Ciência Rural, Santa Maria, v.52:10, e20210518, 2022 http://doi.org/10.1590/0103-8478cr20210518

ISSNe 1678-4596
ANIMAL PRODUCTION

Soybean meal particle size for pigs during the nursery phase

Leopoldo Malcorra de Almeida[1*] **Geovani Costa Senger**[1] **Kariny Fonseca da Silva**[1] **Filipe Augusto Moreno**[1] **Isabella de Camargo Dias**[1] **Antônio João Scandolera**[1] **Alex Maiorka**[1]

[1]Setor Ciências Agrárias, Universidade de Federal do Paraná (UFPR), 80050-035, Curitiba, PR, Brasil. E-mail: almeidamleopoldo@gmail.com.
[*]Corresponding author.

ABSTRACT: *This study evaluated the effect of soybean meal (SBM) particle size on nutrient digestibility and the growth performance of nursery piglets. Sixty-three piglets (BW = 6.86 kg ± 0.56; 23 d of age) were distributed in a randomized block design (by initial weight and sex) with 3 dietary treatments: diets with 1,017 µm (unground); 585 µm; and 411µm SBM, with 7 replicates of 3 piglets each. All diets were offered ad libitum in mash form, formulated differently according to three growing phases: (1) with 20% of SBM, from 23 to 32 d of age; (2) with 25% of SBM, from 32 to 44 d of age, and (3) with 30% of SBM, from 44 to 63 d of age. For the first 21 d, pigs fed diets with a medium particle size of SBM (585µm) had better average weight gain and feed/gain ratio (P<0.05). The average feed intake, average body weight gain, and feed/gain ratio from 44 to 63 d improved (P<0.05) with increasing SBM particle sizes, and the average live weight for the overall period increased with coarser SBM (P<0.05). There was a marginally improvement (P < 0.1) on digestible energy as particle size of SBM decreased; although, no differences (P > 0.05) in the coefficients of apparent digestibility of dry matter and crude protein for the assessed SBM particle sizes were observed. It was concluded that the grinding of dietary SBM is not required for piglets during the nursery phase.*
Key words: *particle size, growth performance, digestibility, Glycine max, piglets.*

Tamanho da partícula do farelo de soja em suínos no período de creche

RESUMO: *O objetivo deste estudo foi avaliar o efeito do tamanho da partícula do farelo de soja (FS) sobre o desempenho e digestibilidade de leitões no período de creche. 63 leitões (6,86 kg ± 0,56; 23 dias de idade) foram distribuídos aleatoriamente em um delineamento de blocos casualizados (peso inicial e sexo) entre os tratamentos. As dietas experimentais foram produzidas a partir de diferentes tamanhos médios de partículas do FS moídos ou não: 1,017 µm (sem moer), 585 µm (moído em peneira de 10 mm), e 411µm (moído em peneira de 3 mm), totalizando três tratamentos com sete repetições de três animais cada. Todas as dietas foram fornecidas na forma farelada e ad libitum, sendo divididas em três fases: 1) com 20% de FS, dos 23 a 32 dias de idade; 2) com 25% de FS, dos 32 a 44 dias de idade; e 3) com 30% de FS, dos 44 a 62 dias de idade. Nos primeiros 21 dias de experimento, os animais consumindo a dieta com o tamanho médio (585 µm) das partículas do FS apresentaram melhores resultados para o ganho de peso médio e conversão alimentar. No período seguinte (44 a 63 d), houve (P<0.05) aumento do consumo de ração médio, do ganho do peso médio e melhor conversão alimentar dos leitões conforme o aumento do tamanho da partícula de FS incluída na ração. Consequentemente, ao final do experimento houve melhora linear do peso vivo médio dos animais com o aumento do tamanho do FS consumido. Foi observado melhora marginalmente significativa (P < 0.1) da energia digestível conforme a redução no tamanho do FS, entretanto, não houve diferença (P > 0.05) no coeficiente de digestibilidade aparente da matéria seca e da proteína bruta dos animais entre os diferentes tamanhos do FS. Em conclusão, de acordo com as condições deste estudo, não se faz necessária a moagem do farelo de soja para leitões no período de creche.*
Palavras-chave: *tamanho de partícula, desempenho, digestibilidade, Glycine max, leitões.*

INTRODUCTION

Soybean meal (*Glycine max*; SBM) is the most widely utilized source of protein in pig diets because of its high-quality protein and relatively high concentrations of highly digestible limiting amino acids (lysine, threonine and tryptophan), compared to other plant ingredients; SBM also has high energy and low fiber contents. However, to be obtained and safely used in animal feeding and nutrition, the soybeans must undergo several processes, such as the use of solvents, different thermal treatments (e.g., toasting and extrusion), or recently developed enzymatic and fermentative treatments, in order to reduce the concentrations of oligosaccharides, trypsin inhibitors, and other antinutritional factors and mitigate their effects (STEIN et al., 2013).

