu, and Stein (2016). Density and angle of repose are associated with physical properties such as porosity (Rosentrater, 2012) of particle size and characteristics of grinding processes such as wear on the hammer in the hammermill (Chiodelli, Folador, Boiago, Carvalho, & Paiano, 2018). The angle of repose as associated with the crude fat of corn (Groesbeck et al., 2003); however, we used the same batch of corn for all grinding, and crude fat content should be better studied in the future.

Some variables may explain the quadratic relationship observed for some treatments. The increase of the sieve aperture area of the hammermill screen sieve to dimensions close to those of the corn grains leads to a reduction of the friction between particles before leaving the mill chamber, reducing the hammermill sieve blinding. It is notable that the sieve aperture area of the hammermill screen sieve did not increase linearly with the diameter of the apertures (Table 1).

The intensification of the degree of grinding increases the surface area/mass and makes the particles more susceptible to interaction with electrical charges. These interactions lead to a blinding of the particles in the test sieves with small apertures. Blinding corn particles in the test sieves leads to overestimated values of PS and underestimated SD values, especially when corn is milled at higher intensities. Considering the best passage of ground corn in the finer test sieves and the lower PS and higher GSD, the proposed methodology change (reverse and agitator) were positive with better corn physical characterization.

We also observed that a sieve process without previous drying resulted in higher values of PS in both stacked and reverse sieving, suggesting that humidity decreases the efficiency of the process and highlights the need for pre-drying. However, pre-drying requires 24 hours, making it a time-consuming method for the feed industry. This can compromise the calibration of the hammermills in real time. However, our data allowed the quantification of the differences between methods without drying and the prior drying methods, thereby facilitating the use of methods without prior drying as complementary analysis tools to methods with prior drying for feed industries.

Taken together, the results show that the standard method overestimates PS and underestimates SD, especially with higher intensity of grinding. By contrast, the reverse sieve and agitators improves PS estimation and these combinations allow better characterization of the grinding process.

In a study with wheat flour, the reverse sieve method improved sieve efficiency over the stacked set test sieve method; the better sieve result was attributed to the beneficial effect of oversized particles on reducing sieve blinding by near- or sub-sieve-sized particles (Liu, 2009). Sieving with rubber spheres as agitators improved the efficiency of the process (Stark & Chewning, 2012), behavior associated with the mechanical effect of the agitators, forcing the particulate material against the holes in the test screen sieves and thereby reducing blinding effect.

Regarding GSD, we observed a linear increase with increased hammermill sieve for M.2 (stacked, dried and agitators) and quadratic increases ($p < 0.05$) for all the other treatments, suggesting that the largest heterogeneity of grinded corn occurred with low-intensity grinding the similar results were obtained by Nemechek et al. (2016) and Gebhardt et al. (2018) with higher GSD with reduced milling intensity.

The reverse sieving method combined with drying and the use of the rubber spheres provided more efficiency to the sieving process of the physical characterization of milling corn. This behavior can be attributed to the reduction of the sieve blinding effect, which entails the blocking of the apertures by particles. However, reverse sieving increases the operational work and requires more attention in conducting each particle size test.

Similar results were obtained with the use of agitators (Kalivoda, Jones, & Stark, 2015) for physical characteristics of different cereal obtained by screening with better passage of tiny particle and biggest mass of milling corn in the test sieves with small apertures and pan associated with the best flow of particles through the test sieves.

Various authors correlated the zootechnical performance with the ideal PS for corn: 400 – 600 μm in second-parity sows (Wondra, Hancock, Kennedy, Behnke, & Wondra 1995b); 500 μm for nursery pigs (Wondra, Hancock, Behnke, & Stark, 1995c); 400 μm for improvement sow and litter performance (Healy et al., 1994); 650 μm for growth performance in finishing pigs (Nemechek et al., 2016); and 460 μm for broilers at 21 days of age (Benedetti et al., 2011). These findings demonstrate the substantial influence of the PS on the performance with various requirements of PS between phases and species.

The traditional method indicates overestimated results of PS, especially when milling was carried out when the hammermill was set with grinding sieves with hole diameters less than 3 mm, suggesting inaccurate corn particle size recommendations for species/categories may occur. Excessive milling in addition to increasing the time and cost of electricity for grinding (Wondra et al., 1995a and Chiodelli et al., 2018) reduces the fluidity of corn and feed. Consequently, less fluidity of the feed mash impairs fluidity in the feed transport or feeder in automated systems. Furthermore, smaller PS can negatively affect the health of gastro-intestinal tract of pigs, leading to higher incidence of stomach ulceration and other negative alterations of gastric mucosa as keratinization and erosions (Vukmirovic et al., 2017).