Reducing the particle size (grinding) of the ingredients modifies their structure (ROJAS & STEIN, 2017), and is a commonly used option to

Received 07.06.21 Approved 11.08.21 Returned by the author 01.29.22
CR-2021-0518.R3
Editors: Rudi Weiblen Charles Kiefer

maximize the availability of dietary nutrients, which is associated with an increase in digestibility of some dietary fractions and improves the feed efficiency in pigs (LANCHEROS et al., 2020). Feeding costs can be reduced; in addition, grinding facilitates further processing of the diets, such as the capacity/uniformity of mixing, transportation, pelleting, extrusion, and expansion (LUNDBLAD et al., 2011). Moreover, the use of diets with coarser particles (e.g., 23.8% of particles > 1000 µm or medium size > 700 µm) has been associated with improved intestinal health and broader microbial diversity in the gastrointestinal tract of pigs, providing an additional barrier against potentially harmful anaerobic bacteria (KIARIE & MILLS, 2019).

The piglets' growth performance and nutrient digestibility during the nursery phase can be influenced by both the choice of ingredients used to reduce dietary particle size and the age of the animals (HEALY et al., 1994; ALBAR et al., 2000; LAWRENCE et al., 2003; ALMEIDA et al., 2021). Therefore, selecting the ideal particle size will depend not only on the animal's response, but also on the productive capacity of feed mills, as altering the particle size of ingredients and diets will affect the production rate (BAO et al., 2016).

Information on how SBM particle size affects piglets in the nursery phase is limited, despite SBM forming a large part of their diets. Based on these considerations, the objective of this study was to assess the effect of unground SBM or ground SBM with different particle sizes on nutrient digestibility and the growth performance of nursery piglets.

MATERIALS AND METHODS

This study included 42 barrows and 21 females piglets of commercial lineage (PIC®, Hendersonville, TN, USA), with a mean initial weight of 6.86 kg ± 0.56 and 23 d of age. They were housed in 2.8 m^2 pens with partially slatted flooring (approximately 65%) and supplied with a trough feeder, an automatic nipple drinker, and a brooder. Each pen contained three pigs of the same sex, resulting in five pens with males and two pens with females per treatment. Room temperature was initially set to 32 °C at weaning and was reduced weekly to meet the comfort level of the piglets.

The experimental diets were formulated to meet the requirements of nursery pigs, which were divided into three growing phases: pre-initial 1, from 23 to 32 d of age; pre-initial 2, from 32 to 44 d of age; and initial, from 44 to 63 d of age (Table 1). Diets were offered in mash form and contained soybean meal (SBM) with different particle sizes. A single lot of solvent-extracted SBM was ground using a hammer mill (TN-8, Nogueira S/A Máquinas Agrícolas, Itapira, SP, Brazil) driven by a 30 HP electric motor with a rotation speed of 3,500 rpm to achieve three different particle sizes: 1,017 µm (unground), 585 µm (10 mm screen), or 411 µm (3 mm screen) with a geometric standard deviation (GSD) of 1.86, 1.85, and 1.87, respectively. Feed and water were offered ad libitum. The corresponding whole-diet distributions and mean particle sizes for each growth phase are presented in figure 1 and table 2, respectively.

The particle size distribution of SBM and of each complete diet was determined using a dry sieving method described by ZANOTTO & BELLAVER (1996). Initially, a 200 g sample of SBM or feed was dried in a forced-air ventilation oven at 105 ºC for 24 h, equilibrated to room temperature, and weighed. Afterwards, the samples were passed through a sieve stack (Bertel Ind. Metalúrgica Ltda., Caieiras, SP, Brazil) with a set of six sieves (4.0, 2.0, 1.2, 0.6, 0.3, 0.15, and 0.0 mm) and shaken for 10 min. The amount of sample retained on each sieve was weighed, and the geometric mean diameter (GMD) and GSD were calculated for each sample.

The piglets were weighed individually at 23, 32, 44, and 63 days of age to evaluate their average body weight (BW) and average daily weight gain (DWG). Both the feed supplied and the leftovers were weighed to determine the average daily feed intake (DFI) and feed/gain ratio (F/G). Daily partial feces collection was conducted from 49 to 53 d of age, and the material was frozen until used. The fecal samples were thawed, homogenized, and dried in a forced-ventilation oven at 55 ºC until a constant weight was achieved. After drying, feces and feed samples were ground to 1 mm and analyzed for dry matter (DM) and crude protein (CP, method 954.01) according to the AOAC (1995). Gross energy (GE) levels were determined using a calorimetric bomb (IkaWerke C2000 Control Oxygen Bomb Calorimeter; Ika-Werke GmbH & Co, Staufen, Germany). Acid insoluble ash (AIA) was added to the initial diets and used as an insoluble marker compound to calculate the digestibility coefficients, and AIA content in feed and feces samples was determined using the adapted gravimetric method proposed by VAN KEULEN & YOUNG (1977).

The apparent digestibility coefficient (ADC) of nutrients was calculated using the following formula:

Table 1 - Ingredients and calculated nutrient content of the diet (as-fed basis, g/kg).

Ingredients	Phase 1	Phase 2	Phase 3
Corn	385.00	490.00	634.00
Soybean meal	200.00	250.00	300.00
Soybean oil	15.00	10.00	15.00
Basic mixture	400.00[1]	250.00[2]	50.00[3]
Celite[4]	-	-	1.0
---Calculated Composition---			
Metabolizable energy, Mcal/kg	3.48	3.44	3.26
Lactose	100.00	21.50	-
Crude protein	200.6	195.34	188.8
Ether extract	37.01	33.66	42.55
Crude Fiber	23.11	29.16	34.76
Lysine	15.39	14.66	12.51
Methionine	5.69	5.63	3.45
Methionine + cysteine	9.54	8.69	6.63
Total calcium	6.99	7.45	8.69
Total phosphorus	6.73	5.22	4.66
Sodium	3.09	2.28	2.24

[1]Main ingredients: pregelatinized maize, dried whey, whole milk powder, soy protein concentrate, sugar, calcium formate, dicalcium phosphate, vanilla flavor, aspartame, dried blood plasma, spray-dried porcine blood, sodium chloride, lysine, methionine, tryptophan, and threonine. Provided per kilogram of diet: Fe, 57.3 mg; Cu, 8 mg; Mn, 25.48 mg; Zn, 475 mg; I, 0.496 mg; Se, 0.248 mg; vitamin A, 9,900 IU; vitamin D3, 1,980 IU; vitamin E, 49.88 IU; vitamin K3, 2.56 mg; vitamin B1, 1.96 mg; vitamin B2, 5 mg; vitamin B6, 3.96 mg; vitamin B12, 30 mcg; niacin, 40 mg; pantothenic acid, 19.6 mg; folic acid, 1.48 mg; biotin, 0.1 mg.

[2]Main ingredients: soy protein concentrate, dried whey, pregelatinized maize, palm oil, dicalcium phosphate, calcitic limestone, vanilla flavor, aspartame, sugar, sodium chloride, lysine, methionine, tryptophan, and threonine. Provided per kilogram of diet: Fe, 68.5 mg; Cu, 8.12 mg; Mn, 28.27 mg; Zn, 1800 mg; I, 0.3 mg; Se, 0.25 mg; vitamin A, 9,900 IU; vitamin D3, 1,980 IU; vitamin E, 49.87 IU; vitamin K3, 2.55 mg; vitamin B1, 1.96 mg; vitamin B2, 5 mg; vitamin B6, 3.97 mg; vitamin B12, 30 mcg; niacin, 40.22 mg; pantothenic acid, 19.6 mg; folic acid, 1.5 mg; biotin, 0.1 mg.

[3]Main ingredients: sodium chloride, sugar, dicalcium phosphate, calcitic limestone, vanilla flavor, aspartame, lysine, and methionine. Provided per kilogram of diet: Fe, 40.5 mg; Cu, 170 mg; Mn, 25.5 mg; Zn, 100 mg; I, 0.5 mg; Se, 0.25 mg; vitamin A, 6,000 IU; vitamin D3, 1,100 IU; vitamin E, 30 IU; vitamin K3, 1 mg; vitamin B1, 0.75 mg; vitamin B2, 4 mg; vitamin B6, 2 mg; vitamin B12, 30 mcg; niacin, 18 mg; pantothenic acid, 11 mg; folic acid, 1 mg; biotin, 0.15 mg.

[4]Insoluble marker (Celite Hyflo; Imerys, Arica, Chile).

ADC = [dietary nutrient – (feces nutrient × IF)]/ dietary nutrient

where IF is the indigestibility factor, calculated as the ratio between AIA levels of diet and feces. The digestible energy (DE) was calculated using the following formula:

DE = GE of diet − (GE of fecal content × IF).

The data were analyzed as a randomized block design; the block (initial weight and gender) was considered a random effect and the pen was an experimental unit, with three treatments (SBM particle size) and seven replicates (five male and two female) of three pigs each. Orthogonal contrasts adjusted for unequal spacing between treatments (SBM particle size) were constructed to evaluate the linear and quadratic effects of reducing SBM particle size on performance and digestibility variables. All results were considered significant at $P \leq 0.05$ and marginally significant at $0.05 \leq P \leq 0.1$. All statistical procedures were performed using the Linear Mixed-Effects Models package (BATES et al., 2015) in R (R CORE TEAM, 2018).