We did not explicitly consider variables such as the speed and power of the electric motor of the hammermill, crude fat corn content, corn cultivar and open area of hammermill sieves; these factors should be considered in the future studies to generalize our results. On the other hand, it is necessary to verify the correlation between sieving methodology and animal performance to confirm the best characterization of reverse sieving and agitator use in PS and GSD characterization.

Conclusion

Reverse sieving combined with sieve agitators allowed greater passage of corn particles through test sieves and allowed better characterization of particle size of ground corn.

References

American Society of Agricultural and Biological Engineers [ASAE]. (2008). *Method of determining and expressing fineness of feed materials by sieving* (Standard S319.4). St. Joseph, MI: ASAE.

Brasil. (1991). Portaria nº 108, de 04 de setembro de 1991. Aprova os Métodos Analíticos para Controle de Alimentos para uso Animal. *Diário Oficial da União*, 17/09/1991, Seção 1, p. 19813.

Benedetti, M. P., Sartori, J. R., Carvalho, F. B., Pereira, L. A., Fascina, V. B., Stradiotti, A. C., ... Ferreira, J. G. (2011). Corn texture and particle size in broiler diets. *Brazilian Journal of Poultry Science*, *13*(4), 227-234. DOI: https://doi.org/10.1590/S1516-635X2011000400002

Chiodelli, D., Folador, D., Boiago, M. M., Carvalho, P. L. O., & Paiano, D. (2018). Worn hammers affect negatively grinding aspects and physical characteristics of the processed corn by hammer mill. *Boletim de Indústria Animal*, *75*, 1-9. DOI: https://doi.org/10.17523/bia.2018.v75.e1423

Gebhardt, J. T., Paulk, C. B., Tokach, M. D., Derouchey, J. M., Goodband, R. D., Woodworth, J. C., ... Dritz, S. S. (2018). Effect of roller mill configuration on growth performance of nursery and finishing pigs and milling characteristics. *Journal of Animal Science, 96*(6), 2278-2292. DOI: https://doi.org/10.1093/jas/sky147

Groesbeck, C. N., Lawrence, K. R., Hastad, C. W., Goodband, R. D., Tokach, M. D., Nelssen, J. L., & Dritz, S. S. (2003). Particle size, mill type, and added fat influence flow ability of ground corn. *Kansas Agricultural Experiment Station Research Reports*, *0*(10), 203-208. DOI: https://doi.org/10.4148 / 2378-5977.6842

Healy, B. J., Hancock, J. D., Kennedy, G. A., Bramel-Cox, P. J., Behnke, K. C. & Hines, R. H. (1994). Optimum particle size of corn and hard and soft sorghum for nursery pigs. *Journal of Animal Science*, *72*(9), 2227-2236. DOI: https://doi.org/10.2527/1994.7292227x

Henderson, S. M., & Perry, R. L. (1955). *Agricultural Process Engineering.* New York, US: John Wiley and Sons.

Kalivoda, J. R., Jones, C. K., & Stark, C. R. (2015). Effects of varying methodologies on grain particle size analysis. *Kansas Agricultural Experiment Station Research Reports*, *1*(7), 1-6. DOI: https://doi.org/10.4148/2378-5977.1125

Liu, K. (2009). Some factors affecting sieving performance and efficiency. *Powder Technology, 193*(2), 208-213. DOI: https://doi.org/ 10.1016/j.powtec.2009.03.027

Lyu, F., Thomasb, M., Hendriks, W. H., & Van Der Poel, A. F. B. (2020a). Size reduction in feed technology and methods for determining, expressing and predicting particle size: A review. *Animal Feed Science and Technology*, *261*, 1-20. DOI: https://doi.org/10.1016/j.anifeedsci.2019.114347

Lyu, Z., Wang, L., Wu, Y., & Huang, C. (2020b). Effects of particle size and lipid form of corn on energy and nutrient digestibility in diets for growing pigs. *Asian-Australasian Journal of Animal Sciences, 33*(2), 286-293. DOI: https://doi.org/10.5713/ajas.19.0196