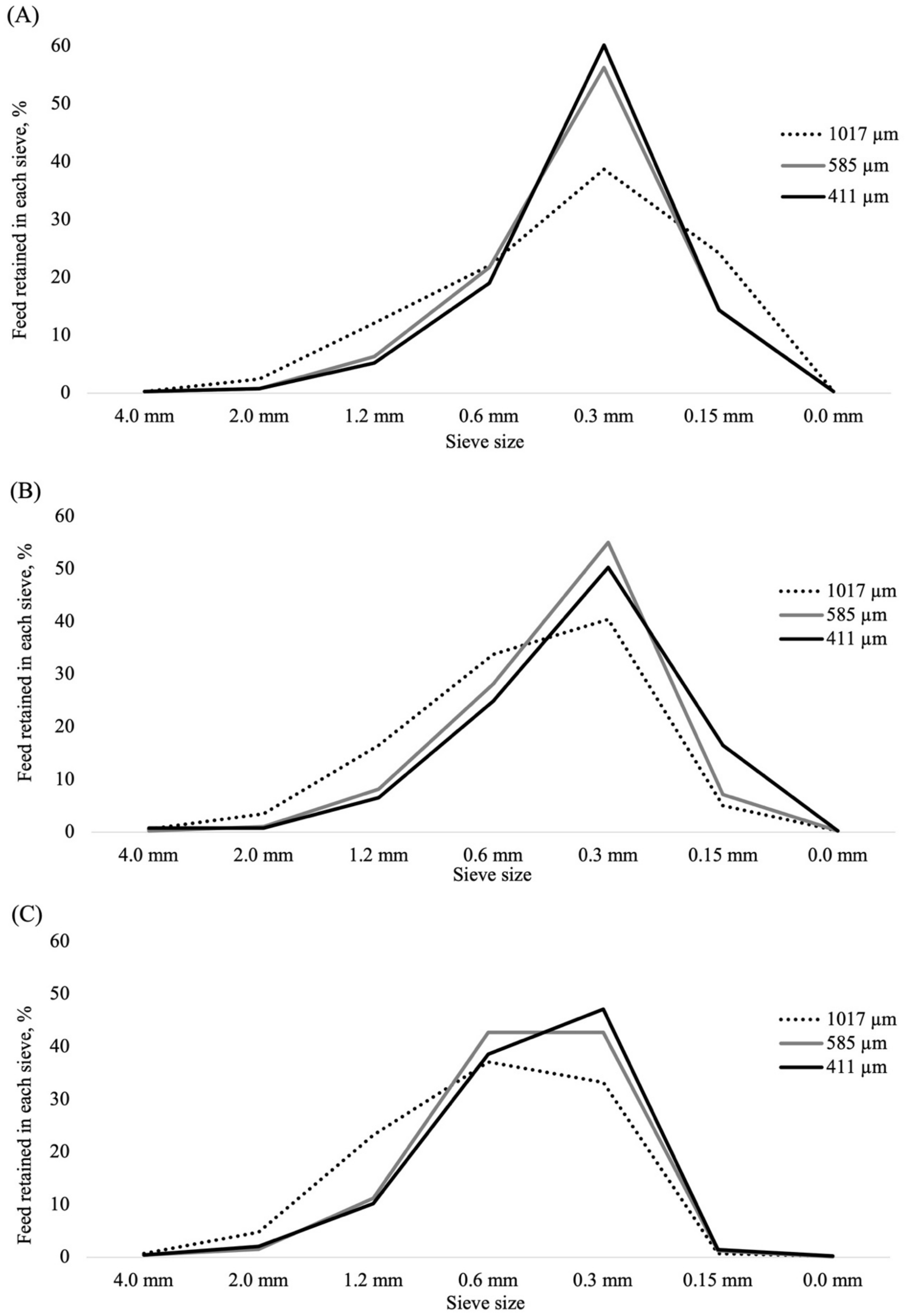

Figure 1 - Particle size distribution of the complete diet, expressed as a percentage of the total sample, according to the soybean meal particle size in growth phases 1 (A), 2 (B) and 3 (C).

Table 2 - Geometric mean diameter (GMD), and geometric standard deviation (GSD) of the complete diet according to SBM particle size in each growth phase.

	---------Phase 1 (20% SBM)-------			----------Phase 2 (25% SBM)--------			------Phase 3 (30% SBM)------		
	1,017	585	411	1,017	585	411	1,017	585	411
GMD, µm	543	522	506	730	591	535	864	717	694
GSD, %	2.02	1.74	1.70	1.86	1.71	1.83	1.82	1.67	1.69

RESULTS AND DISCUSSION

During phase 1 (23 to 32 d of age), reducing SBM particle size from 1,017 to 411 µm did not affect ($P > 0.05$) DFI or BW (Table 3). However, as the SBM particle size increased it marginally increased DWG (linear, $P < 0.1$) and improved F/G (linear, $P < 0.05$). During the post-weaning period, piglets undergo radical social, environmental, and nutritional changes, usually leading to low voluntary feed intake and, consequently, morphological, enzymatic, and inflammatory alterations. It is possible to observe atrophy of the intestinal villi, followed by other issues such as hyperplasia of the crypts, increases in the permeability of the mucous membrane, difficulty with pH balance, and reduced enzymatic activity of pepsin, trypsin, carboxypeptidases A and B, chymotrypsin, amylase, and lipase (HEDEMANN & JENSEN, 2004; MONTAGNE et al., 2007; BARSZCZ & SKOMIAŁ, 2011; MODINA et al., 2019). Even though the difference in average particle size of the complete diet of phase 1 was small only 37 µm - it influenced the piglet's consumption and; consequently, their digestive and absorption capacity could have been depressed.

In the next phase (32 to 44 d of age), a quadratic response was observed ($P < 0.05$) for DFI, DWG, and F/G as the best results were obtained with piglets fed diets with the medium (585 µm) SBM particle size (Table 3). In a similar age period, LAWRENCE et al. (2003) did not detect any difference in performance variables between pigs fed diets containing 444 to 1,226 µm SBM. According to the authors, SBM had little effect on the average diet particle size (maximum difference of 103 µm between diets) due to its low dietary inclusion. In the present study, the distinct SBM particle sizes led to a difference of 195 µm between phase 2 diets, and both the coarser and finer SBM negatively affected performance. Other studies assessed different ingredients to change dietary particle size for pigs: HEALY et al. (1994) reported a linear reduction on DFI and DWG when corn and sorghum particle sizes were reduced from 900 to 300 µm; MAVROMICHALIS et al. (2000) observed lower DFI when wheat particle size was reduced from 1300 to 400 µm; ALMEIDA et al. (2021) reported a quadratic response on F/G when the particle size of the whole diet was varied between 394 to 695 µm, as the best results were obtained with 534 µm. According to the current study, when looking at the overall pre-initial period (Phase 1 + 2; 23 to 44 d of age), the best results for DWG and F/G (quadratic, $P < 0.05$), and BW (quadratic, $P < 0.1$) were observed in piglets fed the medium particle size of SBM, although, DFI was not affected by particle size (Table 3).

In phase 3 (44 to 63 d of age), the alteration of SBM particle size did not influence DFI ($P > 0.05$), but there was a marginally increased (quadratic, $P < 0.1$) on DWG and a linear improvement ($P < 0.05$) on F/G when increasing SBM particle size. When analyzing the overall period (23 to 63 d) DFI, DWG, F/G, and BW were affected (linear, $P<0.1$), as every 100 µm increase in SBM particle sizes led to an increased feed intake of 5.1 g and an average live weight gain of 189 g, and a 0.009 improvement on F/G. ALMEIDA et al. (2021) evaluated distinct particle sizes of pelleted feed for pigs and reported a notable impact on feed intake, where higher particle size linearly increased DFI; and consequently DWG. Similar results were observed by HEALY et al. (1994), who suggested that the ideal particle size for piglets increases as the pigs grow older.

Reducing the particle size of a feed or ingredient will increase the surface area exposed to digestive enzymes (HEALY et al., 1994), thus improving the digestibility of some dietary fractions (WONDRA et al., 1995; ALBAR et al., 2000; GUILLOU & LANDEAU, 2000; ROJAS & STEIN, 2015). In the current study, reducing SBM particle size marginally increased (linear, $P < 0.1$) DE; however, feeding diets containing different particle sizes did

Table 3 - Effect of soybean meal particle size on average daily feed intake (DFI), average daily weight gain (DWG), feed/gain ratio (F/G) and average body weight of piglets in the nursery phase.