Nemechek, J. E., Tokach, M. D., Dritz, S. S., Goodband, R. D., Derouchey, J. M., & Woodworth, J. C. (2016). Effects of diet form and corn particle size on growth performance and carcass characteristics of finishing pigs. *Animal Feed Science and Technology, 214*, 136-141. DOI: https://doi.org/10.1016/j.anifeedsci.2016.02.002

Rojas, o. J., & Stein, H. H. (2016). Use of feed technology to improve the nutritional value of feed ingredients. *Animal Production Science, 56*(8), 1312-1316. DOI: https://doi.org/10.1071/AN15354

Rojas, O. J. & Stein, H. H. (2017). Processing of ingredients and diets and effects on nutritional value for pigs. *Journal of Animal Science and Biotechnology,8*(48), 1-13. DOI: https://doi.org/10.1186/s40104-017-0177-1

Rojas, O.J., Liu, Y., & Stein, H. H. (2016). Effects of particle size of yellow dent corn on physical characteristics of diets and growth performance and carcass characteristics of growing–finishing pigs. *Journal of Animal Science, 94*(2), 619-628. DOI: https://doi.org/10.2527/jas.2015-9054

Rosentrater, K. A. (2012). Physical properties of DDGS. In K. Liu, & K. A. Rosentrater (Orgs.), *Distiller grains: Production, properties, and utilization* (p. 121-142). Boca Raton, FL: CRC Press.

Rostagno, H. S., Albino, L. F. T., Hannas, M. I., Donzele, J. L., Sakomura, N. K., Perazzo, F. G., ... Brito, C. O. (2017). *Tabelas Brasileiras para aves e suínos: composição de alimentos e exigências nutricionais* (4a. Ed.). Viçosa, MG: DZO/UFV.

Scott, A. J., & Knott, M. (1974). A cluster analysis method for grouping means in the analysis of variance. *Biometrics*, *30*(3), 507-512. DOI: https://doi.org/10.2307/2529204

Silva, D. D., & Queiroz, A. (2002). *Análise de alimentos: métodos químicos e biológicos*. Viçosa, MG: UFV.

Stark, C. R., & Chewning, C. G. (2012). The effect of sieve agitators and dispersing agent on the method of determining and expressing fineness of feed materials by sieving. *Animal Production Science*, *52*(1), 69-72. DOI: https://doi.org/10.1071/AN11124

Syamsu, J. A., Yusuf, M., & Abdullah, A. (2015). Evaluation of physical properties of feedstuffs in supporting the development of feed mill at farmers group scale. *Journal of Advanced Agricultural Technologies*, *2*(2), 147-150. DOI: https://doi.org/10.12720/joaat.2.2.147-150

Vukmirović, D., Colović, R., Rakita, S., Brleka, T., Đuragića, O., & Solà-Orio, D. (2017). Importance of feed structure (particle size) and feed form (mash vs. pellets) in pig nutrition – A review. *Animal Feed Science and Technology*, *233*, 133-144. DOI: https://doi.org/10.1016/j.anifeedsci.2017.06.016

Wolf, P., Rust, P., & Kamphues. J. (2010). How to assess particle size distribution in diets for pigs? *Livestock Science*, *133*(1-3), 78-80. DOI: https://doi.org/10.1016/j.livsci.2010.06.030

Wondra, K. J., Hancock, J. D., Behnke, K. C., Hines, R. H., & Stark, C. R. (1995a). Effects of particle size and pelleting on growth performance, nutrient digestibility, and stomach morphology in finishing pigs. *Journal of Animal Science*, *73*(3), 757-763. DOI: https://doi.org/10.2527/1995.733757x

Wondra, K. J., Hancock, J. D., Kennedy, G. A., Behnke, K. C., & Wondra, K. R. (1995b). Effects of reducing particle size of corn in lactation diets on energy and nitrogen metabolism in second-parity sows. *Journal of Animal Science*, *73*(2), 427-432. DOI: https://doi.org/10.2527/1995.732427x

Wondra, K. J., Hancock, J. D., Behnke, K. C., & Stark, C. R. (1995c). Effects of mill type and particle size uniformity on growth performance, nutrient digestibility, and stomach morphology in finishing pigs. *Journal of Animal Science*, *73*(9), 2564-2573. DOI: https://doi.org/10.2527/1995.7392564x