Item	----------------------Soybean meal particle size[1]--------------------			SE	L[2]	Q[2]
	1,017 µm	585 µm	411 µm			
-----Phase 1, 23 to 32 days of age[3]-----						
DFI, g	229	218	214	6.6	0.149	0.412
DWG, g	165	155	139	10.0	0.059	0.852
F/G	1.424	1.446	1.566	0.081	0.018	0.849
-----Phase 2, 32 to 44 days of age[4]-----						
DFI, g	615	647	624	11.9	0.934	0.022
DWG, g	326	380	357	13.3	0.185	0.003
F/G	2.094	1.989	2.054	0.067	0.144	0.026
-----Overall period of phase 1 and 2, 23 to 44 days of age-----						
DFI, g	457	461	443	9.1	0.218	0.504
DWG, g	243	263	246	6.9	0.768	0.041
F/G	1.876	1.763	1.803	0.033	0.308	0.041
-----Phase 3, 44 to 63 days of age[5]-----						
DFI, g	1004	960	964	16.1	0.180	0.134
DWG, g	639	593	573	11.0	0.001	0.071
F/G	1.731	1.781	1.841	0.040	0.027	0.638
-----Overall period, 23 to 63 days of age-----						
DFI, g	715	698	684	9.4	0.036	0.496
DWG, g	430	420	401	8.3	0.011	0.855
F/G	1.662	1.662	1.716	0.027	0.091	0.610
-----Average body weight, kg-----						
32 days old	8.33	8.21	8.05	0.235	0.123	0.787
44 days old	11.90	12.42	12.00	0.283	0.895	0.052
63 days old	24.10	23.76	22.95	0.450	0.017	0.966

[1]Each treatment had seven replicates (five male and two female) of three pigs each.
[2]Linear (L) and quadratic (Q) effect for soybean particle size.
[3]Geometric mean diameter of the complete diets Phase 1 were: 543, 522 and 506 µm, respectively.
[4]Geometric mean diameter of the complete diets Phase 2 were: 730, 591 and 535 µm, respectively.
[5]Geometric mean diameter of the complete diets Phase 3 were: 864, 717 and 694 µm, respectively.

not influence (P > 0.05) the apparent digestibility coefficients of the DM and CP (Table 4).

The extent of the pigs' response to different dietary particle sizes on either performance or nutrient digestibility seems to depend on the raw materials selected as a tool to establish these different sizes. ALBAR et al. (2000) verified distinct responses in DM digestibility and energy when comparing two particle sizes of barley meal, corn, and pea; ALMEIDA et al. (2021) reported linear responses for DM and CP digestibility and a quadratic response for DE when working with different corn particle sizes. KAMPHUES et al. (2007) found that coarse particle size did not affect DM digestibility but had a positive effect on gut microbiota and gut health.

The use of diets with coarser particles (23.8% of particles >1000 µm or with a medium size >700 µm) will likely increase the amount of DM in the stomach and reduce transit time, eventually increasing the number of anaerobic bacteria and the production of short-chain fatty acids, mainly lactic acid (MIKKELSEN et al., 2004; CANIBE et al., 2005). Lactic acid bacteria can compete with other

Table 4 - Effect of soybean meal particle size on the apparent digestibility coefficients (ADC) of dry matter (DM) and crude protein (CP), and the digestible energy (DE) of piglets aged 49 to 53 days[3].

Item	-----------------Soybean meal particle size[1]--------------			SE	L[2]	Q[2]
	1,017 µm	585 µm	411 µm			
ADC of DM, %	76.13	76.89	77.17	0.60	0.151	0.414
ADC of CP, %	69.51	69.55	69.30	0.83	0.810	0.917
DE, kcal	3266	3326	3344	30.66	0.097	0.293

[1]Each treatment had seven replicates (five male and two female) of three pigs each.
[2]Linear (L) and quadratic (Q) effect for soybean particle size.
[3]Geometric mean diameter of the complete diets Phase 3 were: 864, 717 and 694 µm, respectively.

bacteria for nutrients and binding sites in the gut, and may increase the intestinal production of mucins and antioxidants and influence the immune system (YANG et al. 2015). The undissociated form of these acids can pass through the membrane of these bacteria; although, they dissociate inside them and reduce intracellular pH, resulting in cell death (RUSSELL & DIEZ-GONZALEZ, 1998). In other words, the gastric and intestinal conditions established by feeding coarse particles can be seen as an additional protective barrier against the transmission of undesirable anaerobic bacteria, such as *Salmonella* and *Escherichia coli* (KIARIE & MILLS, 2019). Therefore, diets with coarser SBM may have contributed to improved gut health of the piglets, which resulted in improved growth performance.

CONCLUSION

The results obtained in this study demonstrated that the particle size of soybean meal influences the growth of nursery piglets. Diets containing soybean meal with 585 µm particles were ideal during the first half of the nursery period, from 23 to 44 d of age. During the following period, from 44 to 63 d of age, diets containing unground soybean meal (average particle size of 1,017 µm) were optimal. However, considering the overall evaluation period, the grinding of soybean meal is not required for piglets during the nursery phase.

ACKNOWLEDGMENTS

This study was carried out with the support of the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - Funding Code 001.

BIOETHICS AND BIOSECURITY COMMITTEE APPROVAL

The experimental procedures involving animals were approved by the Animal Ethics Committee of the Universidade Federal do Paraná, Curitiba, Brazil.

DECLARATION OF CONFLICT OF INTERESTS

The authors declare no conflict of interest. Funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

All the authors contributed equally to designing and preparing the manuscript. All the authors critically reviewed and approved the final version of the manuscript.

REFERENCES

ALBAR, J. et al. Incidence de la granulométrie sur les performances en post-sevrage et la digestibilité de quatre aliments à base d ' orge, de blé, de maïs et de pois. **Journées de la Recherche Porcine en France**, v.32, p.193-200, 2000. Available from: <https://www.researchgate.net/publication/282320150_Incidence_de_la_granulometrie_sur_les_performances_en_post-sevrage_et_la_digestibilite_de_quatre_aliments_a_base_d%27orge _de_ble_de_mais_et_de_pois>. Accessed: Mar. 20, 2021.

ALMEIDA, L. M. et al. Effect of feed particle size in pelleted diets on growth performance and digestibility of weaning piglets. **Livestock Science**, v.244, p.104364, 2021. Available from: <https://doi.org/10.1016/j.livsci.2020.104364>. Accessed: Feb. 28, 2021. doi: 10.1016/j.livsci.2020.104364.

AOAC - Association of the Official Analitical Chemists. **Official and tentative methods of analysis**. 16.ed. Arlington, Virgina: AOAC Internacional, 1995.

BAO, Z. et al. Effect of particle size of wheat on nutrient digestibility, growth performance, and gut microbiota in growing pigs. **Livestock Science**, v.183, p.33–39, 2016. Available from: <https://doi.org/10.1016//j.livsci.2015.11.013>. Accessed: Mar. 20, 2021. doi: 10.1016/j.livsci.2015.11.013.

BARSZCZ, M.; SKOMIAŁ, J. The development of the small intestine of piglets - Chosen aspects. **Journal of Animal and Feed Science**, v.20, p.3–15, 2011. Available from: <https://doi.org/10.22358/jafs/66152/2011>. Accessed: Mar. 20, 2021. doi: 10.22358/jafs/66152/2011.

BATES, D. et al. Fitting linear mixed-effects models using lme4. **Journal of Statistical Software**, v.67, 2015. Available from: <https://doi.org/10.18637/jss.v067.i01>. Accessed: Jan. 20, 2021. doi: 10.18637/jss.v067.i01.

CANIBE, N. et al. Feed physical form and formic acid addition to the feed affect the gastrointestinal ecology and growth performance of growing pigs. **Journal of Animal Science**, v.83, p.1287–1302, 2005. Available from: <https://doi.org/10.2527/2005.8361287x>. Accessed: Mar. 23, 2021. doi: 10.2527/2005.8361287x.

GUILLOU, D.; LANDEAU, E. Granulométrie et nutrition procine. **INRA Productions Animales**, v.12, p.137–144, 2000. Available from: <https://doi.org/10.20870/productions-animales.2000.13.2.3775>. Accessed: Mar. 17, 2021. doi: 10.20870/productions-animales.2000.13.2.3775.

HEALY, B. J. et al. Optimum particle size of corn and hard and soft sorghum for nursery pigs. **Journal of Animal Science**, v.72, p.2227–2236, 1994. Available from: <https://doi.org/10.2527/1994.7292227x>. Accessed: Mar. 15, 2021. doi: 10.2527/1994.7292227x.

HEDEMANN, M. S.; JENSEN, B.B. Variations in enzyme activity in stomach and pancreatic tissue and digesta in piglets around weaning. **Archives of Animal Nutrition**, v.58, p.47–59, 2004. Available from: <https://doi.org/10.1080/00039420310001656677>. Accessed: Apr. 2, 2021. doi: 10.1080/00039420310001656677.

KAMPHUES, J. et al. Lower grinding intensity of cereals for dietetic effects in piglets? **Livestock Science**, v.109, p.132–134, 2007. Available from: <https://doi.org/10.1016/j.livsci.2007.01.120>. Accessed: Mar. 24, 2021 doi: 10.1016/j.livsci.2007.01.120.

KIARIE, E. G.; MILLS, A. Role of feed processing on gut health and function in pigs and poultry: conundrum of optimal particle size and hydrothermal regimens. **Frontiers in Veterinary Science**, v.6, p.1–13, 2019. Available from: <https://doi.org/10.3389/fvets.2019.00019>. Accessed: Apr. 01, 2021. doi: 10.3389/fvets.2019.00019.

LANCHEROS, J. P. et al. Effects of particle size reduction, pelleting, and extrusion on the nutritional value of ingredients and diets fed to pigs : A review. **Animal Feed Science and Technology**, v.268, p.114603, 2020. Available from: <https://doi.org/10.1016/j.anifeedsci.2020.114603>. Accessed: Mar. 15, 2021. doi: 10.1016/j.anifeedsci.2020.114603.

LAWRENCE, K. R. et al. Effects of soybean meal particle size on growth performance of nursery pigs. **Journal of Animal Science**, v.81, p.2118–2122, 2003. Available from: <https://doi.org/10.4148/2378-5977.6699>. Accessed: Aug. 15, 2020. doi: 10.4148/2378-5977.6699.

LUNDBLAD, K. K. et al. Effects of steam conditioning at low and high temperature, expander conditioning and extruder processing prior to pelleting on growth performance and nutrient digestibility in nursery pigs and broiler chickens. **Animal Feed Science and Technology**, v.169, p.208–217, 2011. Available from: <https://doi.org/10.1016/j.anifeedsci.2011.06.008>. Accessed: Mar. 16, 2021. doi: 10.1016/j.anifeedsci.2011.06.008.

MAVROMICHALIS, I. et al. Enzyme supplementation and particle size of wheat in diets for nursery and finishing pigs. **Journal of Animal Science**, v.78, p.3086–3095, 2000. Available from: <https://doi.org/10.2527/2000.78123086x>. Accessed: Mar. 14, 2021. doi: 10.2527/2000.78123086X.

MIKKELSEN, L. L. et al. Effects of physical properties of feed on microbial ecology and survival of Salmonella enterica serovar typhimurium in the pig gastrointestinal tract. **Applied and Environmental Microbiology**, v.70, p.3485–3492, 2004. Available from: <https://doi.org/10.1128/AEM.70.6.3485-3492.2004>. Accessed: Mar. 22, 2021. doi: 10.1128/AEM.70.6.3485-3492.2004.

MODINA, S.C. et al. Nutritional regulation of gut barrier integrity in weaning piglets. **Animals**, v.9, p.1–15, 2019. Available from: <https://doi.org/10.3390/ani9121045>. Accessed: Apr. 03, 2021. doi: 10.3390/ani9121045.

MONTAGNE, L. et al. Main intestinal markers associated with the changes in gut architecture and function in piglets after weaning. **British Journal of Nutrition**, v.97, p.45–57, 2007. Available from: <https://doi.org/10.1017/S000711450720580X>. Accessed: Apr. 04, 2021. doi: 10.1017/S000711450720580X.

R CORE TEAM. **R:** A language and environment for statistical computing. R Foundation for Statistical Computing, 2018.

ROJAS, O. J.; STEIN, H.H. Effects of reducing the particle size of corn grain on the concentration of digestible and metabolizable energy and on the digestibility of energy and nutrients in corn grain fed to growing pigs. **Livestock Science**, v.181, p.187–193, 2015. Available from: <https://doi.org/10.1016/j.livsci.2015.09.013>. Accessed: Mar. 17, 2021 doi: 10.1016/j.livsci.2015.09.013.

ROJAS, O. J.; STEIN, H.H. Processing of ingredients and diets and effects on nutritional value for pigs. **Journal of Animal Science and Biotechnology**, v.8, p.1–13, 2017. Available from: <https://doi.org/10.1186/s40104-017-0177-1>. Accessed: Mar. 14, 2021. doi: 10.1186/s40104-017-0177-1.

RUSSELL, J. B.; DIEZ-GONZALEZ, F. The effects of fermentation acids on bacterial growth. **Advances in Microbiology Physiology**, v.39, p.228–234, 1998. Available from: <https://doi.org/10.1016/s0065-2911(08)60017-x>. Accessed: Apr. 03, 2021. doi: 10.1016/s0065-2911(08)60017-x.

STEIN, H.H. et al. **Nutrional value of soy products fed to pigs**. Swine Focus #004, IIinois, 2013.

VAN KEULEN, J.; YOUNG, B.A. Evaluation of acid-insoluble ash as a natural marker in ruminant digestibility studies. **Journal of Animal Science**, v.44, p.282–287, 1977. Available from: <https://doi.org/10.2527/jas1977.442282x>. Accessed: Mar. 05, 2021. doi:10.2527/jas1977.442282x.

WONDRA, K. J. et al. Effects of particle size and pelleting on growth performance, nutrient digestibility, and stomach morphology in finishing pigs. **Journal of Animal Science**, v.73, p.757–763, 1995. Available from: <https://doi.org/10.2527/1995.733757x>. Accessed: Mar. 05, 2021. doi: 10.2527/1995.733757x.

YANG, F. et al. The use of lactic acid bacteria as a probiotic in swine diets. **Pathogens**. v.4, p.34–45, 2015. Available from: <https://doi.org/10.3390/pathogens4010034>. Accessed: Apr. 04, 2021. doi: 10.3390/pathogens4010034.

ZANOTTO, D. L.; BELLAVER, C. Método de determinação da granulometria de ingredientes para uso em rações de suínos e aves. **Embrapa Comunicado Técnico**, p.1–5, 1996.